Exceptional Unification and intermediate Symmetries

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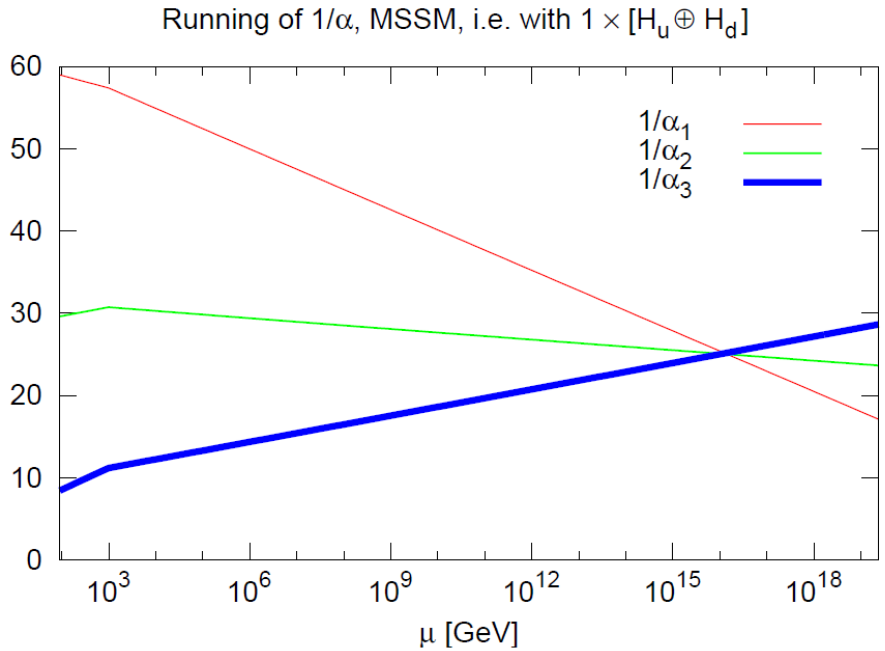
Partly based on:

F. Braam, AK, J. Reuter, arXiv:1001.4074 [hep-ph]

Grand Unification

Why do we study GUTs?

- Gauge couplings approach each other (MSSM: meet) at high energies



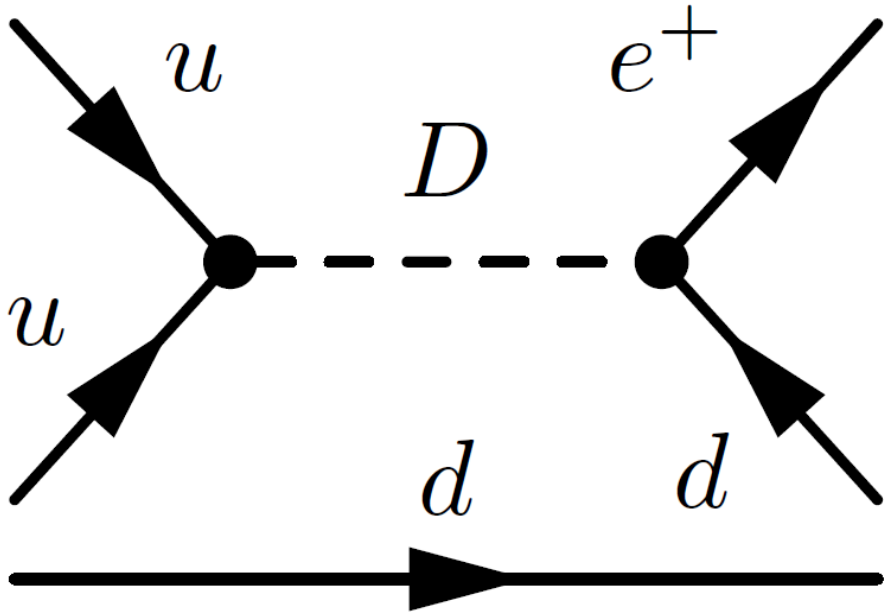
- SM particles fit into smallest representations of **simple** groups

$SU(5)$:	$d^c, L_L = \mathbf{5}, Q_L, u^c, e^c = \mathbf{10}, \nu^c = \mathbf{1} \quad H^u, H^d \in \mathbf{5} + \overline{\mathbf{5}}$
$SO(10)$:	$d^c, L_L, Q_L, u^c, e^c, \nu^c = \mathbf{16}, \quad H^u, H^d \in \mathbf{10}$

- Charge quantization...

Higgs Triplets and Proton Decay

The $\mathbf{5} + \overline{\mathbf{5}}$ also contain color charged exotics D, D^c.
Higgs coupling in $\mathcal{W}$: $\overline{\mathbf{5}}\,\mathbf{10}\,\overline{\mathbf{5}} + \mathbf{5}\,\mathbf{10}\,\mathbf{10}$



- Exotics spoil unification, proton decays!
- Strong constraint, need Higgs doublet-triplet splitting to suppress PD, still no observation
- PD the only experimental signature of unification?

If new exotic matter not fitting into MSSM is found e.g. at LHC

- An unexpected chance: study Grand Unification at the Collider?
- E_6 inspired models

E_6 and Higgs-Matter Unification

- E_6 is contained in $E_8 \times E_8$ ocurring in heterotic compactifications
- Contains standard groups

$$SU(5) \subset SO(10) \subset E_6$$

- Matter and Higgs in the fundamental

$$\underbrace{10, \overline{5}, 1}_{\textbf{Matter}} + \underbrace{5, \overline{5}}_{\textbf{Higgs}} \subset \underbrace{16}_{\textbf{Matter}} + \underbrace{10}_{\textbf{Higgs}} + \underbrace{1}_{\textbf{NMSSM}} = \mathbf{27}$$

- NMSSM-Like SM Singlets!
- Higgs-likes in every generation!
  Doublet-Triplet-splitting $\longrightarrow$ Doublet-Triplet-Decouplet splitting?

