The Phenomenology of E_6-inspired SUSY GUTs

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Exceptional Supersymmetric Models - Motivation

Properties of E_6 Unification with intermediate G_{32211} Symmetry

LHC Phenomenology with WHIZARD - Leptoquarks and Leptoquarkinos

Ongoing Work and Conclusion

Bottom-Up: Improving the MSSM

The MSSM solves the $m_{EW} \ll \Lambda_P$ stability problem, but...

- No superpartners observed yet, $m_{SUSY} > m_{EW}$, $m_H > 114$ GeV
- CDM Relic Densities generally too large

Fine tuning at percent level

- Why is $\mu \ll \Lambda_P$?

Stable under quantum correction, but why so small?

Solution: extending the MSSM with extra $U(1)'$ and Singlet

- μ-Term from $\langle S \rangle H_u H_d$
- s Potential from $U(1)'$ D-Term
- larger Higgs masses natural
- no S^3 term, no EW Domain Walls

An E_6 inspired extra $U(1)$

Wishlist for $U(1)'$ charge assignments in descending importance:

- anomaly free
- compatible with MSSM potential
- compatible with Leptogenesis (ν^c Masses)
- generation-independent (FCNCs)

E_6 inspired candidate

$$U(1)' \in U(1)_R \times U(1)_{B-L} \times U(1)_\chi \in E_6!$$

Anomaly cancellation $\Rightarrow$ E_6-like spectrum at TeV scale!

Different varieties - ESSM, E_6SSM,PSSSM etc.

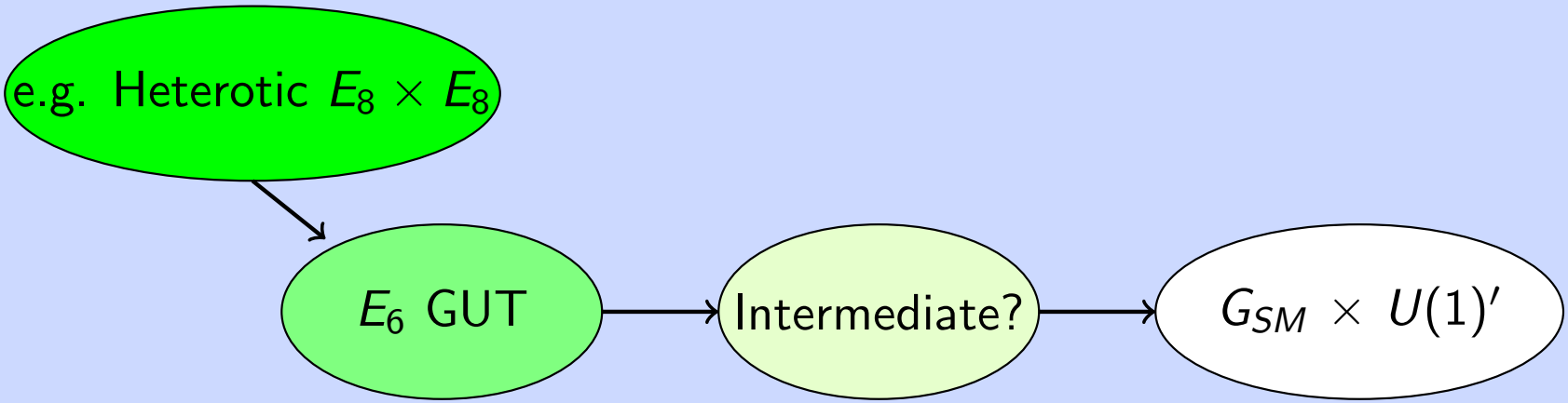
[Reuter, Kilian '06],[King et al '06],[Howl et al '07], ...

Decomposition of the fundamental 27

	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_\chi$	$U(1)'$
$\hat{Q}$	$\mathbf{3}$	$\mathbf{2}$	1/3	1/2	Q'_Q
$\hat{u}^c$	$\bar{\mathbf{3}}$	$\mathbf{1}$	-4/3	1/2	Q'_u
$\hat{d}^c$	$\bar{\mathbf{3}}$	$\mathbf{1}$	2/3	1/2	Q'_d
$\hat{L}$	$\mathbf{1}$	$\mathbf{2}$	-1	1/2	Q'_L
$\hat{e}^c$	$\mathbf{1}$	$\mathbf{1}$	2	1/2	Q'_e
$\hat{H}^u$	$\mathbf{1}$	$\mathbf{2}$	1	-1	Q'_{H^u}
$\hat{H}^d$	$\mathbf{1}$	$\mathbf{2}$	-1	-1	Q'_{H^d}
$\hat{D}$	$\mathbf{3}$	$\mathbf{1}$	-2/3	-1	Q'_D
$\hat{D}^c$	$\bar{\mathbf{3}}$	$\mathbf{1}$	2/3	-1	Q'_{D^c}
$\hat{\nu}^c$	$\mathbf{1}$	$\mathbf{1}$	0	1/2	$Q'_{\nu^c} = 0$
$\hat{S}$	$\mathbf{1}$	$\mathbf{1}$	0	2	Q'_S

- Particle content per generation
- $U(1)'$ charges Q' are non-rational and scheme-dependent!

Top-Down: E_6 Unification



Challenge of E_6 GUTs with light exotics: Proton Decay!
Renormalizable Superpotential is unique:

$$\mathcal{W} \sim \mathbf{27}^3 \qquad \text{breaks B via TLQ + TQQ}$$

The full E_6 potential $\mathbf{27}^3$ is too restrictive! - Use incomplete irreps - justification?

