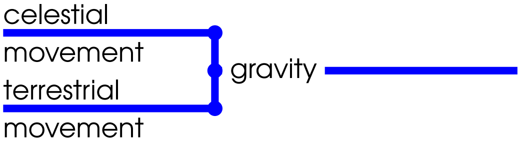
Towards a unified description of Nature

Michael Ratz

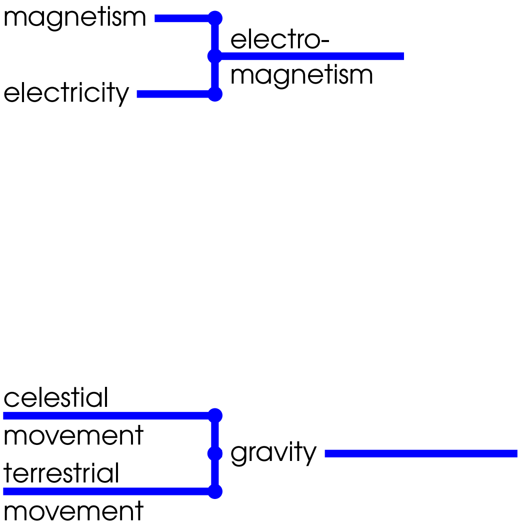
Oklahoma, October 5, 2017

Based on collaborations with:
F. Brümmer, W. Buchmüller, M.–C. Chen, M. Fallbacher, K. Hamaguchi, R. Kappl, T. Kobayashi, O. Lebedev, H.M. Lee, A. Mütter, H.P. Nilles, B. Petersen, F. Plöger, S. Raby, S. Ramos–Sánchez, G. Ross, R. Schieren, K. Schmidt–Hoberg, A. Trautner, V. Takhistov, P. Vaudrevange & A. Wingerter