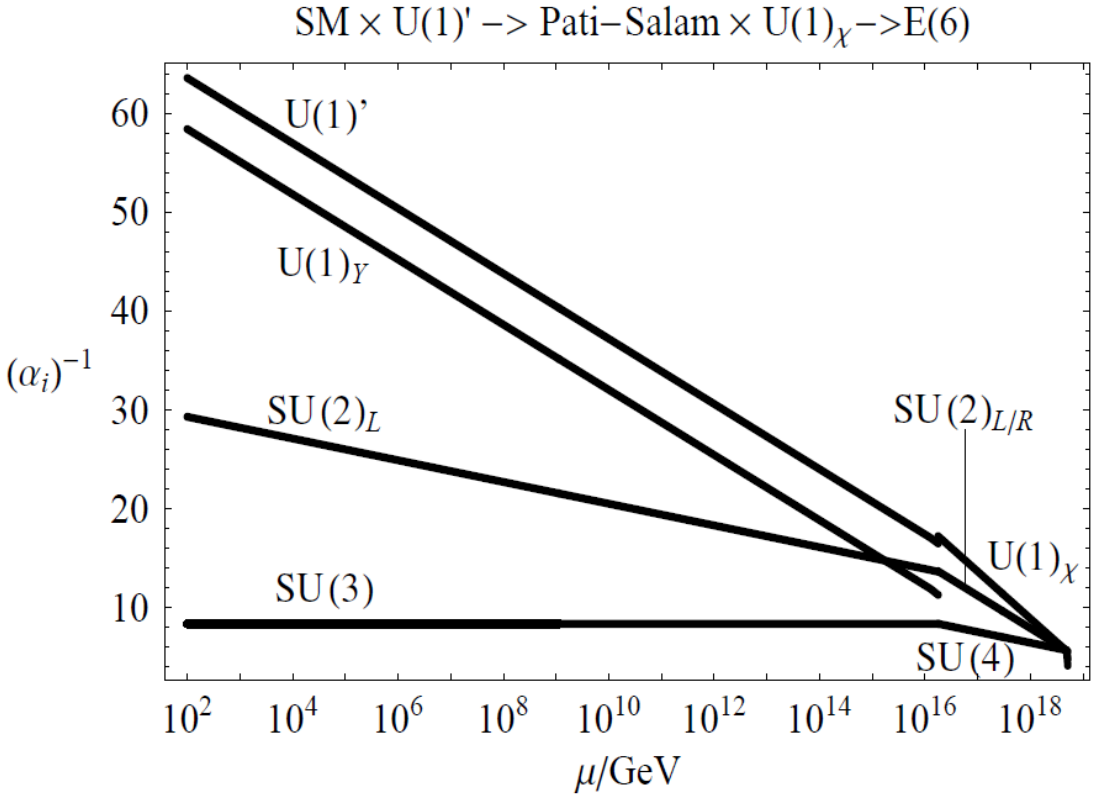
Exceptional Supersymmetric Standard Models

Recent Proposal (Reuter, Kilian '06)(King et al '06):

1. Postulate unknown E_6 breaking mechanism to intermediate symmetry,

$$\text{e.g. } E_6 \longrightarrow SU(4)_C \times SU(2)_L \times SU(2)_R \times U(1)_\chi$$

2. Keep all E_6 d.o.f. (apart from ν^c) at low energies (extra $U(1)$)



- Intermediate breaking restores unification
- Planck scale unification possible
- Phenomenological superpotential **subset of full E_6 potential**

The E_6 Superpotential

What is the most general renormalizable superpotential for **27** Matter?

$$\mathcal{W} = \mathbf{27} \otimes \mathbf{27} \otimes \mathbf{27}$$

This includes:

$$\mathbf{27}^3 \sim \underbrace{SH_uH_d}_{\mu\text{ Term}} + \underbrace{STT^c}_{\text{Mass}} + \underbrace{HQ_LQ_R + HL_LL_R}_{\text{Matter Mass}}$$

$$+ \underbrace{T^cQ_LL_L + TQ_RL_R}_{\text{Leptoquark}} + \underbrace{TQ_LQ_L + T^cQ_RQ_R}_{\text{Diquark!}}$$

- Proton decay, **either LQ or DQ terms have to go...**
- FCNCs from extra Higgs multiplets: $\mathbb{Z}_2$ **H Parity**

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Baryon and H Parities not compatible with E_6 potential

$\mathcal{W}_{ESSM}$ strongly affected/generated in E_6 breaking

- Proton decay, **either LQ or DQ terms have to go...**
- FCNCs from extra Higgs multiplets, **$\mathbb{Z}_2$ H Parity**

E_6 breaking $\longrightarrow$ LHC pheno

Low Energy/Collider Phenomenology (King et al.)

- NMSSM-like Model, but

  $$\text{no } \mathcal{W} \sim S^3 \longrightarrow \text{D-Term Potential from } U(1)'$$

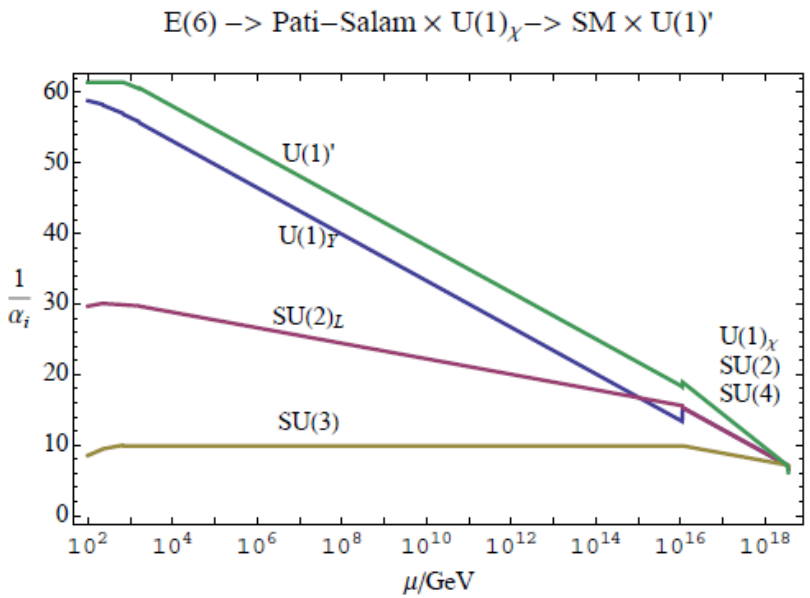
  otherwise, domain walls $\rightarrow$ nonrenorm. $\mathbb{Z}_3$ violating operators
- ν^c masses from D=5 operators at intermediate breaking
- Strong constraints from $Z - Z'$ mixing,

  $$\langle S_3 \rangle \gtrsim 1.5 \text{ TeV}, \quad m_{Z'} \gtrsim 600 \text{ GeV (King et al, '07)}$$

- 6 standard neutralinos: $\tilde{H}, \tilde{h}, \tilde{\chi}_0^1, \tilde{\chi}_0^2, \tilde{S}_3, \tilde{B}'$
- **H**-odd un-higgs(inos): $\tilde{H}_{1,2}, \tilde{h}_{1,2}, \tilde{S}_{1,2}$; mass from $S_3 H_i H_j + S_i H_j H_3$
- Vanishing 1-loop QCD β function!
  gluino tends to be light in sugra models (cE_6SSM, King et al, '08)
- Two parities, complex DM structure possible!

