Precision gauge unification from strings

Michael Ratz

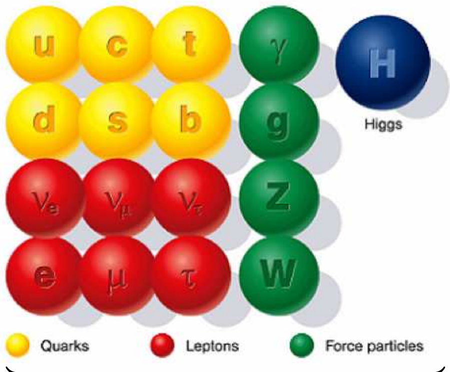
Planck 2013, May 23, 2013

Based on:

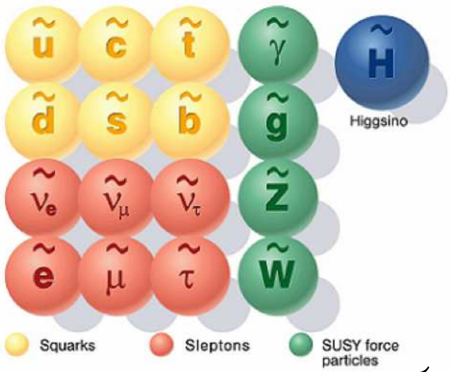
- M. Blaszczyk, S. Groot Nibbelink, M.R., F. Ruehle, M. Trapletti & P. Vaudrevange, Phys. Lett. **B683**, 340 (2010)
- S. Raby, M.R. & K. Schmidt-Hoberg, Phys. Lett. **B687**, 342-348 (2010)
- R. Kappl, B. Petersen, S. Raby, M.R., R. Schieren & P. Vaudrevange, Nucl. Phys. **B** 847, 325-349 (2011)
- S. Krippendorf, H.P. Nilles, M.R. & M. Winkler, Phys. Lett. **B712**, 87 (2012)
- M. Fischer, M.R., J. Torrado & P. Vaudrevange, **JHEP** 1301 (2013) 084
- S. Krippendorf, H.P. Nilles, M.R. & M. Winkler, in preparation
- M. Fischer et al., in preparation

(Minimal) supersymmetric standard model

☞ The minimal supersymmetric standard model (MSSM) provides an attractive scheme for physics beyond the SM



SM particles



superpartners

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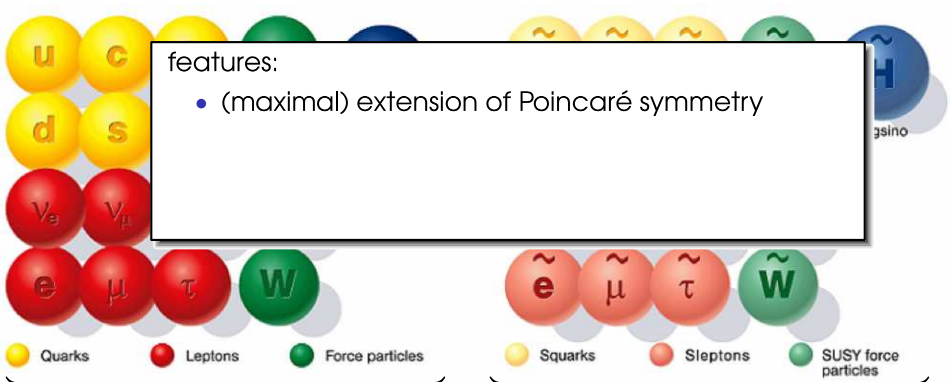
features:

- (maximal) extension of Poincaré symmetry



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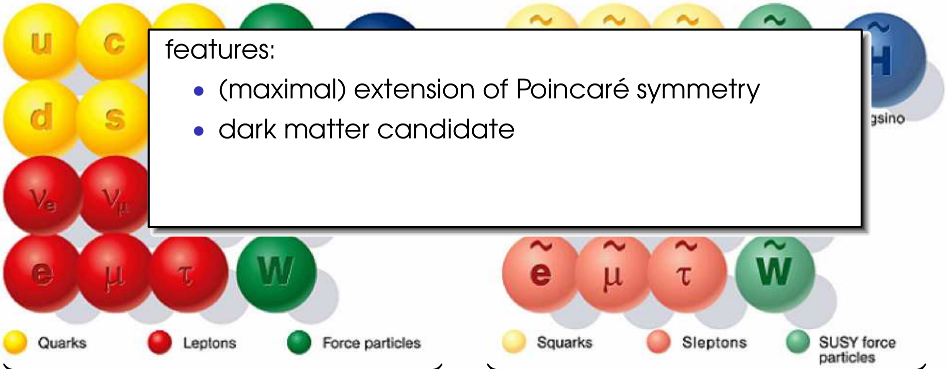

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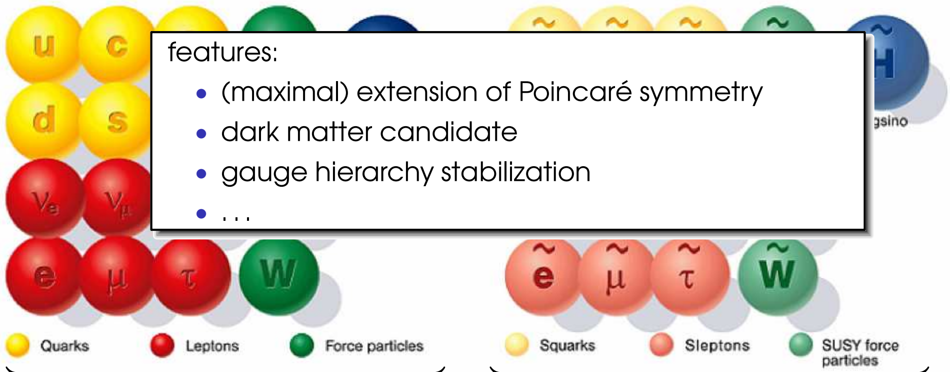
- gauge hierarchy stabilization
- ...



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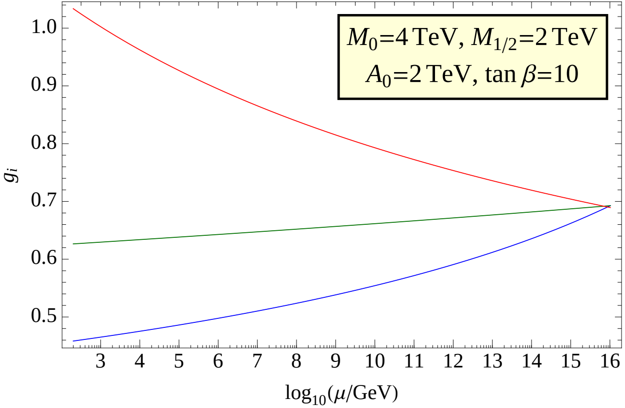
Gauge coupling unification in the MSSM

- Running couplings in the (minimal) supersymmetric standard model (MSSM)

Dimopoulos, Raby & Wilczek (1981)



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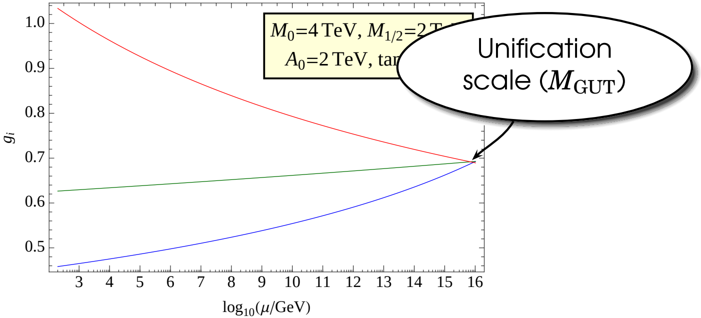

- Gauge coupling unification might be a consequence of $G_{\mathrm{SM}} = \mathrm{SU}(3) \times \mathrm{SU}(2) \times \mathrm{U}(1) \subset \mathrm{SU}(5) \subset \cdots \subset \mathrm{E}_8$

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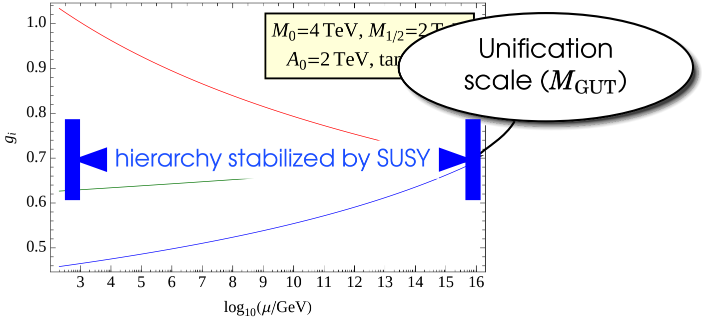

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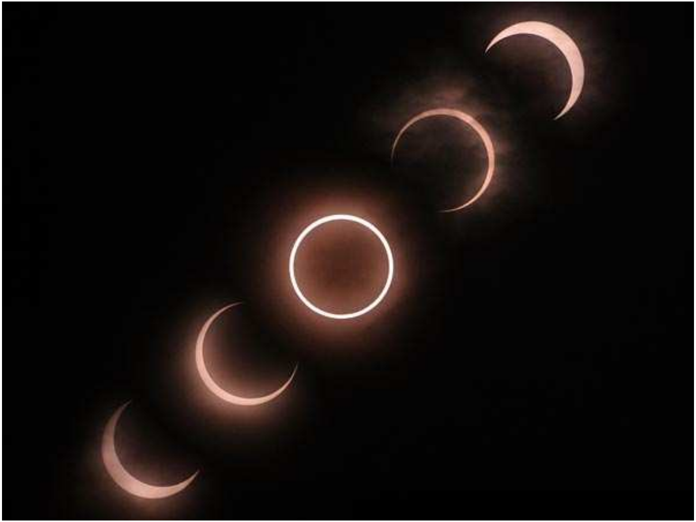
Accidents in Nature



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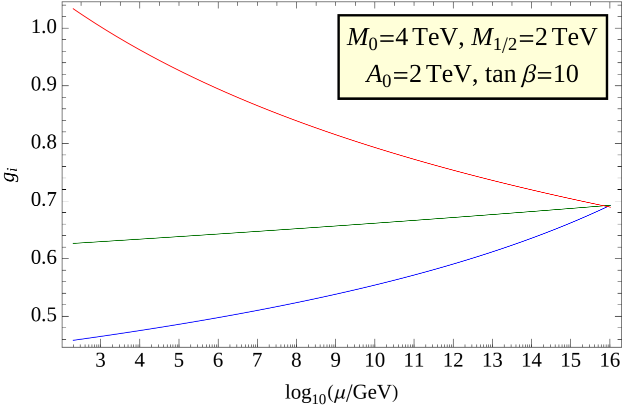
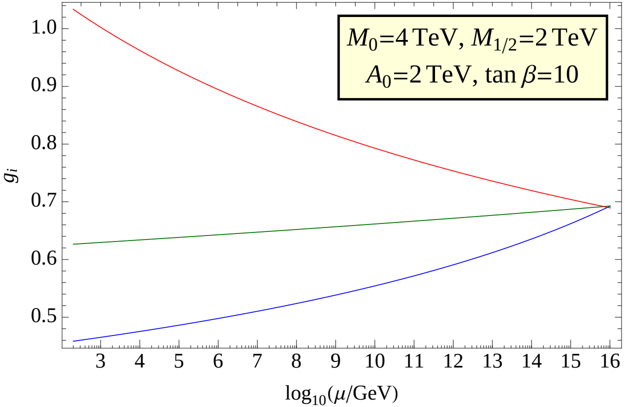


