"Anomalous" discrete symmetries

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Bonn, August 27, 2010

Based on:

- M. Blaszczyk, S. Groot Nibbelink, F. Ruehle, M.R., M. Trapletti & P. Vaudrevange, Phys. Lett. B 683, 340-348 (2010)
- F. Brümmer, R. Kappl, M.R. & K. Schmidt-Hoberg, JHEP 1004:006 (2010)
- R. Kappl, B. Petersen, M.R., R. Schieren & P. Vaudrevange, to appear
- H.M. Lee, S. Raby, G. Ross, M.R., R. Schieren, K. Schmidt-Hoberg & P. Vaudrevange, to appear

MSSM: good features and open questions

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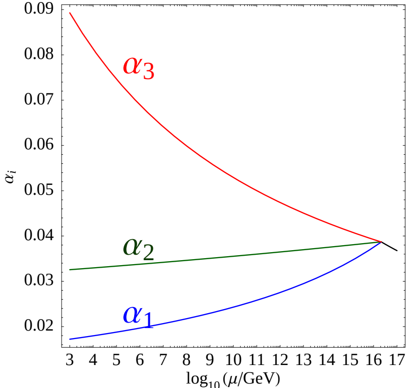

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➥ Supersymmetry alone seems not to be enough

Outline

1. Introduction & Motivation ✓
2. A simple $\mathbb{Z}_4^R$ symmetry can explain
   - suppressed μ term
   - proton stability
3. String theory realization
4. Summary

Proton decay operators

- Gauge invariant superpotential terms up to order 4 include

$$
\begin{aligned}
\mathscr{W} &= \mu H_d H_u + \kappa_i L_i H_u \\
&\quad + Y_e^{ij} L_i H_d \overline{E}_j + Y_d^{ij} Q_i H_d \overline{D}_j + Y_u^{ij} Q_i H_u \overline{U}_j \\
&\quad + \lambda_{ijk} L_i L_j \overline{E}_k + \lambda'_{ijk} L_i Q_j \overline{D}_k + \lambda''_{ijk} \overline{U}_i \overline{D}_j \overline{D}_k \\
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forbidden by matter parity

Farrar & Fayet (1978); Dimopoulos, Raby & Wilczek (1981)

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Dreiner, Luhn & Thormeier (2006)

- Proton hexality $=$ matter parity $+$ baryon triality

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Proton hexality

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☞ Proton hexality P_6 = matter parity $\mathbb{Z}_2^{\mathcal{M}}$ × baryon triality B_3

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- However:
  - ☹ not consistent with unification for matter (i.e. inconsistent with universal discrete charges for all matter fields)

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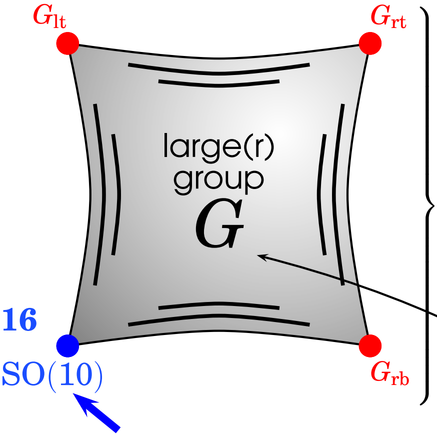
  - ☹ embedding into string theory not yet fully convincing

Förste, Nilles, Ramos-Sánchez, Vaudrevange (2010)

Local grand unification (using **small** extra dimensions)



Buchmüller, Hamaguchi, Lebedev, M.R. (2004-2006)
Lebedev, Nilles, Raby, Ramos-Sánchez, M.R., Vaudrevange, Wingerter (2006)

'low-energy' effective theory → standard model as an intersection of $G_{\rm rb}$, $G_{\rm rt}$, $G_{\rm lt}$ & $\mathrm{SO}(10)$ in G

SM generation(s):
localized in region with $\mathrm{SO}(10)$ symmetry

Higgs doublets:
live in the 'bulk'

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↪ Two prejudices from string model building:

1. Local Grand Unification
2. 'anomalous' discrete symmetries whose anomalies are canceled the Green-Schwarz mechanism

From anomaly freedom to anomaly universality

Dine & Graesser (2004); Araki, Kobayashi, Kubo, Ramos-Sánchez, M.R. & Vaudrevange (2008)

☞ Important lesson from explicit string-derived (MSSM) models

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Dynkin index

discrete charges

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⬇ ⬇ ⬇ ⬇ ⬇

anomaly universality:
all A coefficients equal

A unique $\mathbb{Z}_4^R$ symmetry

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- Assumptions:
  - anomaly universality
  - universal charges for quarks and leptons
  - μ term forbidden at perturbative level
  - Yukawa couplings and Weinberg neutrino mass operator allowed
- Want to prove:
  There is a unique $\mathbb{Z}_4^R$ symmetry in the MSSM with these features

Claim 1: it has to be an R symmetry

- ☞ Anomaly coefficients for non-R symmetry with SU(5) relations for matter charges

$$A_{\mathrm{SU}(3)_C^2-\mathbb{Z}_N} = \frac{9}{2} q_{\mathbf{10}} + \frac{3}{2} q_{\overline{\mathbf{5}}}$$

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- Anomaly universality

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\begin{aligned}
A_{\mathrm{SU}(2)_\mathrm{L}^2-\mathbb{Z}_N} - A_{\mathrm{SU}(3)_C^2-\mathbb{Z}_N} &= 0 \\
\curvearrowright \quad \frac{1}{2} \left(q_{H_u} + q_{H_d} \right) &= 0 \mod \begin{cases} N & \text{for } N \text{ odd} \\ N/2 & \text{for } N \text{ even} \end{cases}
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$$A_{\mathrm{SU}(2)_\mathrm{L}^2-\mathbb{Z}_N} - A_{\mathrm{SU}(3)_C^2-\mathbb{Z}_N} = 0$$

$$\curvearrowright \quad \frac{1}{2}\left(q_{H_u} + q_{H_d}\right) = 0 \mod \begin{cases} N & \text{for } N \text{ odd} \\ N/2 & \text{for } N \text{ even} \end{cases}$$

bottom-line:

non-R $\mathbb{Z}_N$ symmetry cannot forbid μ term

Claim 2: Higgs discrete charges have to vanish

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Claim 3: The order has to be 4 (or 2)