E_6 Breaking

Breaking E_6 to G_{4221} or G_{32211} by Higgs

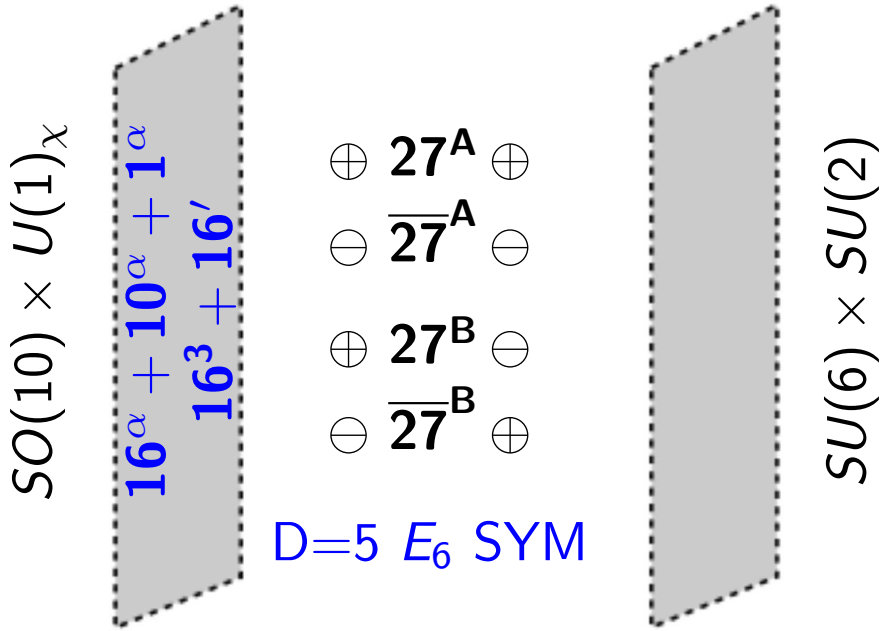
- Smallest viable VEV: $\langle \mathbf{650} \rangle$ or $\langle \mathbf{78} \rangle$ respectively. Alternatively: $\langle \mathbf{27}\,\overline{\mathbf{27}} \rangle$
- generating a B-Conserving superpotential is difficult!
- Can try to generate $\mathcal{W}_{eff} \subset \mathbf{27^3}$ from $\frac{1}{\Lambda}\langle \mathbf{650} \rangle \times \mathbf{27} \times \mathbf{27} \times \mathbf{27}$
- Stable?

Maybe the most natural solution: breaking E_6 on an Orbifold!

- E_6 can always be made anomaly free in $D \leq 6$
- $E_6 \longrightarrow G_{4221}$ works in D=5
- $E_6 \longrightarrow G_{32211}$ requires D=6

A Simple Orbifold for the intermediate G_{4221} Model

- Minimal Setup on a $S^1/\mathbb{Z}_2\times\mathbb{Z}_2'$ Orbifold: Higgs in the Bulk



Light Bulk Particle Content: T, T^c from $\mathbf{27^A}$ + H_u, H_d, S from $\mathbf{27^B}$ $\sim$ $\mathbf{10+1}$

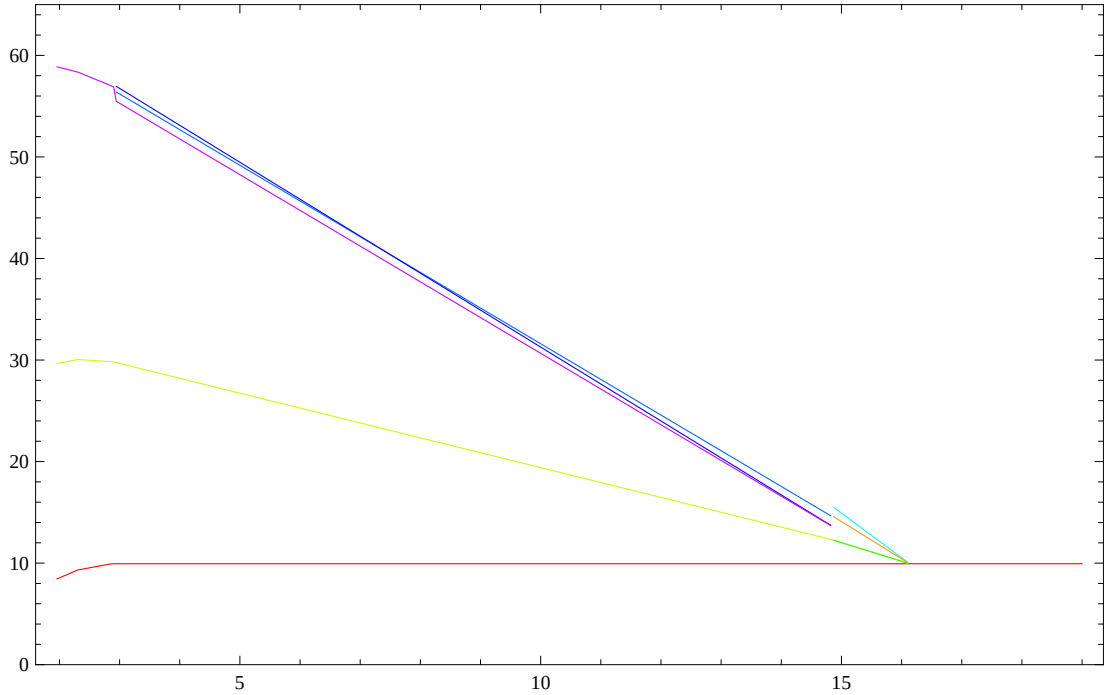
B-Conserving SP: $\mathcal{W} \sim \delta(y)\left(\mathbf{10^B 16^i 16^j} + \mathbf{1^B 10^A 10^A} + \mathbf{1^B 10^B 10^B} + \mathbf{1^\alpha 10^\beta 10^B}\right)$

Lepto-Diquark SP: $\mathcal{W} \sim \delta(y)\left(\mathbf{10^A 16^i 16^j}\right)$: must be suppressed $\approx 10^{-7}$

- G_{32211} in $T^2/\mathbb{Z}_6$ more intricate!