☞ Main assumption: this is **not** an accident

Gauge coupling unification in the MSSM



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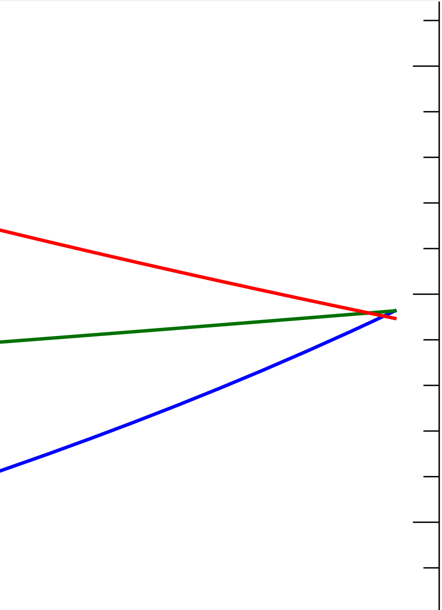

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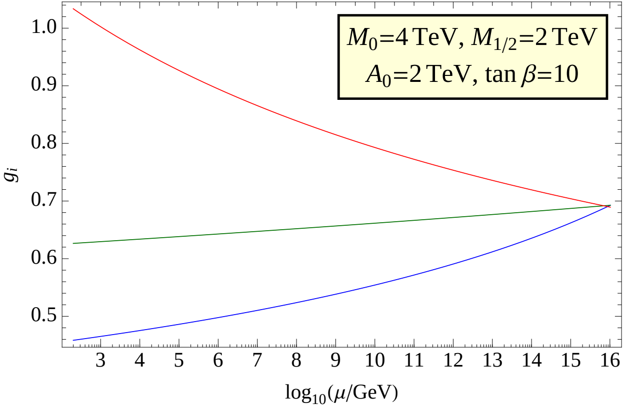


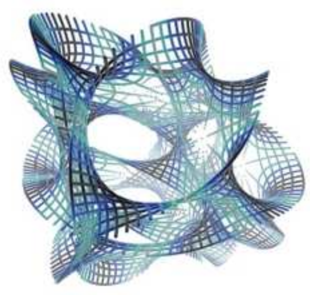
- ☞ Main assumption: this is **not** an accident
- ☞ **Note**: gauge unification not precise with 'traditional' patterns of soft masses

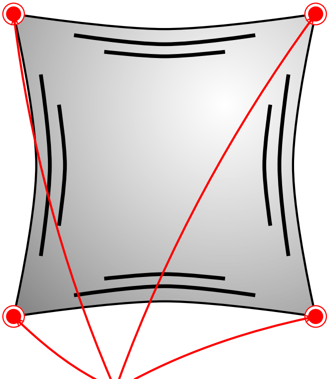
Local vs. non–local GUT breaking

Gauge symmetry breaking in heterotic models

- Traditional prejudice

Calabi–Yau compactification | orbifold compactification





non–local breaking

cf. the models in Lara's talk

local breaking

Gauge symmetry breaking in heterotic models

- Traditional prejudice: $\left\{\begin{array}{lcl}\text{CY} & : & \text{non–local}\\ \text{orbifold} & : & \text{local}\end{array}\right\}$ breaking

- Local vs. non–local breaking

feature	non–local	local
local GUTs	✗	✓

explain matter in GUT irreps

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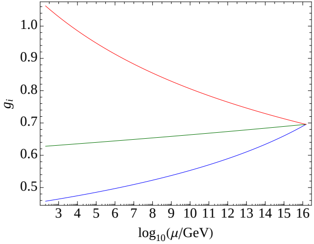

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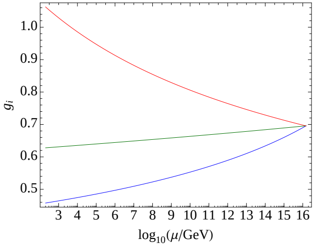

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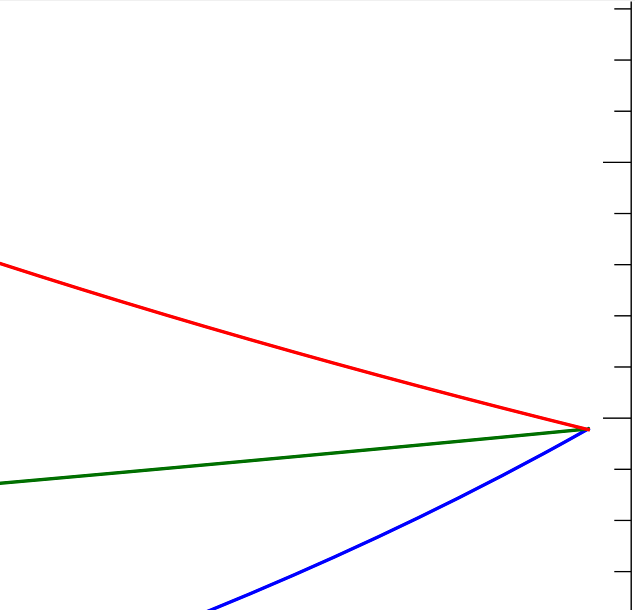

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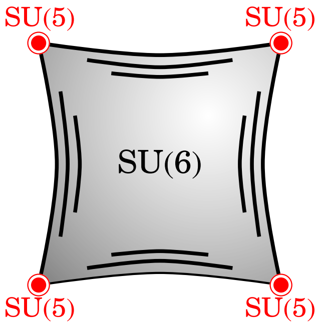
obvious question:

Can we have a hybrid scheme?

Local vs. non–local GUT breaking in field theory

Hall, Murayama & Nomura (2002) ; Hebecker (2004)



1. step: construct $\mathbb{T}^2/\mathbb{Z}_2$ orbifold which breaks $\mathrm{SU}(6)$ locally to $\mathrm{SU}(5)$

$$\mathbb{Z}_2 \quad : \quad (x_5, x_6) \;\to\; (-x_5, -x_6)$$

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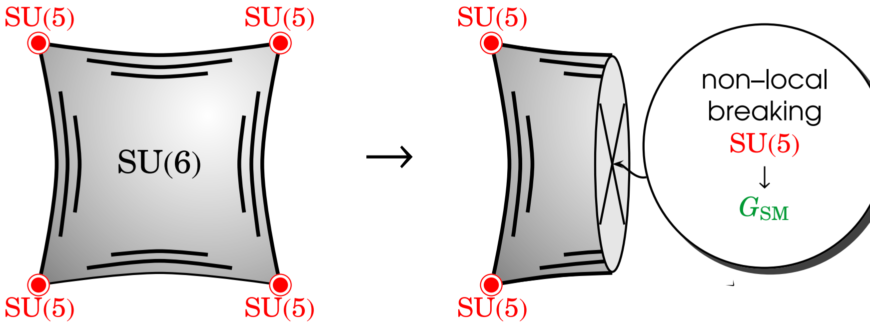

❶ step: construct $\mathbb{T}^2/\mathbb{Z}_2$ orbifold which breaks $\mathrm{SU}(6)$ locally to $\mathrm{SU}(5)$

❷ step: mod out a freely acting $\mathbb{Z}_2'$ symmetry which breaks $\mathrm{SU}(5) \to \mathrm{SU}(3)_C \times \mathrm{SU}(2)_\mathrm{L} \times \mathrm{U}(1)_Y$

$$\mathbb{Z}_2' \quad : \quad (x_5, x_6) \;\to\; (-x_5 + \pi R_5, -x_6 + \pi R_6)$$

Non–local breaking in 6D

Anandakrishnan and Raby (2013)

- Eigenstates and parity operations

$$
\begin{aligned}
\mathbb{Z}_2 \quad &: \quad \phi_{\pm\widehat{\pm}}(x_\mu, -x_5, -x_6) \;=\; \pm\; \phi_{\pm\widehat{\pm}}(x_\mu, x_5, x_6) \\
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'local'

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'local' 'non–local'

- General mode expansion

$$\phi_{\pm\hat{\pm}}(x, x_5, x_6) \;=\; \frac{1}{4\sqrt{2R_5 R_6}}$$

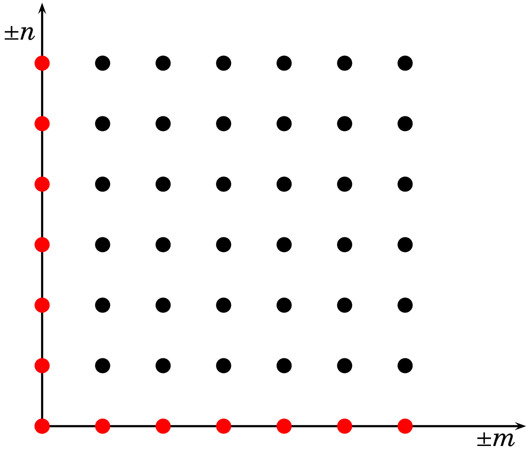
$$\cdot \sum_{m,n} \left[\left(\phi^{(m,n)} \pm \phi^{(-m,-n)}\right) \hat{\pm} (-1)^{m-n} \left(\phi^{(-m,n)} \pm \phi^{(m,-n)}\right)\right]$$

$$\cdot \exp\left[\mathrm{i}\left(\frac{m}{R_5} x_5 + \frac{n}{R_6} x_6\right)\right]$$

Modes for $\mathbb{T}^2/\mathbb{Z}_2$ (local breaking)

Trapletti (2006)

- Non–zero $\phi^{(m,n)}$ for $+$ modes



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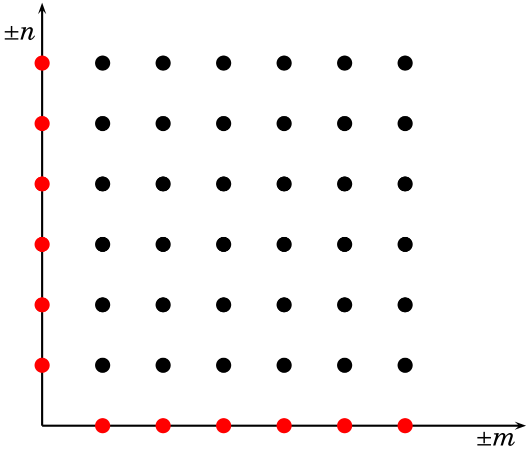

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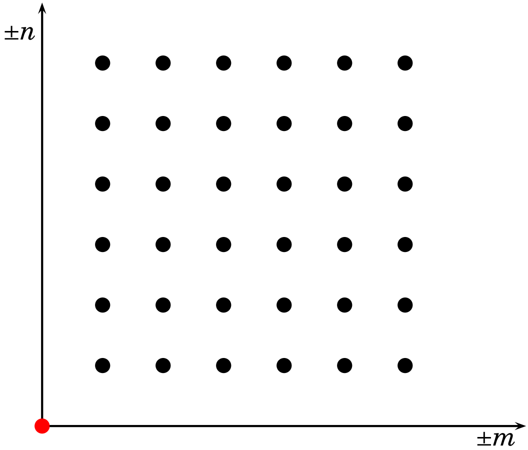
☞ Mismatch

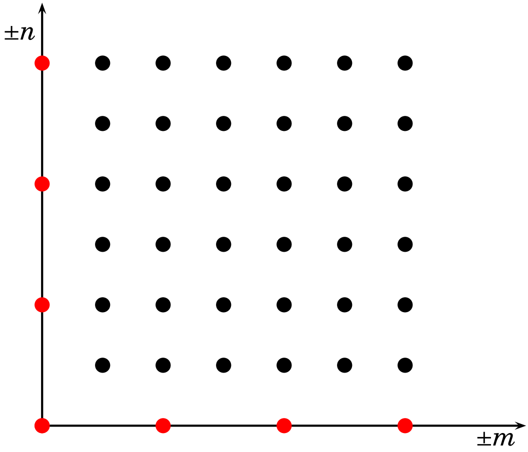


Running does not stop at the compactification scale

Modes for non–local breaking

Anandakrishnan and Raby (2013)

- Non–zero $\phi^{(m,n)}$ for $+\widehat{+}$ modes



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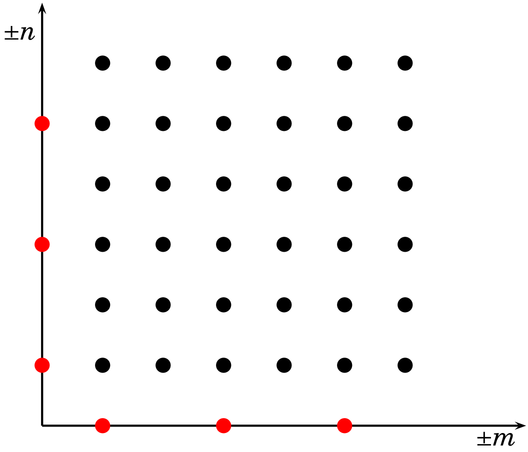