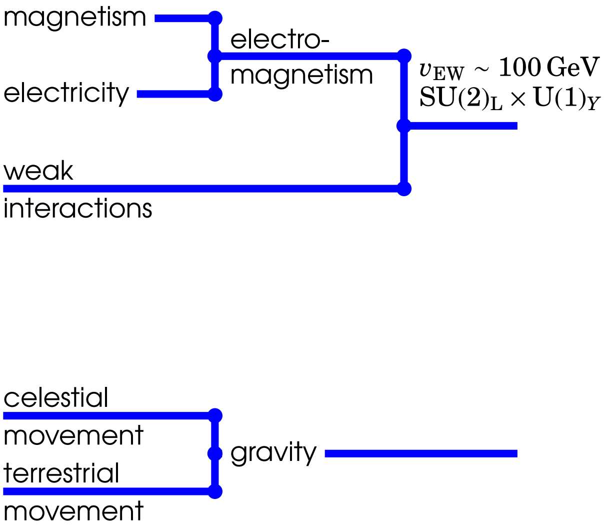
Unification of all forces



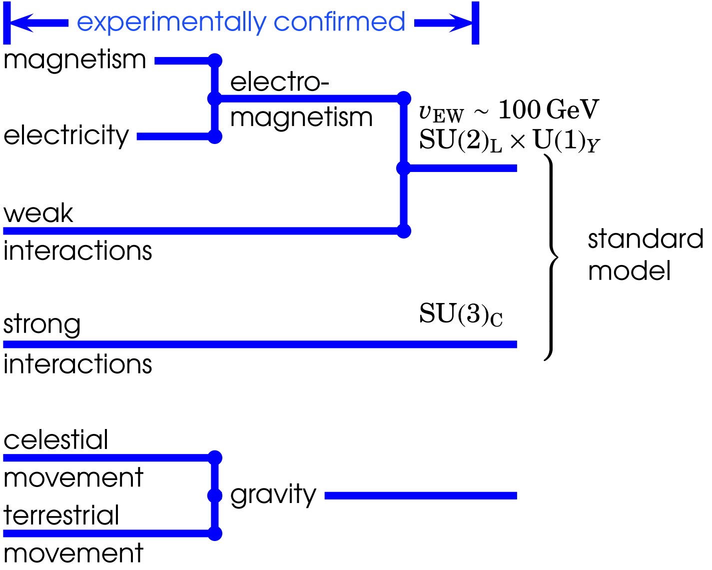
Unification of all forces



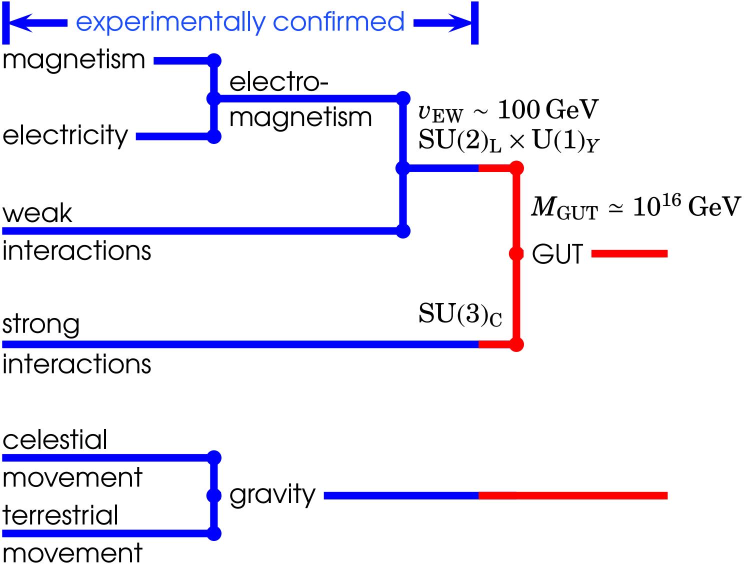
Unification of all forces



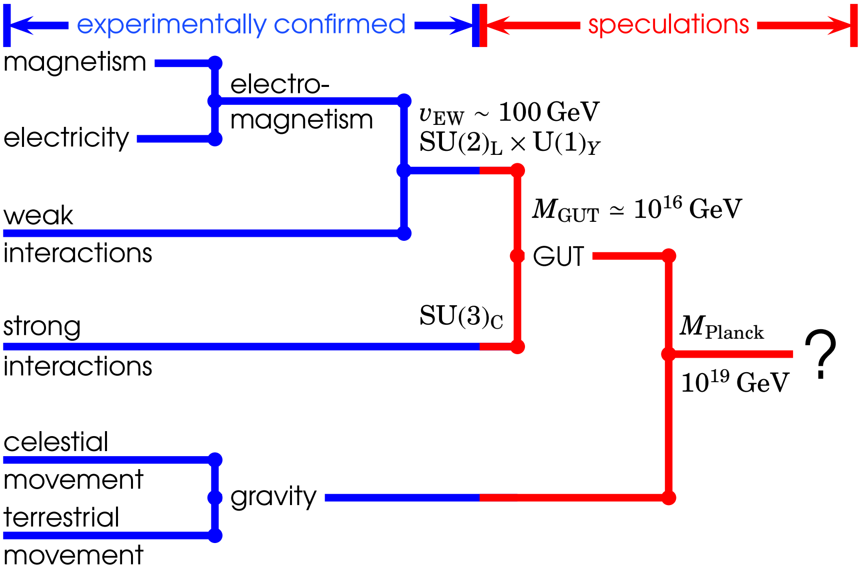
Unification of all forces



Unification of all forces



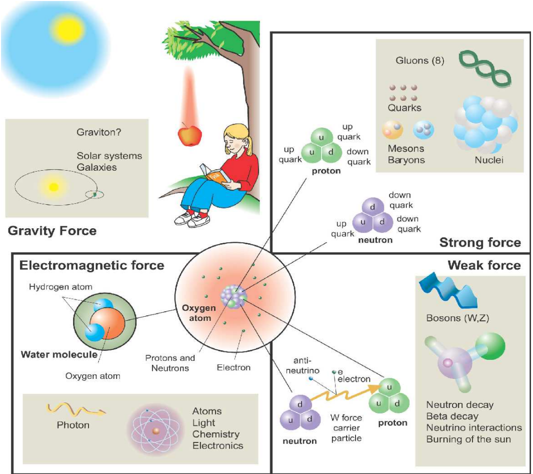
Unification of all forces

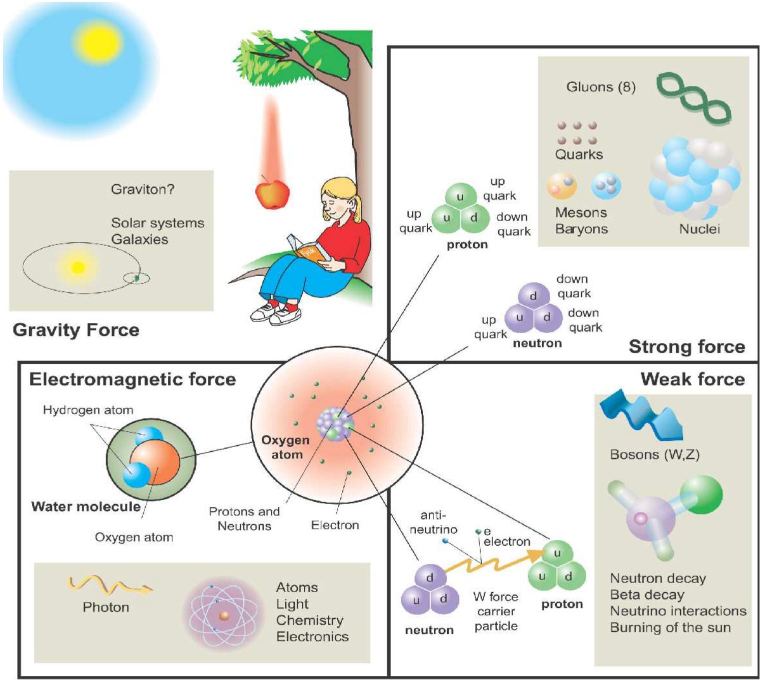


The

standard model of particle phyics

is extremely successful in describing observation.



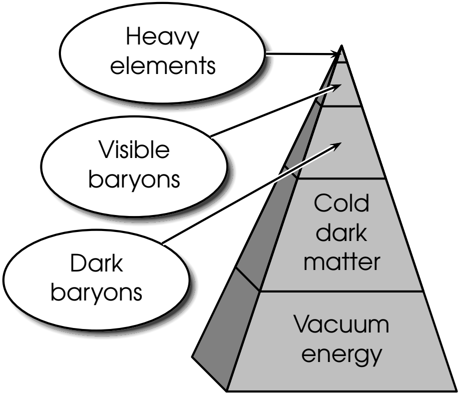


picture taken from http://www.nobelprize.org/

Physics beyond the standard model

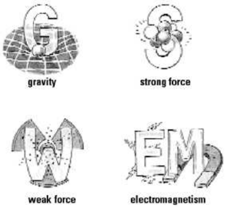
☞ Main reasons for going beyond the standard model of particle physics:

1. **Observation**: neither the observed cold dark matter nor the baryon asymmetry can be explained in the standard model.



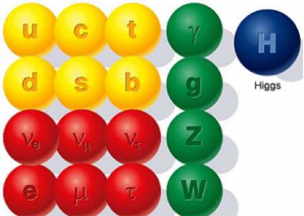
Physics beyond the standard model

- Main reasons for going beyond the standard model of particle physics:
  1. **Observation**: neither the observed cold dark matter nor the baryon asymmetry can be explained in the standard model.
  2. **Conceptual**: the standard model is based on a quantum field theory, in which, however, it appears difficult to incorporate gravity.



Physics beyond the standard model

- Main reasons for going beyond the standard model of particle physics:
  1. **Observation**: neither the observed cold dark matter nor the baryon asymmetry can be explained in the standard model.
  2. **Conceptual**: the standard model is based on a quantum field theory, in which, however, it appears difficult to incorporate gravity.
  3. **Aesthetics**: the structure and the large amount of parameters in the standard model ask for a simple, arguably more fundamental explanation.



Physics beyond the standard model

- Main reasons for going beyond the standard model of particle physics:
  1. **Observation**: neither the observed cold dark matter nor the baryon asymmetry can be explained in the standard model.
  2. **Conceptual**: the standard model is based on a quantum field theory, in which, however, it appears difficult to incorporate gravity.
  3. **Aesthetics**: the structure and the large amount of parameters in the standard model ask for a simple, arguably more fundamental explanation.

bottom–line:

New physics needed to describe our world at the microscopic level!