E_6-inspired Leptoquarks (Braam, Reuter, Wiesler '09)

Assume vanishing DQ couplings + large LQ couplings

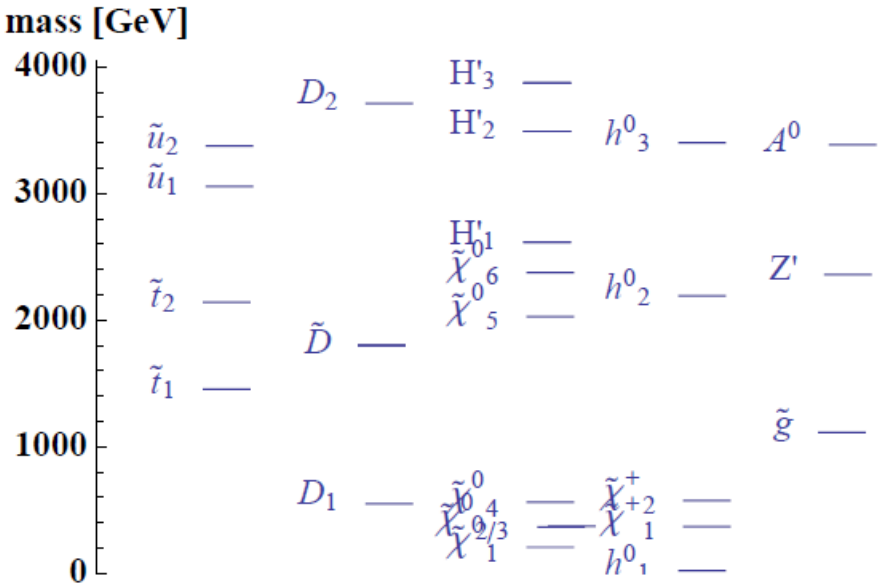


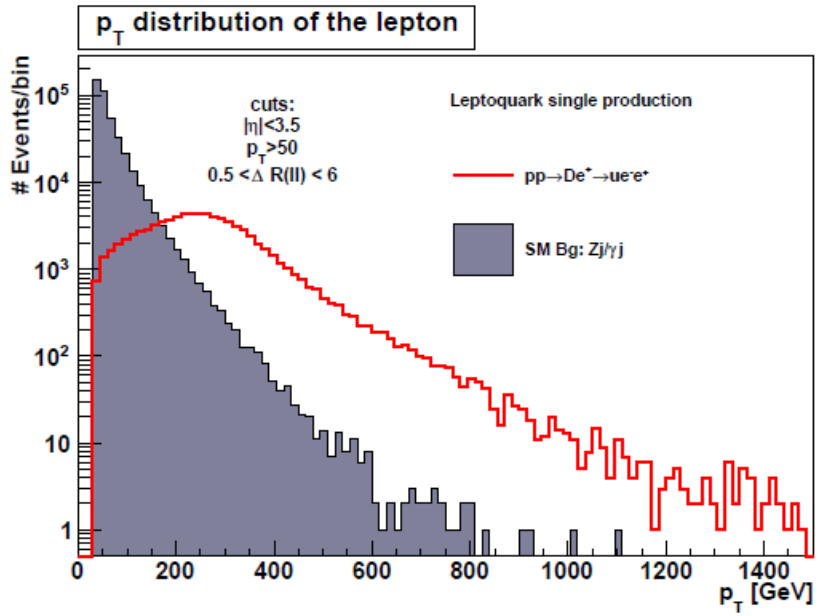
parameters		
$\tan\beta = 17.52$	$\mathbf{A}^{\tilde{f}} = -1861$	$\mathbf{m}_{1/2} = 1178$
$\mathbf{Y}^D = 0.263$	$\mathbf{A}^D = 653.3$	$\mathbf{m}^0_{\tilde{f}} = 2770$
$\mathbf{Y}^{D^c} = 0.928$	$\mathbf{A}^{D^c} = 653.3$	$\mathbf{m}^0_D = 2428$
$\mathbf{Y}^{SD} = 0.438$	$\mathbf{A}^{SD} = 653.3$	$\mathbf{m}^0_H = 3956$
$\mathbf{Y}^{SH} = 0.093$	$\mathbf{A}^{SH} = -3697$	$\mathbf{m}^0_S = 1918$
$@\mu_{\text{eff}} = 615$	$@\Lambda_{PS} = 10^{16}$	$@\Lambda_{PS} = 10^{16}$

E_6-inspired Leptoquarks

Assume vanishing DQ couplings + large LQ couplings

only consistent (perturbative) for $SU(4)_C \to SU(3)_C \times U(1)_{B-L}$ at $\sim \Lambda_{Pl}$,





(Braam, Reuter, Wiesler '09)

E_6 ~~inspired~~ Models

Unsatisfactory points

- All these models assume an unspecified E_6 breaking mechanism
- Justification to employ phenomenological, E_6 violating Superpotential

More explicit roads to a realistic low energy ESSM

Possible Roads

- Spurion analysis: $\mathcal{W} \sim \mathbf{650} \times \mathbf{27^3} \xrightarrow{\langle \mathbf{650} \rangle} \mathcal{W}_{ESSM}$
- "Quantum Gravity":
  - Orbifold compactifications
  - Scherk-Schwarz/Hosotani mechanism

String-inspired Orbifold Compactifications

(Braam, AK, Reuter, '10)

Heterotic string models: $D = 10$, $E_8 \times E_8$ (or $SO(32)$)