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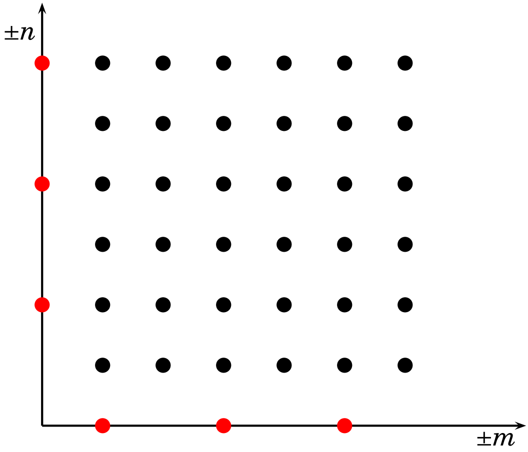

Modes for non–local breaking

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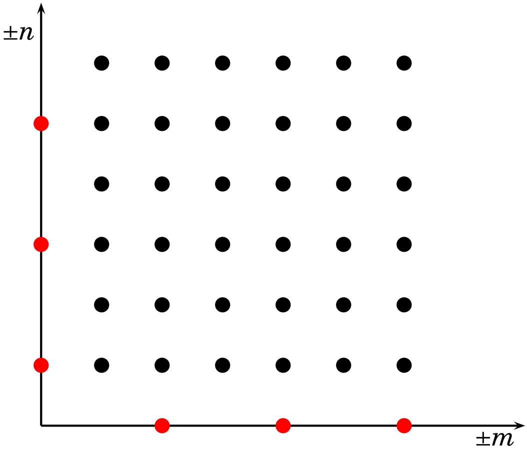
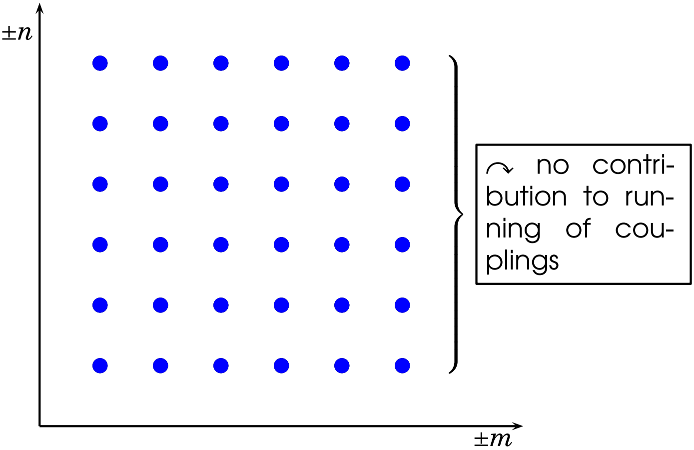
- Non–zero $\phi^{(m,n)}$ for $-\widehat{-}$ modes



Modes for non–local breaking

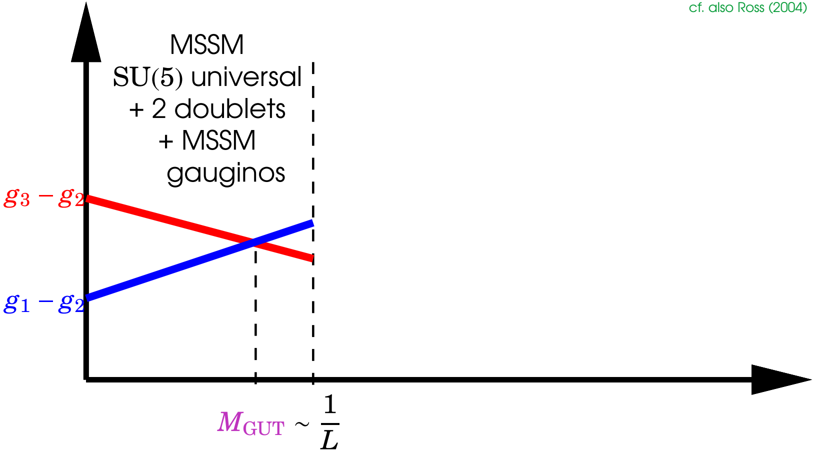
Anandakrishnan and Raby (2013)

- Non–zero $\phi^{(m,n)}$ for all modes



Gauge unification: non–local GUT breaking

cf. also Ross (2004)



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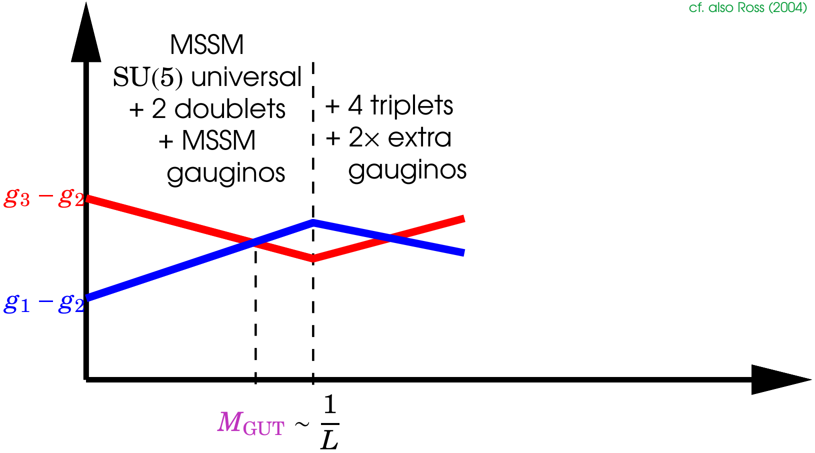

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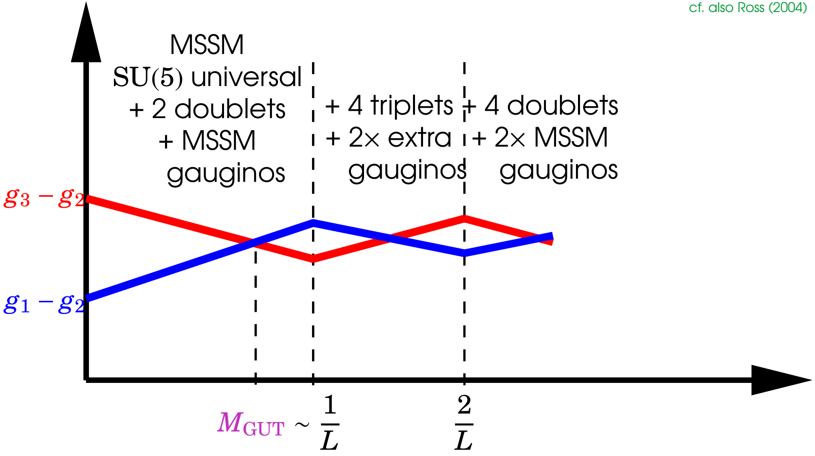

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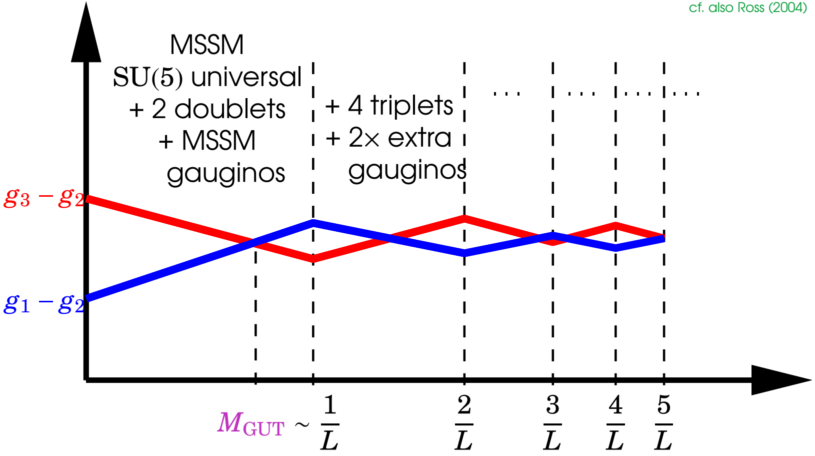
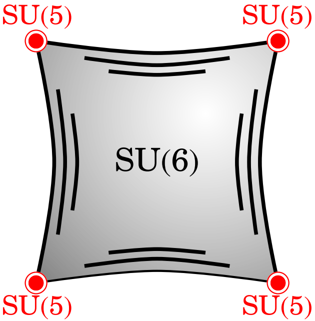


☞ Effect can be absorbed in a slight shift of the GUT scale:

$$M_{\mathrm{GUT}} \sim \frac{2}{3} \cdot \frac{1}{L}$$

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

Blaszczyk, Groot Nibbelink, M.R., Ruehle, Trapletti & Vaudrevange (2010) ; Kappl, Petersen, Raby, M.R., Schieren & Vaudrevange (2011)



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

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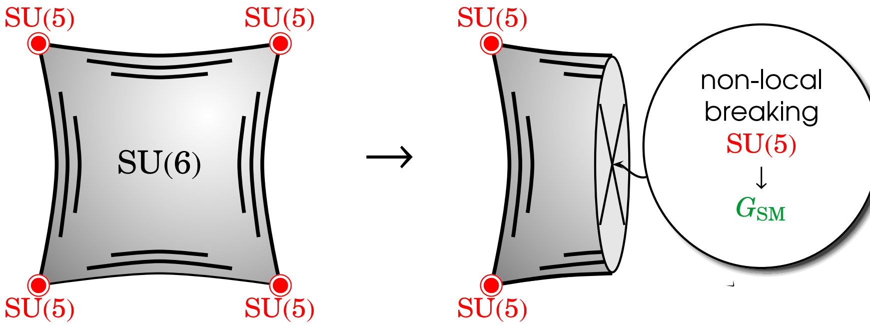

step ❶ : 6 generation $\mathbb{Z}_2 \times \mathbb{Z}_2$ model with $\mathrm{SU}(5)$ symmetry

step ❷ : 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 and Donagi (2006)

Braun, He, Ovrut & Pantev (2005)

Main features

Blaszczyk, Groot Nibbelink, M.R., Ruehle, Trapletti & Vaudrevange (2010) ; Kappl, Petersen, Raby, M.R., Schieren & Vaudrevange (2011)

1. GUT symmetry breaking non–local
   $\curvearrowright$ (almost) no 'logarithmic running above the GUT scale'

Hebecker and Trapletti (2005) ; Anandakrishnan and Raby (2013)

Main features

Blaszczyk, Groot Nibbelink, M.R., Ruehle, Trapletti & Vaudrevange (2010) ; Kappl, Petersen, Raby, M.R., Schieren & Vaudrevange (2011)

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

Main features

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1. GUT symmetry breaking non–local
2. No localized flux in hypercharge direction
3. No fractionally charged exotics
4. Vacua with
   - exact MSSM spectrum
   - $\mathbb{Z}_4^R$ symmetry $\curvearrowright$ $\begin{cases} \text{solution to } \mu \text{ problem} \\ \text{realistic proton life–time} \end{cases}$
   - almost all moduli fixed in a supersymmetric way
   - gauge–top unification
   - . . .