Outline

1. Introduction ✓
2. Grand unification in four & more dimensions
3. Stringy models of particle physics
4. Expectations and tests
5. Summary

Grand Unification

. . . in 4 dimensions

Gauge structure of the standard model

- Interactions come from gauge symmetries

$$G_{\mathrm{SM}} = \mathrm{SU}(3)_{\mathrm{C}} \times \mathrm{SU}(2)_{\mathrm{L}} \times \mathrm{U}(1)_{Y}$$

Gauge structure of the standard model

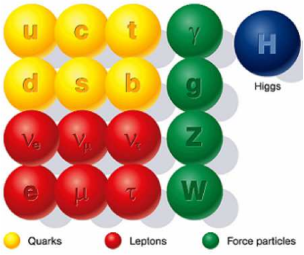
- Interactions come from gauge symmetries

$$G_{\mathrm{SM}} = \mathrm{SU(3)_C} \times \mathrm{SU(2)_L} \times \mathrm{U(1)}_Y$$

- Matter multiplets: 3 copies of   why 3 generations?

$$(\mathbf{3},\mathbf{2})_{1/6} \oplus (\overline{\mathbf{3}},\mathbf{1})_{-2/3} \oplus (\mathbf{1},\mathbf{1})_{1} \oplus (\overline{\mathbf{3}},\mathbf{1})_{1/3} \oplus (\mathbf{1},\mathbf{2})_{-1/2}$$

left–handed quark doublets	right–handed u type quarks	right–handed charged leptons	right–handed d type quarks	left–handed lepton doublets



Gauge structure of the standard model

- Interactions come from gauge symmetries

$$G_{\mathrm{SM}} = \mathrm{SU}(3)_{\mathrm{C}} \times \mathrm{SU}(2)_{\mathrm{L}} \times \mathrm{U}(1)_{Y}$$

- Matter multiplets: 3 copies of

$$(\mathbf{3},\mathbf{2})_{1/6} \oplus (\overline{\mathbf{3}},\mathbf{1})_{-2/3} \oplus (\mathbf{1},\mathbf{1})_{1} \oplus (\overline{\mathbf{3}},\mathbf{1})_{1/3} \oplus (\mathbf{1},\mathbf{2})_{-1/2}$$

hypercharge quantization: why?

stated differently: why are atoms neutral?

- electric charge = hypercharge + weak isospin

Gauge structure of the standard model

☞ Interactions come from gauge symmetries

$$G_{\rm SM} \;=\; {\rm SU}(3)_{\rm C} \times {\rm SU}(2)_{\rm L} \times {\rm U}(1)_Y$$

☞ Matter multiplets: 3 copies of

$$(\mathbf{3},\mathbf{2})_{1/6} \oplus (\overline{\mathbf{3}},\mathbf{1})_{-2/3} \oplus (\mathbf{1},\mathbf{1})_{1} \oplus (\overline{\mathbf{3}},\mathbf{1})_{1/3} \oplus (\mathbf{1},\mathbf{2})_{-1/2}$$

Local SU(3) rotation : e.g. down quark

$$\begin{pmatrix} \psi_q \\ \psi_q \\ \psi_q \end{pmatrix} \to \begin{pmatrix} * & * & * \\ * & * & * \\ * & * & * \end{pmatrix} \quad \begin{pmatrix} \psi_q \\ \psi_q \\ \psi_q \end{pmatrix}$$

Gauge structure of the standard model

- Interactions come from gauge symmetries

$$G_{\mathrm{SM}} = \mathrm{SU}(3)_{\mathrm{C}} \times \mathrm{SU}(2)_{\mathrm{L}} \times \mathrm{U}(1)_Y$$

- Matter multiplets: 3 copies of

$(\mathbf{3},\mathbf{2})_{1/6} \oplus (\overline{\mathbf{3}},\mathbf{1})_{-2/3} \oplus (\mathbf{1},\mathbf{1})_{1} \oplus (\overline{\mathbf{3}},\mathbf{1})_{1/3} \oplus (\mathbf{1},\mathbf{2})_{-1/2}$

Local SU(2) rotation : e.g. lepton doublet

$$\begin{pmatrix} \psi_\nu \\ \psi_e \end{pmatrix} \to \begin{pmatrix} * & * \\ * & * \end{pmatrix}\begin{pmatrix} \psi_\nu \\ \psi_e \end{pmatrix}$$

Gauge structure of the standard model

- Interactions come from gauge symmetries

$$G_{\rm SM} = \mathrm{SU}(3)_{\rm C} \times \mathrm{SU}(2)_{\rm L} \times \mathrm{U}(1)_Y \subset \mathrm{SU}(5)$$

- Matter multiplets: 3 copies of

$(\mathbf{3},\mathbf{2})_{1/6} \oplus (\overline{\mathbf{3}},\mathbf{1})_{-2/3} \oplus (\mathbf{1},\mathbf{1})_{1} \oplus (\overline{\mathbf{3}},\mathbf{1})_{1/3} \oplus (\mathbf{1},\mathbf{2})_{-1/2}$

Local SU(5) rotation

Georgi & Glashow (1974)

$$\begin{pmatrix} \psi_q \\ \psi_q \\ \psi_q \\ \psi_\nu \\ \psi_e \end{pmatrix} \to \begin{pmatrix} * & * & * & * & * \\ * & * & * & * & * \\ * & * & * & * & * \\ * & * & * & * & * \\ * & * & * & * & * \end{pmatrix} \begin{pmatrix} \psi_q \\ \psi_q \\ \psi_q \\ \psi_\nu \\ \psi_e \end{pmatrix}$$

Gauge structure of the standard model

- Interactions come from gauge symmetries

$$G_{\mathrm{SM}} = \mathrm{SU}(3)_{\mathrm{C}} \times \mathrm{SU}(2)_{\mathrm{L}} \times \mathrm{U}(1)_{Y} \subset \mathrm{SU}(5)$$

