Gauge Unification on Highly Anisotropic Orbifolds

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Outline

- the GUT scale / String scale problem
- non-local gauge symmetry breaking on orbifolds ("non-local, discrete Wilson lines")
- comparison with other (heterotic) mechanisms of gauge symm. breaking
- towards the embedding in a complete heterotic model

String-scale / GUT scale problem

- SUSY-GUTs remain one of the best-motivated options for new physics (coupling unification, ν-mass scale, group-theory: $SM \subset GUT \subset E_8 \times E_8 / SO_{32}$)

- mass scales: (with $m_H = 2/\sqrt{\alpha'}$)

$$\alpha_{GUT} \simeq \frac{g_s^{\,2}}{(R\, m_H)^6}$$

$$M_P^{\,2} \alpha_{GUT}/2 \simeq m_H^{\,2} \simeq \left(2 \cdot 10^{18}\, \mathrm{GeV}\right)^2$$

- problem:

$$R \simeq M_{GUT}^{-1} \gg m_H^{-1} \implies g_s \gg 1$$

significant improvement:

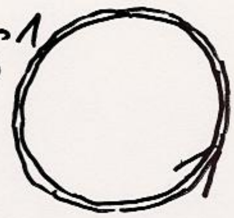
$$R^6 \longrightarrow \underset{\text{large}}{\underset{\uparrow}{(R_\ell)^d}}\; \underset{\text{small}}{\underset{\uparrow}{(R_s)^{6-d}}}$$

(Witten, '95)

("anisotropic models")

Non-local gauge symmetry breaking on orbifolds

want: $M_{GUT}^{-1} \sim R_l$

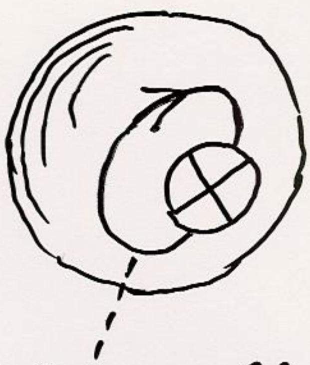
(a) S^1 

$\langle \text{Wilson line} \rangle \neq \mathbb{1}$

$\Updownarrow$

$\langle \text{GUT Higgs} \rangle \neq 0$

$\Rightarrow$ all typical 4d-GUT-problems arise (undetermined VEV, 2-3-splitting)

(b) 

$\langle \text{Wilson line} \rangle \neq \mathbb{1}$

$\uparrow$

discrete by topology

Z_2-Wilson line
($\pi_1 = Z_2$)

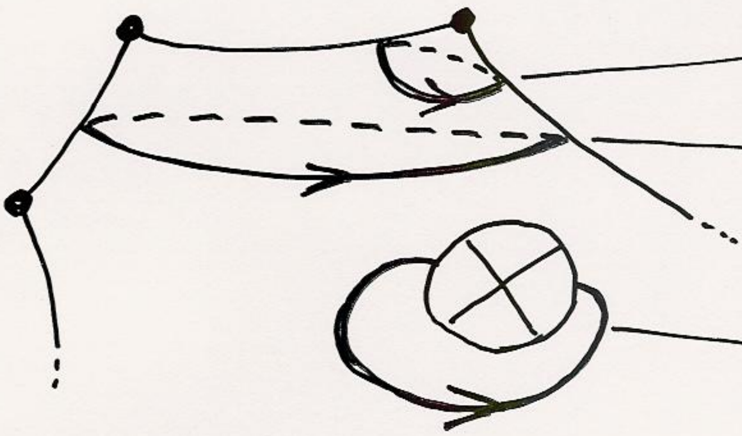
(Witten '85
Hall, Murayama, Nomura '0
...
Scherk-Schwarz ~~SUSY~~
on freely acting orbif.)

