"Anomalous" discrete symmetries

Michael Ratz

TECHNISCHE
UNIVERSITÄT
MÜNCHEN

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 & P. Vaudrevange, to appear

MSSM: good features and open questions

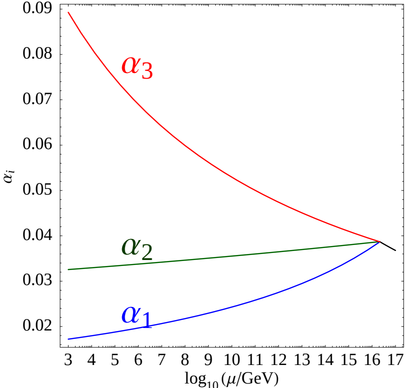
- ☞ Many studies focus on the minimal supersymmetric extension of the standard model (MSSM)

MSSM: good features and open questions

- ☞ Many studies focus on the minimal supersymmetric extension of the standard model (MSSM)
- ☞ Why?
  - ☺ stabilization of hierarchies

MSSM: good features and open questions

- ☞ Many studies focus on the minimal supersymmetric extension of the standard model (MSSM)
- ☞ Why?
    - ☺ stabilization of hierarchies
    - ☺ MSSM gauge coupling unification



MSSM: good features and open questions

- ☞ Many studies focus on the minimal supersymmetric extension of the standard model (MSSM)
- ☞ Why?
  - ☺ stabilization of hierarchies
  - ☺ MSSM gauge coupling unification
  - ☺ radiative electroweak symmetry breaking

MSSM: good features and open questions

- ☞ Many studies focus on the minimal supersymmetric extension of the standard model (MSSM)
- ☞ Why?
  - ☺ stabilization of hierarchies
  - ☺ MSSM gauge coupling unification
  - ☺ radiative electroweak symmetry breaking
  - ☺ dark matter candidate

MSSM: good features and open questions

☞ Many studies focus on the minimal supersymmetric extension of the standard model (MSSM)

☞ Why?
  ☺ stabilization of hierarchies
  ☺ MSSM gauge coupling unification
  ☺ radiative electroweak symmetry breaking
  ☺ dark matter candidate
  ☺ . . .

MSSM: good features and open questions

- Many studies focus on the minimal supersymmetric extension of the standard model (MSSM)
- Why?
  - ☺ stabilization of hierarchies
  - ☺ MSSM gauge coupling unification
  - ☺ radiative electroweak symmetry breaking
  - ☺ dark matter candidate
  - ☺ . . .
- However:
  - ☹ $\mu/B\mu$ problem

MSSM: good features and open questions

- ☞ Many studies focus on the minimal supersymmetric extension of the standard model (MSSM)
- ☞ Why?
  - ☺ stabilization of hierarchies
  - ☺ MSSM gauge coupling unification
  - ☺ radiative electroweak symmetry breaking
  - ☺ dark matter candidate
  - ☺ ...
- ☞ However:
  - ☹ $\mu/B\mu$ problem
  - ☹ dimension four and five proton decay operators

MSSM: good features and open questions

☞ Many studies focus on the minimal supersymmetric extension of the standard model (MSSM)

☞ Why?

- ☺ stabilization of hierarchies
- ☺ MSSM gauge coupling unification
- ☺ radiative electroweak symmetry breaking
- ☺ dark matter candidate
- ☺ . . .

☞ However:

- ☹ $\mu/B\mu$ problem
- ☹ dimension four and five proton decay operators
- ☹ CP and flavor problems

MSSM: good features and open questions

- ☞ Many studies focus on the minimal supersymmetric extension of the standard model (MSSM)
- ☞ Why?
  - ☺ stabilization of hierarchies
  - ☺ MSSM gauge coupling unification
  - ☺ radiative electroweak symmetry breaking
  - ☺ dark matter candidate
  - ☺ . . .
- ☞ However:
  - ☹ $\mu/B\mu$ problem
  - ☹ dimension four and five proton decay operators
  - ☹ CP and flavor problems

➥ 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

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

Proton decay operators

☞ Gauge invariant superpotential terms up to order 4 include

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

need to be strongly suppressed

Proton decay operators

- Gauge invariant superpotential terms up to order 4 include

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

forbidden by matter parity

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

Proton decay operators

- Gauge invariant superpotential terms up to order 4 include

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

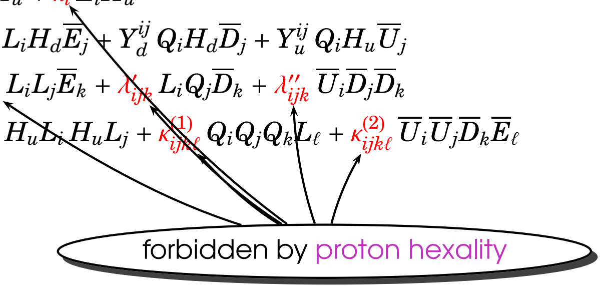
forbidden by baryon triality

Ibáñez & Ross (1992)

Proton decay operators

- Gauge invariant superpotential terms up to order 4 include

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



forbidden by proton hexality

Dreiner, Luhn & Thormeier (2006)

- Proton hexality = matter parity + baryon triality

Ibáñez & Ross (1992)

Dreiner, Luhn & Thormeier (2006)

Proton hexality

Ibáñez & Ross (1992); Dreiner, Luhn & Thormeier (2006)

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

	Q	U	D	L	E	H_u	H_d	$\overline{\nu}$
$\mathbb{Z}_2^\mathcal{M}$	1	1	1	1	1	0	0	1
B_3	0	-1	1	-1	2	1	-1	0
P_6	0	1	-1	-2	1	-1	1	3

Proton hexality

Ibáñez & Ross (1992); Dreiner, Luhn & Thormeier (2006)

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

	Q	U	D	L	E	H_u	H_d	$\overline{\nu}$
$\mathbb{Z}_2^{\mathcal{M}}$	1	1	1	1	1	0	0	1
B_3	0	-1	1	-1	2	1	-1	0
P_6	0	1	-1	-2	1	-1	1	3

- ☞ Appealing features
  - ☺ forbids dimension four and five proton decay operators

Proton hexality

Ibáñez & Ross (1992); Dreiner, Luhn & Thormeier (2006)

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

	Q	U	D	L	E	H_u	H_d	$\bar{\nu}$
$\mathbb{Z}_2^{\mathcal{M}}$	1	1	1	1	1	0	0	1
B_3	0	-1	1	-1	2	1	-1	0
P_6	0	1	-1	-2	1	-1	1	3

- Appealing features
  - ☺ forbids dimension four and five proton decay operators
  - ☺ allows Yukawa couplings, Weinberg operator $\kappa_{ij}^{(0)} H_u L_i H_u L_j$ and μ term

Proton hexality

Ibáñez & Ross (1992); Dreiner, Luhn & Thormeier (2006)

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

	Q	U	D	L	E	H_u	H_d	$\overline{\nu}$
$\mathbb{Z}_2^{\mathcal{M}}$	1	1	1	1	1	0	0	1
B_3	0	−1	1	−1	2	1	−1	0
P_6	0	1	−1	−2	1	−1	1	3

- Appealing features
  - forbids dimension four and five proton decay operators
  - allows Yukawa couplings, Weinberg operator $\kappa_{ij}^{(0)} H_u L_i H_u L_j$ and μ term
  - unique anomaly-free symmetry with the above features

Proton hexality

Ibáñez & Ross (1992); Dreiner, Luhn & Thormeier (2006)

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

	Q	U	D	L	E	H_u	H_d	$\overline{\nu}$
$\mathbb{Z}_2^{\mathcal{M}}$	1	1	1	1	1	0	0	1
B_3	0	-1	1	-1	2	1	-1	0
P_6	0	1	-1	-2	1	-1	1	3

- Appealing features
  - ☺ forbids dimension four and five proton decay operators
  - ☺ allows Yukawa couplings, Weinberg operator $\kappa_{ij}^{(0)}\,H_uL_i\,H_uL_j$ and μ term
  - ☺ unique anomaly-free symmetry with the above features
- However:
  - ☹ not consistent with unification for matter (i.e. inconsistent with universal discrete charges for all matter fields)

Proton hexality

Ibáñez & Ross (1992); Dreiner, Luhn & Thormeier (2006)

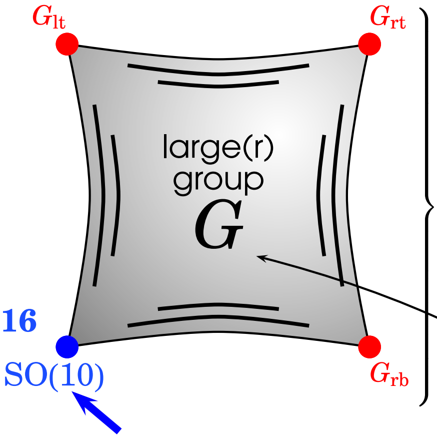
- Proton hexality P_6 = matter parity $\mathbb{Z}_2^{\mathcal{M}}$ × baryon triality B_3