- Matter multiplets: 3 copies of

$$\underbrace{(\mathbf{3},\mathbf{2})_{1/6} \oplus (\overline{\mathbf{3}},\mathbf{1})_{-2/3} \oplus (\mathbf{1},\mathbf{1})_{1}}_{=\,\mathbf{10}} \oplus \underbrace{(\overline{\mathbf{3}},\mathbf{1})_{1/3} \oplus (\mathbf{1},\mathbf{2})_{-1/2}}_{=\,\overline{\mathbf{5}}}$$

Local SU(5) rotation

Georgi & Glashow (1974)

$$\begin{pmatrix} \psi_q \\ \psi_q \\ \psi_q \\ \psi_\nu \\ \psi_e \end{pmatrix} \to \begin{pmatrix} * & * & * & * & * \\ * & * & * & * & * \\ * & * & * & * & * \\ * & * & * & * & * \\ * & * & * & * & * \end{pmatrix} \begin{pmatrix} \psi_q \\ \psi_q \\ \psi_q \\ \psi_\nu \\ \psi_e \end{pmatrix}$$

Gauge structure of the standard model

- Interactions come from gauge symmetries

$$G_{\mathrm{SM}} = \mathrm{SU}(3)_{\mathrm{C}} \times \mathrm{SU}(2)_{\mathrm{L}} \times \mathrm{U}(1)_{Y} \subset \mathrm{SU}(5)$$

- Matter multiplets: 3 copies of

$$\underbrace{(\mathbf{3},\mathbf{2})_{1/6} \oplus (\overline{\mathbf{3}},\mathbf{1})_{-2/3} \oplus (\mathbf{1},\mathbf{1})_{1}}_{=\,\mathbf{10}} \oplus \underbrace{(\overline{\mathbf{3}},\mathbf{1})_{1/3} \oplus (\mathbf{1},\mathbf{2})_{-1/2}}_{=\,\overline{\mathbf{5}}}$$

Local SU(5) rotation

Georgi & Glashow (1974)

$$\begin{pmatrix} \psi_q \\ \psi_q \\ \psi_q \\ \psi_\nu \\ \psi_e \end{pmatrix} \to \begin{pmatrix} * & * & * & * & * \\ * & * & * & * & * \\ * & * & * & * & * \\ * & * & * & * & * \\ * & * & * & * & * \end{pmatrix} \begin{pmatrix} \psi_q \\ \psi_q \\ \psi_q \\ \psi_\nu \\ \psi_e \end{pmatrix}$$

extra X gauge bosons mediate transitions between quarks and leptons

Gauge structure of the standard model

- Interactions come from gauge symmetries

$$G_{\mathrm{SM}} = \mathrm{SU}(3)_{\mathrm{C}} \times \mathrm{SU}(2)_{\mathrm{L}} \times \mathrm{U}(1)_{Y} \subset \mathrm{SU}(5)$$

- Matter multiplets: 3 copies of

$$\underbrace{(\mathbf{3},\mathbf{2})_{1/6} \oplus (\overline{\mathbf{3}},\mathbf{1})_{-2/3} \oplus (\mathbf{1},\mathbf{1})_{1}}_{=\,\mathbf{10}} \oplus \underbrace{(\overline{\mathbf{3}},\mathbf{1})_{1/3} \oplus (\mathbf{1},\mathbf{2})_{-1/2}}_{=\,\overline{\mathbf{5}}}$$

Local SU(5) rotation

Georgi & Glashow (1974)

$$\begin{pmatrix} \psi_q \\ \psi_q \\ \psi_q \\ \psi_\nu \\ \psi_e \end{pmatrix} \to \begin{pmatrix} * & * & * & * & * \\ * & * & * & * & * \\ * & * & * & * & * \\ * & * & * & * & * \\ * & * & * & * & * \end{pmatrix} \begin{pmatrix} \psi_q \\ \psi_q \\ \psi_q \\ \psi_\nu \\ \psi_e \end{pmatrix}$$

bottom–line:

All known (gauge) interactions can be unified!

SU(5)

$\mathrm{SU}(5)$ grand unified theory (GUT) ...

- explains charge quantization
- simplifies matter content

SM generation $= \mathbf{10} + \overline{\mathbf{5}}$

SU(5) and SO(10)

$\mathrm{SU}(5)$ grand unified theory (GUT) ...

- explains charge quantization
- simplifies matter content

SM generation $= \mathbf{10} + \overline{\mathbf{5}}$

further simplification of matter sector

Fritzsch & Minkowski (1975)

$$\begin{array}{rcl} \mathrm{SO}(10) & \supset & \mathrm{SU}(5) \\ \mathbf{16} & = & \mathbf{10} \oplus \overline{\mathbf{5}} \oplus \mathbf{1} \\ & = & \text{SM generation with `right–handed' neutrino} \end{array}$$

SU(5) and SO(10)

$\mathrm{SU}(5)$ grand unified theory (GUT) . . .

- explains charge quantization
- simplifies matter content

SM generation $=$ $\mathbf{10} + \overline{\mathbf{5}}$

further simplification of matter sector

Fritzsch & Minkowski (1975)

$$\begin{aligned} \mathrm{SO}(10) &\supset \mathrm{SU}(5) \\ \mathbf{16} &= \mathbf{10} \oplus \overline{\mathbf{5}} \oplus \mathbf{1} \\ &= \text{SM generation with `right–handed' neutrino} \end{aligned}$$

➥ Once there is an electron, $\mathrm{SO}(10)$ tells us that there are also u and d quarks, i.e. protons and neutrons!

SU(5) and SO(10)

$\mathrm{SU}(5)$ grand unified theory (GUT) . . .