Unification

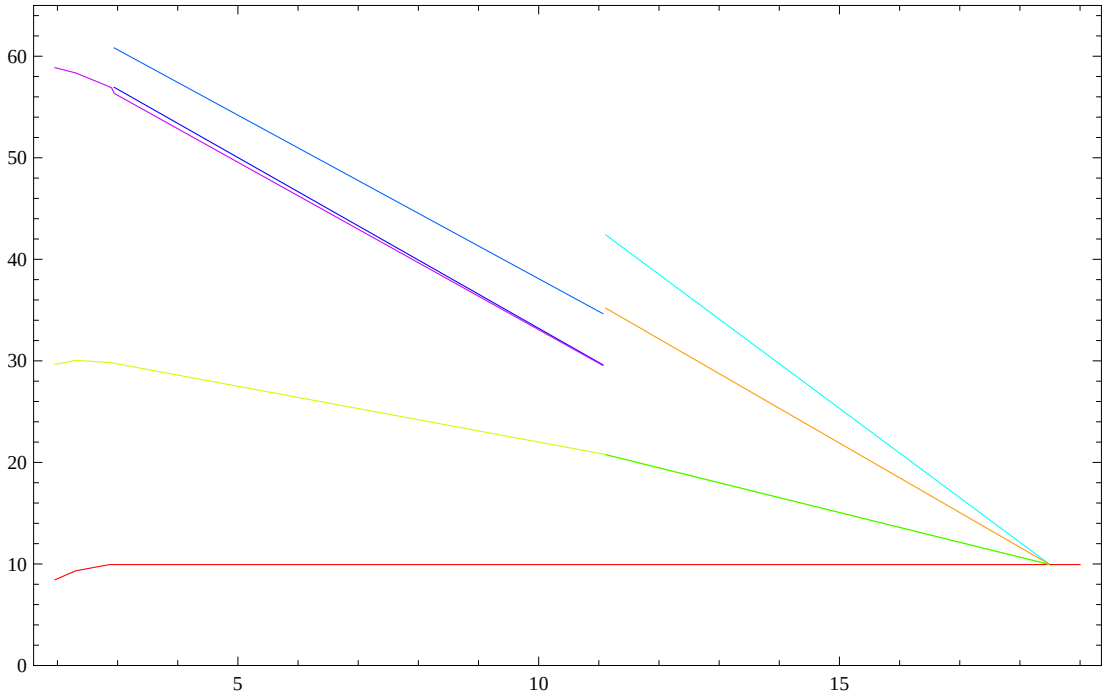
1) Two extra vectorlike Higgs doublets $\Rightarrow$ three complete extra $5 + \overline{5}$, $\Lambda_I \sim \Lambda_{E6}$



- Intermediate Breaking with $\langle \tilde{\nu}'_R \rangle$ from incomplete multiplet (generates seesaw scale).
- $\alpha_s \sim$ const at 1-Loop, $\alpha_{E6} \sim 0.1$
- No justification for light extra doublets in terms of symmetries...

Unification

2) Two step unification with intermediate G_{32211}, $\Lambda_I \ll \Lambda_{E6}$



- Scheme in principle observable at TeV scale (Q', g')
- For a prediction of unification scheme need to know threshold corrections!
- But: will be absorbed in a change of Λ_I.

Leptoquarks and Leptoquarkinos

Important difference to intermediate G_{4221} Model

- Lepto-Diquark interactions now two separate singlets
  Non-suppressed Leptoquark interactions at the TeV scale!
- No problem with stable color-charged exotics
- Interesting additional phenomenology
  Scalar Leptoquarks + Fermionic Leptoquarkinos!

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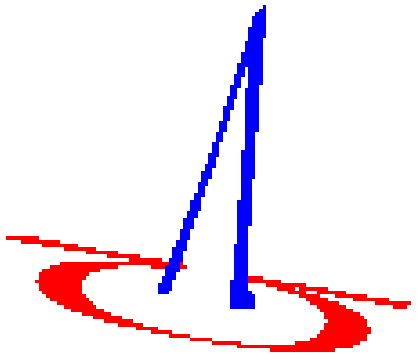
LHC Phenomenology with WHIZARD - Leptoquarks and Leptoquarkinos

Ongoing Work and Conclusion

WHIZARD

Simulation & Event generation with WHIZARD 1.93:

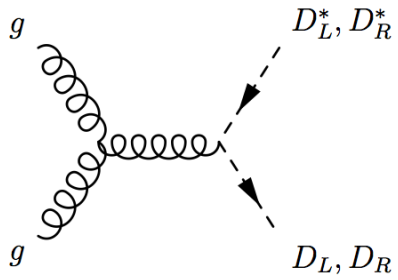
- Calculation and implementation of feynman rules for Leptoquarks and Leptoquarkinos into WHIZARD / O'Mega
- Crosschecked: numerical cross sections in agreement with eariler studies
  Kramer, Plehn, Spira, Zerwas; PRD71:057503
- Generation and analysis of events for the production and decay of the exotics
- *new* version **2.03** is available!

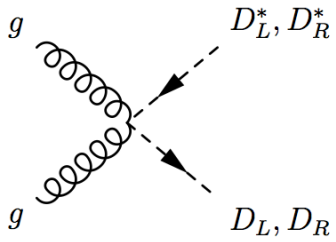


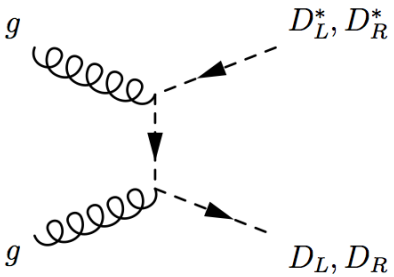
http://whizard.event-generator.org

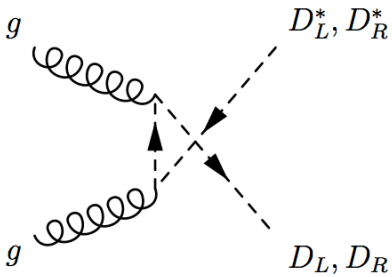
Production of scalars

gluon fusion:

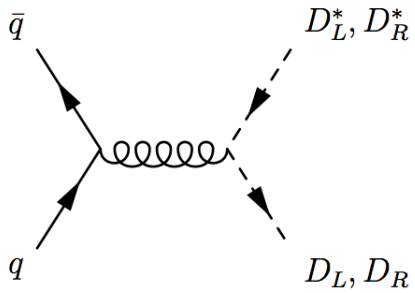




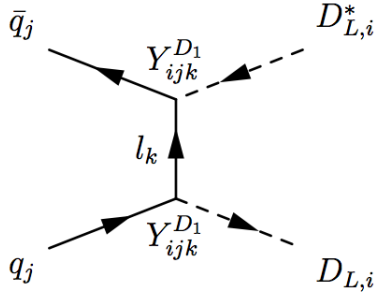




$q\bar{q}$ annihilation:

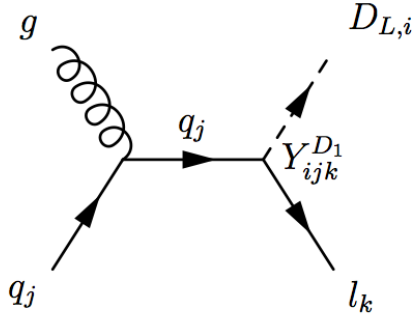


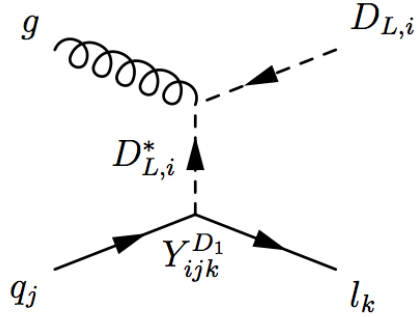
(a)



(b)

gq fusion:

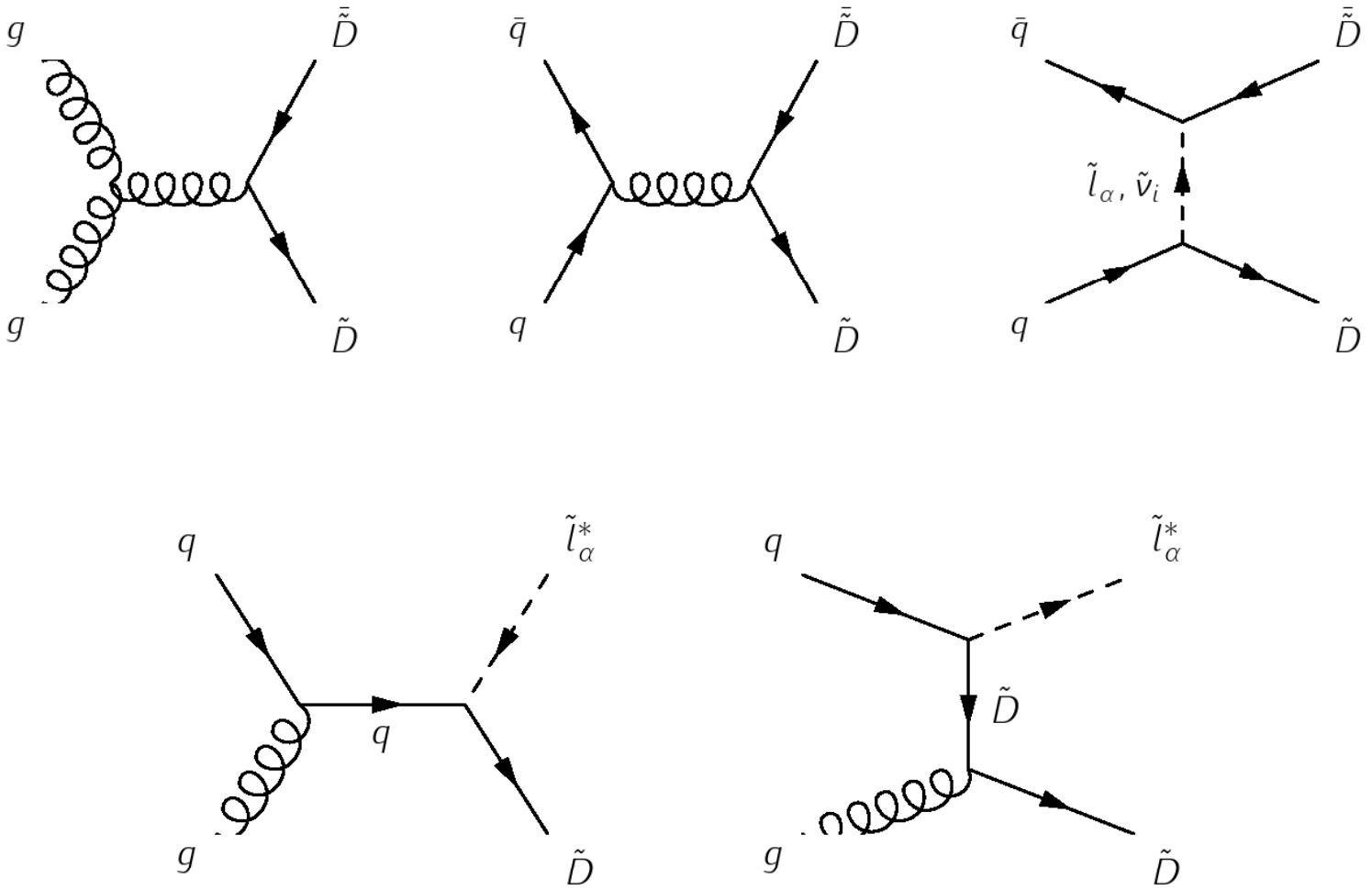




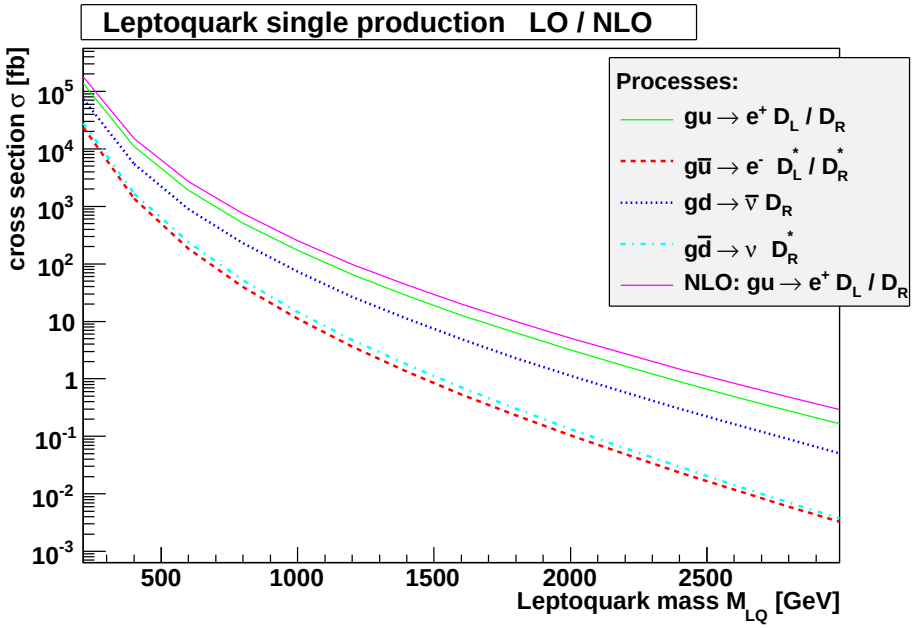
Note: gluon fusion independent of Yukawa coupling Y^{D_i}