	Q	U	D	L	E	H_u	H_d	$\bar{\nu}$
$\mathbb{Z}_2^{\mathcal{M}}$	1	1	1	1	1	0	0	1
B_3	0	-1	1	-1	2	1	-1	0
P_6	0	1	-1	-2	1	-1	1	3

- Appealing features
  - ☺ forbids dimension four and five proton decay operators
  - ☺ allows Yukawa couplings, Weinberg operator $\kappa_{ij}^{(0)}\,H_uL_i\,H_uL_j$ and μ term
  - ☺ unique anomaly-free symmetry with the above features
- However:
  - ☹ not consistent with unification for matter
  - ☹ 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)

$\xrightarrow[\text{effective theory}]{\text{`low-energy'}}$

standard model as an intersection of $G_{\mathrm{rb}}, G_{\mathrm{rt}}, G_{\mathrm{lt}}$ & $\mathrm{SO}(10)$ in G

SM generation(s):

localized in region with $\mathrm{SO}(10)$ symmetry

Higgs doublets:

live in the 'bulk'

Proton hexality

- ☞ Disturbing aspects of proton hexality
  - ☹ not consistent with (local grand) unification for matter

Proton hexality

- ☞ Disturbing aspects of proton hexality
  - ☹ not consistent with (local grand) unification for matter
  - ☹ embedding into string theory not yet fully convincing

Proton hexality

☞ Disturbing aspects of proton hexality

- ☹ not consistent with (local grand) unification for matter
- ☹ embedding into string theory not yet fully convincing
- ☹ does not address μ problem

Proton hexality

☞ Disturbing aspects of proton hexality
- ☹ not consistent with (local grand) unification for matter
- ☹ embedding into string theory not yet fully convincing
- ☹ does not address μ problem

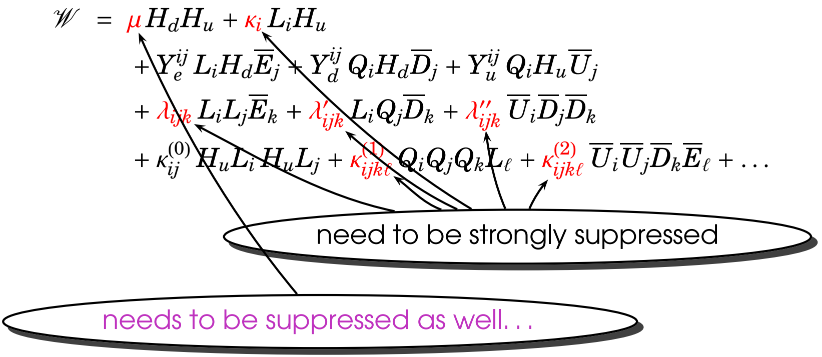
$$\begin{aligned}\mathscr{W} \;=\; & \mu H_d H_u + \kappa_i L_i H_u \\ & + Y_e^{ij} L_i H_d \overline{E}_j + Y_d^{ij} Q_i H_d \overline{D}_j + Y_u^{ij} Q_i H_u \overline{U}_j \\ & + \lambda_{ijk} L_i L_j \overline{E}_k + \lambda'_{ijk} L_i Q_j \overline{D}_k + \lambda''_{ijk} \overline{U}_i \overline{D}_j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

need to be strongly suppressed

Proton hexality

☞ Disturbing aspects of proton hexality

- ☹ not consistent with (local grand) unification for matter
- ☹ embedding into string theory not yet fully convincing
- ☹ does not address μ problem



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

need to be strongly suppressed

needs to be suppressed as well. . .

Origin of discrete symmetries

☞ Where can the discrete symmetries come from?

Origin of discrete symmetries

- ☞ Where can the discrete symmetries come from?
- ☞ Possible answer: higher dimensions and strings

Origin of discrete symmetries

- ☞ Where can the discrete symmetries come from?
- ☞ Possible answer: higher dimensions and strings
- ☞ What does string theory give us?

Origin of discrete symmetries

- ☞ Where can the discrete symmetries come from?
- ☞ Possible answer: higher dimensions and strings
- ☞ What does string theory give us?
  - unification with gravity

Origin of discrete symmetries

- ☞ Where can the discrete symmetries come from?
- ☞ Possible answer: higher dimensions and strings
- ☞ What does string theory give us?
  - unification with gravity
  - extra gauge symmetries

Origin of discrete symmetries

- ☞ Where can the discrete symmetries come from?
- ☞ Possible answer: higher dimensions and strings
- ☞ What does string theory give us?
  - unification with gravity
  - extra gauge symmetries
  - discrete symmetries

Origin of discrete symmetries

☞ Where can the discrete symmetries come from?

☞ Possible answer: higher dimensions and strings

☞ What does string theory give us?
- unification with gravity
- extra gauge symmetries
- discrete symmetries
- Green-Schwarz anomaly cancellation

Origin of discrete symmetries

☞ Where can the discrete symmetries come from?

☞ Possible answer: higher dimensions and strings

☞ What does string theory give us?

- unification with gravity
- extra gauge symmetries
- discrete symmetries
- Green-Schwarz anomaly cancellation
- MSSM models with Local Grand Unification

Origin of discrete symmetries

- ☞ Where can the discrete symmetries come from?
- ☞ Possible answer: higher dimensions and strings
- ☞ What does string theory give us?
  - unification with gravity
  - extra gauge symmetries
  - discrete symmetries
  - Green-Schwarz anomaly cancellation
  - MSSM models with Local Grand Unification
  - . . .

Origin of discrete symmetries

☞ Where can the discrete symmetries come from?

☞ Possible answer: higher dimensions and strings

☞ What does string theory give us?

- unification with gravity
- extra gauge symmetries
- discrete symmetries
- Green-Schwarz anomaly cancellation
- MSSM models with Local Grand Unification
- . . .

↪ 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

‘anomalous’ discrete symmetries:

Anomalies of discrete symmetries canceled by 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

‘anomalous’ discrete symmetries:

Anomalies of discrete symmetries canceled by Green-Schwarz mechanism

➥ Anomaly freedom gets relaxed to anomaly universality

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

'anomalous' discrete symmetries:

Anomalies of discrete symmetries canceled by Green-Schwarz mechanism

➥ Anomaly freedom gets relaxed to anomaly universality

Example: anomaly coefficients for $\mathbb{Z}_N$

$$A_{G^2-\mathbb{Z}_N} = \sum_f \ell^{(f)} \cdot q^{(f)}$$

$$A_{\mathrm{grav}^2-\mathbb{Z}_N} = \sum_m q^{(m)}$$

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

‘anomalous’ discrete symmetries:

Anomalies of discrete symmetries canceled by Green-Schwarz mechanism

➥ Anomaly freedom gets relaxed to anomaly universality

Example: anomaly coefficients for $\mathbb{Z}_N$

$$A_{G^2-\mathbb{Z}_N} = \sum_{f} \ell^{(f)} \cdot q^{(f)}$$

sum over all representations of G

$$A_{\mathrm{grav}^2-\mathbb{Z}_N} = \sum_{m} q^{(m)}$$

sum over all fermions

From anomaly freedom to anomaly universality

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

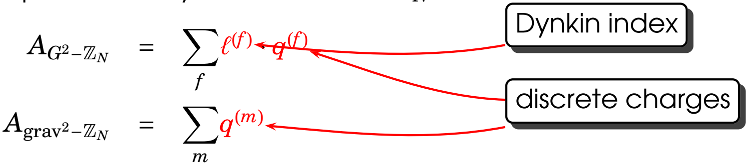
☞ Important lesson from explicit string-derived (MSSM) models

‘anomalous’ discrete symmetries:

Anomalies of discrete symmetries canceled by Green-Schwarz mechanism

➥ Anomaly freedom gets relaxed to anomaly universality

Example: anomaly coefficients for $\mathbb{Z}_N$



$$A_{G^2-\mathbb{Z}_N} = \sum_f \ell^{(f)}\, q^{(f)}$$

$$A_{\mathrm{grav}^2-\mathbb{Z}_N} = \sum_m q^{(m)}$$

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

‘anomalous’ discrete symmetries:

Anomalies of discrete symmetries canceled by Green-Schwarz mechanism

➥ Anomaly freedom gets relaxed to anomaly universality

Example: anomaly coefficients for $\mathbb{Z}_N$

$$
\begin{aligned}
A_{G^2-\mathbb{Z}_N} &= \sum_f \ell^{(f)} \cdot q^{(f)} \overset{!}{=} 0 \mod N(/2) \\
A_{\text{grav}^2-\mathbb{Z}_N} &= \sum_m q^{(m)} \overset{!}{=} 0 \mod N(/2)
\end{aligned}
$$

anomaly freedom:

all A coefficients vanish

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

‘anomalous’ discrete symmetries:

Anomalies of discrete symmetries canceled by Green-Schwarz mechanism

➥ Anomaly freedom gets relaxed to anomaly universality

Example: anomaly coefficients for $\mathbb{Z}_N$

$$A_{G^2-\mathbb{Z}_N} = \sum_f \ell^{(f)} \cdot q^{(f)} \overset{!}{=} \gamma \mod N(/2)$$

$$A_{\mathrm{grav}^2-\mathbb{Z}_N} = \sum_m q^{(m)} \overset{!}{=} \gamma \mod N(/2)$$

anomaly freedom:

all A coefficients vanish

⬇ ⬇ ⬇ ⬇ ⬇

anomaly universality:

all A coefficients equal

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

☞ Assumptions:

  - anomaly universality

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

☞ Assumptions:

- anomaly universality
- universal charges for quarks and leptons

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

☞ Assumptions:

- anomaly universality
- universal charges for quarks and leptons
- μ term forbidden at perturbative level

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

☞ Assumptions:

- anomaly universality
- universal charges for quarks and leptons
- μ term forbidden at perturbative level
- Yukawa couplings and Weinberg neutrino mass operator allowed

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

☞ 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

$$\begin{aligned} A_{\mathrm{SU}(3)^2-\mathbb{Z}_N} &= \frac{9}{2} q_{\mathbf{10}} + \frac{3}{2} q_{\overline{\mathbf{5}}} \\ A_{\mathrm{SU}(2)^2-\mathbb{Z}_N} &= \frac{9}{2} q_{\mathbf{10}} + \frac{3}{2} q_{\overline{\mathbf{5}}} + \frac{1}{2}\left(q_{H_u} + q_{H_d}\right) \end{aligned}$$

Claim 1: it has to be an R symmetry

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

$$\begin{aligned} A_{\mathrm{SU}(3)^2-\mathbb{Z}_N} &= \frac{9}{2}q_{\mathbf{10}} + \frac{3}{2}q_{\overline{\mathbf{5}}} \\ A_{\mathrm{SU}(2)^2-\mathbb{Z}_N} &= \frac{9}{2}q_{\mathbf{10}} + \frac{3}{2}q_{\overline{\mathbf{5}}} + \frac{1}{2}\left(q_{H_u} + q_{H_d}\right) \end{aligned}$$

- ☞ Anomaly universality

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

Claim 1: it has to be an R symmetry

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

$$\begin{aligned} A_{\mathrm{SU}(3)^2-\mathbb{Z}_N} &= \frac{9}{2} q_{\mathbf{10}} + \frac{3}{2} q_{\overline{\mathbf{5}}} \\ A_{\mathrm{SU}(2)^2-\mathbb{Z}_N} &= \frac{9}{2} q_{\mathbf{10}} + \frac{3}{2} q_{\overline{\mathbf{5}}} + \frac{1}{2}\left(q_{H_u} + q_{H_d}\right) \end{aligned}$$

- ☞ Anomaly universality

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

bottom-line:

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

Claim 2: Higgs discrete charges have to vanish

☞ Assumption: quarks and leptons have universal charge r

Claim 2: Higgs discrete charges have to vanish

- ☞ Assumption: quarks and leptons have universal charge r
- ☞ u- and d-type Yukawas allowed requires that

$$2r + r_{H_u} \;=\; 2 \mod N \quad \text{and} \quad 2r + r_{H_d} \;=\; 2 \mod N$$

Claim 2: Higgs discrete charges have to vanish

- ☞ Assumption: quarks and leptons have universal charge r
- ☞ u- and d-type Yukawas allowed requires that

$$2r + r_{H_u} = 2 \mod N \quad \text{and} \quad 2r + r_{H_d} = 2 \mod N$$

$$\curvearrowright \quad r_{H_u} - r_{H_d} = 0 \mod N$$

Claim 2: Higgs discrete charges have to vanish

- ☞ Assumption: quarks and leptons have universal charge r
- ☞ u- and d-type Yukawas allowed requires that

$$2r + r_{H_u} = 2 \mod N \quad \text{and} \quad 2r + r_{H_d} = 2 \mod N$$

$$\curvearrowright \quad r_{H_u} - r_{H_d} = 0 \mod N$$

- ☞ u-type Yukawa and Weinberg operator allowed requires that

$$2r + r_{H_u} = 2 \mod N \quad \text{and} \quad 2r + 2r_{H_u} = 2 \mod N$$

Claim 2: Higgs discrete charges have to vanish

- ☞ Assumption: quarks and leptons have universal charge r
- ☞ u- and d-type Yukawas allowed requires that

$$2r + r_{H_u} = 2 \mod N \quad \text{and} \quad 2r + r_{H_d} = 2 \mod N$$

$$\curvearrowright \quad r_{H_u} - r_{H_d} = 0 \mod N$$

- ☞ u-type Yukawa and Weinberg operator allowed requires that

$$2r + r_{H_u} = 2 \mod N \quad \text{and} \quad 2r + 2r_{H_u} = 2 \mod N$$

$$\curvearrowright \quad r_{H_u} = 0 \mod N$$

Claim 2: Higgs discrete charges have to vanish

- Assumption: quarks and leptons have universal charge r
- u- and d-type Yukawas allowed requires that

$$2r + r_{H_u} = 2 \mod N \quad \text{and} \quad 2r + r_{H_d} = 2 \mod N$$

$$\curvearrowright \quad r_{H_u} - r_{H_d} = 0 \mod N$$

- u-type Yukawa and Weinberg operator allowed requires that

$$2r + r_{H_u} = 2 \mod N \quad \text{and} \quad 2r + 2r_{H_u} = 2 \mod N$$

$$\curvearrowright \quad r_{H_u} = 0 \mod N$$

bottom-line:

$$r_{H_u} = r_{H_d} = 0 \mod N$$

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

☞ Anomaly coefficients for Abelian discrete R symmetry

$$\begin{aligned} A_{\mathrm{SU}(3)^2-\mathbb{Z}_N^R} &= 6(r-1)+3 = 6r-3 \\ A_{\mathrm{SU}(2)^2-\mathbb{Z}_N^R} &= 6r+\frac{1}{2}\left(r_{H_u}+r_{H_d}\right)-5 \end{aligned}$$

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

☞ Anomaly coefficients for Abelian discrete R symmetry

$$\begin{aligned} A_{\mathrm{SU}(3)^2-\mathbb{Z}_N^R} &= 6(r-1)+3 \;=\; 6r-3 \\ A_{\mathrm{SU}(2)^2-\mathbb{Z}_N^R} &= 6r+\frac{1}{2}\left(r_{H_u}+r_{H_d}\right)-5 \end{aligned}$$

☞ Anomaly universality

$$A_{\mathrm{SU}(2)^2-\mathbb{Z}_N^R} - A_{\mathrm{SU}(3)^2-\mathbb{Z}_N^R} = 0$$

$$\curvearrowright \quad r_{H_u}+r_{H_d} = 4 \mod \begin{cases} 2N & \text{for } N \text{ odd} \\ N & \text{for } N \text{ even} \end{cases}$$

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

- ☞ Anomaly coefficients for Abelian discrete R symmetry

$$\begin{aligned} A_{\mathrm{SU}(3)^2-\mathbb{Z}_N^R} &= 6(r-1)+3 = 6r-3 \\ A_{\mathrm{SU}(2)^2-\mathbb{Z}_N^R} &= 6r+\frac{1}{2}\left(r_{H_u}+r_{H_d}\right)-5 \end{aligned}$$

- ☞ Anomaly universality

$$A_{\mathrm{SU}(2)^2-\mathbb{Z}_N^R} - A_{\mathrm{SU}(3)^2-\mathbb{Z}_N^R} = 0$$

$$\curvearrowright \quad r_{H_u}+r_{H_d} = 4 \mod \begin{cases} 2N & \text{for } N \text{ odd} \\ N & \text{for } N \text{ even} \end{cases}$$

- ☞ but we know already that $r_{H_u} = r_{H_d} = 0 \mod N$

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

- ☞ Anomaly coefficients for Abelian discrete R symmetry

$$\begin{aligned} A_{\mathrm{SU}(3)^2-\mathbb{Z}_N^R} &= 6(r-1)+3 \;=\; 6r-3 \\ A_{\mathrm{SU}(2)^2-\mathbb{Z}_N^R} &= 6r+\frac{1}{2}\left(r_{H_u}+r_{H_d}\right)-5 \end{aligned}$$

- ☞ Anomaly universality

$$A_{\mathrm{SU}(2)^2-\mathbb{Z}_N^R} - A_{\mathrm{SU}(3)^2-\mathbb{Z}_N^R} \;=\; 0$$

$$\curvearrowright \quad r_{H_u}+r_{H_d} \;=\; 4 \mod \begin{cases} 2N & \text{for } N \text{ odd} \\ N & \text{for } N \text{ even} \end{cases}$$

- ☞ but we know already that $r_{H_u} = r_{H_d} = 0 \mod N$

bottom-line:

$N = 2$ or $N = 4$

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

- Anomaly coefficients for Abelian discrete R symmetry

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

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

- Anomaly universality

$$A_{\mathrm{SU}(2)^2-\mathbb{Z}_N^R} - A$$

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

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

$$\Leftrightarrow \quad r_{H_u}+r_{H_d} = 4 \mod \Big\{ N \quad \text{for } N \text{ even}$$

- but we know already that $r_{H_u} = r_{H_d} = 0 \mod N$

bottom-line:

$N = 2$ or $N = 4$

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

- Anomaly coefficients for Abelian discrete R symmetry

$$
\begin{aligned}
A_{\mathrm{SU}(3)^2-\mathbb{Z}_N^R} &= 6(r-1)+3 \;=\; 6r-3 \\
A_{\mathrm{SU}(2)^2-\mathbb{Z}_N^R} &= 6r+\frac{1}{2}\left(r_{H_u}+r_{H_d}\right)-5
\end{aligned}
$$

- Anomaly universality

$$
\begin{aligned}
A_{\mathrm{SU}(2)^2-\mathbb{Z}_N^R} - A_{\mathrm{SU}(3)^2-\mathbb{Z}_N^R} &= 0 \\
\curvearrowright \quad r_{H_u}+r_{H_d} &= 4 \mod \begin{cases} 2N & \text{for } N \text{ odd} \\ N & \text{for } N \text{ even} \end{cases}
\end{aligned}
$$

- but we know already that $r_{H_u} = r_{H_d} = 0 \mod N$

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 $r_{H_u} = r_{H_d} = 0 \mod 4$

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

☞ We know:

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

➥ Yukawa couplings and Weinberg operator allowed $\curvearrowright$ matter has charge $r = 1$

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

☞ We know:

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

↪ Yukawa couplings and Weinberg operator allowed ↷ matter has charge $r = 1$

☞ Consistent with anomaly universality

$$\begin{aligned}
A_{\mathrm{SU}(3)^2-\mathbb{Z}_N^R} &= 6(r-1)+3 \;=\; 6r-3 \;=\; 1 \mod 4/2 \\
A_{\mathrm{SU}(2)^2-\mathbb{Z}_N^R} &= 6r+\frac{1}{2}\left(r_{H_u}+r_{H_d}\right)-5 \;=\; 1 \mod 4/2 \\
A_{\mathrm{grav}^2-\mathbb{Z}_N^R} &= -61+48r+2r_{H_u}+2r_{H_d} \;=\; 1 \mod 4/2
\end{aligned}$$

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

☞ We know:

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

↪ Yukawa couplings and Weinberg operator allowed $\curvearrowright$ matter has charge $r = 1$

☞ Consistent with anomaly universality

$$\begin{aligned}
A_{\mathrm{SU}(3)^2-\mathbb{Z}_N^R} &= 6(r-1)+3 \;=\; 6r-3 \;=\; 1 \mod 4/2 \\
A_{\mathrm{SU}(2)^2-\mathbb{Z}_N^R} &= 6r + \frac{1}{2}\left(r_{H_u} + r_{H_d}\right) - 5 \;=\; 1 \mod 4/2 \\
A_{\mathrm{grav}^2-\mathbb{Z}_N^R} &= -61 + 48r + 2r_{H_u} + 2r_{H_d} \;=\; 1 \mod 4/2
\end{aligned}$$

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

Kurosawa, Maru & Yanagida (2001)

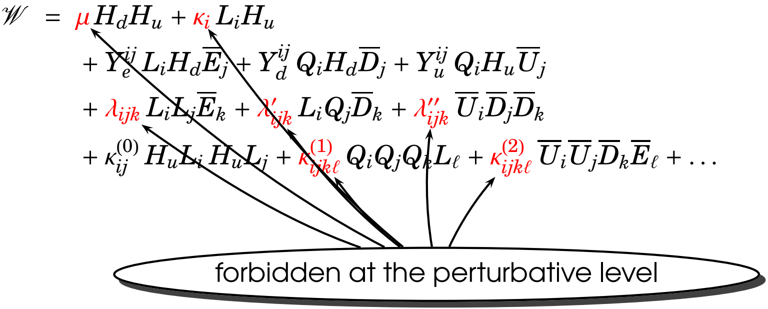
Implications of $\mathbb{Z}_4^R$

☞ Gauge invariant superpotential terms up to order 4

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

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

- Gauge invariant superpotential terms up to order 4



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

forbidden at the perturbative level

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

- ☞ Gauge invariant superpotential terms up to order 4

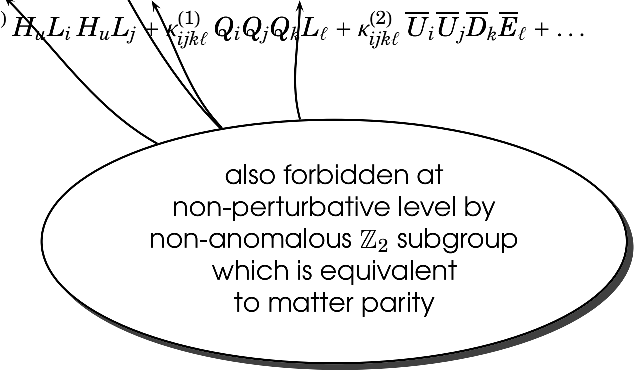
$$\begin{aligned}\mathscr{W} \;=\; & \mu\, H_d H_u + \kappa_i\, L_i H_u \\ & + Y_e^{ij}\, L_i H_d \overline{E}_j + Y_d^{ij}\, Q_i H_d \overline{D}_j + Y_u^{ij}\, Q_i H_u \overline{U}_j \\ & + \lambda_{ijk}\, L_i L_j \overline{E}_k + \lambda'_{ijk}\, L_i Q_j \overline{D}_k + \lambda''_{ijk}\, \overline{U}_i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