- ☞ explains charge quantization
- ☞ simplifies matter content

  SM generation $= \mathbf{10} + \overline{\mathbf{5}}$

further simplification of matter sector

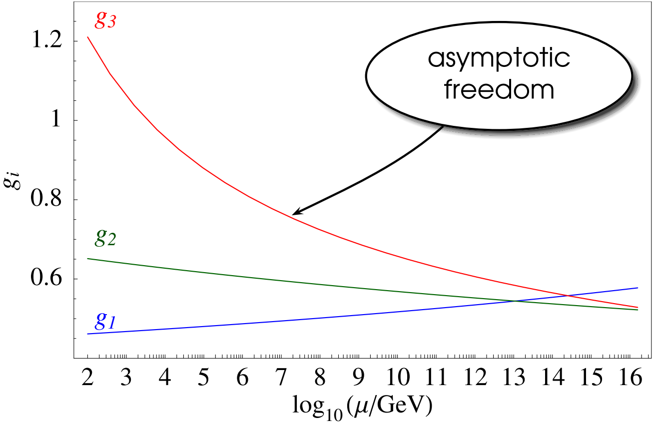
Fritzsch & Minkowski (1975)

$$\begin{array}{rcl} \mathrm{SO}(10) & \supset & \mathrm{SU}(5) \\ \mathbf{16} & = & \mathbf{10} \oplus \overline{\mathbf{5}} \oplus \mathbf{1} \\ & = & \text{SM generation with `right–handed' neutrino} \end{array}$$

➥ Once there is an electron, $\mathrm{SO}(10)$ tells us that there are also u and d quarks, i.e. protons and neutrons!

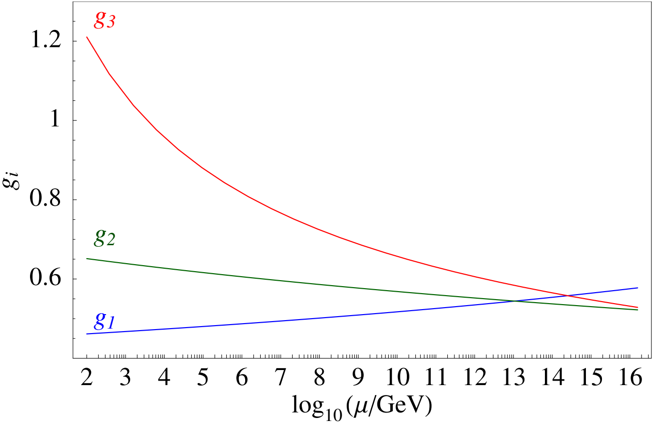
☞ **However**: coupling strengths are measured to be different

Gauge coupling (non-)unification



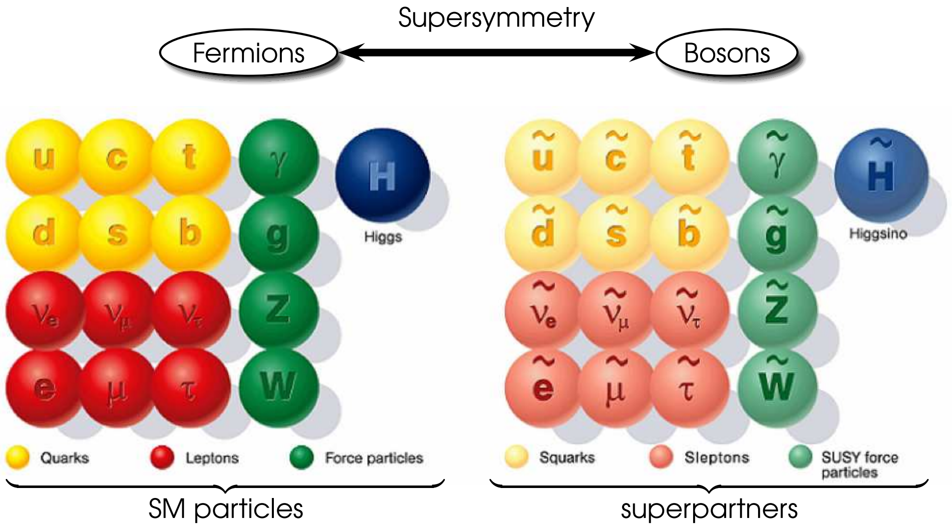
☞ Gauge coupling evolution in the SM:
qualitatively nice: couplings run towards each other

Gauge coupling (non-)unification

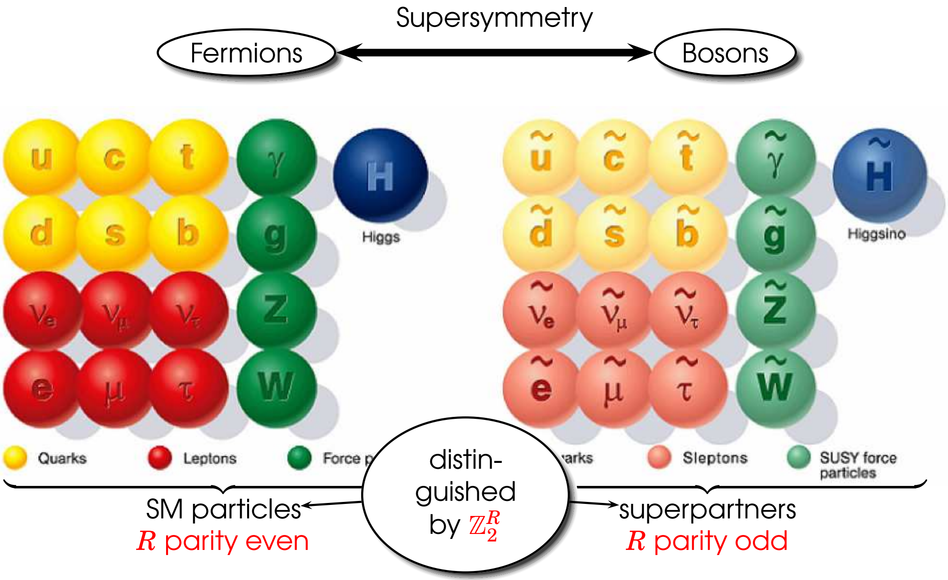


- Gauge coupling evolution in the SM:
  qualitatively nice: couplings run towards each other
- **However**: couplings do not meet at a point

(Minimal) supersymmetric standard model



(Minimal) supersymmetric standard model

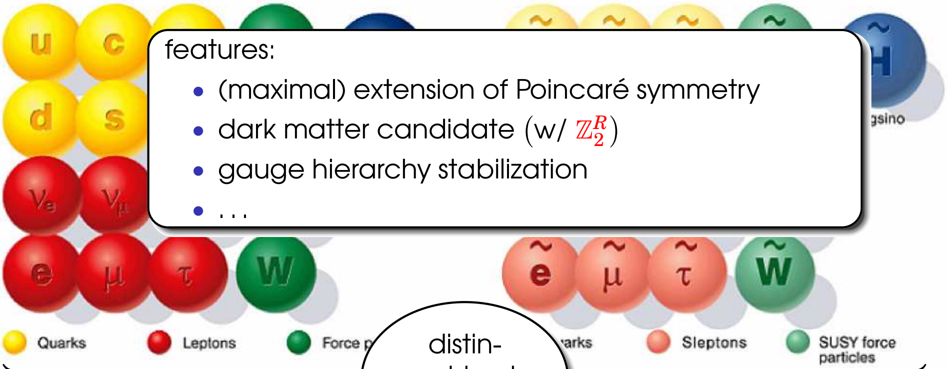


(Minimal) supersymmetric standard model

Fermions ⟵ Supersymmetry ⟶ Bosons

features:

- (maximal) extension of Poincaré symmetry
- dark matter candidate (w/ $\mathbb{Z}_2^R$)
- gauge hierarchy stabilization
- ...