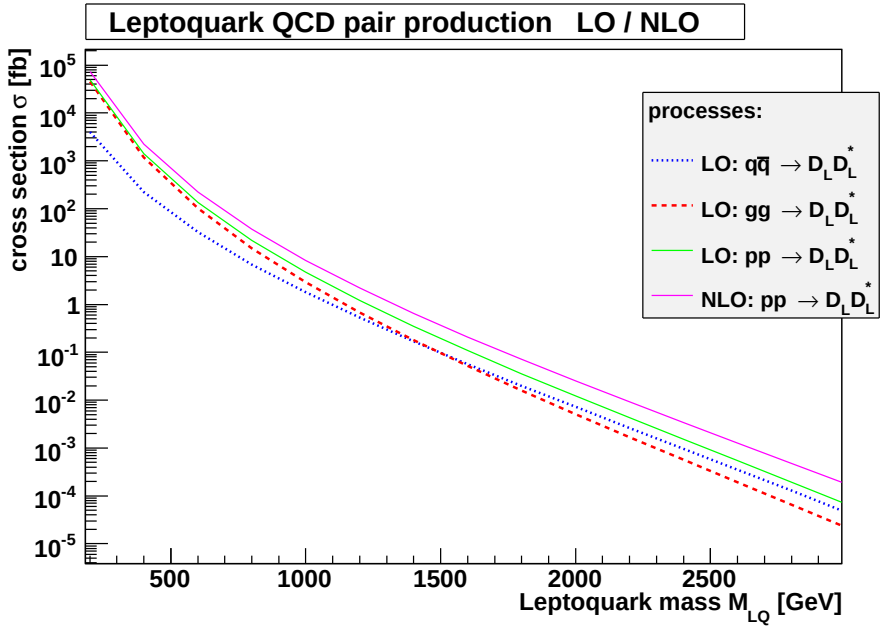
Production of fermions

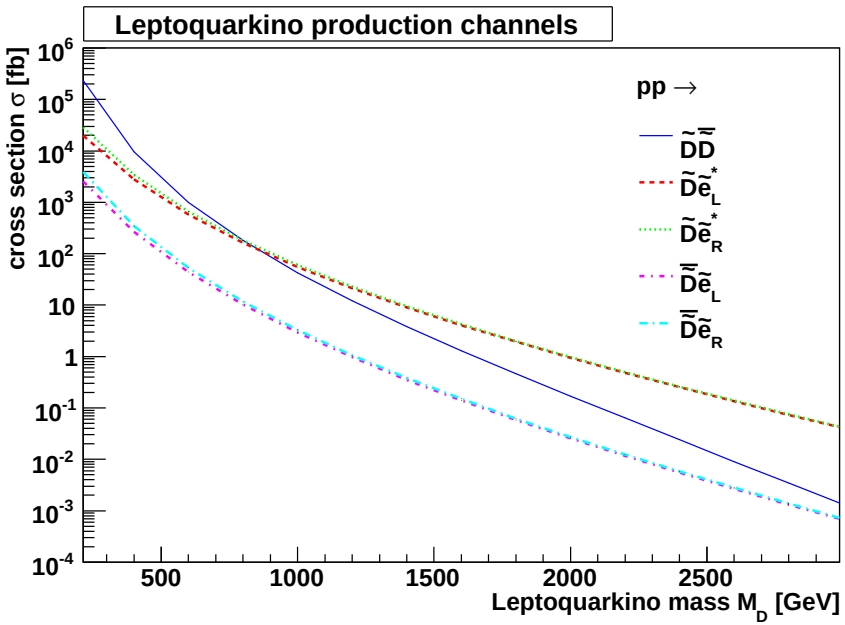
Leptoquarkino production just supersymmetrized variants of the scalar diagrams, e.g.:



Results: cross sections



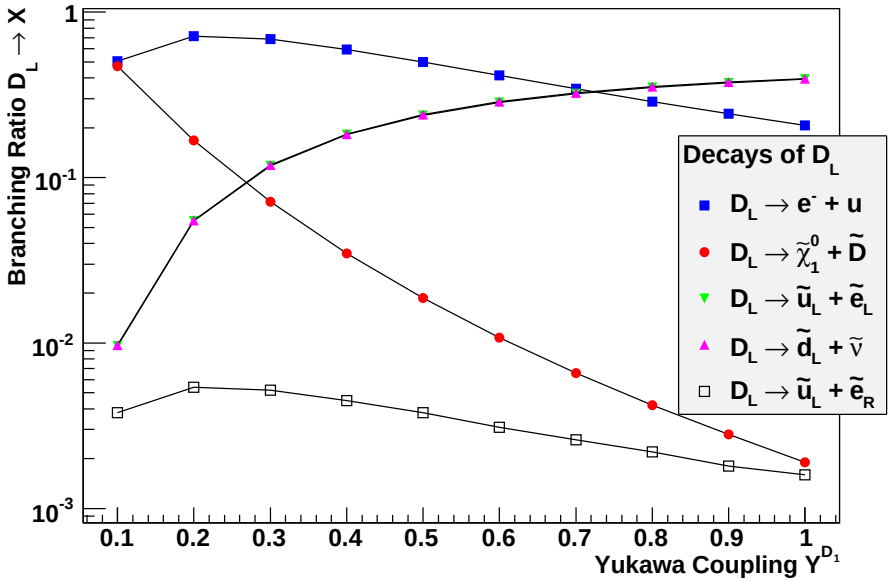


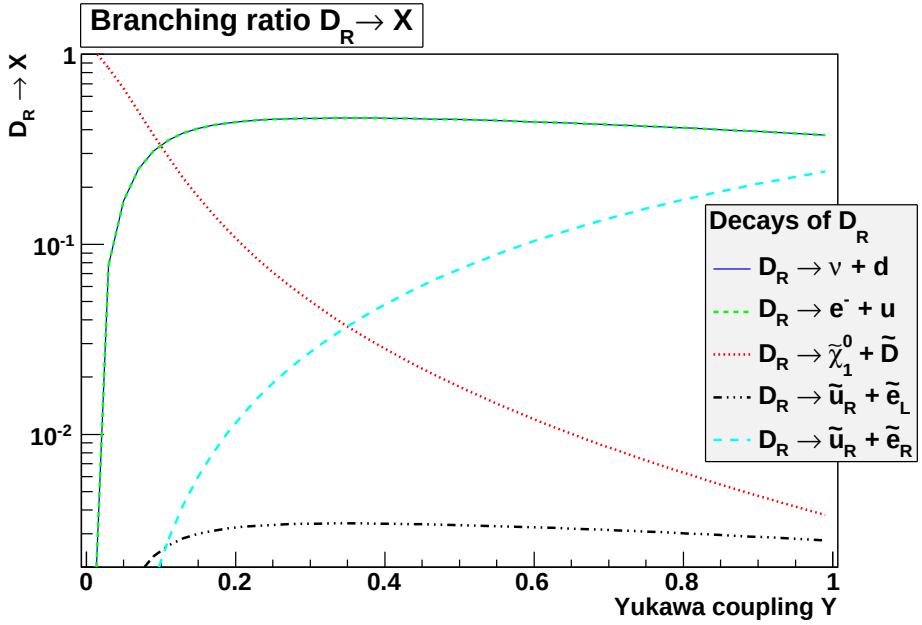


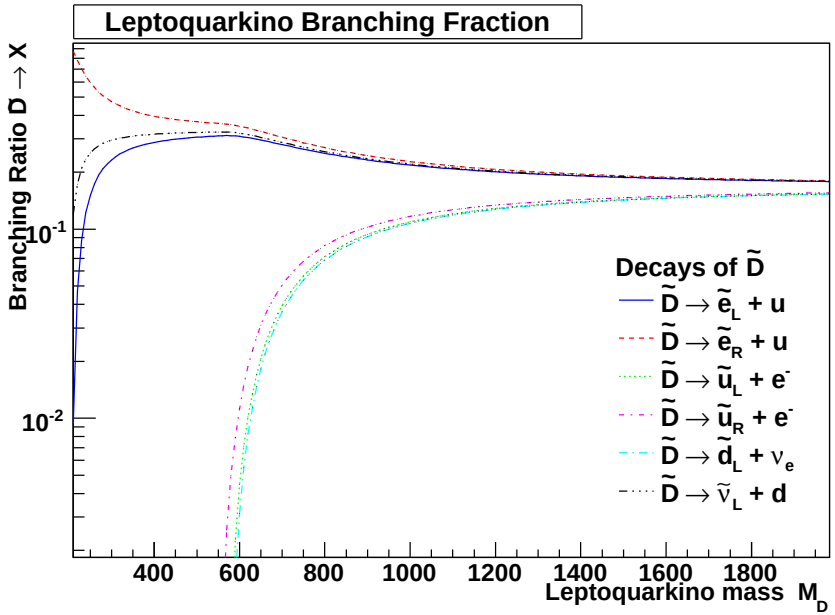
$\sqrt{s} = 14$ TeV, CTEQ6L1, $Y^D = 0.312$

- cross-sections ranging from 10^{-1} fb to 10^1 pb
- LHC mass reach: $1.5 - 2$ TeV (dep. on Y^D)

Results: branching ratios





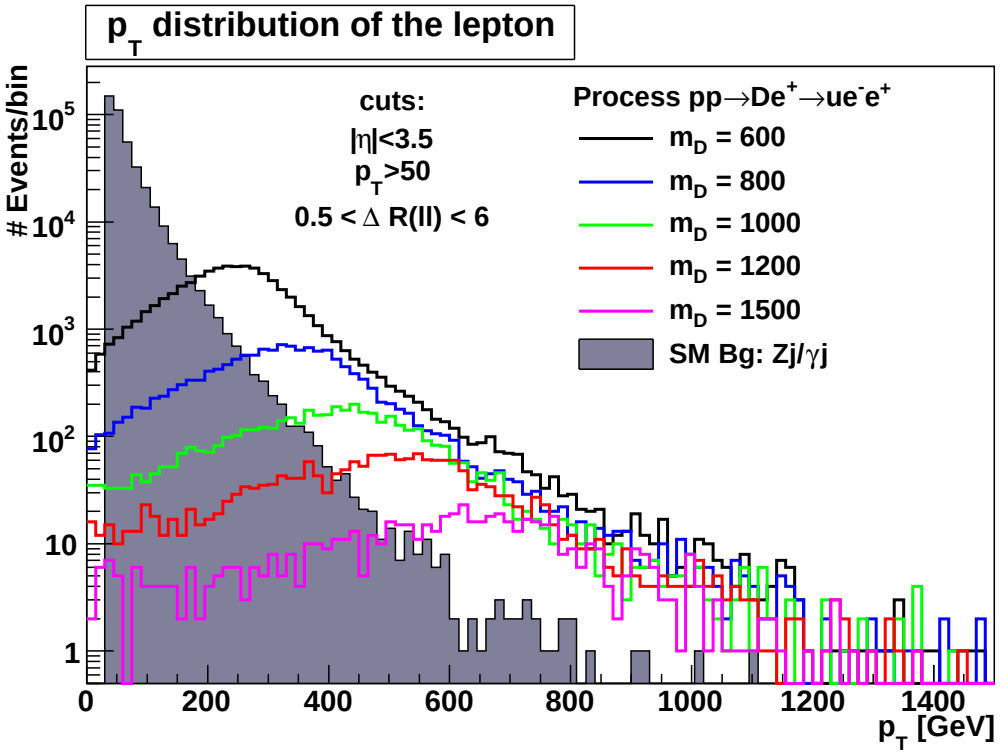


$M_{D_{L/R}} = 1$ TeV, $M_{\tilde{D}=0.6}$ TeV

- one decay independent of Y^D: $D_{L/R} \to \tilde{\chi}_i^0 \tilde{D}$
- at our point of investigation: dominating decay into SM fermions

p_T distribution and significance estimates

Example: $pp \to D_L e^+ + X \to e^+ e^- u + X$
where the Background mainly consists of $Z + j$.