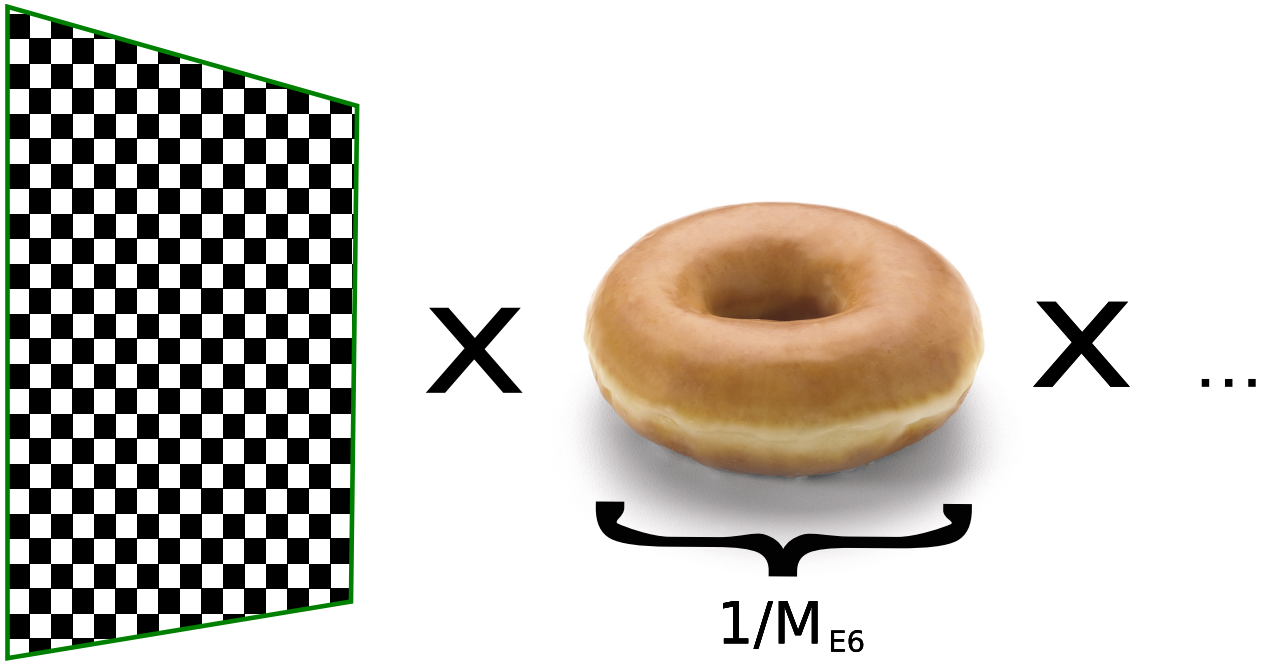
- Huge landscape of different possibilities
- Model building simplification:
  Assume partial compactification

$$D = 10, E_8 \times E_8, \mathcal{N} = 4 \longrightarrow D = 6, E_6, \mathcal{N} = 2$$

- Explicit orbifold compactification $D = 6 \rightarrow D = 4$
  Adress breaking to $\mathcal{N} = 1$, $SU(3) \times SU(2)^2 \times U(1)^2$ or Pati-Salam
- See which E_6 features are preserved...

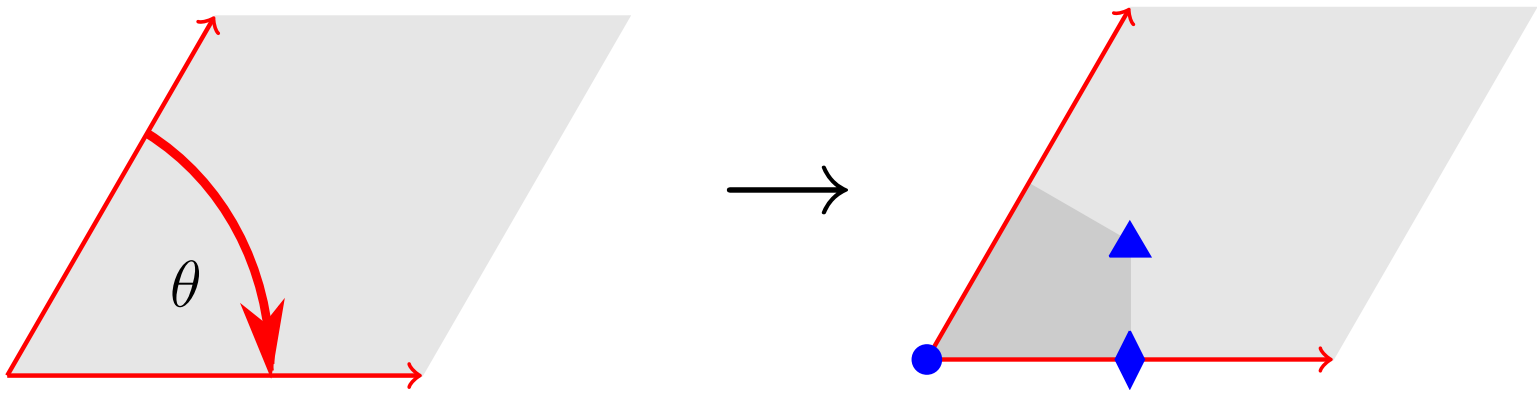
Field-Theoretic Orbifold Compactification

E6 Breaking on a torus



The $\mathbb{T}^2/\Gamma$ Orbifolds

Modding out a $360°/n$, i.e. $\mathbb{Z}_n$ rotation:

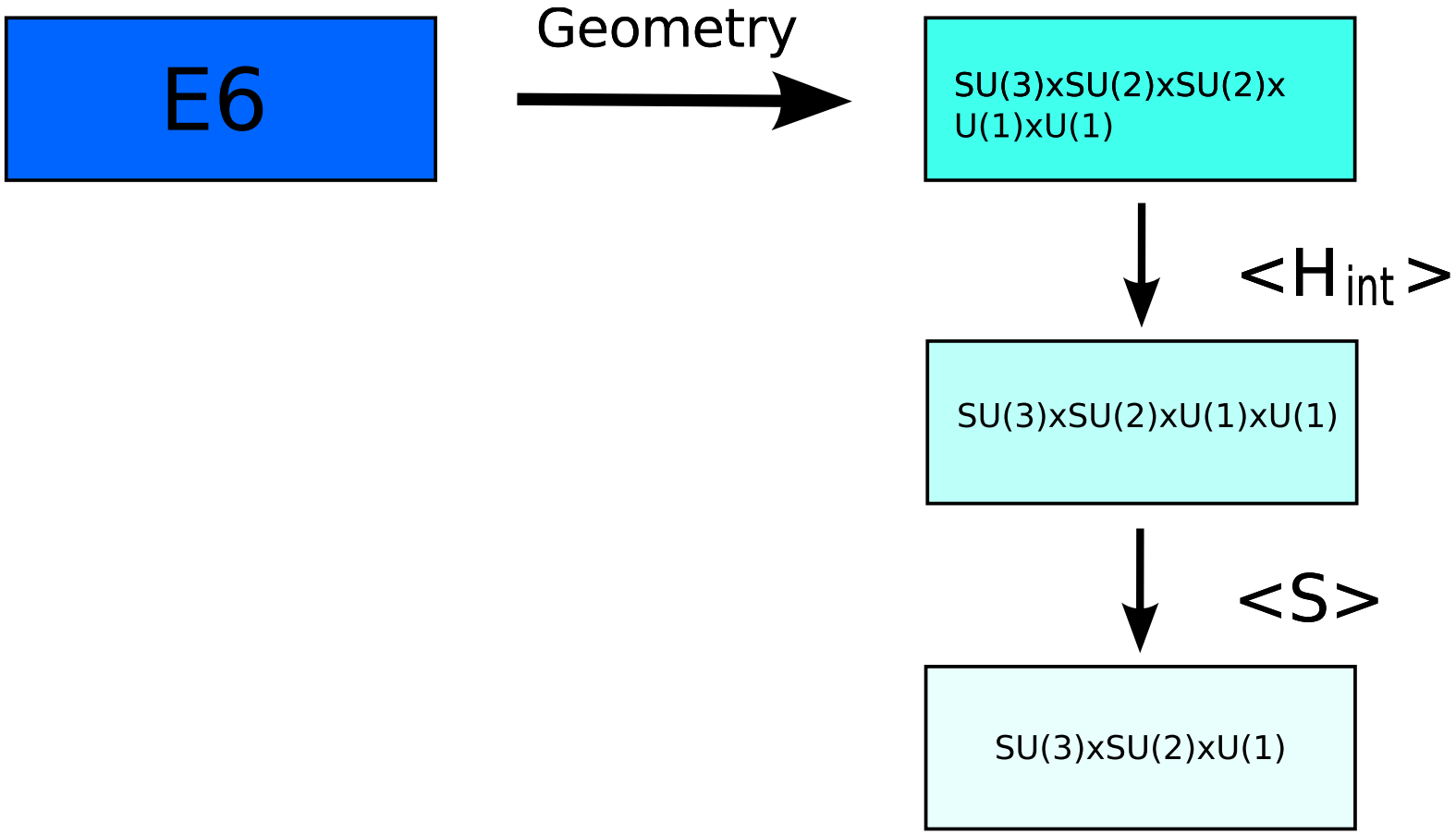


Orbifold breaking: Associate θ with a shift V in the gauge group algebra

$$|\mu\rangle \xrightarrow{\theta} e^{i\,V\cdot H}|\mu\rangle$$

Here: only abelian shifts, rank is preserved

Further breaking and unification



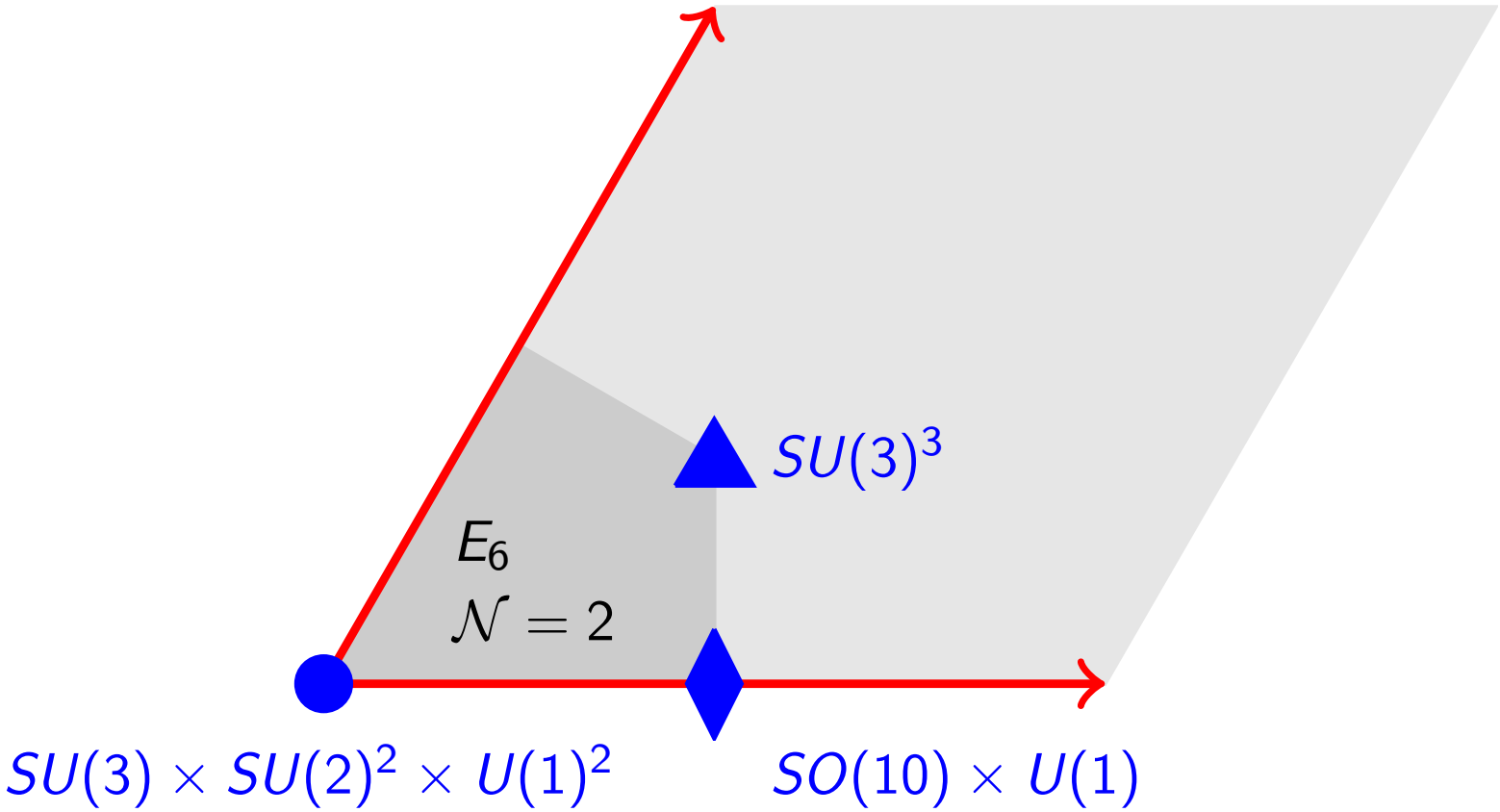
E_6 breaking $\mathbb{Z}_n$ shifts with $G_{LR} \times U(1)_\chi \subset H$