SM particles
R parity even

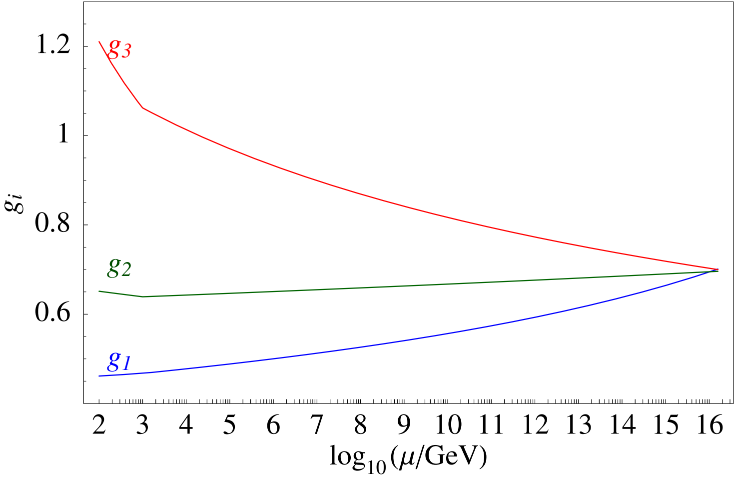
distinguished by $\mathbb{Z}_2^R$

superpartners
R parity odd

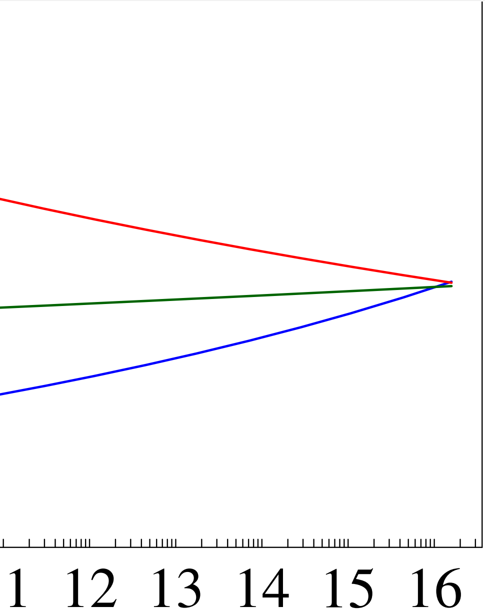
Gauge coupling unification in the MSSM

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

Dimopoulos, Raby & Wilczek (1981)



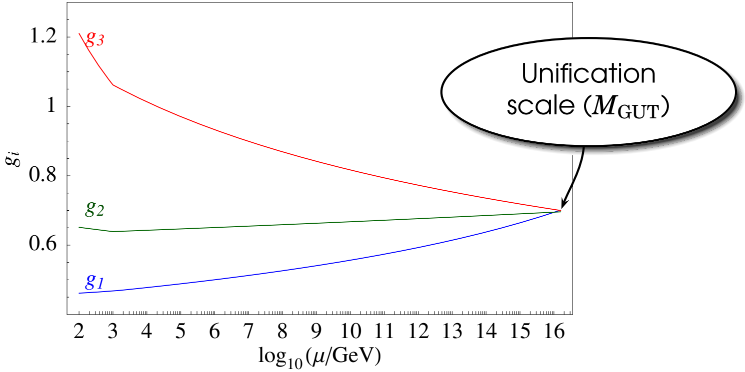
Gauge coupling unification in the MSSM



Gauge coupling unification in the MSSM

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

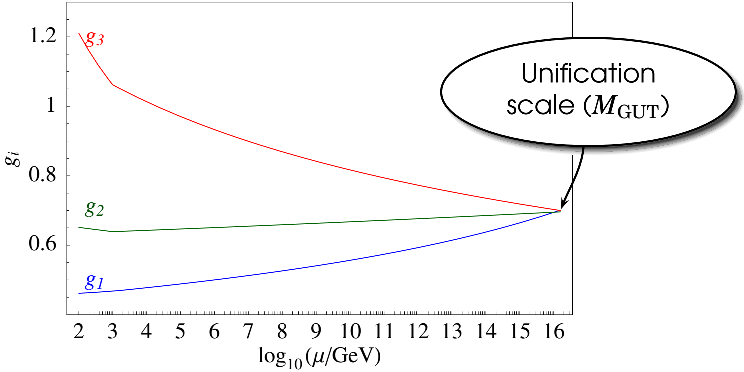
Dimopoulos, Raby & Wilczek (1981)



Gauge coupling unification in the MSSM

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

Dimopoulos, Raby & Wilczek (1981)

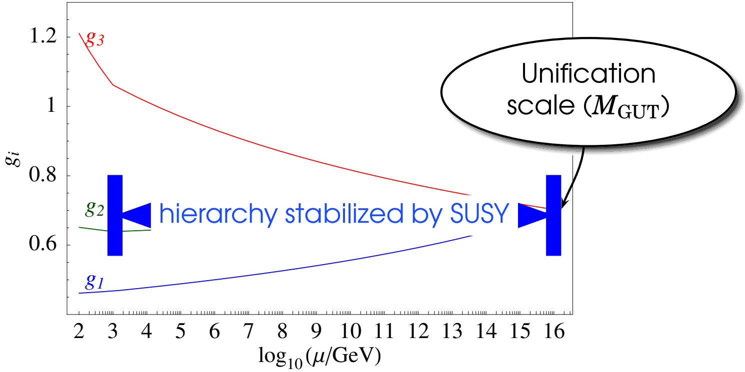


- There is **only one coupling**, we observe different coupling strengths only because of **quantum effects**