appear at non-perturbative level

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

- Gauge invariant superpotential terms up to order 4

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



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

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

☞ Gauge invariant superpotential terms up to order 4

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

non-perturbative generation of μ solves the μ problem

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

☞ Gauge invariant superpotential terms up to order 4

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

non-perturbatively generated terms harmless

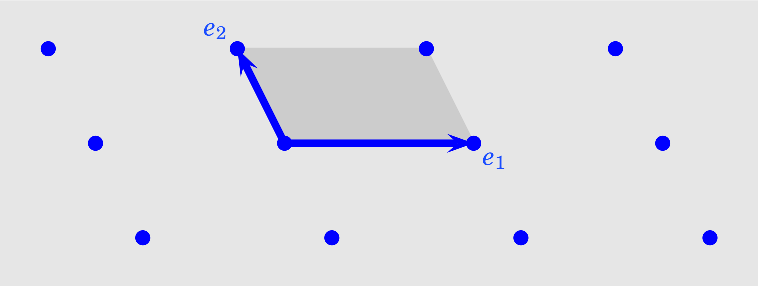
An explicit string-derived example

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

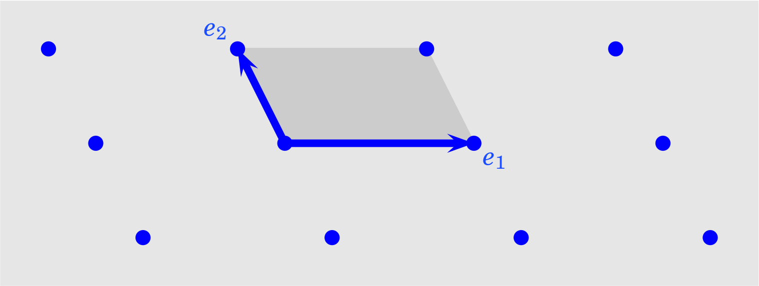
The $\mathbb{Z}_2$ orbifold plane

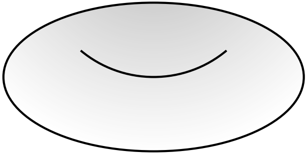
2D space with SO(2) rotational symmetry

The $\mathbb{Z}_2$ orbifold plane

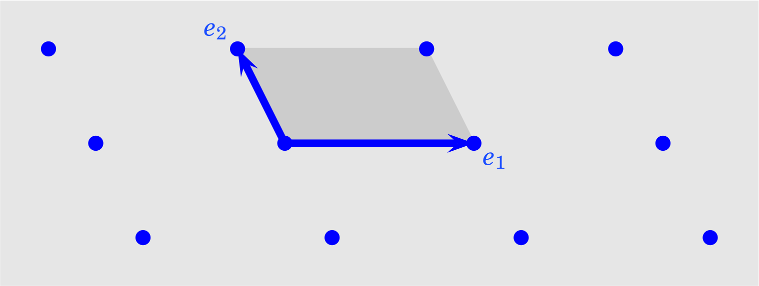


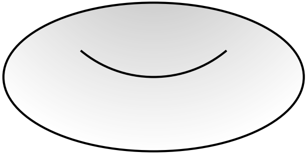
The $\mathbb{Z}_2$ orbifold plane



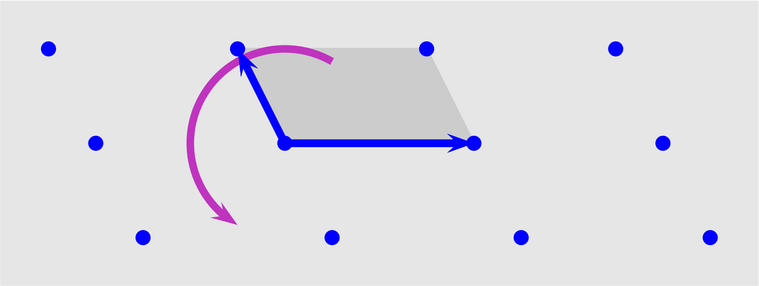


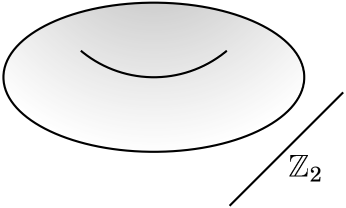
The $\mathbb{Z}_2$ orbifold plane



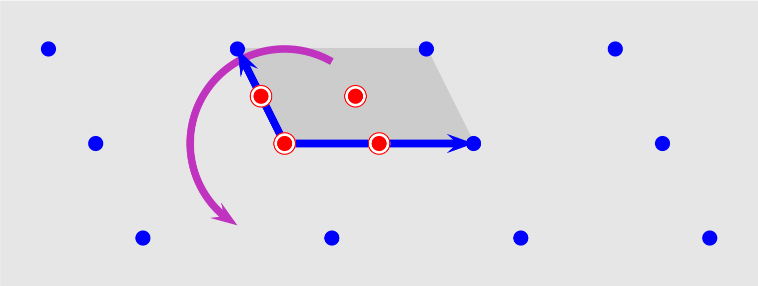


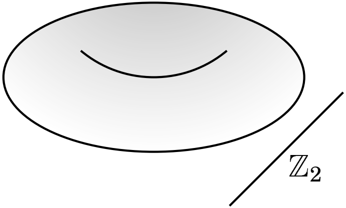
The $\mathbb{Z}_2$ orbifold plane



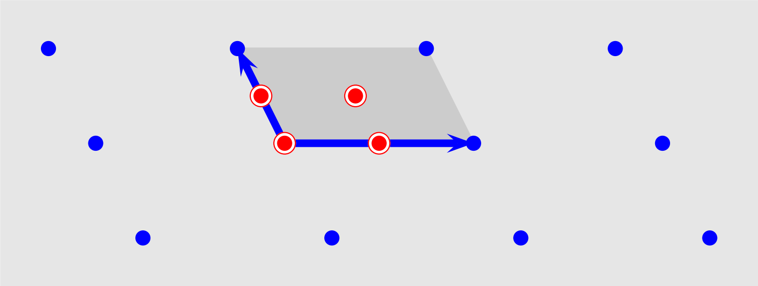


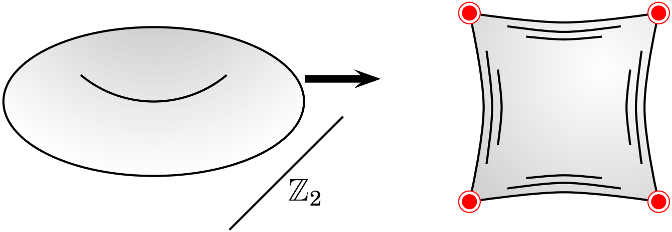
The $\mathbb{Z}_2$ orbifold plane



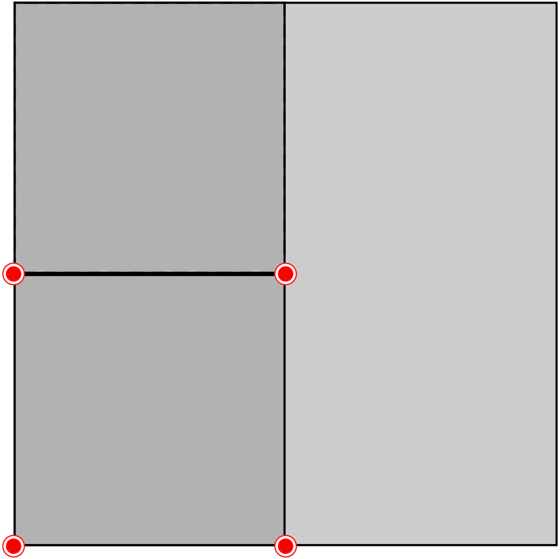


The $\mathbb{Z}_2$ orbifold plane

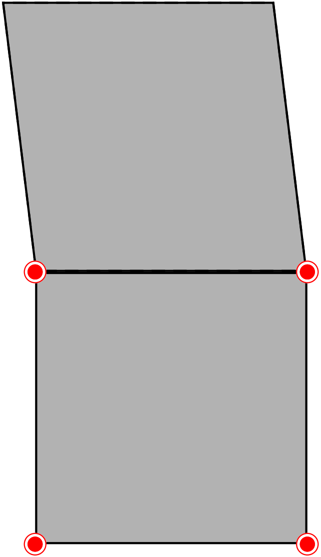




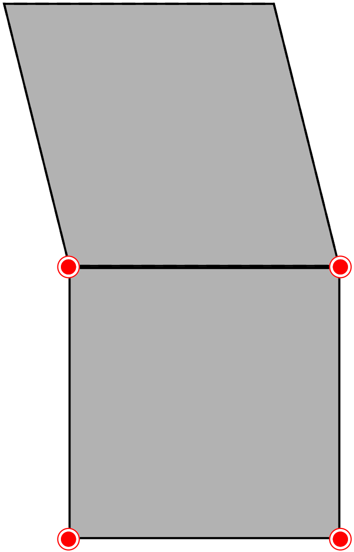
$\mathbb{Z}_2$ orbifold pillow



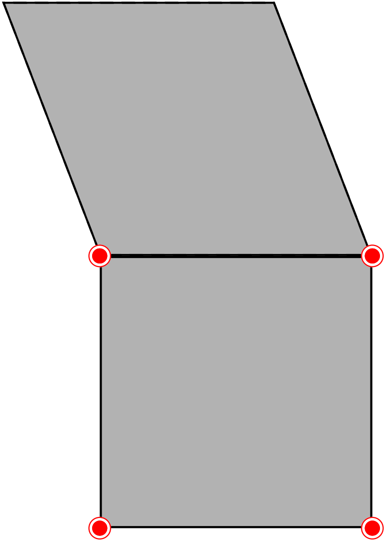
$\mathbb{Z}_2$ orbifold pillow