$\mathbb{Z}_2$	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 $4\overline{V}$
	$SU(5) \times U(1) \times SU(2)_L$	$(-1,-7,-1,5,-7,0)$
	$SU(5) \times U(1) \times SU(2)_R$	$(6,-2,5,-4,-2,0)$
	$SU(4)_C \times SU(2)_L \times SU(2)_R \times U(1)_\chi$	$(-7,3,2,9,-1,0)$
	$SU(3)_C \times SU(3)_L \times SU(2)_R \times U(1)$	$(0,0,1,2,0,0)$
	$SU(3)_C \times SU(3)_R \times SU(2)_L \times U(1)$	$(-1,1,1,1,1,0)$
$\mathbb{Z}_6$	Subgroup H	Shift $6\overline{V}$
	$SU(3)_C \times SU(3)_L \times SU(2)_R \times U(1)$	$(-8,-4,7,6,8,0)$
	$SU(3)_C \times SU(3)_R \times SU(2)_L \times U(1)$	$(5,1,5,-9,7,0)$
	$SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times U(1)_\chi$	$(-9,-3,-4,7,9,0)$

H Parity,**DQ**,**H+LQ/DQ**,**H+DQ**

Orbifold breaking of E_6 to LR Symmetric Model

Example: $V = (-\frac{1}{2}, \frac{1}{2}, \frac{1}{3}, \frac{1}{6}, \frac{1}{2}, 0)$



Brane/Bulk Anomalies

Surviving chiral modes on fixed points (not in light spectrum)?

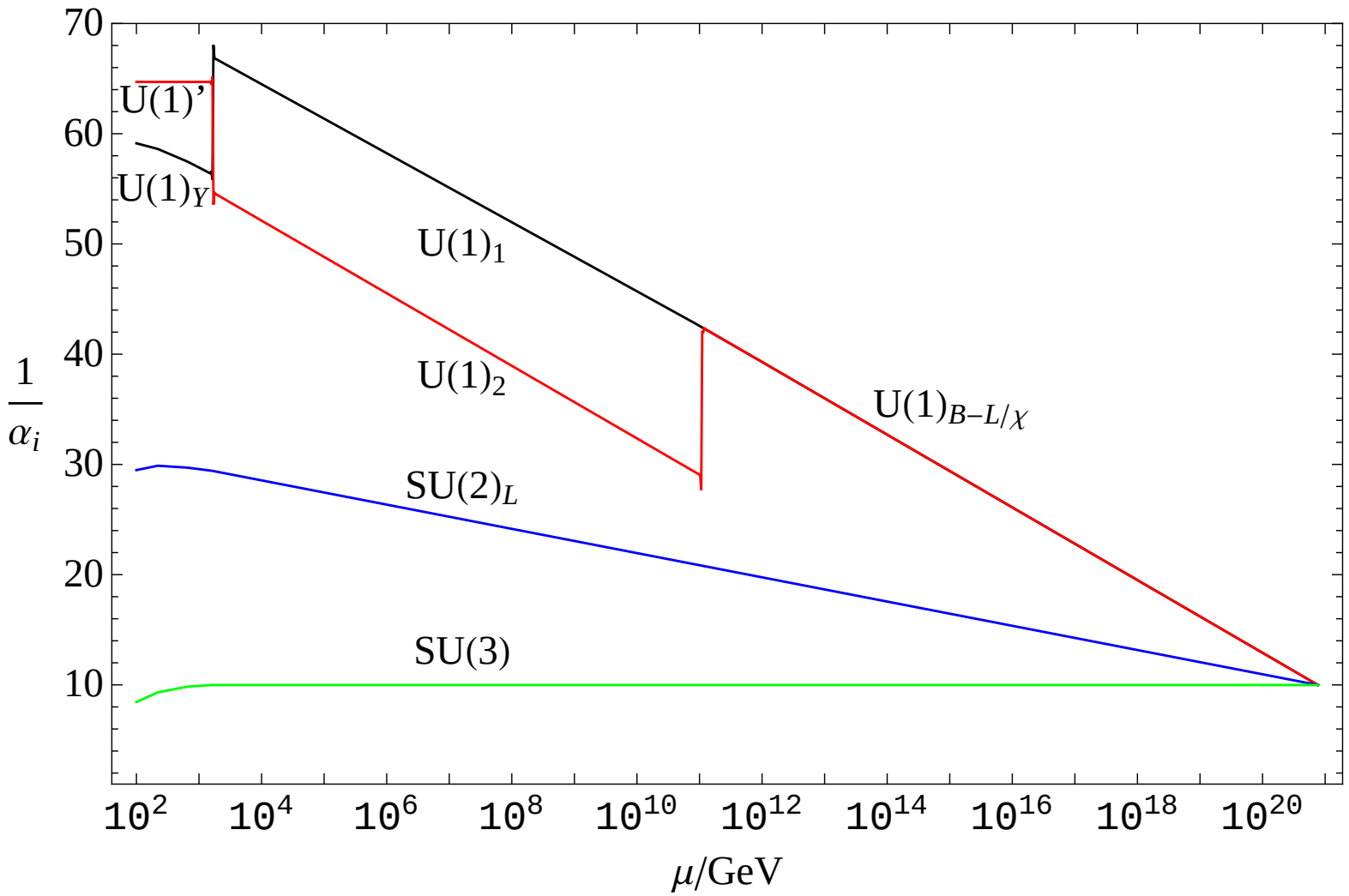
- $\mathbb{Z}_6$: $(\mathbf{3},\mathbf{2},\mathbf{1})_{-\mathbf{3/2}} + (\mathbf{3},\mathbf{1},\mathbf{2})_{\mathbf{3/2}}$
- $\mathbb{Z}_2$: $\mathbf{16}_{-\mathbf{3/2}} + \overline{\mathbf{16}}_{\mathbf{3/2}}$
- $\mathbb{Z}_3$: $(\mathbf{3},\mathbf{3},\overline{\mathbf{3}})$

Massless chiral mode: $(\mathbf{3},\mathbf{2},\mathbf{1})_{-\mathbf{3/2}} + (\mathbf{3},\mathbf{1},\mathbf{2})_{\mathbf{3/2}}$

Solutions

- Put $(\overline{\mathbf{3}},\mathbf{2},\mathbf{1}) + (\overline{\mathbf{3}},\mathbf{1},\mathbf{2})$ on $\mathbb{Z}_6$ FP - cancels 4D anomaly
- Partial doubling of bulk matter: **78** Hypermultiplet
  $\longrightarrow$ cancel massless modes and brane anomalies