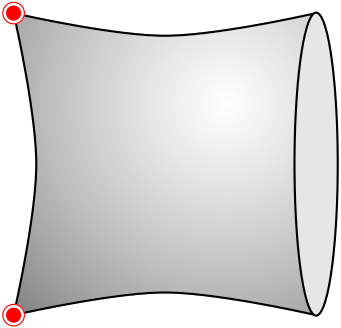
✏ recent re–analysis of R symmetries in orbifolds

→ talk by D. Pena

Bizet, Kobayashi, Pena, Parameswaran, Schmitz & Zavala (2013)

Anisotropic orbifold compactifications

back



Anisotropic orbifold compactifications

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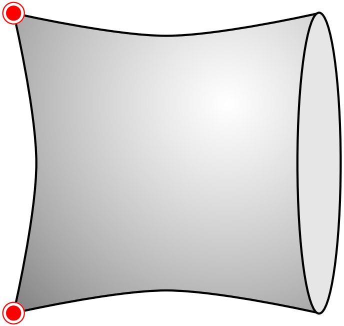

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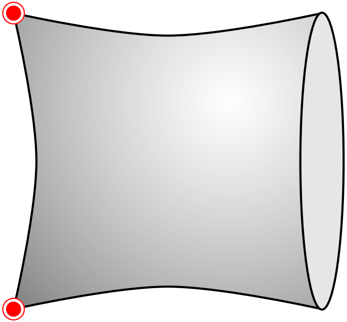

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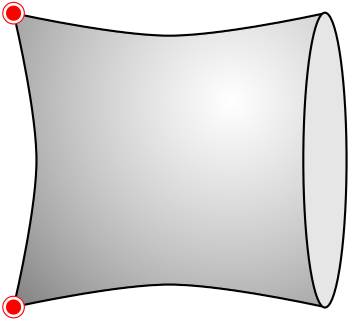

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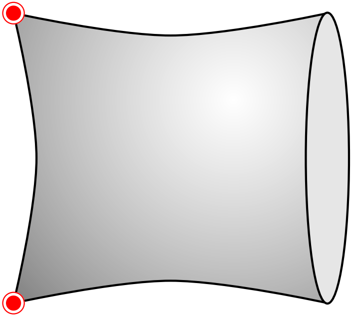

Anisotropic orbifold compactifications

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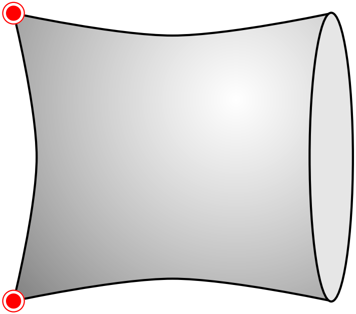

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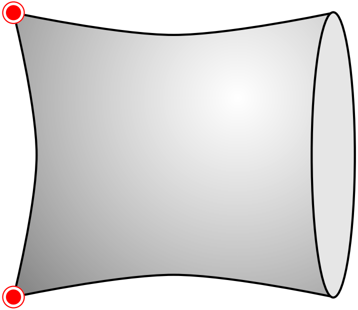

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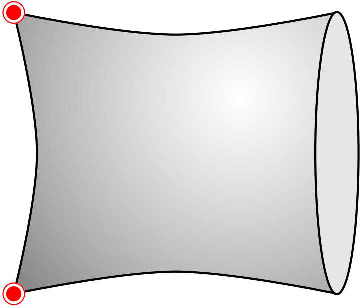

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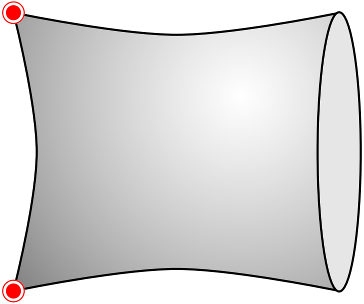

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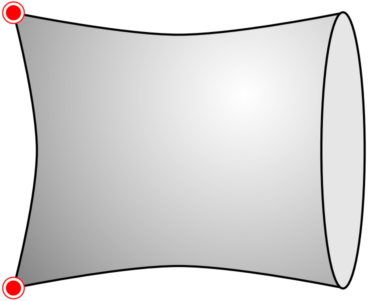

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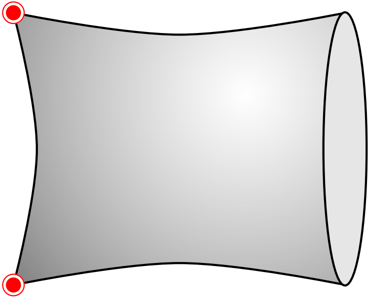

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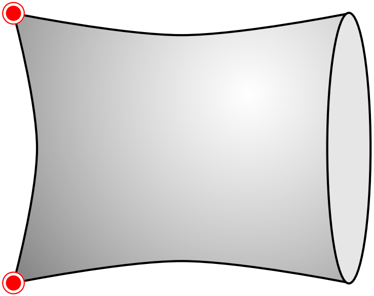

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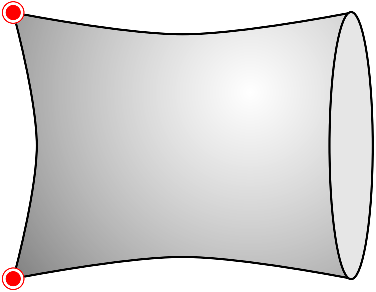

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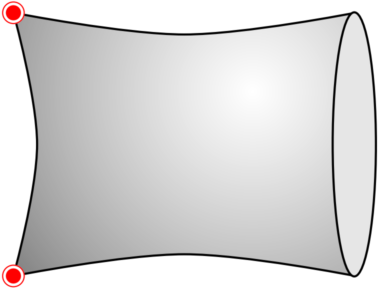

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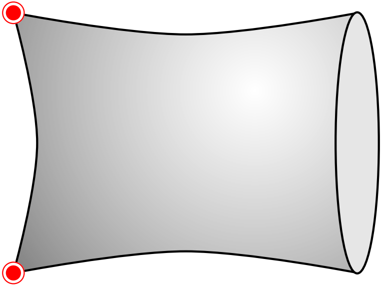

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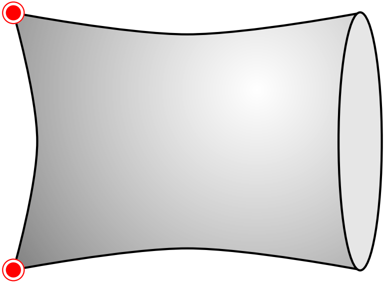

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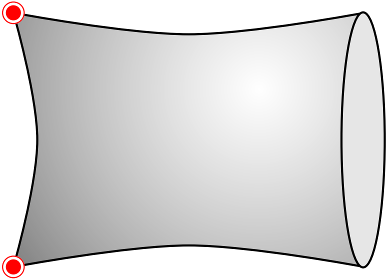

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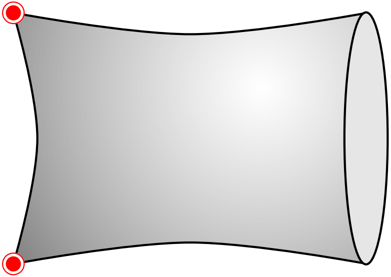

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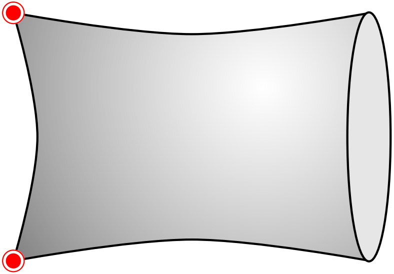

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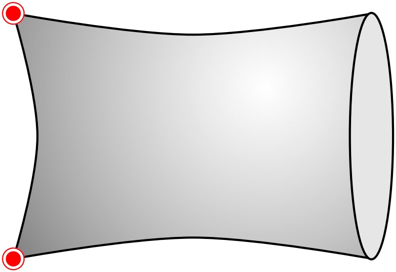

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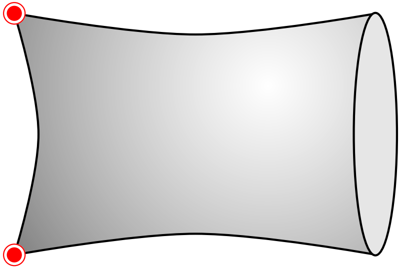

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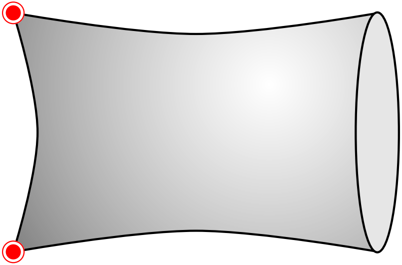

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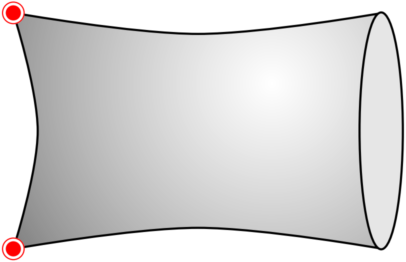

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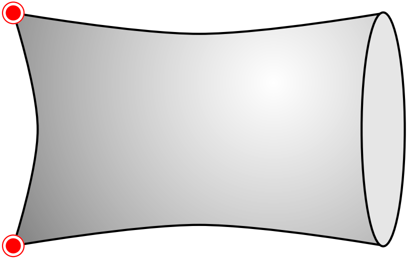

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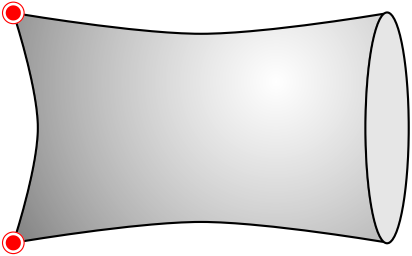

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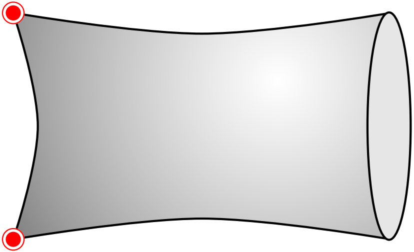

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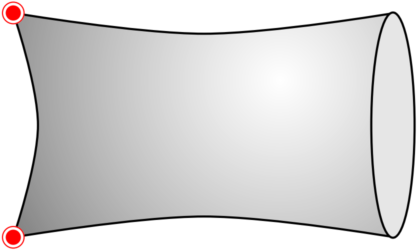

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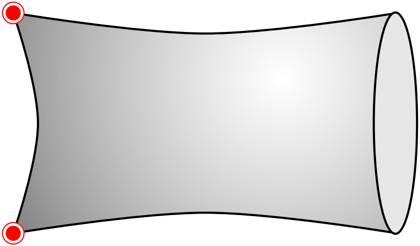

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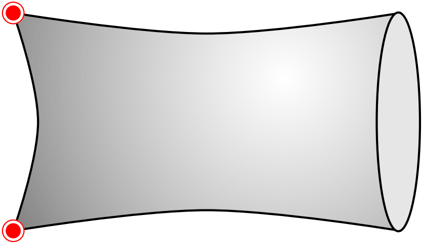

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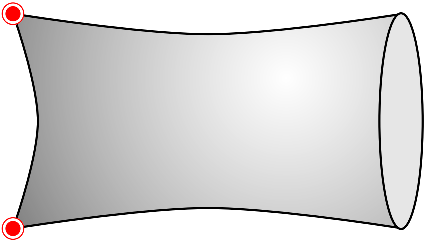

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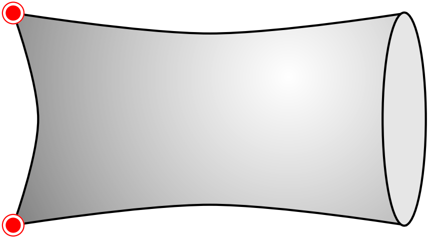

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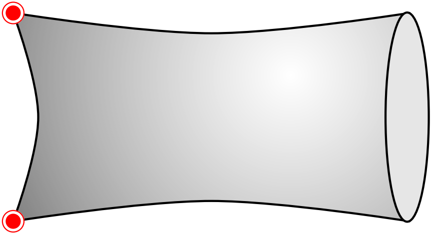

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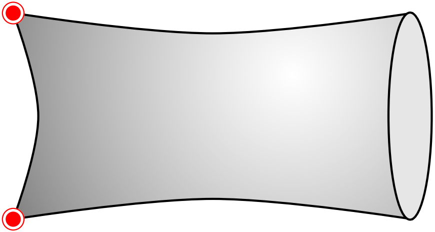