☞ Anomaly coefficients for Abelian discrete R symmetry

$$A_{\mathrm{SU}(3)_C^2-\mathbb{Z}_N^R} = 6(r-1)+3 = 6r-3$$

$$A_{\mathrm{SU}(2)_\mathrm{L}^2-\mathbb{Z}_N^R} = 6r+\frac{1}{2}\left(r_{H_u}+r_{H_d}\right)-5$$

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- Anomaly universality

$A_{\mathrm{SU}(2)_\mathrm{L}^2-\mathbb{Z}_N^R} -$ … $r_{H_u} + r_{H_d} = 1 \mod$ … $N/2$ for N even

however: there is no meaningful $\mathbb{Z}_2^R$ symmetry

cf. e.g. Dine & Kehayias (2009)

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bottom-line:

$N = 4$ unique

Unique $\mathbb{Z}_4^R$ symmetry

☞ We know:

- it is a $\mathbb{Z}_4^R$ symmetry
- Higgs fields have charge $r_{H_u} = r_{H_d} = 0 \mod 4$

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- Anomaly-free version of this $\mathbb{Z}_4^R$ with extra matter has been discussed previously

Kurosawa, Maru & Yanagida (2001)

Implications of $\mathbb{Z}_4^R$

- Gauge invariant superpotential terms up to order 4

$$\begin{aligned}\mathscr{W} &= \mu\, H_d H_u + \kappa_i\, L_i H_u \\ &\quad + Y_e^{ij}\, L_i H_d \overline{E}_j + Y_d^{ij}\, Q_i H_d \overline{D}_j + Y_u^{ij}\, Q_i H_u \overline{U}_j \\ &\quad + \lambda_{ijk}\, L_i L_j \overline{E}_k + \lambda'_{ijk}\, L_i Q_j \overline{D}_k + \lambda''_{ijk}\, \overline{U}_i \overline{D}_j \overline{D}_k \\ &\quad + \kappa_{ij}^{(0)}\, H_u L_i\, H_u L_j + \kappa_{ijk\ell}^{(1)}\, Q_i Q_j Q_k L_\ell + \kappa_{ijk\ell}^{(2)}\, \overline{U}_i \overline{U}_j \overline{U}_k \overline{E}_\ell + \dots\end{aligned}$$

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forbidden at the perturbative level (μ, κ_i, λ_{ijk}, λ'_{ijk}, λ''_{ijk}, $\kappa_{ijk\ell}^{(1)}$, $\kappa_{ijk\ell}^{(2)}$)

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appear at non-perturbative level (μ, $\kappa_{ijk\ell}^{(1)}$, $\kappa_{ijk\ell}^{(2)}$)

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\end{aligned}
$$

also forbidden at non-perturbative level by non-anomalous $\mathbb{Z}_2$ subgroup which is equivalent to matter parity

Implications of $\mathbb{Z}_4^R$

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non-perturbative generation of μ solves the μ problem

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non-perturbatively generated terms harmless

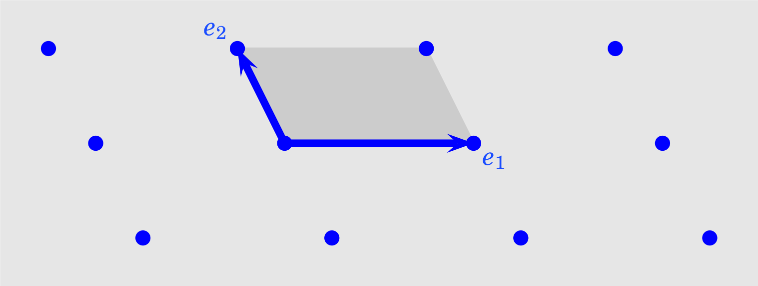
An explicit string-derived example

. . . string theory allows us to understand the non-perturbative 'violation' of 'anomalous' discrete symmetries

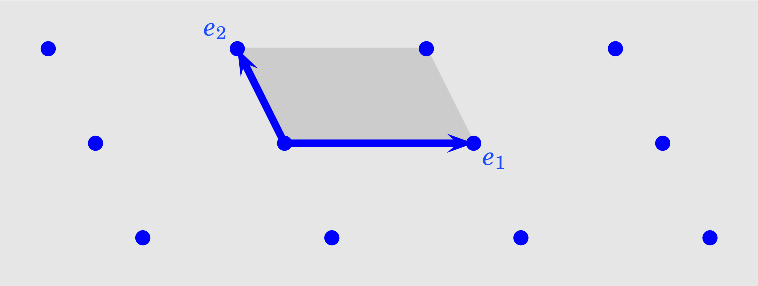
The $\mathbb{Z}_2$ orbifold plane

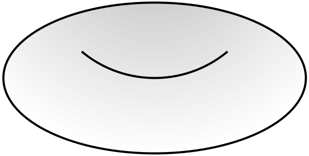
2D space with SO(2) rotational symmetry

The $\mathbb{Z}_2$ orbifold plane



The $\mathbb{Z}_2$ orbifold plane





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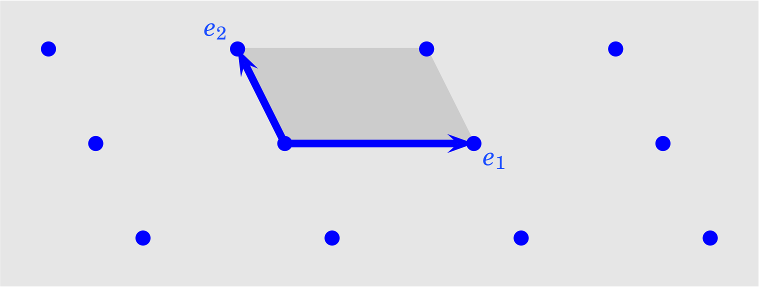