Gauge coupling unification in the MSSM

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

Dimopoulos, Raby & Wilczek (1981)



- There is **only one coupling**, we observe different coupling strengths only because of **quantum effects**

Grand unification: virtues & predictions

- GUTs explain charge quantization

Grand unification: virtues & predictions

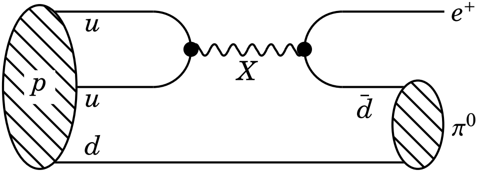
- GUTs explain charge quantization
- In $SO(10)$: understanding of the structure of SM matter

Grand unification: virtues & predictions

- GUTs explain charge quantization
- In $\mathrm{SO}(10)$: understanding of the structure of SM matter
- Gauge coupling unification (. . . with supersymmetry)

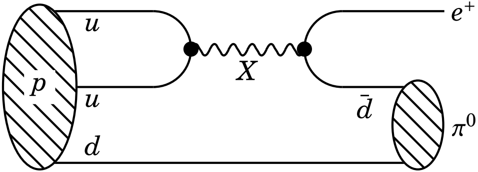
Grand unification: virtues & predictions

- GUTs explain charge quantization
- In $\mathrm{SO}(10)$: understanding of the structure of SM matter
- Gauge coupling unification (. . . with supersymmetry)
- Prediction: proton decay



Grand unification: virtues & predictions

- GUTs explain charge quantization
- In $\mathrm{SO}(10)$: understanding of the structure of SM matter
- Gauge coupling unification (. . . with supersymmetry)
- Prediction: proton decay

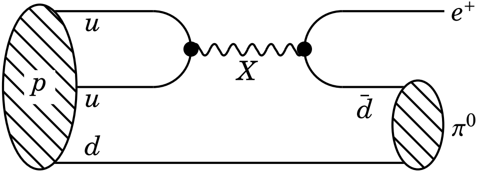


main prediction of GUTs:

matter unstable

Grand unification: virtues & predictions

- GUTs explain charge quantization
- In $\mathrm{SO}(10)$: understanding of the structure of SM matter
- Gauge coupling unification (. . . with supersymmetry)
- Prediction: proton decay



main prediction of GUTs:

matter unstable $\curvearrowright$ one day our universe will be 'empty'

Doublet–triplet splitting problem

- GUTs also predict color triplets

smallest SO(10) representation containing Higgs

$$\mathbf{10} = \mathbf{5} \oplus \overline{\mathbf{5}} \rightarrow (\mathbf{1},\mathbf{2})_{1/2} \oplus (\mathbf{1},\mathbf{2})_{-1/2} \oplus (\mathbf{3},\mathbf{1})_{-1/3} \oplus (\overline{\mathbf{3}},\mathbf{1})_{1/3}$$

doublets: needed

triplets: problematic

Doublet–triplet splitting problem

- GUTs also predict color triplets

smallest SO(10) representation containing Higgs

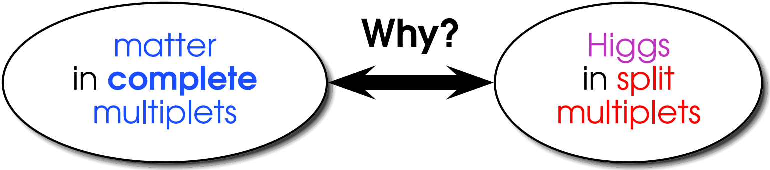
$$\mathbf{10} = \mathbf{5} \oplus \overline{\mathbf{5}} \rightarrow (\mathbf{1},\mathbf{2})_{1/2} \oplus (\mathbf{1},\mathbf{2})_{-1/2} \oplus (\mathbf{3},\mathbf{1})_{-1/3} \oplus (\overline{\mathbf{3}},\mathbf{1})_{1/3}$$

doublets: needed

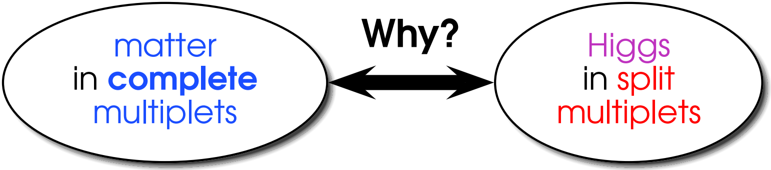
triplets: problematic

- Triplets $\left\{ \begin{array}{l} \bullet \text{ spoil gauge coupling unification} \\ \bullet \text{ mediate proton decay} \end{array} \right.$

Doublet–triplet splitting in four dimensions



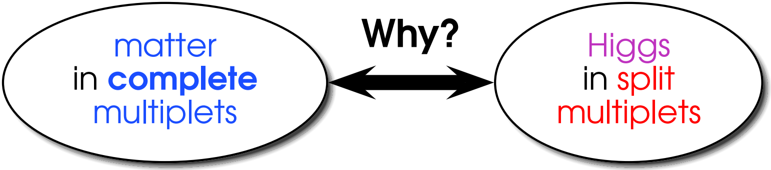
Doublet–triplet splitting in four dimensions



☞ there exist proposals to solve the doublet–triplet splitting problem, e.g.

- Dimopoulos–Wilczek mechanism — Dimopoulos & Wilczek (1981)
- Missing partner mechanism — Masiero, Nanopoulos, Tamvakis & Yanagida (1982)
- ...

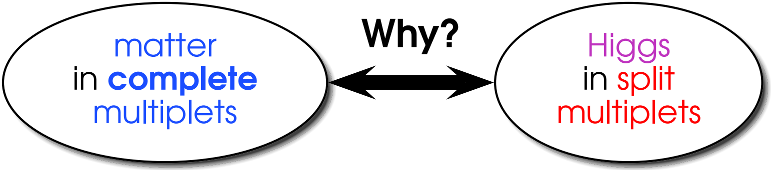
Doublet–triplet splitting in four dimensions



- there exist proposals to solve the doublet–triplet splitting problem, e.g.
  - Dimopoulos–Wilczek mechanism — Dimopoulos & Wilczek (1981)
  - Missing partner mechanism — Masiero, Nanopoulos, Tamvakis & Yanagida (1982)
  - . . .