Unification scheme (no intermediate Higgs in RGE)



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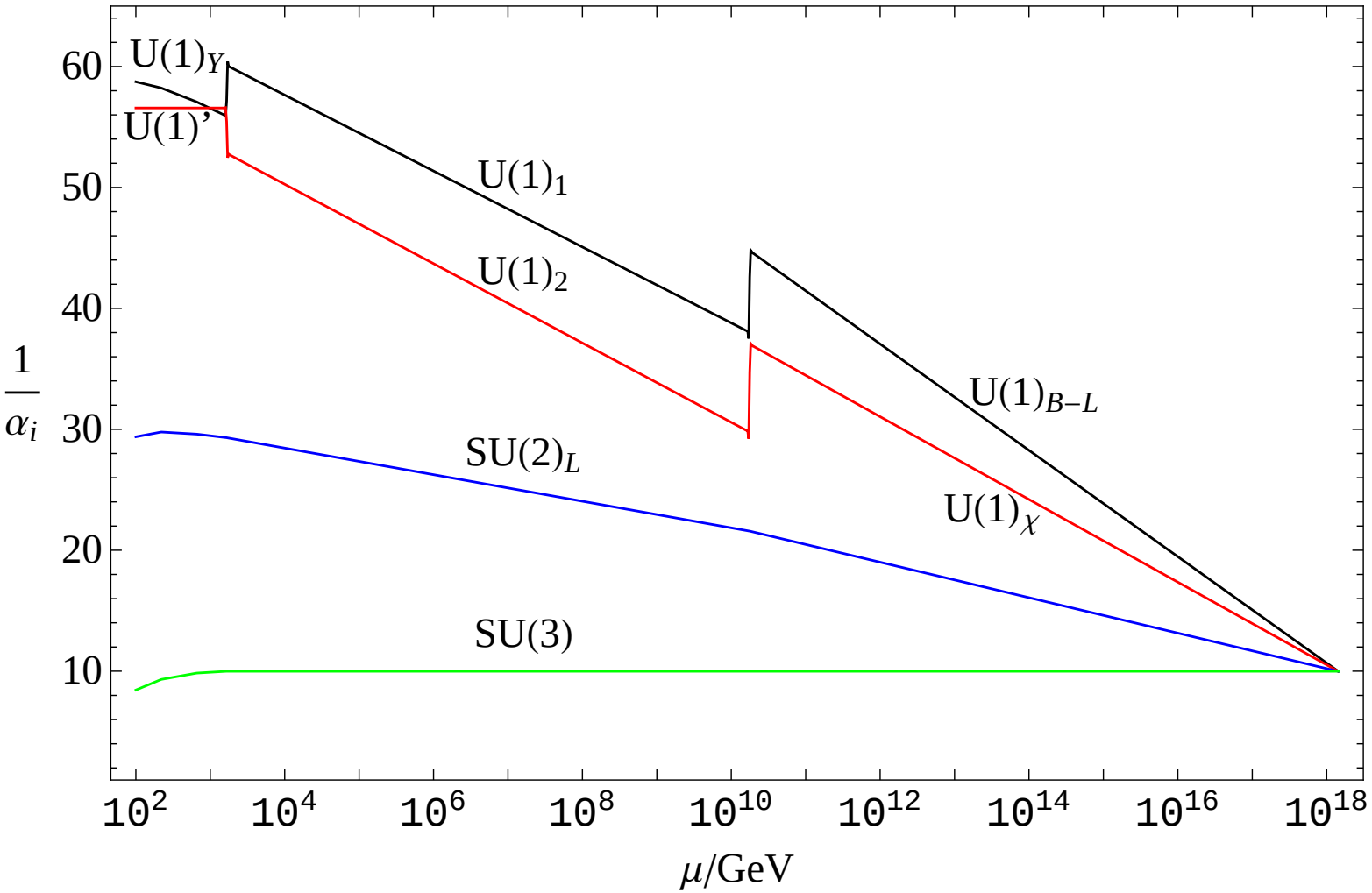
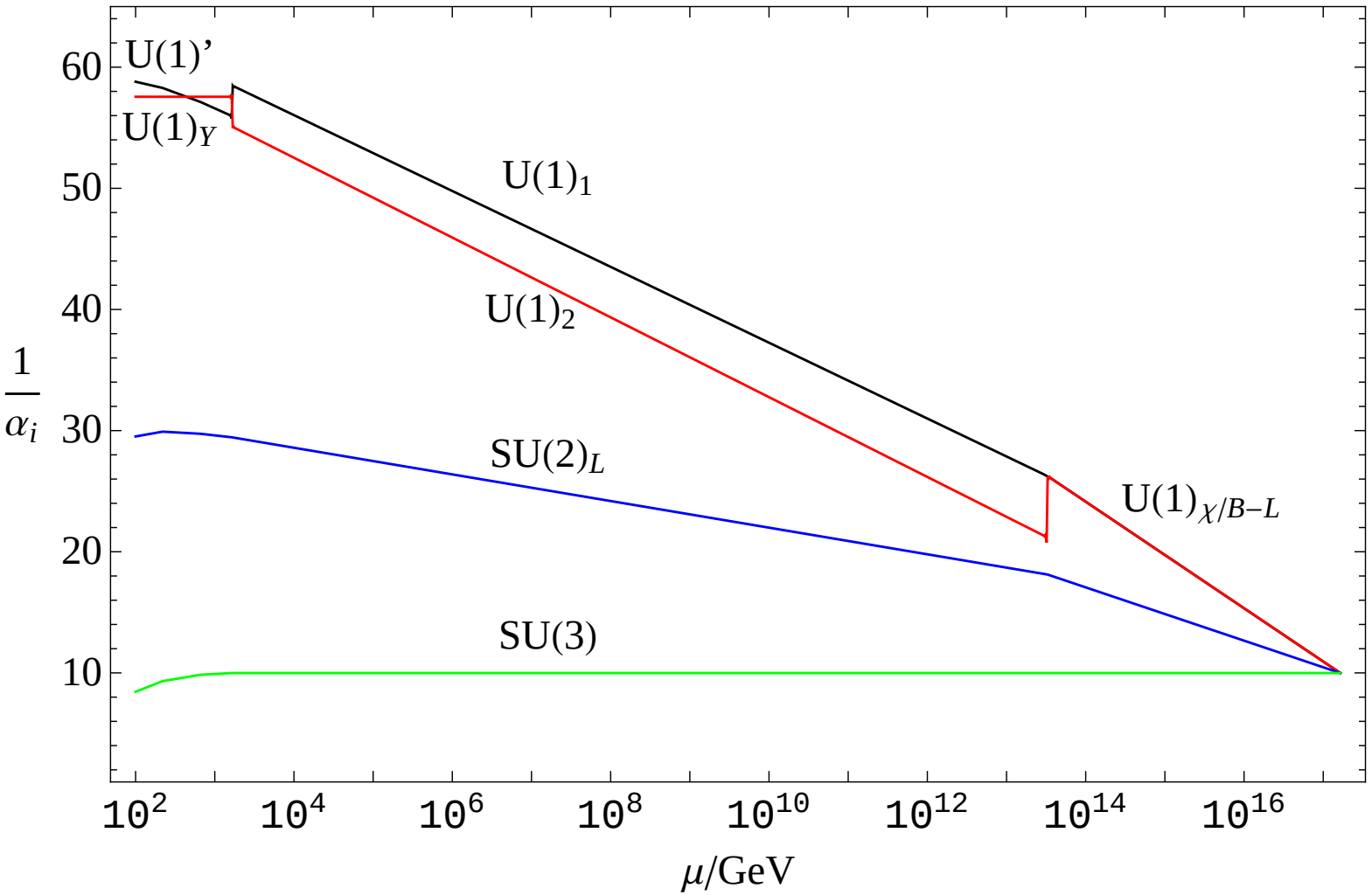