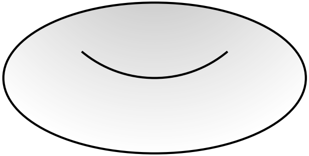

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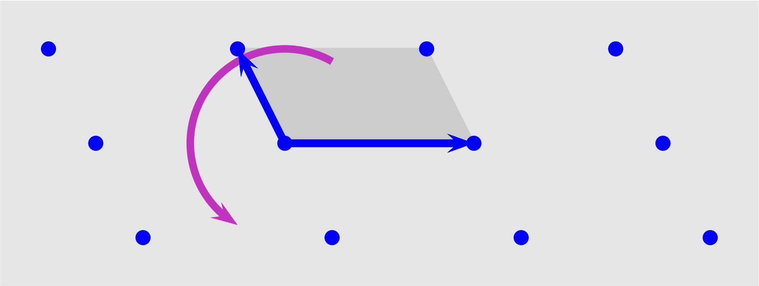

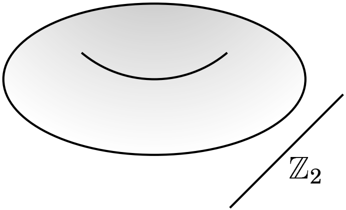

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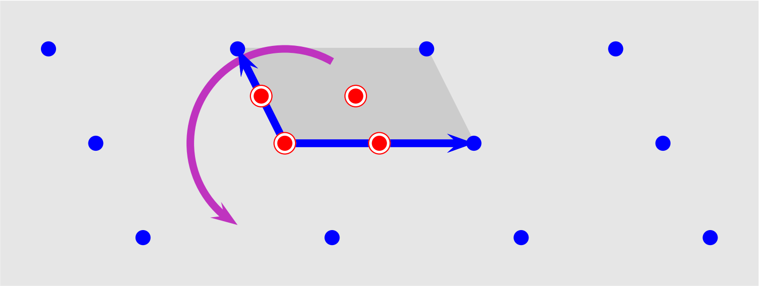

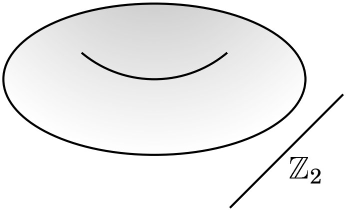

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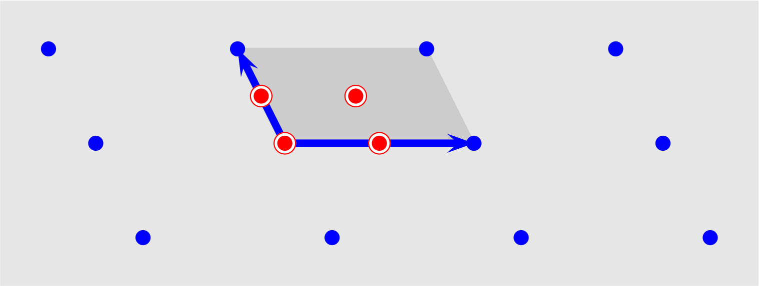
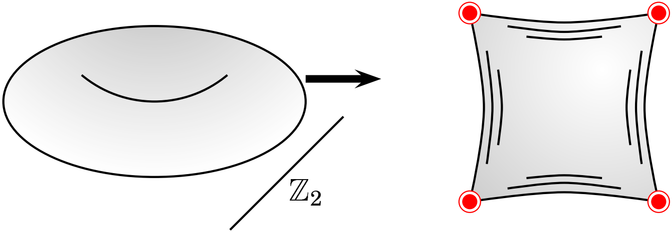
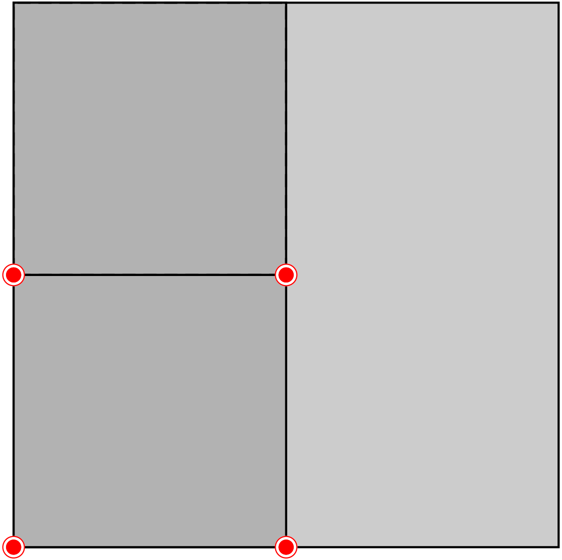




$\mathbb{Z}_2$ orbifold pillow



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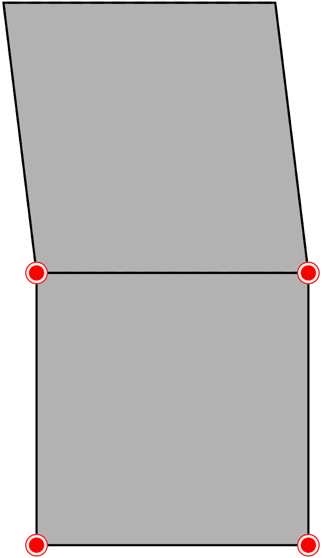