<u>our paper:</u> explicit realization in heterotic string orbifold models

Options for gauge symm. breaking in heterotic orbifold models

- take the phys. space (<u>not covering space!</u>) perspective:

<u>Wilson lines:</u>



discrete, local

continuous, non-local

<u>discrete, non-local</u>

– <u>discrete, local</u> (= breaking at fixed-point)

$$\Rightarrow M_{GUT} \simeq M_{string}$$

– <u>discrete, non-local</u> $\Rightarrow M_{GUT} \simeq R^{-1} \; (\equiv R_\ell^{-1})$

(in CY-context: Witten '85 ... Ovrut et al. '03)

– <u>continuous, non-local</u>

(Ibanez, Mas, Nilles, Quevedo '87
Lopes-Cardoso, Lüst, Mohaupt, '93
...
work in 'orbifold GUT' context)

↪

Illustration of breaking by continuous Wilson lines

$SU_5 \times U_1$ $\quad SO_{10} \quad$ $SU_5' \times U_1'$

$\updownarrow$ gauge transformation

$SU_5 \times U_1$ $\quad SO_{10} \quad$ $SU_5 \times U_1$ (Wilson line)

$\langle A_5 \rangle \neq 0$

2 problems:

1) VEV undetermined
(relative orientation of boundary-SU_5 & SU_5' subgroups undetermined)

(→ A.H., Trapletti, '04
Förste, Nilles, Wingerter, '05)

2) "differential running"
(i.e., running of $\alpha_i^{-1} - \alpha_j^{-1}$ with $i,j = 1,2,3$ for $U_1 \times SU_2 \times SU_3$)
continues above $M_c \simeq 1/R$

$\Rightarrow$ The GUT scale is not linked to $1/R$.

field-theoretic understanding:

$SU_5 \times U_1$ $\quad$ SO_{10} $\quad$ $SU_5 \times U_1$

$\langle A_5 \rangle \neq 0$

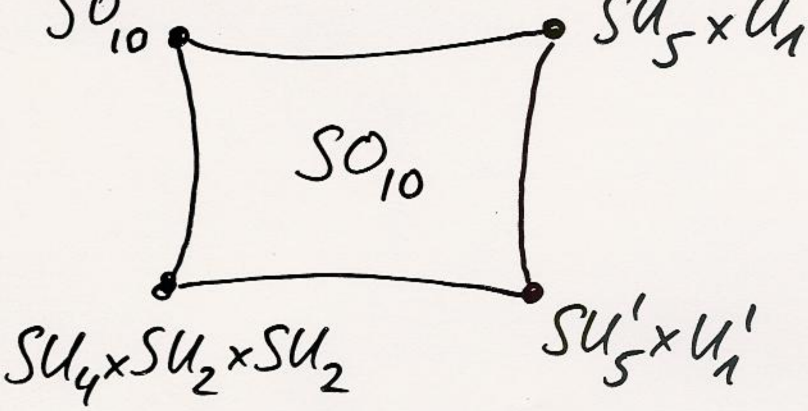
4d field theory:
(in the spirit of "deconstruction")

$$SM \subset SO_{10} \times SO_{10}$$

breaking by bifundamental Higgs

<u>not surprisingly:</u>
no field-theoretic unification
(<u>in spite of soft breaking</u>)
since the GUT group is <u>not</u> simple.

problem 1) (unfixed VEV) may be avoided:



(Asaka, Buchmüller, Covi, '01
...
Kobayashi, Raby, Zhang, '04
Förste et al. '04
Buchmüller et al., '04)

- all Wilson lines fixed (discrete)
- overall breaking stronger than by any of the Wilson lines ($SO_{10} \to SM \times U_1$)

But: problem 2) (non-GUT running above M_c) persists

(in contrast to our case of non-local, discrete Wilson lines)

Towards a complete model with GUT-breaking by non-local discrete Wilson-lines:

10 d theory, parameters m_H, g_s

$\downarrow$ 4 compact radii R_s

6d theory

$\downarrow$ 2 compact radii $R_\ell \sim M_{GUT}^{-1}$

4d theory (MSSM ?)

$$\alpha_{GUT} \simeq \frac{g_s^{\,2}}{(R_\ell m_H)^2 (R_s m_H)^{4}}$$ still doesn't allow $g_s \ll 1$

But: using a duality network à la Antoniadis/Pioline '99 we can show that:

- the non-pert. UV completion of the 6d theory has no new light states below M_{GUT}
- the (purely field-theoretic) step 6d $\rightarrow$ 4d should be unaffected by the strongly-coupled 10d heterotic theory

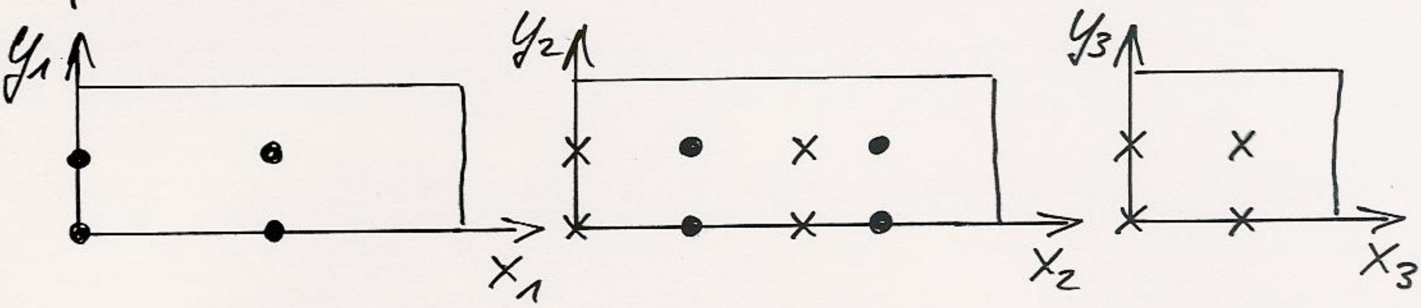
Explicit examples:

geometry: $T^6/(\mathbb{Z}_2 \times \mathbb{Z}_2')$

$$P: \quad z_1 \to -z_1, \quad z_2 \to -z_2 + \pi R_2, \quad z_3 \to z_3$$

$$\boxed{P': \quad z_1 \to z_1 + \pi R_1, \quad z_2 \to -z_2, \quad z_3 \to -z_3}$$

free action



• – fixed points of $\mathbb{Z}_2$

× – "would be" fixed points of $\mathbb{Z}_2'$

<u>shift vectors</u> (SO_{32})

$$V = \tfrac{1}{2}(0^3, 1^2, 0^4, 1^4, 0^3)$$

$$V' = \tfrac{1}{2}(1^{10}, 0^6)$$

$$\left.\begin{aligned} A_{y_1} &= \tfrac{1}{2}(0^6, 1^8, 0^2) \\ A_{y_2} &= \tfrac{1}{2}(0^5, 1, 0^3, 1^2, 0^4, 1) \end{aligned}\right\} \text{conventional discrete Wilson-lines}$$

Result:

$$SO_{32} \xrightarrow{} SO_{10} \times \cdots \xrightarrow{} SU_4 \times SU_2 \times SU_2 \cdots$$

local breaking, including Wilson-lines (leading to a 6d SO_{10} GUT)

non-local GUT-breaking associated with large radii R_1, R_2

Comment:

The choice of the $\underline{Z_2 \text{ and } Z_2'}$ generators $\underline{P \text{ and } P'}$ is not completely arbitrary:

P - non-free and GUT-preserving

$\underline{P' \text{ - free}}$ and GUT-breaking

$\Rightarrow$ $P \cdot P'$ - GUT-breaking

$\Rightarrow$ need to ensure that $\underline{P \cdot P' \text{ acts freely}}$

Conclusions

- the string-scale/GUT scale problem can be addressed by
  - GUT breaking through <u>non-local discrete Wilson lines</u>
  - increasing the relevant large radii to $R_\ell \sim (M_{GUT})^{-1} \sim (2 \cdot 10^{16} GeV)^{-1}$
- simple heterotic orbifold models with this feature are available
- no doublet-triplet splitting problem as in 4d models
- no tunable large thresholds or modified logarithmic running required
- need to explore this <u>new class of heterotic orbifolds</u>
- for non-local discrete Wilson-lines in D-brane models → M. Trapletti's talk