$H_{int} \sim (\mathbf{1}, \overline{\mathbf{3}}, \overline{\mathbf{3}}) \cap \mathbf{16} + h.c.$

Unification scheme (intermediate Higgs in RGE)



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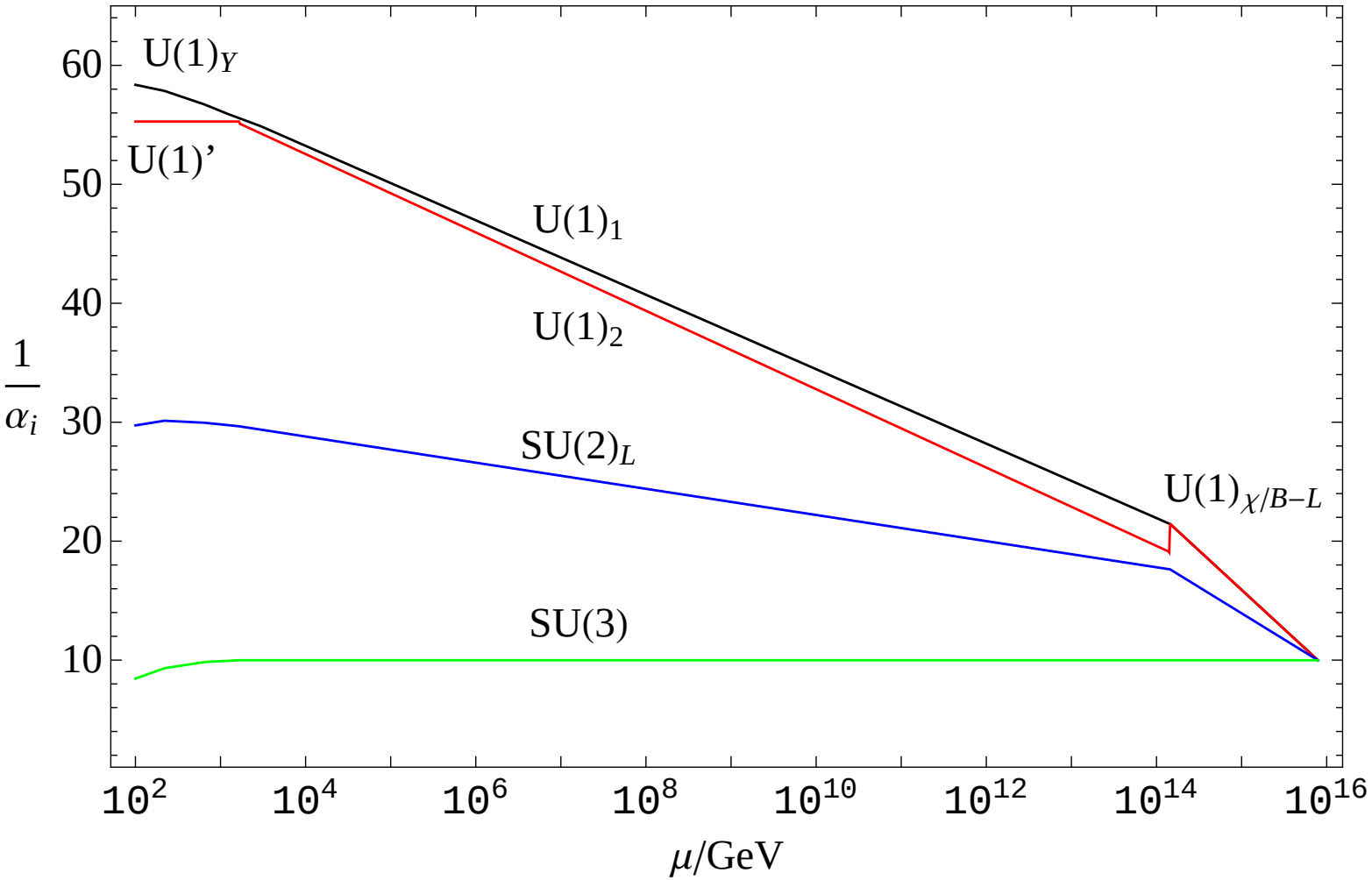

$H_{int} \sim 3 \times (\mathbf{1}, \overline{\mathbf{3}}, \overline{\mathbf{3}}) + h.c.$

Extra $U(1)$ at low energies

$H_{\text{int}}, \bar{H}_{\text{int}}$	$i)$	$ii)$	$3ii)$	$i) + 2ii)$
$\Lambda_{\text{int}}/\text{GeV}$	1.6×10^{10}	3.0×10^{13}	1.3×10^{14}	4.9×10^{13}
$\Lambda_{\text{GUT}}/\text{GeV}$	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

Summary & Outlook

- Exceptional unification: exciting prospect for LHC and DM searches
- 6D Orbifold breaking allows light exotics and two step unification

- Parameter scans + Monte Carlo studies for LHC
- Unhiggs/Singino/Neutralino Multicomponent Dark Matter?
- Embedding in $E_8 \times E_8$ heterotic constructions

Thank you for your Attention