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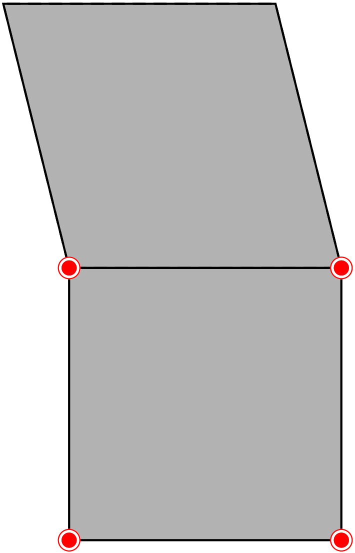

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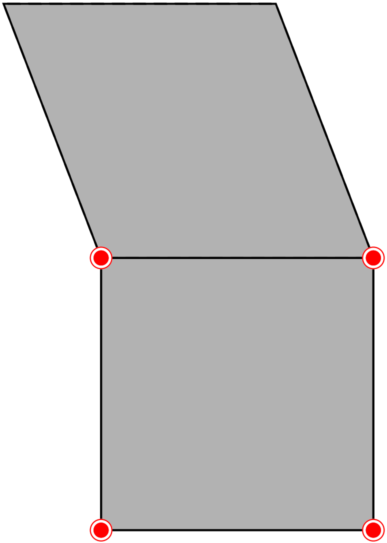

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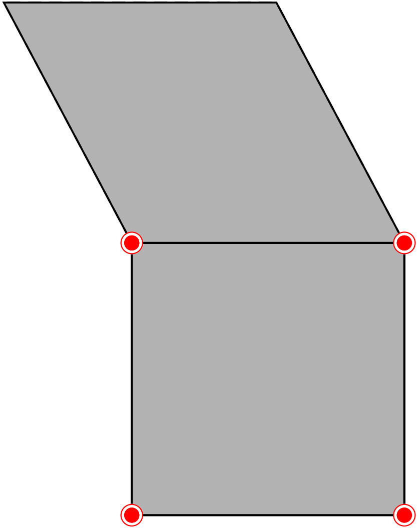

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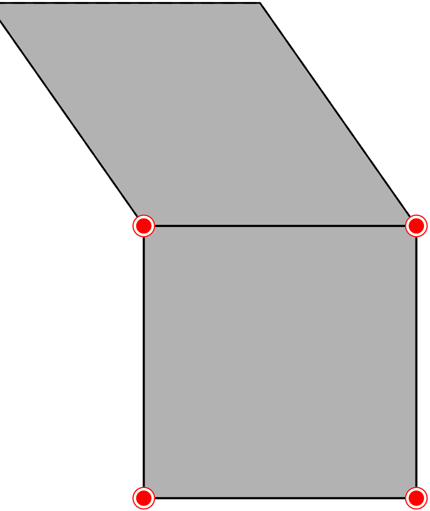

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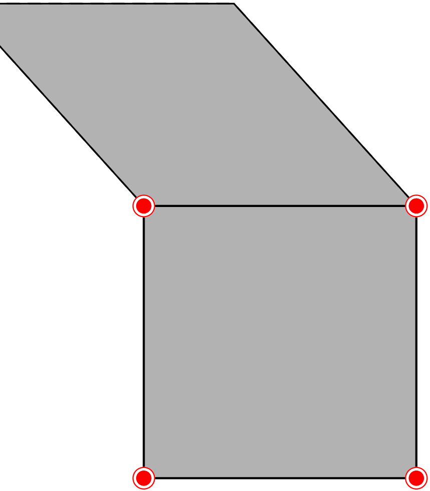

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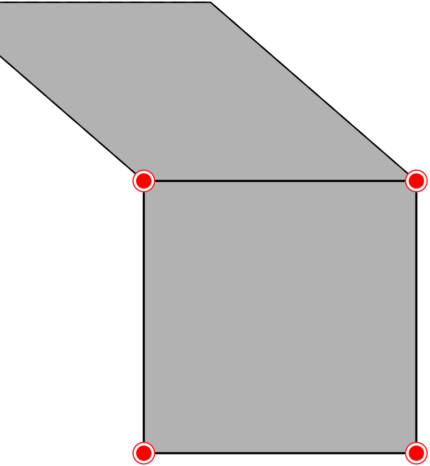

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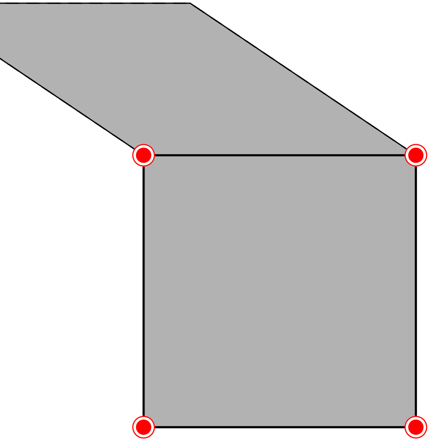

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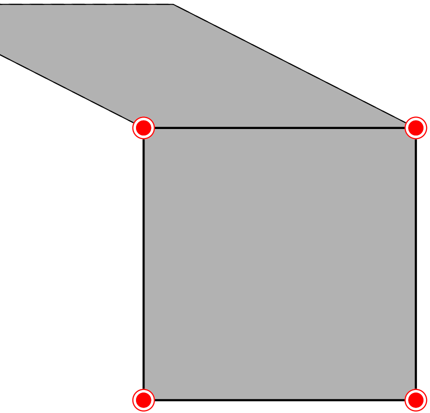

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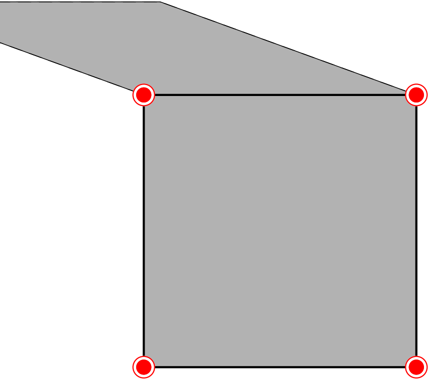