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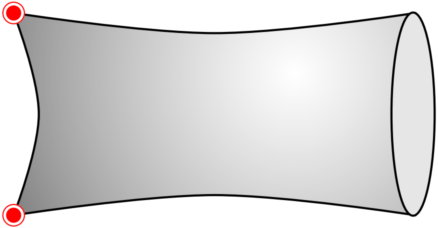

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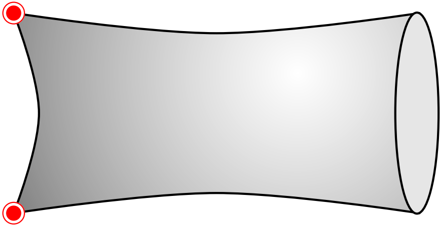

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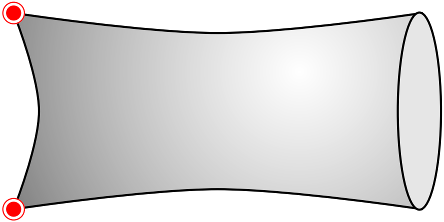

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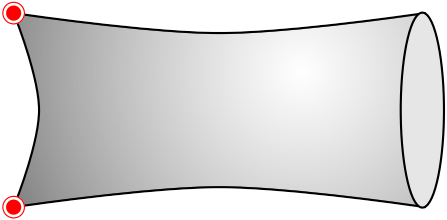

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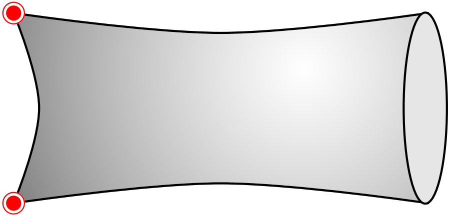

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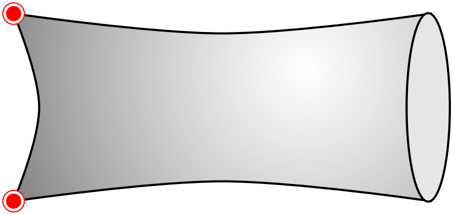

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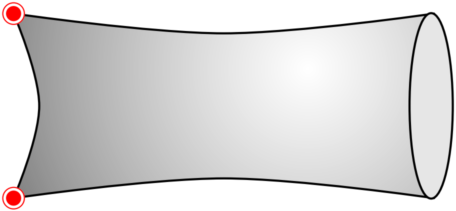

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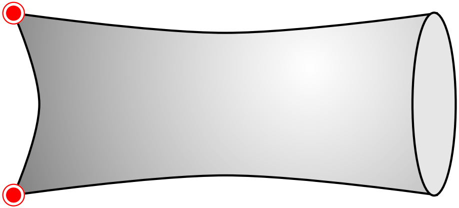

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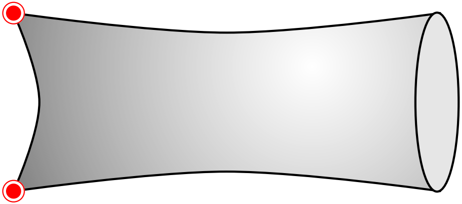

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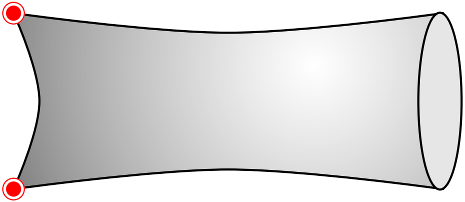

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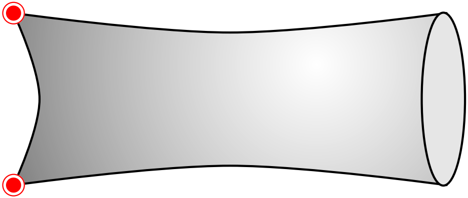

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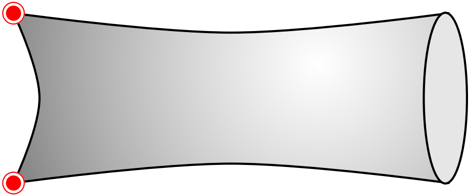

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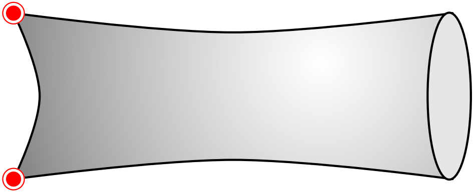

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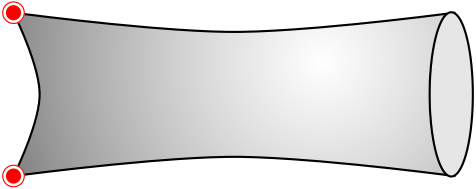

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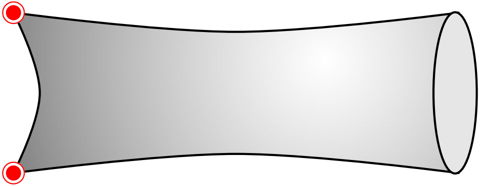

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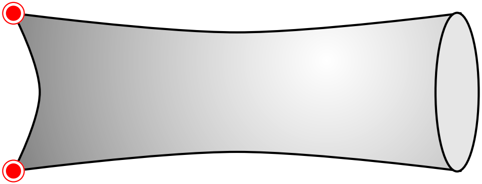

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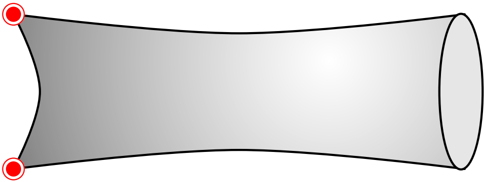

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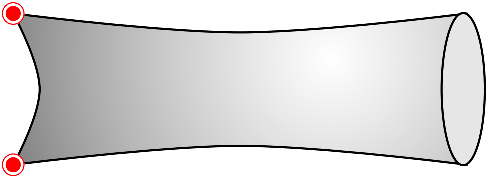

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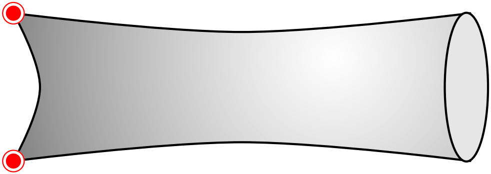

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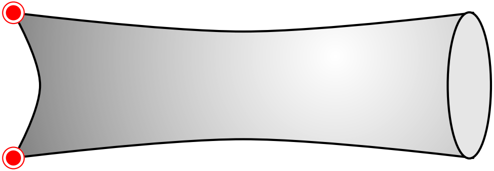

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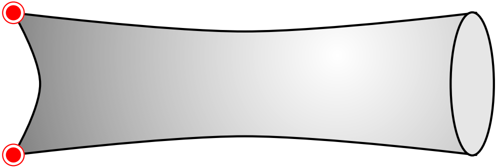

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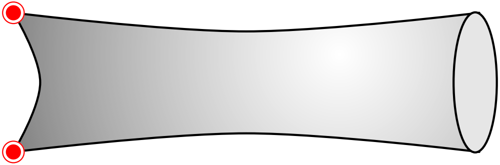

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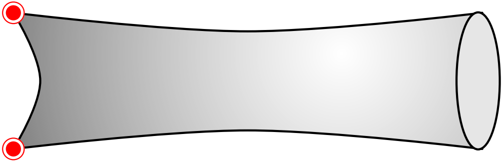

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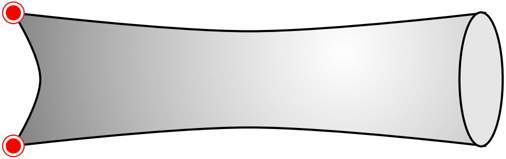

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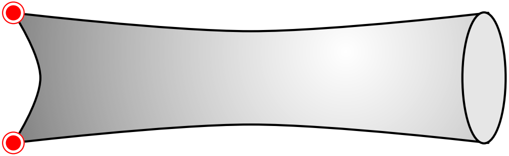

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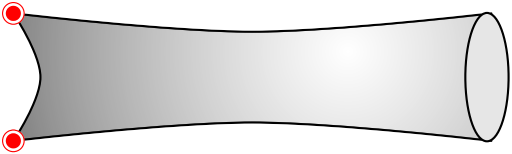

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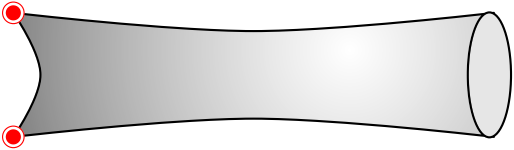

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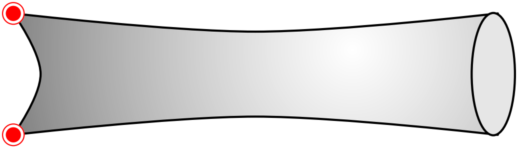

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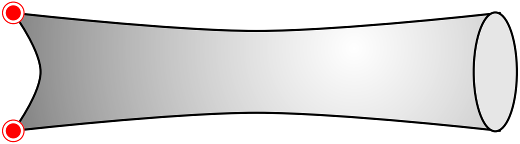

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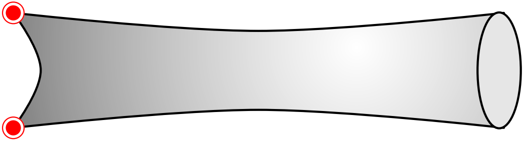

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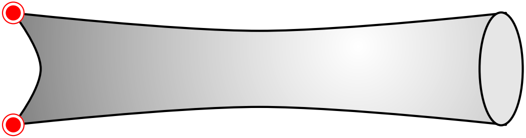

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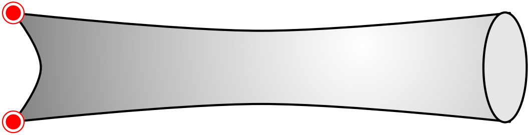

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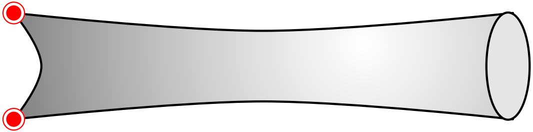

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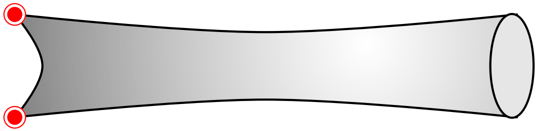

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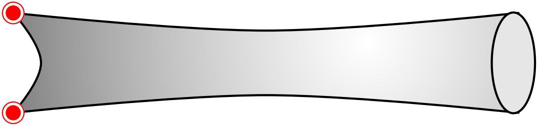

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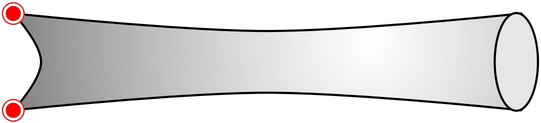

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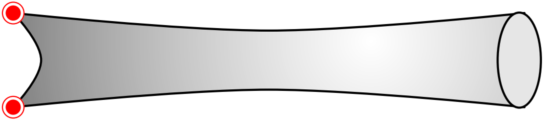

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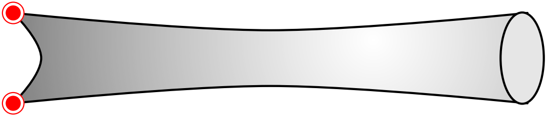

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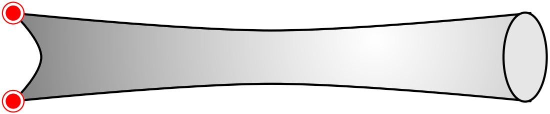

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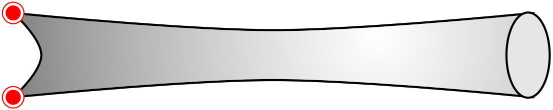