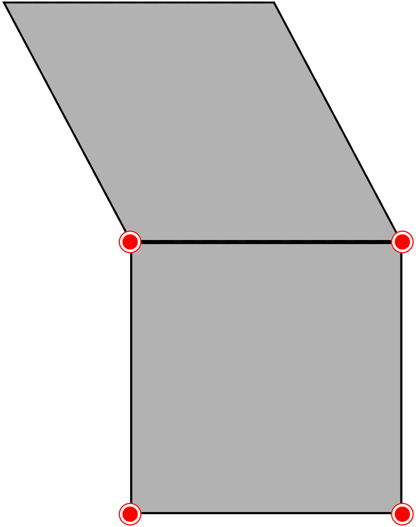
$\mathbb{Z}_2$ orbifold pillow



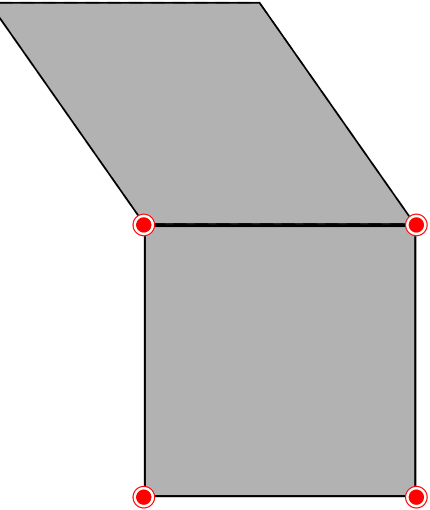
$\mathbb{Z}_2$ orbifold pillow



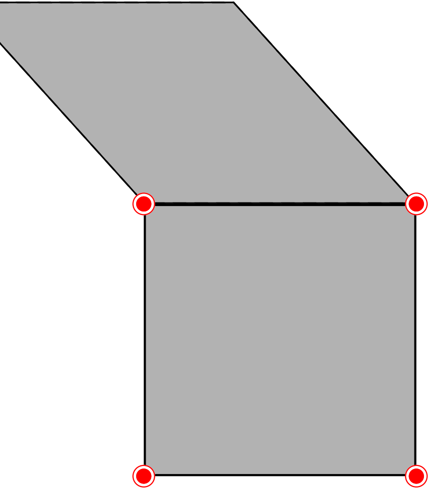
$\mathbb{Z}_2$ orbifold pillow



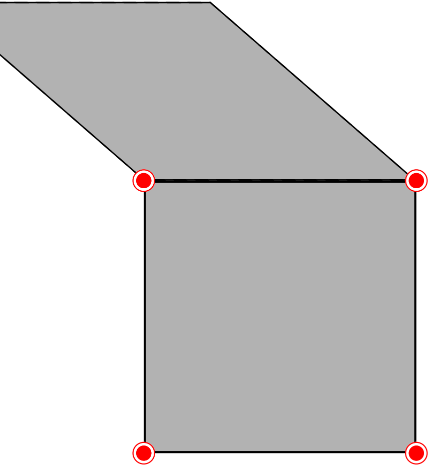
$\mathbb{Z}_2$ orbifold pillow



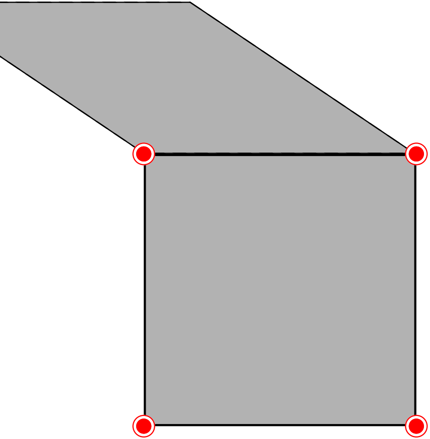
$\mathbb{Z}_2$ orbifold pillow



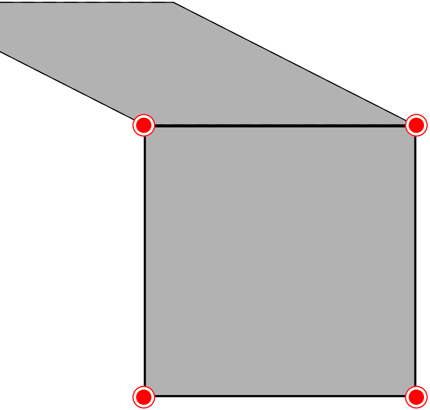
$\mathbb{Z}_2$ orbifold pillow



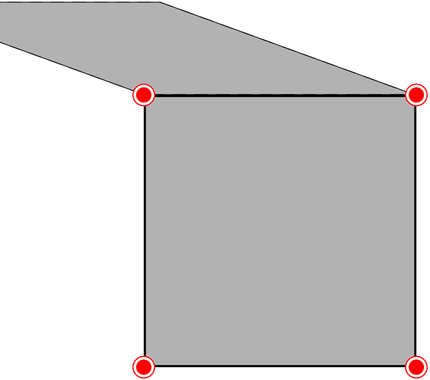
$\mathbb{Z}_2$ orbifold pillow



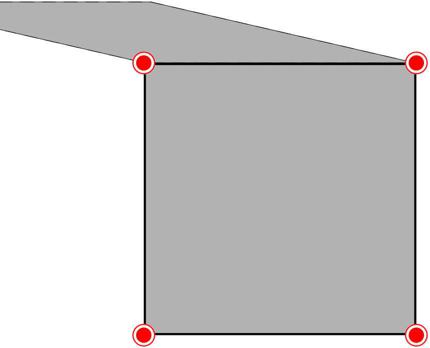
$\mathbb{Z}_2$ orbifold pillow



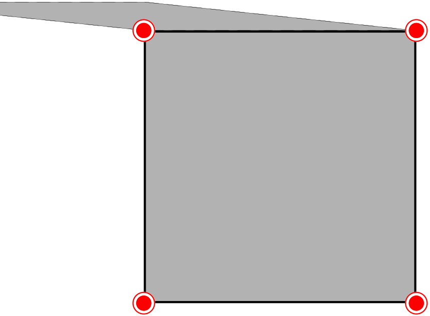
$\mathbb{Z}_2$ orbifold pillow



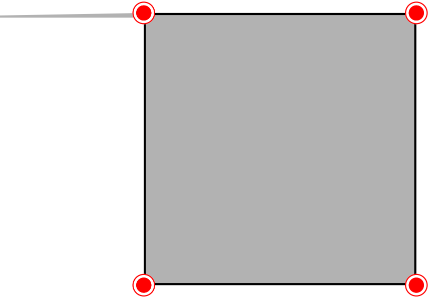
$\mathbb{Z}_2$ orbifold pillow



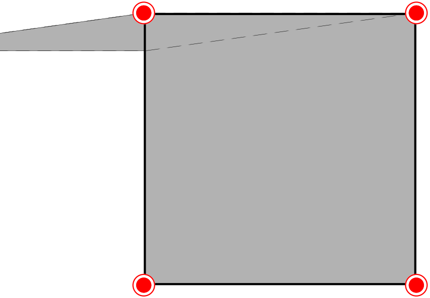
$\mathbb{Z}_2$ orbifold pillow



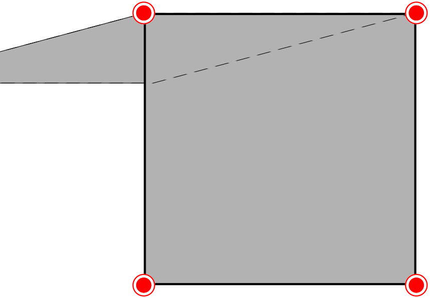
$\mathbb{Z}_2$ orbifold pillow



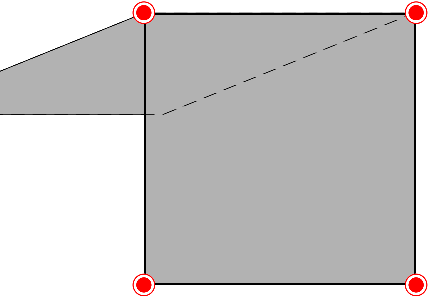
$\mathbb{Z}_2$ orbifold pillow



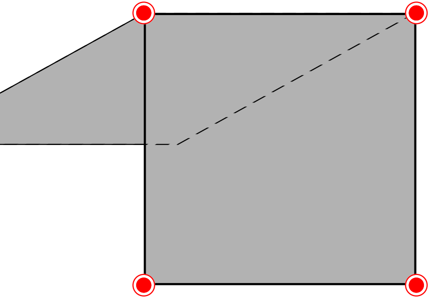
$\mathbb{Z}_2$ orbifold pillow



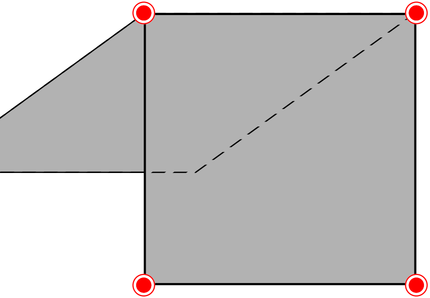
$\mathbb{Z}_2$ orbifold pillow



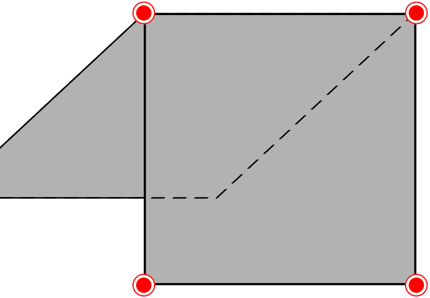
$\mathbb{Z}_2$ orbifold pillow



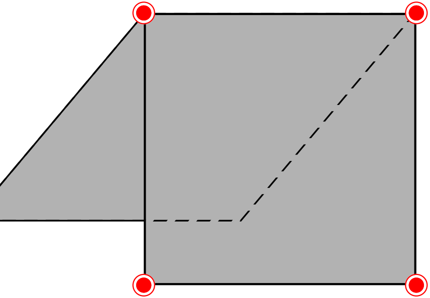
$\mathbb{Z}_2$ orbifold pillow



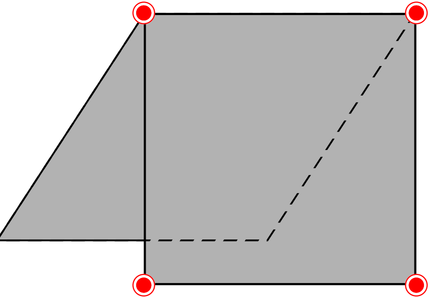
$\mathbb{Z}_2$ orbifold pillow



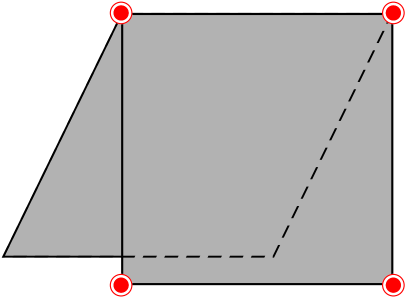
$\mathbb{Z}_2$ orbifold pillow



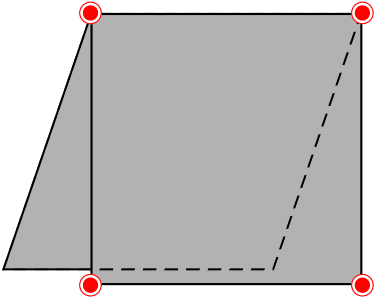
$\mathbb{Z}_2$ orbifold pillow



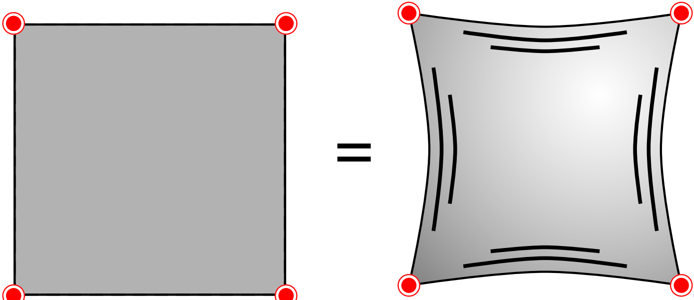
$\mathbb{Z}_2$ orbifold pillow



$\mathbb{Z}_2$ orbifold pillow



$\mathbb{Z}_2$ orbifold pillow



back

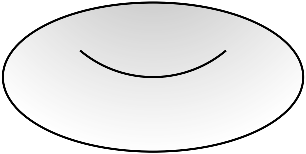
The $\mathbb{Z}_2$ orbifold plane

- ☞ 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:

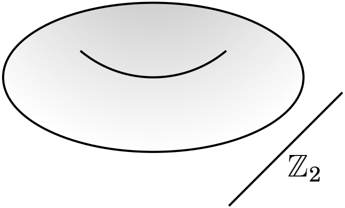
❶ $\mathbb{Z}_4^R$ symmetry arises as a remnant of the Lorentz group in compact dimensions



The $\mathbb{Z}_2$ orbifold plane

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

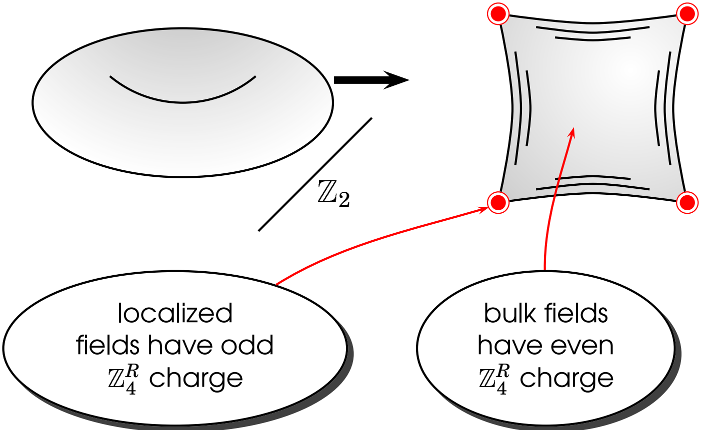
❶ $\mathbb{Z}_4^R$ symmetry arises as a remnant of the Lorentz group in compact dimensions



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



localized fields have odd $\mathbb{Z}_4^R$ charge

bulk fields have even $\mathbb{Z}_4^R$ charge

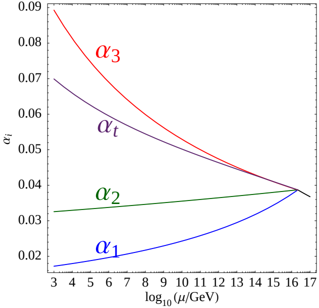
The $\mathbb{Z}_2$ orbifold plane

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

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

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

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



The $\mathbb{Z}_2$ orbifold plane

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

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

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

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

❸ Orbifold GUT limit with $\mathrm{SU}(6)$ bulk symmetry gives us the proportionality between μ term and expectation value of the superpotential $\langle \mathscr{W} \rangle$

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

The $\mathbb{Z}_2$ orbifold plane

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

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

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

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

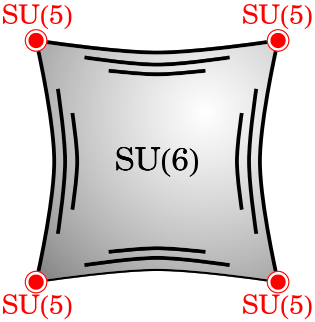
❸ Orbifold GUT limit with $\mathrm{SU}(6)$ bulk symmetry gives us the proportionality between μ term and expectation value of the superpotential $\langle \mathscr{W} \rangle$

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

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

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

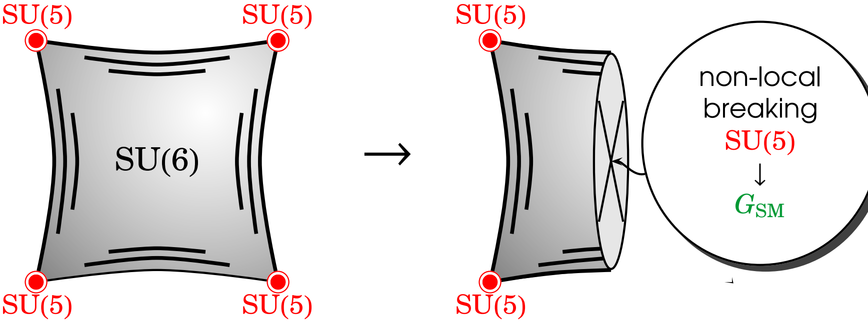
M. Blaszczyk, S. Groot Nibbelink, M.R., F. Ruehle, M. Trapletti, P. Vaudrevange (2009)



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

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

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:

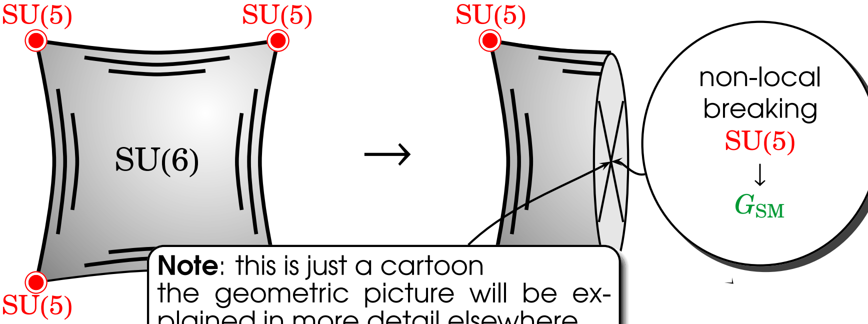
- breaks $\mathrm{SU}(5) \rightarrow \mathrm{SU}(3)_C \times \mathrm{SU}(2)_\mathrm{L} \times \mathrm{U}(1)_Y$
- reduces the number of generations to 3

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)

❶ step: 6 ge

mmetry

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

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
   ↷ complete blow-up without breaking SM gauge symmetry in principle possible

Main features

1. GUT symmetry breaking non-local
2. No localized flux in hypercharge direction
3. 4D gauge group:
   $\mathsf{SU}(3)_C \times \mathsf{SU}(2)_{\mathrm{L}} \times \mathsf{U}(1)_Y \times \mathrm{U}(1)_{B-L} \times [\mathsf{SU}(3) \times \mathsf{SU}(2)^2 \times \mathsf{U}(1)^7]$

Main features

❶ GUT symmetry breaking non-local

❷ No localized flux in hypercharge direction

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

❹ massless spectrum

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

Main features

❶ GUT symmetry breaking non-local

❷ No localized flux in hypercharge direction

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

❹ massless spectrum

spectrum = $3 \times$ generation + vector-like

❺ 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

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

'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

$$\{\phi_i\} \;=\; \{X_3,\dots\}$$

- ☞ This gives us a vacuum with the remnant symmetry $G_\mathrm{SM}\times\mathbb{Z}_4^R\times\mathbb{Z}_2^\mathrm{nasty}$

'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

$$\{\phi_i\} \;=\; \{X_3,\dots\}$$

☞ This gives us a vacuum with the remnant symmetry $G_{\mathrm{SM}} \times \mathbb{Z}_4^R \times \mathbb{Z}_2^{\mathrm{nasty}}$

☹ Unfortunately we cannot get rid of the extra $\mathbb{Z}_2^{\mathrm{nasty}}$, which leads to rank 2 Y_e and Y_d Yukawa couplings

'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

$$\{\phi_i\} \;=\; \{X_3,\dots\}$$

☞ This gives us a vacuum with the remnant symmetry $G_\mathrm{SM} \times \mathbb{Z}_4^R \times \mathbb{Z}_2^\mathrm{nasty}$

☹ Unfortunately we cannot get rid of the extra $\mathbb{Z}_2^\mathrm{nasty}$, which leads to rank 2 Y_e and Y_d Yukawa couplings

☞ Nevertheless: successful string embedding of $\mathbb{Z}_4^R$ possible!