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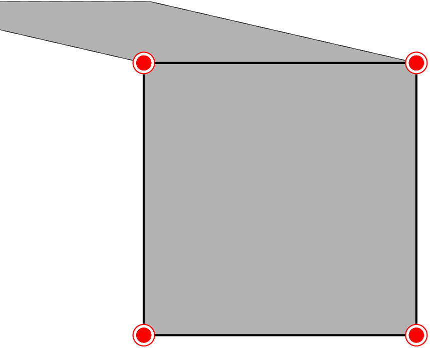

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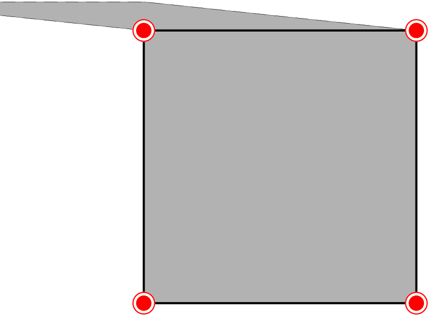

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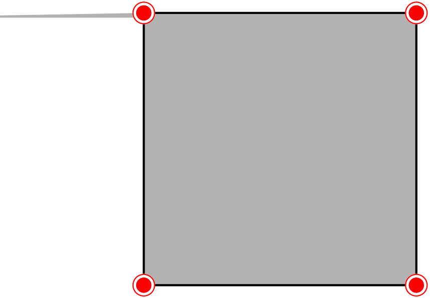

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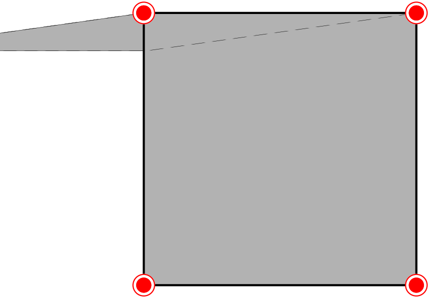

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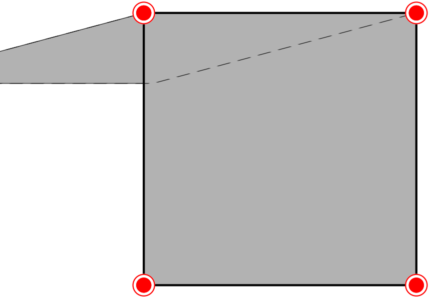

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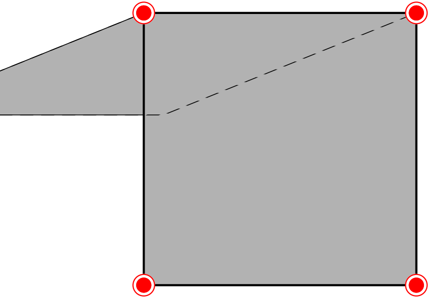

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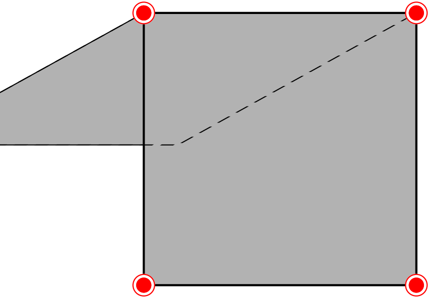

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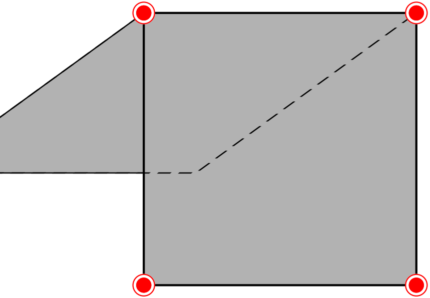

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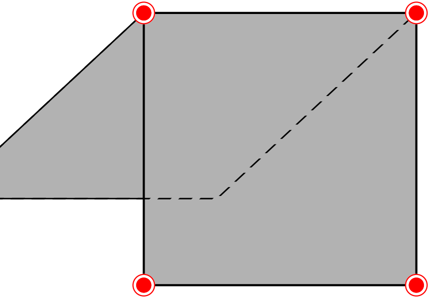

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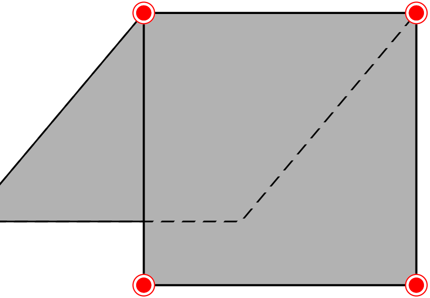

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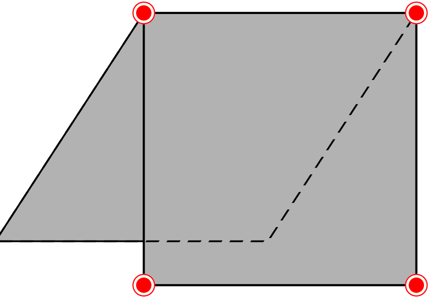

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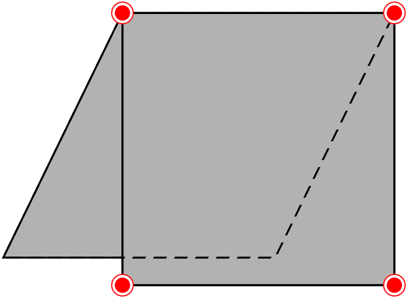

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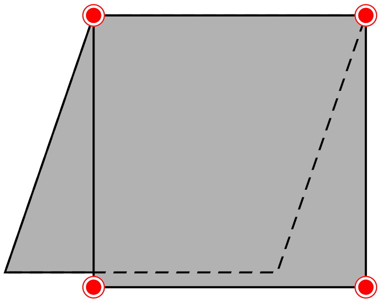