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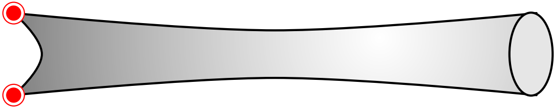

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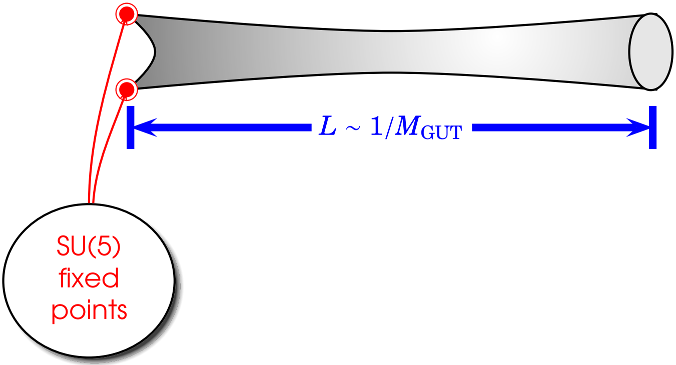

Anisotropic orbifold compactifications

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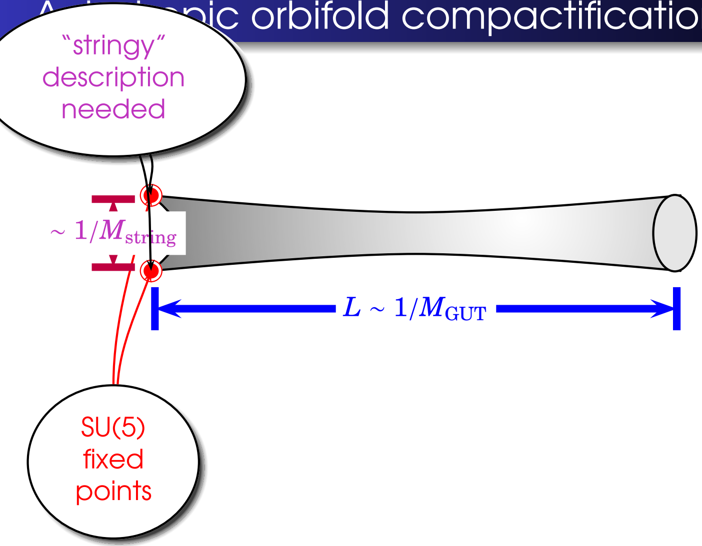

A[illegible]pic orbifold compactifications

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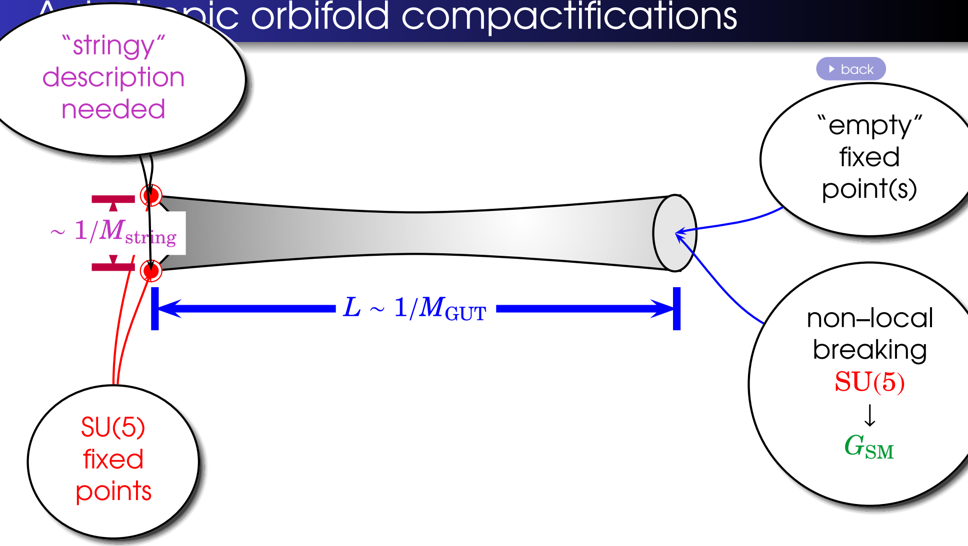
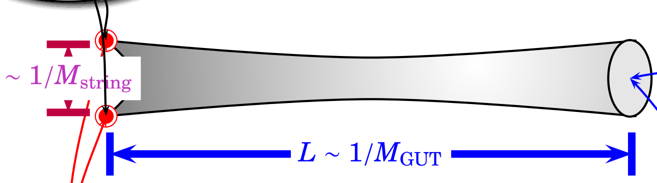


A... pic orbifold compactifications

back

"stringy" description needed

"empty" fixed point(s)

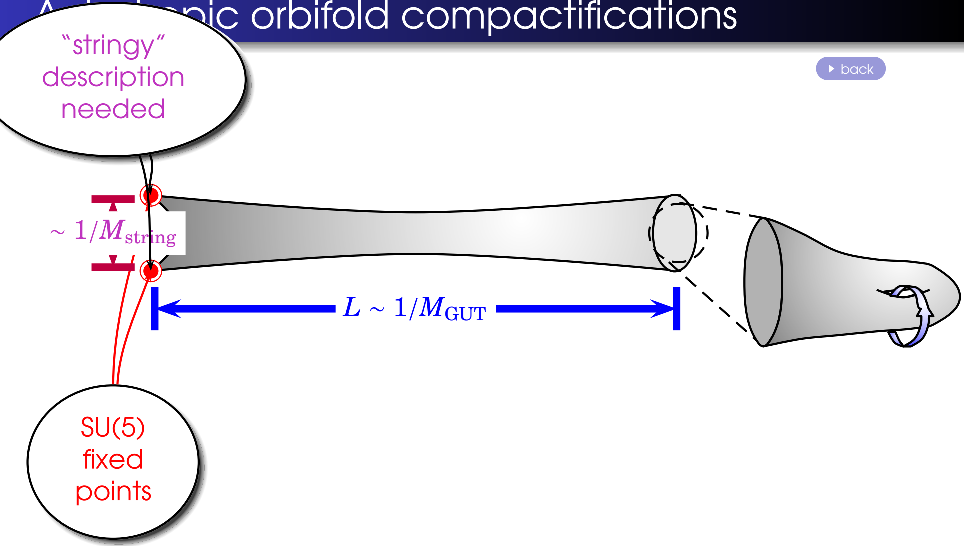


non–local breaking $\mathrm{SU}(5) \downarrow G_{\mathrm{SM}}$

SU(5) fixed points

Anisotropic orbifold compactifications

back



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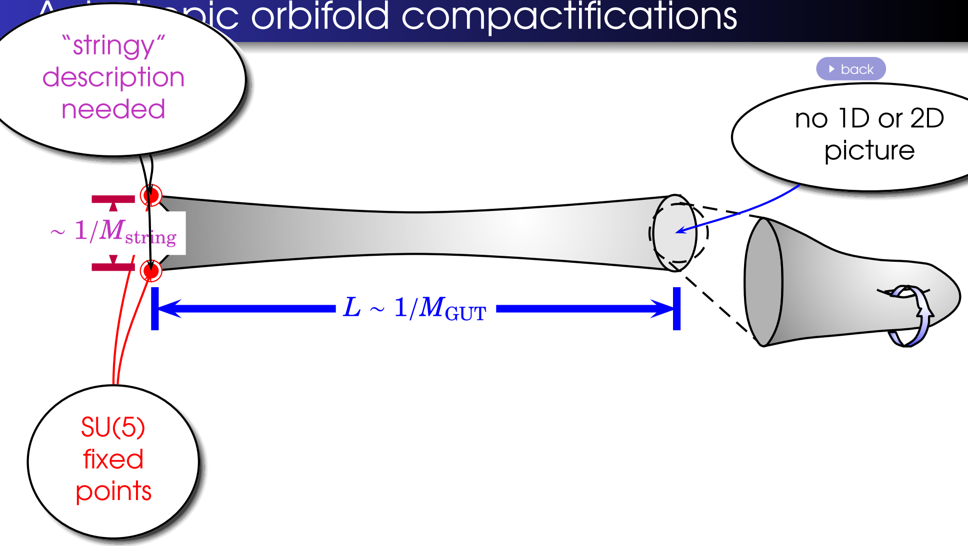

Anisotropic orbifold compactifications

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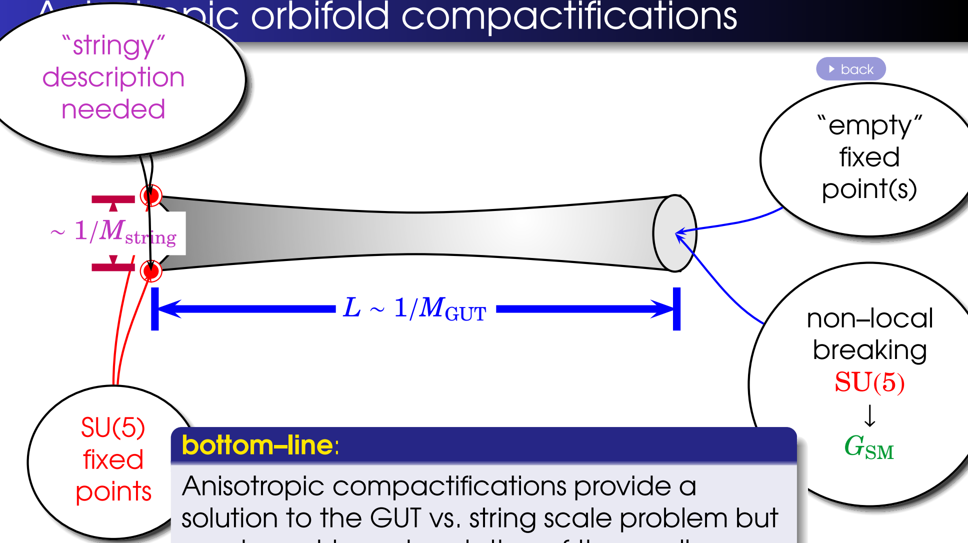

bottom–line:

Anisotropic compactifications provide a solution to the GUT vs. string scale problem but require a stringy description of the small directions

Hebecker and Trapletti (2005) ,. . . Cicoli, de Alwis & Westphal (2013)

Non–local GUT breaking in heterotic orbifolds

Fischer, M.R., Torrado & Vaudrevange (2013b)

☞ **Complete** classification of (symmetric) heterotic orbifolds

✏ more detailled analysis of non–Abelian orbifolds

Konopka (2012) ; Fischer, Ramos-Sánchez & Vaudrevange (2013a)

✏ recent progress in asymmetric orbifolds

Beye, Kobayashi & Kuwakino (2013)

Non–local GUT breaking in heterotic orbifolds

Fischer, M.R., Torrado & Vaudrevange (2013b)

- **Complete** classification of (symmetric) heterotic orbifolds
- 31 geometries with non–trivial fundamental groups (after orbifolding!) with point groups $\mathbb{Z}_2 \times \mathbb{Z}_2$, $\mathbb{Z}_2 \times \mathbb{Z}_4$ and $\mathbb{Z}_3 \times \mathbb{Z}_3$

  - 38 additional geometries with non–trivial fundamental groups in non–Abelian orbifolds
    Fischer, Ramos-Sánchez & Vaudrevange (2013a)
  - some models are non–chiral but chirality may be achieved by adding fluxes
    → talk by S. Groot–Nibbelink
    Groot Nibbelink and Vaudrevange (2013)
  - recent analysis of $\mathbb{Z}_2 \times \mathbb{Z}_4$ models w/ local GUT breaking
    → talk by P. Oehlmann
    Pena, Nilles & Oehlmann (2012)

Non–local GUT breaking in heterotic orbifolds

Fischer, M.R., Torrado & Vaudrevange (2013b)

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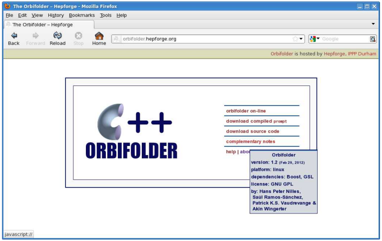
- Geometries online and ready to use



http://orbifolder.hepforge.org

Nilles, Ramos-Sánchez, Vaudrevange & Wingerter (2012)

Non–local GUT breaking in heterotic orbifolds

Fischer, M.R., Torrado & Vaudrevange (2013b)

- **Complete** classification of (symmetric) heterotic orbifolds
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- Geometries online and ready to use with the `C++ orbifolder`

➥ Many promising models w/ non–local GUT breaking

Fischer et al. (in preparation)

Implications for the LHC

Implications for the LHC

- ☞ Al(most al)l moduli fixed in a supersymmetric way in MSSM vacua with residual (discrete and/or approximate) R symmetries
  Kappl, Petersen, Raby, M.R., Schieren & Vaudrevange (2011)

- ✏ Approximate R symmetries can explain an effective small constant in the superpotential
  Kappl, Nilles, Ramos-Sánchez, M.R., Schmidt-Hoberg & Vaudrevange (2009)

- ✏ Approximate/discrete R symmetries provide us with a solution to the μ problem
  Brümmer, Kappl, M.R. & Schmidt-Hoberg (2010) ;
  Lee, Raby, M.R., Ross, Schieren, Schmidt-Hoberg & Vaudrevange (2011) ; . . .