'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

$$\{\phi_i\} \;=\; \{X_3,\dots\}$$

☞ This gives us a vacuum with the remnant symmetry $G_\mathrm{SM}\times\mathbb{Z}_4^R\times\mathbb{Z}_2^\mathrm{nasty}$

☹ Unfortunately we cannot get rid of the extra $\mathbb{Z}_2^\mathrm{nasty}$, which leads to rank 2 Y_e and Y_d Yukawa couplings

☞ Nevertheless: successful string embedding of $\mathbb{Z}_4^R$ possible!

☞ Why can we call the field configuration a 'vacuum'?

'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

$$\{\phi_i\} = \{X_3, \dots\}$$

☞ This gives us a vacuum with the remnant symmetry $G_{\mathrm{SM}} \times \mathbb{Z}_4^R \times \mathbb{Z}_2^{\mathrm{nasty}}$

☹ Unfortunately we cannot get rid of the extra $\mathbb{Z}_2^{\mathrm{nasty}}$, which leads to rank 2 Y_e and Y_d Yukawa couplings

☞ Nevertheless: successful string embedding of $\mathbb{Z}_4^R$ possible!

☞ Why can we call the field configuration a 'vacuum'?

☞ Two conditions:

- vanishing F terms (no time to discuss)
- vanishing D terms

Excursion: FI monomial quantization

☞ D-flat directions ↔ holomorphic invariant monomials

Excursion: FI monomial quantization

- ☞ D-flat directions ↔ holomorphic invariant monomials
- ☞ Practically all MSSM models obtained so far have an 'anomalous' $\mathrm{U}(1)$

Excursion: FI monomial quantization

- ☞ D-flat directions ↔ holomorphic invariant monomials
- ☞ Practically all MSSM models obtained so far have an 'anomalous' $\mathrm{U}(1)$
- ➥ Need invariant monomials $\mathscr{M} = \phi_1^{n_1}\cdots\phi_N^{n_N}$ which carry net negative charge under the 'anomalous' $\mathrm{U}(1)$

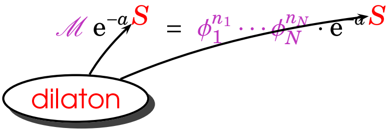
Excursion: FI monomial quantization

☞ *D*-flat directions ↔ holomorphic invariant monomials

☞ Practically all MSSM models obtained so far have an 'anomalous' U(1)

➥ Need invariant monomials $\mathscr{M} = \phi_1^{n_1}\cdots\phi_N^{n_N}$ which carry net negative charge under the 'anomalous' U(1)

➥ Non-perturbative terms can be written down



$$\mathscr{M}\ \mathrm{e}^{-a\,S} = \phi_1^{n_1}\cdots\phi_N^{n_N}\cdot\mathrm{e}^{-a\,S}$$

dilaton

Excursion: FI monomial quantization

- ☞ D-flat directions ↔ holomorphic invariant monomials
- ☞ Practically all MSSM models obtained so far have an 'anomalous' $\mathrm{U}(1)$
- ➥ Need invariant monomials $\mathscr{M} = \phi_1^{n_1} \cdots \phi_N^{n_N}$ which carry net negative charge under the 'anomalous' $\mathrm{U}(1)$
- ➥ Non-perturbative terms can be written down

$$\mathscr{M}\ \mathrm{e}^{-a\,S} = \phi_1^{n_1} \cdots \phi_N^{n_N} \cdot \mathrm{e}^{-a\,S}$$

- ➥ We find: charges of the monomials are quantized in a way that a = integer $\cdot\, 8\pi^2$

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

Excursion: FI monomial quantization

- ☞ *D*-flat directions ↔ holomorphic invariant monomials
- ☞ Practically all MSSM models obtained so far have an 'anomalous' $\mathrm{U}(1)$
- ➥ Need invariant monomials $\mathscr{M} = \phi_1^{n_1}\cdots\phi_N^{n_N}$ which carry net negative charge under the 'anomalous' $\mathrm{U}(1)$
- ➥ Non-perturbative terms can be written down

$$\mathscr{M}\,\mathrm{e}^{-a\,S} = \phi_1^{n_1}\cdots\phi_N^{n_N}\cdot\mathrm{e}^{-a\,S}$$

- ➥ We find: charges of the monomials are quantized in a way that a = integer $\cdot\, 8\pi^2$

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

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’ $\mathbb{Z}_4^R$

$$\underbrace{\phi_1^{n_1}\cdots\phi_N^{n_N}}_{\mathbb{Z}_4^R \text{ charge } 0}\cdot\underbrace{\mathrm{e}^{-8\pi^2\,S}}_{\mathbb{Z}_4^R \text{ charge } 2}$$

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

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

- ☞ Instanton couplings ‘violate’ $\mathbb{Z}_4^R$

$$\underbrace{\phi_1^{n_1}\cdots\phi_N^{n_N}}_{\mathbb{Z}_4^R\text{ charge }0}\cdot\underbrace{\mathrm{e}^{-8\pi^2 S}}_{\mathbb{Z}_4^R\text{ charge }2}$$

- ☞ The model has an hidden sector with gauge group $\mathrm{SU}(N_c=3)$ and $N_f=N_c-1=2$ massless pairs in the $\mathbf{3}$ and $\overline{\mathbf{3}}$ representation

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

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

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

$$\underbrace{\phi_1^{n_1}\cdots\phi_N^{n_N}}_{\mathbb{Z}_4^R\text{ charge }0}\cdot\underbrace{\mathrm{e}^{-8\pi^2\,S}}_{\mathbb{Z}_4^R\text{ charge }2}$$

- The model has an hidden sector with gauge group $\mathrm{SU}(N_c=3)$ and $N_f=N_c-1=2$ massless pairs in the $\mathbf{3}$ and $\overline{\mathbf{3}}$ representation

- We find that the Affleck-Dine-Seiberg potential

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

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

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

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

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

- ☞ Instanton couplings ‘violate’ $\mathbb{Z}_4^R$

$$\underbrace{\phi_1^{n_1}\cdots\phi_N^{n_N}}_{\mathbb{Z}_4^R \text{ charge } 0}\cdot\underbrace{\mathrm{e}^{-8\pi^2 S}}_{\mathbb{Z}_4^R \text{ charge } 2}$$

- ☞ The model has an hidden sector with gauge group $\mathrm{SU}(N_c = 3)$ and $N_f = N_c - 1 = 2$ massless pairs in the $\mathbf{3}$ and $\overline{\mathbf{3}}$ representation

- ☞ We find that the Affleck-Dine-Seiberg potential

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

meson determinant

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

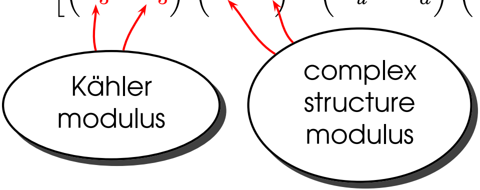
μ from $\mathscr{W}$

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)

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



μ from $\mathscr{W}$

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

☞ Higher-dimensional gauge invariance ↷ Kähler potential

$$K = -\ln\left[\left(T_3+\overline{T_3}\right)\,\left(Z+\overline{Z}\right)-\left(H_u+\overline{H_d}\right)\,\left(H_d+\overline{H_u}\right)\right]$$

Higgs fields
= extra components
of gauge fields

μ from $\mathscr{W}$

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

☞ Higher-dimensional gauge invariance ↷ Kähler potential

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

μ from $\mathscr{W}$

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

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

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

normalized
Higgs
fields

μ from $\mathscr{W}$

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

- ☞ 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 $\widehat{H}_u\widehat{H}_d$

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

$$\begin{aligned} K' &= -\ln\left[\left(T_3+\overline{T_3}\right)\,\left(Z+\overline{Z}\right)\right] + \left[|\widehat{H}_u|^2 + |\widehat{H}_d|^2\right] \\ \mathscr{W}' &= \exp(\widehat{H}_u\,\widehat{H}_d)\,\Omega = \Omega\,\widehat{H}_u\,\widehat{H}_d + \dots \end{aligned}$$

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

$$\begin{aligned} K' &= -\ln\left[\left(T_3+\overline{T_3}\right)\,\left(Z+\overline{Z}\right)\right]+\left[|\widehat{H}_u|^2+|\widehat{H}_d|^2\right] \\ \mathscr{W}' &= \exp(\widehat{H}_u\,\widehat{H}_d)\,\Omega = \Omega\,\widehat{H}_u\,\widehat{H}_d+\dots \end{aligned}$$

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)

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

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)

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

☞ 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 . . .)

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)

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

- ☞ Whatever gives us $\langle\mathscr{W}\rangle$ will be the order parameter for $\mathbb{Z}_4^R$ breaking
- ☞ Dimension 5 proton decay operators will have highly suppressed coefficients

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

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)

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

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

☞ Dimension 5 proton decay operators will have highly suppressed coefficients

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

☞ 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

Summary – bottom-up

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

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

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

Summary – bottom-up

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

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

universal anomaly coefficients
universal charges for matter
forbid μ @ tree-level
allow Yukawa couplings
allow Weinberg operator

$\curvearrowright$ 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

- ☞ 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

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

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!