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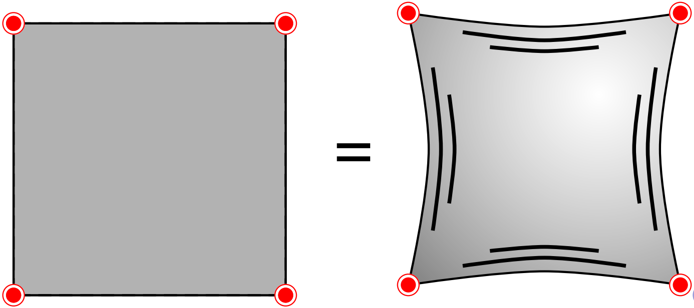


back

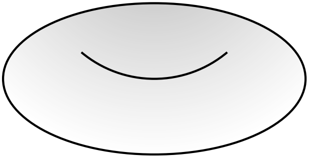
The $\mathbb{Z}_2$ orbifold plane

- Orbifolds with $\mathbb{Z}_2$ plane have three important properties:

The $\mathbb{Z}_2$ orbifold plane

☞ Orbifolds with $\mathbb{Z}_2$ plane have three important properties:

1. $\mathbb{Z}_4^R$ symmetry arises as a remnant of the Lorentz group in compact dimensions



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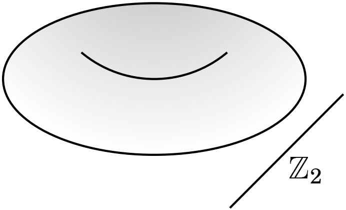

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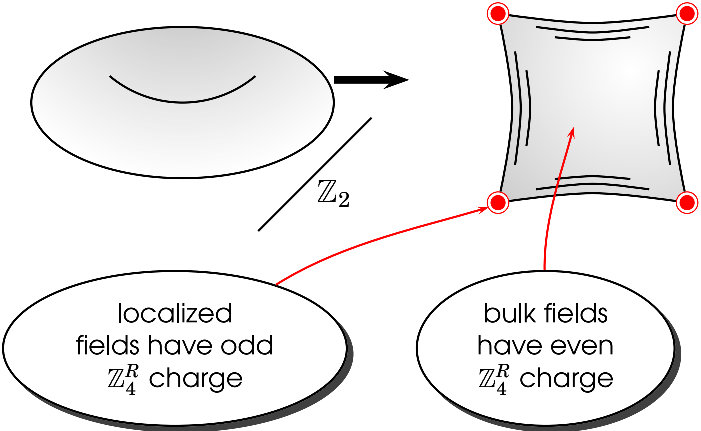

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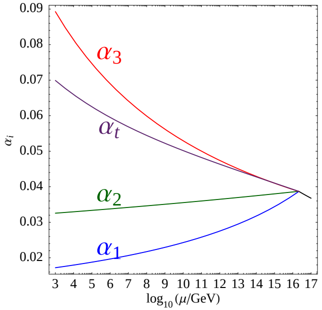
2. Orbifold GUT limit with $\mathbf{SU(6)}$ bulk symmetry gives us gauge-top unification

P. Hosteins, R. Kappl, M.R., K. Schmidt-Hoberg (2009)



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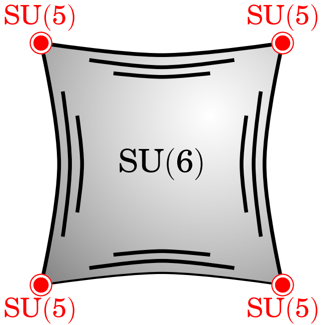
- Rest of this talk: discuss globally consistent string model with these features

$\mathbb{Z}_2 \times \mathbb{Z}_2$ orbifold example

M. Blaszczyk, S. Groot Nibbelink, M.R., F. Ruehle, M. Trapletti, P. Vaudrevange (2009)



1. step: 6 generation $\mathbb{Z}_2 \times \mathbb{Z}_2$ model with $\mathrm{SU}(5)$ symmetry

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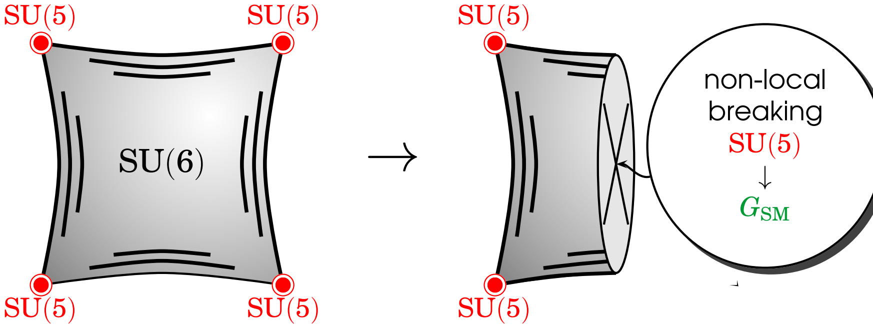
M. Blaszczyk, S. Groot Nibbelink, M.R., F. Ruehle, M. Trapletti, P. Vaudrevange (2009)



❶ step: 6 generation $\mathbb{Z}_2 \times \mathbb{Z}_2$ model with $\mathrm{SU}(5)$ symmetry

❷ step: mod out a freely acting $\mathbb{Z}_2$ symmetry which:

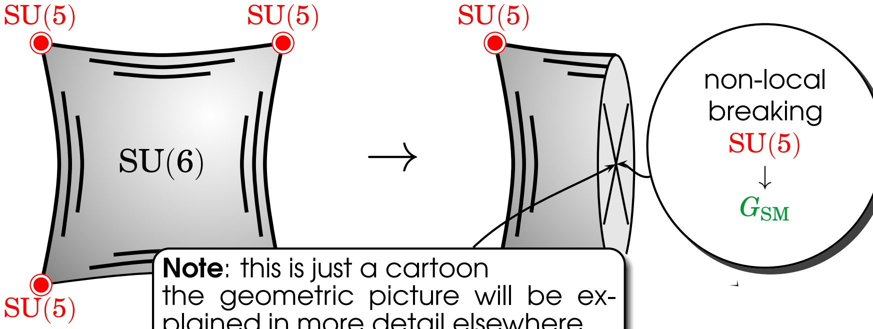
- breaks $\mathrm{SU}(5) \to \mathrm{SU}(3)_C \times \mathrm{SU}(2)_\mathrm{L} \times \mathrm{U}(1)_Y$
- reduces the number of generations to 3

analogous mechanism in CY MSSMs Bouchard & Donagi (2005)