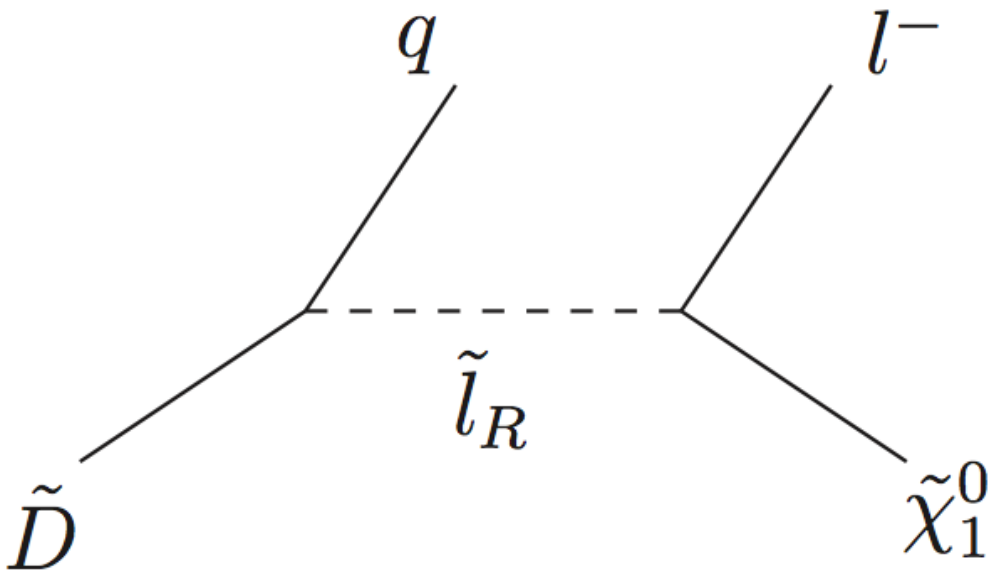


cuts		Background	$m_D = 0.6$ TeV		$m_D = 0.8$ TeV		$m_D = 1.0$ TeV	
p_T	$M_{inv}(ll)$	N_{BG}	N_1	$S_1/\sqrt{B}$	N_2	$S_2/\sqrt{B}$	N_3	$S_3/\sqrt{B}$
50	-	917441	64034	**64**	16081	**17**	5205	**5**
100	150	5031	45295	**202**	12883	**96**	4426	**45**
150	150	1012	29281	**168**	9615	**93**	3657	**54**

Setup: $\int \mathcal{L} = 100$ fb^{-1}, $\sqrt{s} = 14$ TeV and $Y^{D_1} = Y^{D_c} = 0.312 \approx e$. PDF's: CTEQ6L1

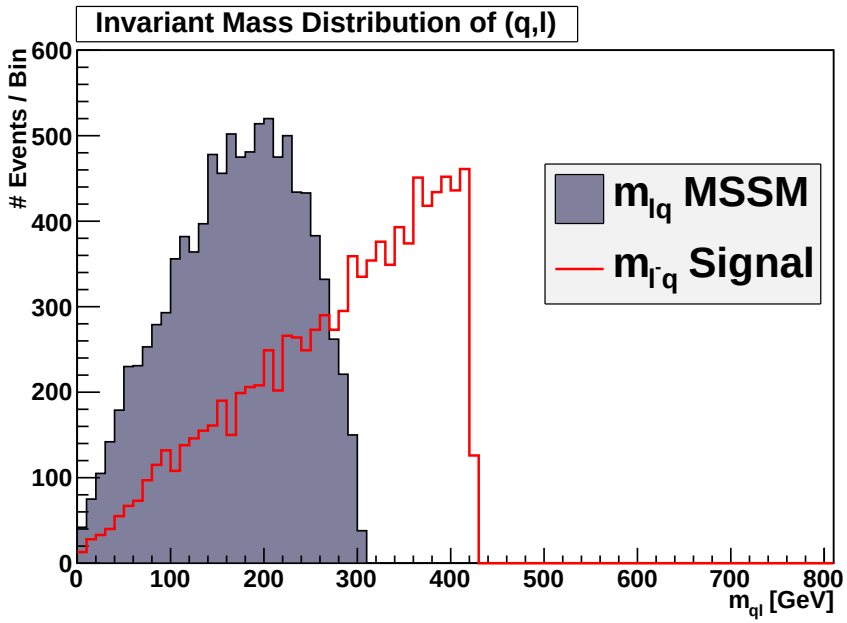
Fermionic analysis

- LQino is R-odd: Cascades!
- Kinematic endpoint of $M_{ql} \sim$ Dilepton edge!



Fermionic analysis - 3

- Direct observation of M_{lq} would yield:

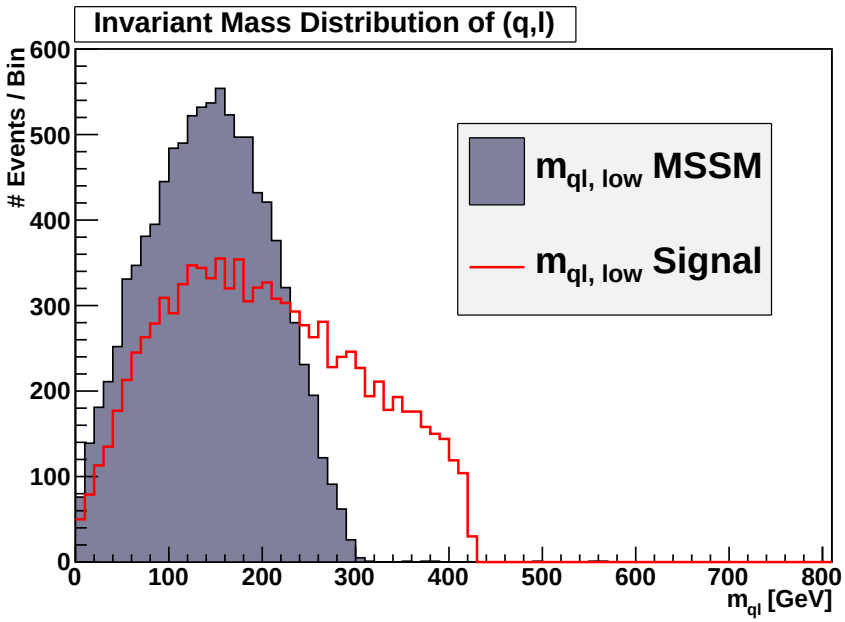


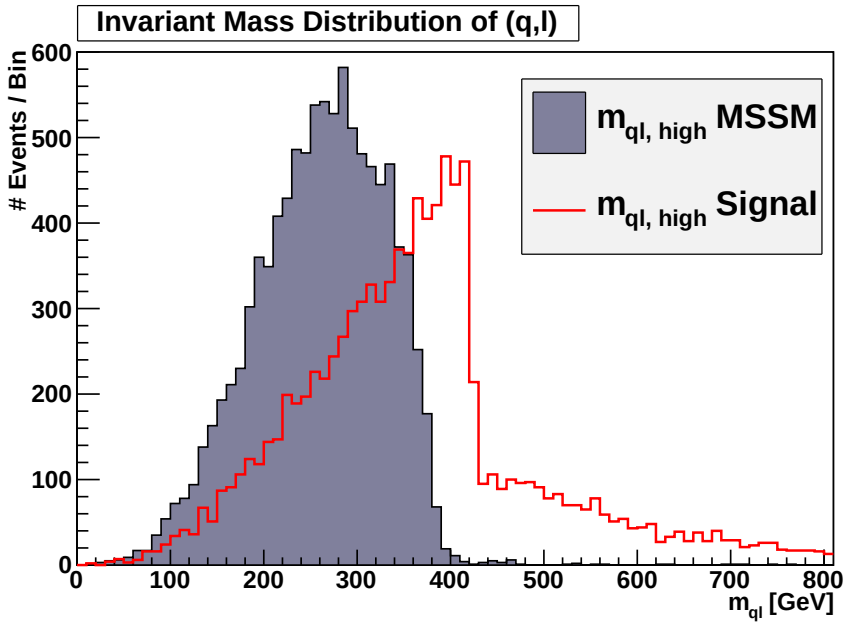
- Unfortunately we're not able to tell which lepton is involved, thus use $M_{ql,high}$ and $M_{ql,low}$ instead:

$$M_{ql,high} = \max\{M_{ql^+}, M_{ql^-}\}$$
$$M_{ql,low} = \min\{M_{ql^+}, M_{ql^-}\}$$

Fermionic analysis - 4

- The resulting spectra show strong deviations from typical SUSY edges
- and may hint towards the intermediate on-shell particle as well as it's origin





all figures calculated using SPS1a as well as an adapted SPS1a version

Summary

- E_6 inspired models are an interesting, testable MSSM alternative
- Embedding such models in E_6 or strings is challenging
- New: intermediate LR symmetry
- Leptoquarks and Leptoquarkinos offer characteristic signatures

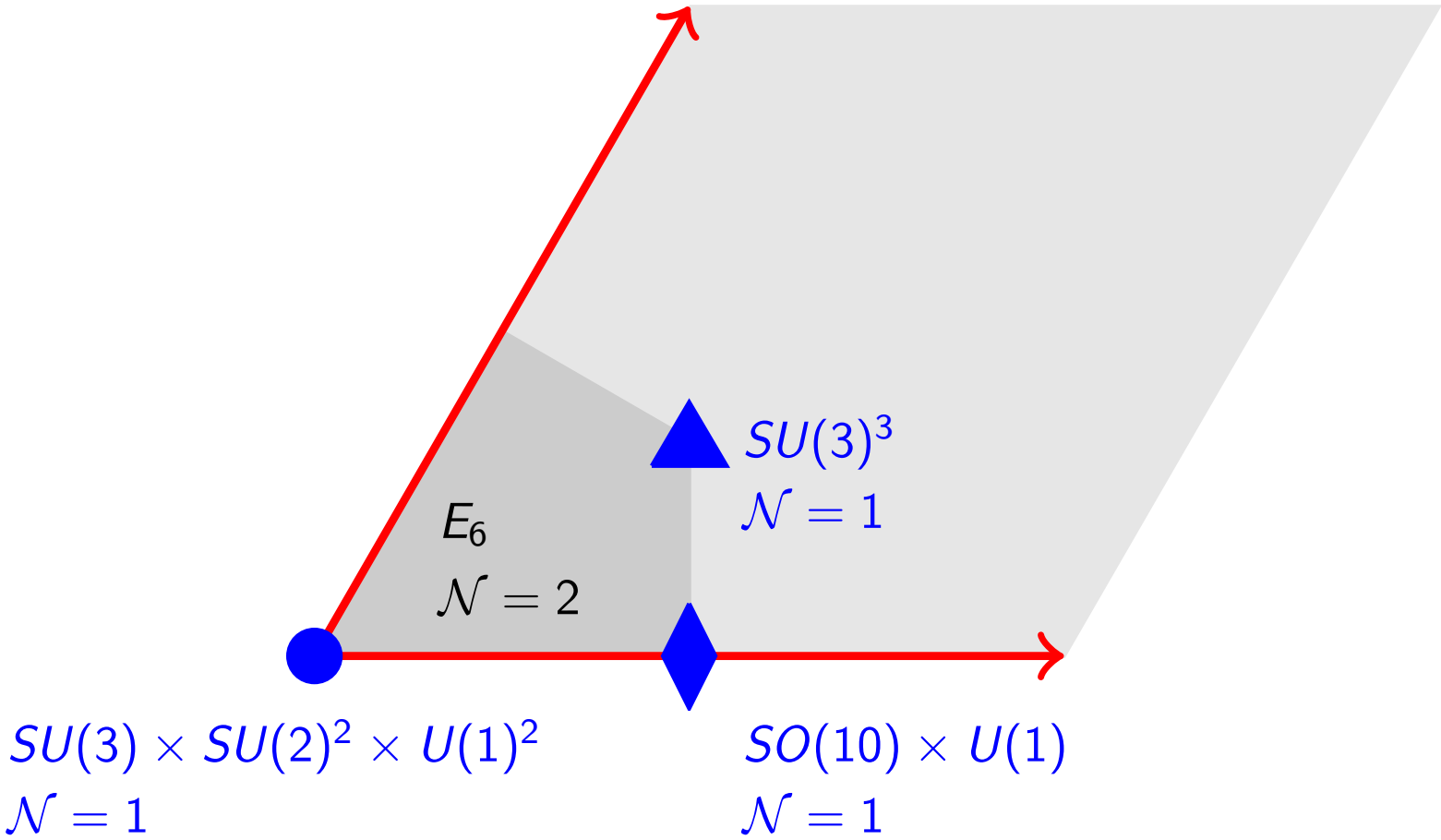
Current Activities

- Thorough study of spectra and phenomenology of intermediate LR model
- Phenomenology of non-Higgs exotics (in collaboration with Siegen group)

Talks on related issues: P.Athron (now), R. Nevzorov (thu), J. Hall (fri)

Thank You for Your Attention!

Not possible in D=5! Need $T^2/\mathbb{Z}_6$ Orbifold



Chiral matter from bulk chiral gauge component $\rightarrow$ more intricate 4D/Brane anomaly cancellation...