- ✏ Approximate/discrete R symmetries provide us with a solution to the proton decay problems of the MSSM
  Lee, Raby, M.R., Ross, Schieren, Schmidt-Hoberg & Vaudrevange (2011) ; . . .

Implications for the LHC

- Al(most al)l moduli fixed in a supersymmetric way in MSSM vacua with residual (discrete and/or approximate) R symmetries

Kappl, Petersen, Raby, M.R., Schieren & Vaudrevange (2011)

- Scenario with ~~SUSY~~ by 'matter field' X + dilaton S

stabilized with large mass from Coleman-Weinberg potential

$m_S \gg m_{3/2}$

$m_{3/2} \sim 10\ldots100\,\mathrm{TeV}$

Lebedev, Nilles & M.R. (2006) ; . . .

Implications for the LHC

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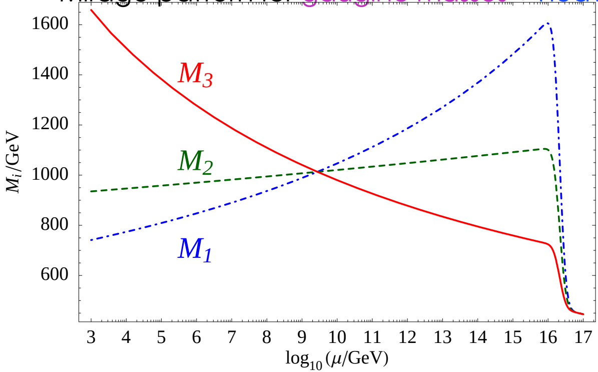
- Mirage pattern for gaugino masses + heavy sfermions



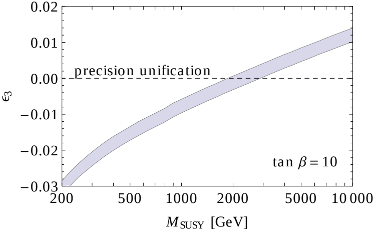
Implications for the LHC

- Al(most al)l moduli fixed in a supersymmetric way in MSSM vacua with residual (discrete and/or approximate) R symmetries
  Kappl, Petersen, Raby, M.R., Schieren & Vaudrevange (2011)
- Scenario with ~~SUSY~~ by 'matter field' X + dilaton S
- Mirage pattern for gaugino masses + heavy sfermions
- Yields natural scenario for precision gauge unification (PGU)
  Carena, Clavelli, Matalliotakis, Nilles & Wagner (1993) ... Raby, M.R. & Schmidt-Hoberg (2010)
  Krippendorf, Nilles, M.R. & Winkler (in preparation)

$$\epsilon_3 = \frac{g_3^2(M_{\mathrm{GUT}}) - g_{1,2}^2(M_{\mathrm{GUT}})}{g_{1,2}^2(M_{\mathrm{GUT}})}$$

$$M_{\mathrm{SUSY}} = \frac{m_{\widetilde{W}}^{32/19}\, m_{\widetilde{h}}^{12/19}\, m_H^{3/19}}{m_{\widetilde{g}}^{28/19}}\, X_{\mathrm{sfermion}}$$

$$X_{\mathrm{sfermion}} \sim 1$$



Implications for the LHC: Highlights

- PGU is consistent w/ small μ

detailled discussion in talk by M. Winkler

$$\epsilon_3 = \frac{g_3^2(M_{\text{GUT}}) - g_{1,2}^2(M_{\text{GUT}})}{g_{1,2}^2(M_{\text{GUT}})}$$

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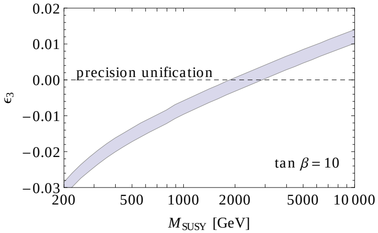


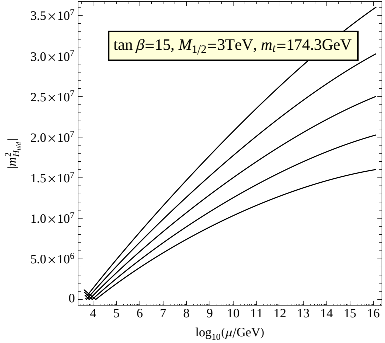
Implications for the LHC: Highlights

detailled discussion in talk by M. Winkler

- PGU is consistent w/ small μ

- Geometric properties of ingredients of top–Yukawa coupling entail ‘focus point’

Krippendorf, Nilles, M.R. & Winkler (2012)



  - H_u, Q_L & t_R bulk fields
  - ➥ Coinciding boundary conditions at high scale
  - ➥ ‘Focus point’

Feng, Matchev & Moroi (2000)

Implications for the LHC: Highlights

- PGU is consistent w/ small μ

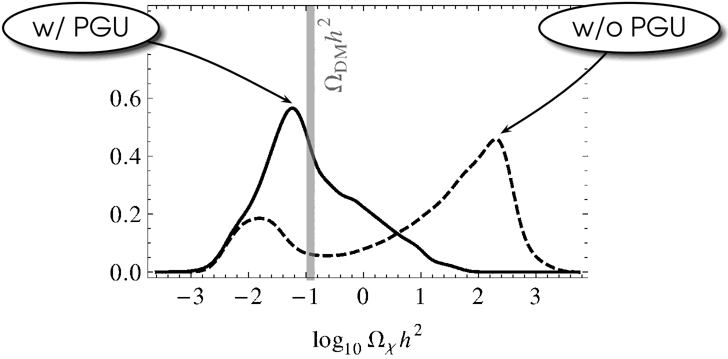
  detailled discussion in talk by M. Winkler

- Geometric properties of ingredients of top–Yukawa coupling entail 'focus point'

  Krippendorf, Nilles, M.R. & Winkler (2012)

- PGU leads to naturally to a relic density of WIMPs which is consistent with observed CDM

  Krippendorf, Nilles, M.R. & Winkler (in preparation)



Implications for the LHC: Highlights

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- PGU is consistent w/ small μ
- Geometric properties of ingredients of top–Yukawa coupling entail 'focus point' Krippendorf, Nilles, M.R. & Winkler (2012)
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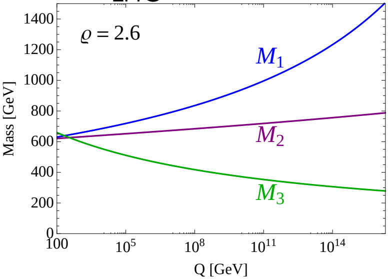
- Compressed gaugino spectra are harder to detect at the LHC Dreiner, Krämer & Tattersall (2012)



picture credits: M. Winkler

- $\varrho = \dfrac{3N - M}{2}$ for hidden $\mathrm{SU}(N)$ w/ M fundamentals

Badziak, Krippendorf, Nilles & Winkler (2013)

Implications for the LHC: Highlights

detailled discussion in talk by M. Winkler

- PGU is consistent w/ small μ
- Geometric properties of ingredients of top–Yukawa coupling entail 'focus point'
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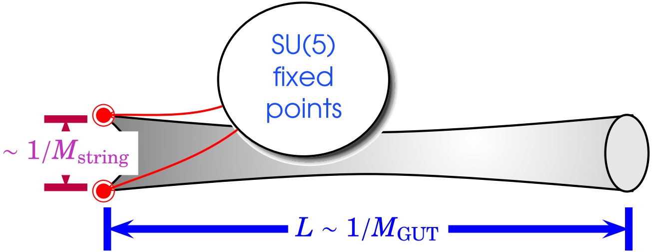
- Compressed gaugino spectra are harder to detect at the LHC
  Dreiner, Krämer & Tattersall (2012)
- Rather long–lived gluino

Summary

‘Hybrid breaking’ of $\mathrm{E}_8 \to G_{\mathrm{SM}}$

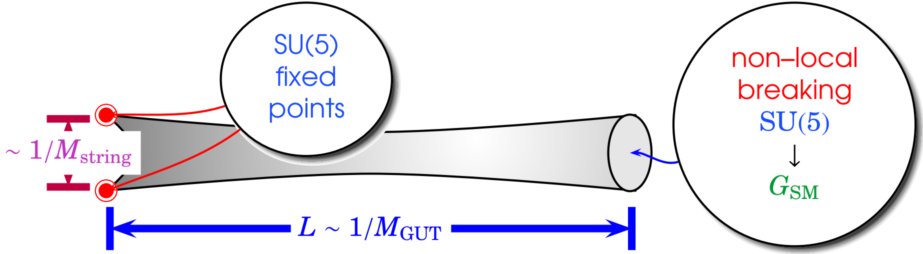


❶ Local breaking $\mathrm{E}_8 \to \mathrm{SU}(5)$

➥ Local GUTs explain complete matter representations

➥ Simple(r) structure of soft masses for sfermions

'Hybrid breaking' of $\mathrm{E}_8 \to G_{\mathrm{SM}}$



❶ Local breaking $\mathrm{E}_8 \to \mathrm{SU}(5)$

➥ Local GUTs explain complete matter representations

➥ Simple(r) structure of soft masses for sfermions

❷ Non–local breaking $\mathrm{SU}(5) \to G_{\mathrm{SM}}$

➥ No fractionally charged exotics

➥ Precision gauge unification

Heterotic moduli stabilization & PGU

- ☞ Heterotic orbifolds yield explicit and consistent stringy exensions of the standard model

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Heterotic moduli stabilization & PGU

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- ~~SUSY~~ by 'matter field'
  - heavy sfermions: $M_0 \sim m_{3/2} = \mathcal{O}(10 - 100)\,\mathrm{TeV}$
    $\curvearrowright$ not accessible at the LHC

Heterotic moduli stabilization & PGU

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  - heavy sfermions: $M_0 \sim m_{3/2} = \mathcal{O}(10 - 100)\,\mathrm{TeV}$
  - mirage pattern: compressed spectra for the gauginos M_i comparable and of $\mathcal{O}\left(m_{3/2}/(4\pi^2)\right) \sim \mathrm{TeV}$

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  - mirage pattern: compressed spectra for the gauginos
  - consistent w/ precision gauge unification w/ small μ
- Interesting correlations between PGU and relic LSP abundance

Thank you very much!

and

Bon(n) appetit!