Braun, He, Ovrut, Pantev (2005)

$\mathbb{Z}_2 \times \mathbb{Z}_2$ orbifold example

M. Blaszczyk, S. Groot Nibbelink, M.R., F. Ruehle, M. Trapletti, P. Vaudrevange (2009)



Note: this is just a cartoon
the geometric picture will be explained in more detail elsewhere

M. Fischer, M.R., P. Vaudrevange (to appear)

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for further discussion of this model see talks by M. Blaszczyk & S. Groot Nibbelink

Main features

1. GUT symmetry breaking non-local
   $\curvearrowright$ no 'logarithmic running above the GUT scale'

   Hebecker, Trapletti (2004)

   $\curvearrowright$ precision gauge unification
   with distinctive pattern of soft masses

   Raby, M.R., Schmidt-Hoberg (2009)

Main features

1. GUT symmetry breaking non-local
2. No localized flux in hypercharge direction
   $\curvearrowright$ complete blow-up without breaking SM gauge symmetry in principle possible

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3. 4D gauge group:
   $\mathsf{SU}(3)_C \times \mathsf{SU}(2)_\mathrm{L} \times \mathsf{U}(1)_Y \times \mathsf{U}(1)_{B-L} \times [\mathsf{SU}(3) \times \mathsf{SU}(2)^2 \times \mathsf{U}(1)^7]$

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4. massless spectrum

$$\text{spectrum} \;=\; 3 \times \text{generation} + \text{vector-like}$$

5. Various appealing features:
   - vacua where exotics decouple at the linear level in SM singlets
   - non-trivial Yukawa couplings
   - gauge-top unification
   - SU(5) relation $y_\tau \simeq y_b$ (but also for light generations)

P. Hosteins, R. Kappl, M.R., K. Schmidt-Hoberg (2009)

for further discussion of this model see talks by M. Blaszczyk & S. Groot Nibbelink

‘Anomalous’ $\mathbb{Z}_4^R$ from the Blaszczyk et al. model

☞ We succeeded in finding vacua with the ‘anomalous’ $\mathbb{Z}_4^R$

. . . e.g. by switching on the fields

$$\{\phi_i\} = \{X_3, X_4, X_5, \overline{X}_4, \overline{X}_5, Y_1, Y_2, Z_1, Z_2, N_1, N_2, N_6, N_{11}, N_{17}, N_{25}, N_{26}, N_{28}, N_{35}, N_{37}, N_{45}, N_{47}, N_{49}, N_{51}, N_{53}, N_{55}\}$$

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- Two conditions:
  - vanishing F terms (no time to discuss)
  - vanishing D terms

Excursion: FI monomial quantization

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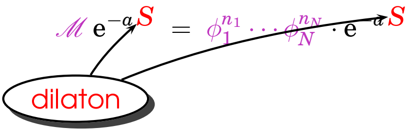

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R. Kappl, B. Petersen, M.R., R. Schieren & P. Vaudrevange (to appear)

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bottom-line:

FI monomials consistent with t’Hooft instantons

Non-perturbative violation of $\mathbb{Z}_4^R$

R. Kappl, B. Petersen, M.R., R. Schieren & P. Vaudrevange (to appear)

- Instanton couplings 'violate' $\mathbb{Z}_4^R$

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- We find that the Affleck-Dine-Seiberg potential

$$\mathscr{W}_{\mathrm{ADS}} = \left(\frac{\Lambda^{3N_c-N_f}}{\det M}\right)^{\frac{1}{N_c-N_f}}$$

$$\Lambda \simeq \mu\exp\left(-8\pi^2\,\frac{1}{3N_c-N_f}\,\frac{1}{g^2(\mu)}\right)$$

is also $\mathbb{Z}_4^R$ covariant

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meson determinant

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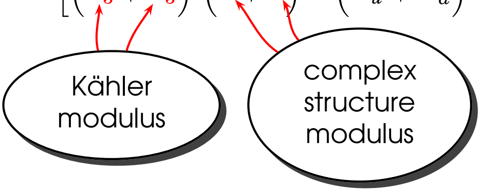
μ from $\mathscr{W}$

F. Brümmer, R. Kappl, M.R., K. Schmidt-Hoberg (2009)

☞ Higher-dimensional gauge invariance ↷ Kähler potential

Antoniadis, Gava, Narain & Taylor (1994); Choi et al. (2003)

$$K = -\ln\left[\left(T_3+\overline{T}_3\right)\left(Z+\overline{Z}\right)-\left(H_u+\overline{H}_d\right)\left(H_d+\overline{H}_u\right)\right]$$



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- Higher-dimensional gauge invariance $\curvearrowright$ Kähler potential

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Higgs fields
$=$ extra components
of gauge fields

μ from $\mathscr{W}$

F. Brümmer, R. Kappl, M.R., K. Schmidt-Hoberg (2009)

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$$
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K &= -\ln\left[\left(T_3+\overline{T_3}\right)\,\left(Z+\overline{Z}\right)-\left(H_u+\overline{H_d}\right)\,\left(H_d+\overline{H_u}\right)\right] \\
&\simeq -\ln\left[\left(T_3+\overline{T_3}\right)\,\left(Z+\overline{Z}\right)\right] \\
&\quad + \frac{1}{\left(T_3+\overline{T_3}\right)\,\left(Z+\overline{Z}\right)}\left[|H_u|^2+|H_d|^2+(H_u H_d+\text{c.c.})\right]
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$$

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&= -\ln\left[\left(T_3+\overline{T_3}\right)\,\left(Z+\overline{Z}\right)\right]+\left[|\widehat{H}_u|^2+|\widehat{H}_d|^2+(\widehat{H}_u\widehat{H}_d+\text{c.c.})\right]
\end{aligned}$$

normalized Higgs fields

μ from $\mathscr{W}$

F. Brümmer, R. Kappl, M.R., K. Schmidt-Hoberg (2009)

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- Consider now superpotential
  $\mathscr{W} = \Omega =$ independent of the monomial $\widehat{H}_u\widehat{H}_d$

μ from $\mathscr{W}$

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- Consider now superpotential
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- K & $\mathscr{W}$ in leading order in $\widehat{H}_u\widehat{H}_d$ equivalent to

$$K' = -\ln\left[\left(T_3+\overline{T_3}\right)\left(Z+\overline{Z}\right)\right]+\left[|\widehat{H}_u|^2+|\widehat{H}_d|^2\right]$$

$$\mathscr{W}' = \exp(\widehat{H}_u\,\widehat{H}_d)\,\Omega = \Omega\,\widehat{H}_u\,\widehat{H}_d+\dots$$

μ from $\mathscr{W}$

F. Brümmer, R. Kappl, M.R., K. Schmidt-Hoberg (2009)

- Higher-dimensional gauge invariance $\curvearrowright$ Kähler potential

$$K \simeq -\ln\left[\left(T_3+\overline{T_3}\right)\left(Z+\overline{Z}\right)\right]+\left[|\widehat{H}_u|^2+|\widehat{H}_d|^2+(\widehat{H}_u\widehat{H}_d+\text{c.c.})\right]$$

- Consider now superpotential
  $\mathscr{W} = \Omega =$ independent of the monomial $\widehat{H}_u\widehat{H}_d$

- K & $\mathscr{W}$ in leading order in $\widehat{H}_u\widehat{H}_d$ equivalent to

$$K' = -\ln\left[\left(T_3+\overline{T_3}\right)\left(Z+\overline{Z}\right)\right]+\left[|\widehat{H}_u|^2+|\widehat{H}_d|^2\right]$$

$$\mathscr{W}' = \exp(\widehat{H}_u\widehat{H}_d)\,\Omega = \Omega\,\widehat{H}_u\widehat{H}_d+\dots$$

bottom-line:

μ term proportional to $\langle\Omega\rangle$

Non-perturbative violation of $\mathbb{Z}_4^R$ (cont'd)

- Since $H_u H_d$ is proportional to $\langle \mathscr{W} \rangle$ we will get a holomorphic contribution to the μ term of the right order

Kim & Nilles (1983); Casas & Muñoz (1992)

$$\mu \sim \frac{\langle \mathscr{W} \rangle}{M_\mathrm{P}^2} \simeq m_{3/2}$$

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- Whatever gives us $\langle \mathscr{W} \rangle$ will be the order parameter for $\mathbb{Z}_4^R$ breaking

... for instance, one may replace/describe hidden sector superpotential by gaugino condensate

Nilles (1982)

$$\langle \mathscr{W} \rangle \simeq \langle \lambda\lambda \rangle \simeq \Lambda^3$$

- this is consistent with a non-perturbative breaking of $\mathbb{Z}_4^R$
- this assumes that the dilaton is fixed somehow (Kähler stabilization ...)

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- Dimension 5 proton decay operators will have highly suppressed coefficients

$$\mathscr{W}_{QQQL}^{\mathrm{np}} \sim \frac{\langle \mathscr{W} \rangle}{M_\mathrm{P}^4} Q\,Q\,Q\,L \sim \frac{m_{3/2}}{M_\mathrm{P}} \frac{1}{M_\mathrm{P}} Q\,Q\,Q\,L \sim 10^{-15}\,\frac{1}{M_\mathrm{P}} Q\,Q\,Q\,L$$

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- No R parity violation because $\mathbb{Z}_4^R$ has a non-anomalous subgroup which is equivalent to matter parity

Summary

&

outlook

Summary – bottom-up

☞ A simple 'anomalous' $\mathbb{Z}_4^R$ symmetry can

- provide a solution to the μ problem
- suppress proton decay operators

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☞ A simple 'anomalous' $\mathbb{Z}_4^R$ symmetry can

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$$\left.\begin{array}{r}\text{universal anomaly coefficients}\\ \text{universal charges for matter}\\ \text{forbid } \mu \text{ @ tree-level}\\ \text{allow Yukawa couplings}\\ \text{allow Weinberg operator}\end{array}\right\} \curvearrowright \text{unique } \mathbb{Z}_4^R$$

Summary – bottom-up

☞ A simple 'anomalous' $\mathbb{Z}_4^R$ symmetry can

- provide a solution to the μ problem
- suppress proton decay operators

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universal charges for matter
forbid μ @ tree-level
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} $\curvearrowright$ unique $\mathbb{Z}_4^R$

$\mathbb{Z}_4^R$ $\curvearrowright$ {
dim. 4 proton decay operators completely forbidden
dim. 5 proton decay operators highly suppressed
μ appears non-perturbatively

Summary – top-down

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Summary – top-down

- Embedding into string theory allows us to understand where the $\mathbb{Z}_4^R$ symmetry comes from: it may arise as a discrete remnant of Lorentz symmetry in extra dimensions
- Such symmetries are on the same footing as the fundamental symmetries C, P and T
- Guided by the (unique) $\mathbb{Z}_4^R$ symmetry we have constructed a globally consistent string model with:
  - exact MSSM spectrum
  - non-trivial Yukawa couplings
  - exact matter parity
  - $\mu \sim m_{3/2}$
  - dimension five proton decay operators sufficiently suppressed

Vielen Dank!