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Backup slides

- Orbifolds and Wilson lines
- Blaszczyk model
- SUSY vacua with residual R symmetries

Orbifolds & Wilson lines

Ibáñez, Nilles & Quevedo (1987) ; Hall, Murayama & Nomura (2002)

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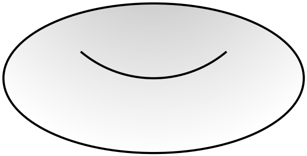

Orbifolds & Wilson lines

Ibáñez, Nilles & Quevedo (1987) ; Hall, Murayama & Nomura (2002)

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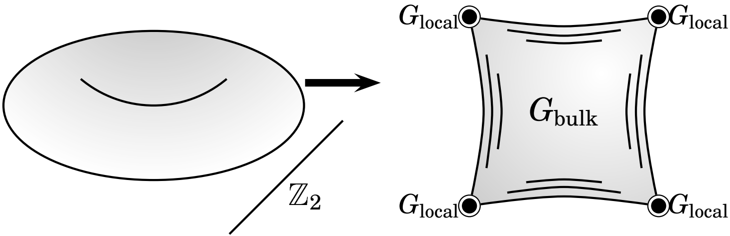

Orbifolds & Wilson lines

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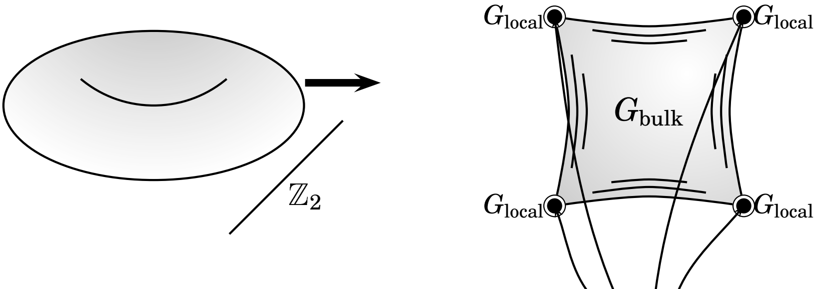
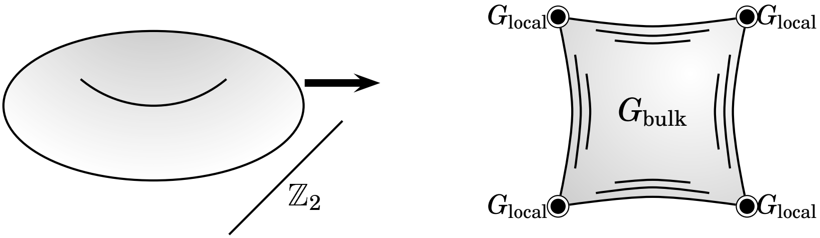
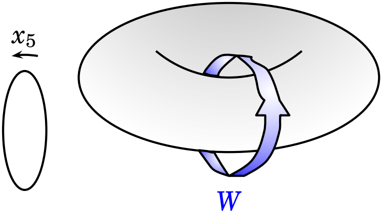


Gauge symmetry is broken **locally** at the fixed points

Orbifolds & Wilson lines

Ibáñez, Nilles & Quevedo (1987) ; Hall, Murayama & Nomura (2002) skip





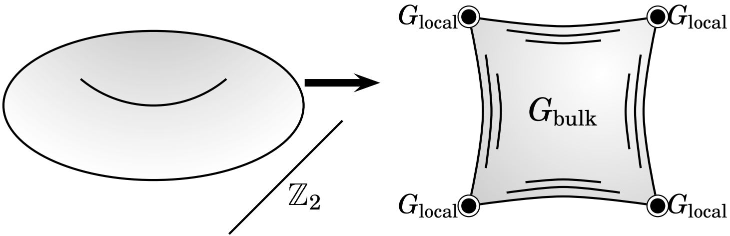
Discrete Wilson line:
going once around the torus leads to a non–trivial phase

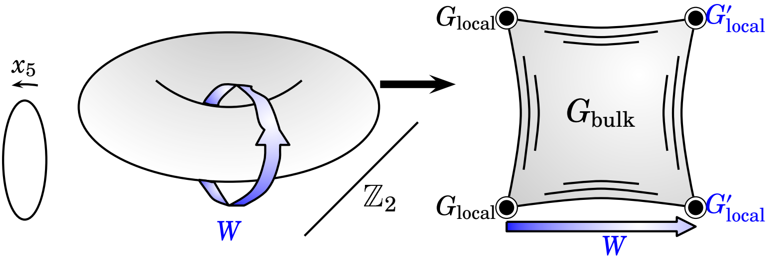
$$W = \oint \mathrm{d}x_5 \, A_5$$

Orbifolds & Wilson lines

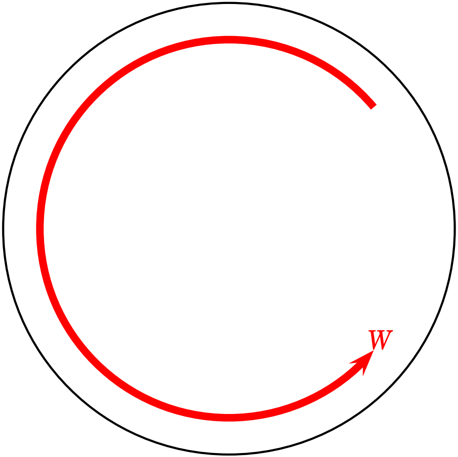
Ibáñez, Nilles & Quevedo (1987) ; Hall, Murayama & Nomura (2002)

skip

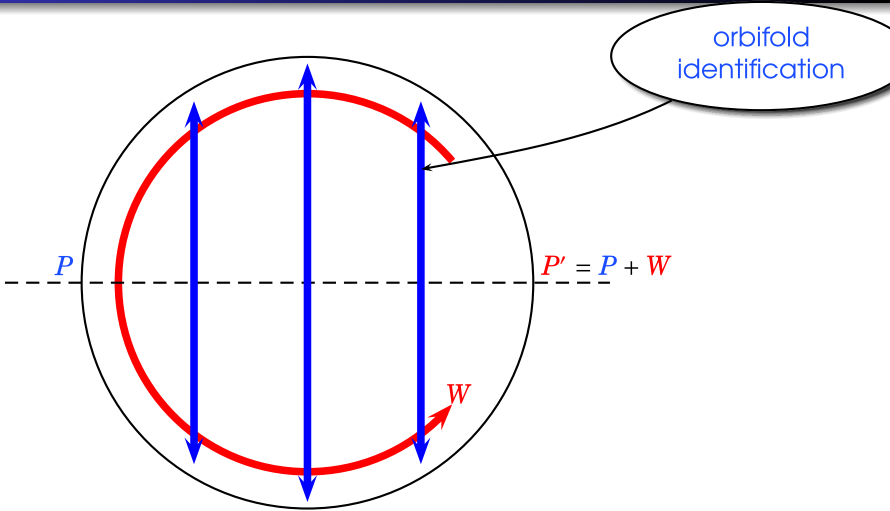




Simplest example : $\mathbb{S}^1/\mathbb{Z}_2$ with $\mathbb{Z}_2$ Wilson line



Simplest example : $\mathbb{S}^1/\mathbb{Z}_2$ with $\mathbb{Z}_2$ Wilson line



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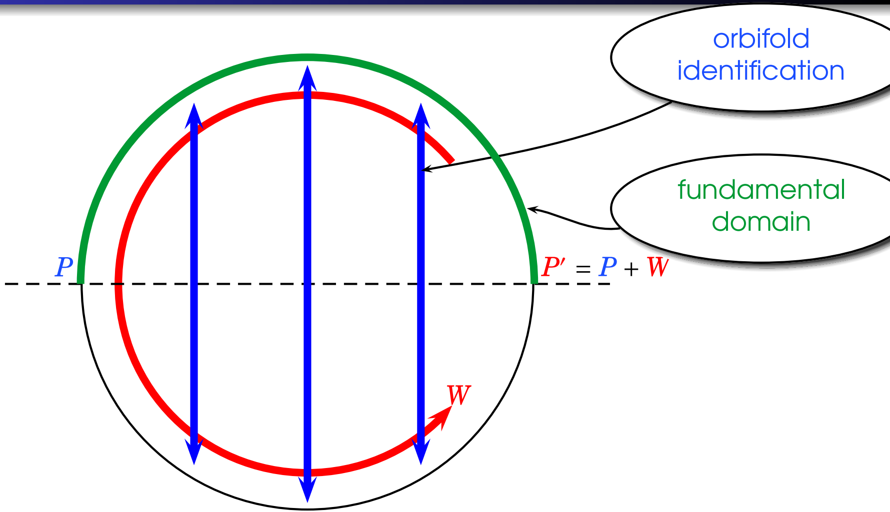

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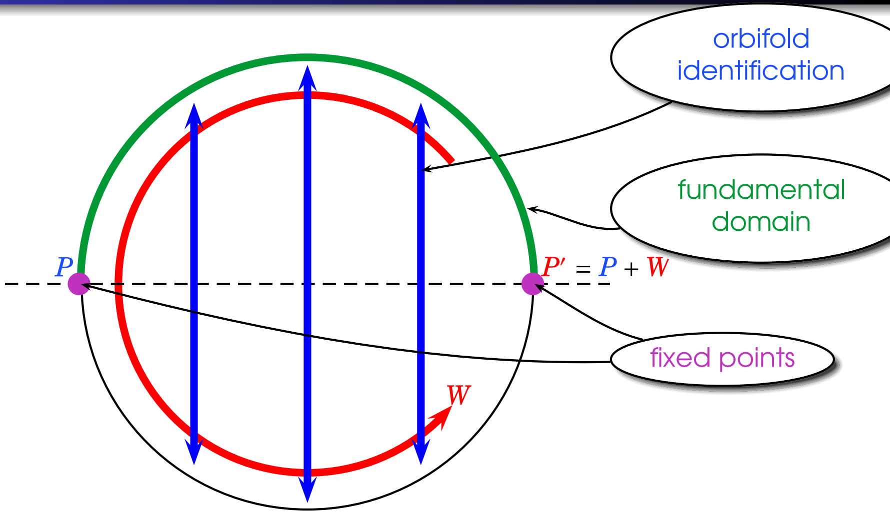
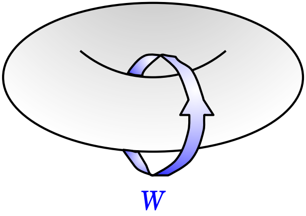
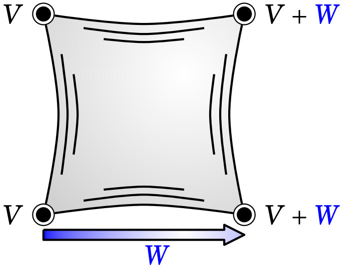


Orbifolds & Wilson lines



$\rightarrow$



Main message:

Discrete Wilson lines on the underlying torus leads to different boundary coditions at the fixed points

$\mathbb{Z}_4^R$ from a $\mathbb{Z}_2 \times \mathbb{Z}_2$ orbifold model

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'vacuum' means a field configuration that preserves supersymmetry perturbatively

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- Various good features
  - ✓ non–local GUT breaking

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☹ However:

- $\mathrm{SU}(5)$ Yukawa relations also for light generations
- hidden sector gauge group only $\mathrm{SU}(3)$

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bottom–line:

Successful string embedding of $\mathbb{Z}_4^R$ possible!

SUSY vacua with $\mathbb{Z}_4^R$

- Recall: situation for gauge theories with generic superpotential e.g. Luty and Taylor (1996)

solutions of D–equations $\cap$ solutions of F–equations $=$ non–trivial

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- Example: consider one field ϕ_0 with R-charge 0 and one field ϕ_2 with R-charge 2

$$\mathscr{W} \;=\; \phi_2 \cdot f(\phi_0) + \mathcal{O}({\phi_2}^3) \qquad \text{with} \quad \langle \mathscr{W} \rangle \;=\; 0 \text{ automatic}$$

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SUSY vacua with $\mathbb{Z}_4^R$ (cont'd)

back

- Generalization: consider N fields $\phi_0^{(i)}$ with R-charge 0 and M fields $\phi_2^{(j)}$ with R-charge 2

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- M non–trivial mass terms (also for T- and Z–moduli!)

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- ➥ expect solutions for $N \geq M$
- ➥ M non–trivial mass terms (also for T- and Z–moduli!)

- Have identified configurations with $N \geq M$ in our $\mathbb{Z}_2 \times \mathbb{Z}_2$ model(s)