. . . however, a closer inspection shows that all of them have certain deficiencies

Doublet–triplet splitting in four dimensions



- ‘Natural’ solution of the doublet–triplet splitting problem requires a symmetry that forbids Higgs mass μ

  According to ’t Hoofts ‘naturalness’ criteria: explaining a (supersymmetric) Higgs mass $\mu \ll M_{\mathrm{GUT}}$ requires a symmetry that forbids μ.

Doublet–triplet splitting in four dimensions

matter in **complete** multiplets ⟷ **Why?** ⟷ Higgs in split multiplets

- ☞ ‘Natural’ solution of the doublet–triplet splitting problem requires a symmetry that forbids Higgs mass μ

- ☞ Only R symmetries can do the job

superpartners have different charges

Hall, Nomura & Pierce (2002) ; Lee, Raby, M.R., Ross, Schieren, et al. (2011) ; Chen, Fallbacher & M.R. (2012)

- anomaly freedom
- fermion masses
  (Yukawa couplings & neutrino mass operator)
- consistency with SU(5)
- gauge coupling unification

$\curvearrowright$ only R symmetries can forbid the μ term in the MSSM

. . . and R parity is not enough

Doublet–triplet splitting in four dimensions

matter in **complete** multiplets ⟷ **Why?** ⟷ Higgs in split multiplets

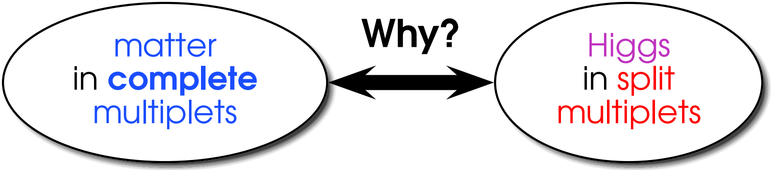
- ‘Natural’ solution of the doublet–triplet splitting problem requires a symmetry that forbids Higgs mass μ
- Only R symmetries can do the job and R parity does not
- **However**: R symmetries are not available in 4D GUTs

Fallbacher, M.R. & Vaudrevange (2011)

- GUT group $G \supset \mathrm{SU}(5)$
- spontaneous breaking
- finite number of fields

$\curvearrowright$ cannot have exact MSSM spectrum & residual R symmetries (which are stronger than R parity) in four dimensions

Doublet–triplet splitting in four dimensions



- ‘Natural’ solution of the doublet–triplet splitting problem requires a symmetry that forbids Higgs mass μ
- Only R symmetries can do the job and R parity does not
- **However**: R symmetries are not available in 4D GUTs

remainder of this talk:

Grand Unification in extra dimensions

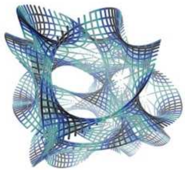
Higher–dimensional GUTs from strings

String compactifications

- Violin: needs to be constructed in such a way that the oscillating strings produce the right sounds

String compactifications

- Violin: needs to be constructed in such a way that the oscillating strings produce the right sounds



- String compactification: twist the string in such a way that the excitations carry the quantum numbers of the standard model particles

How to build a 4D string model

☞ (Super–)String theory predicts six extra dimensions

How to build a 4D string model

☞ (Super–)String theory predicts six extra dimensions

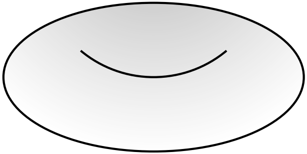
. . . but for simplicity discuss only two of them

How to build a 4D string model

- (Super–)String theory predicts six extra dimensions

... but for simplicity discuss only two of them

- Simple example: $\mathbb{Z}_2$ orbifold plane = $\mathbb{T}^2/\mathbb{Z}_2$

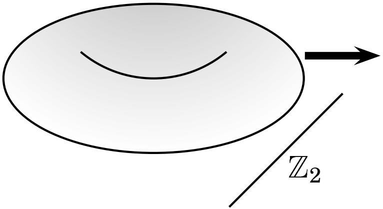


How to build a 4D string model

- (Super–)String theory predicts six extra dimensions

. . . but for simplicity discuss only two of them

- Simple example: $\mathbb{Z}_2$ orbifold plane = $\mathbb{T}^2/\mathbb{Z}_2$

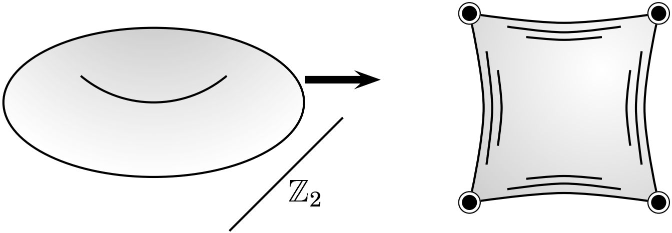


How to build a 4D string model

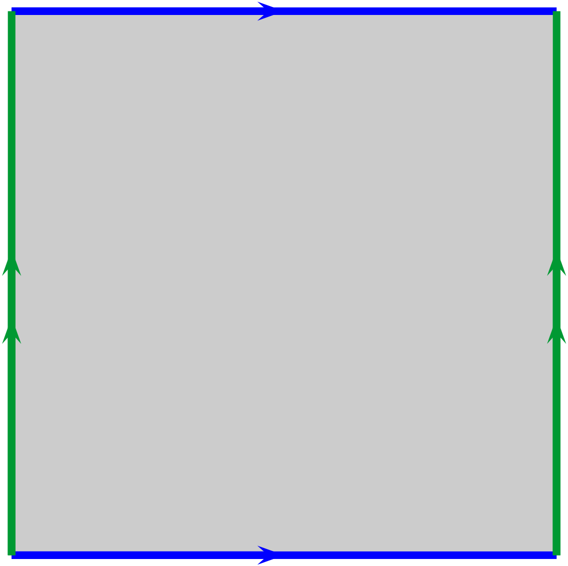
- (Super–)String theory predicts six extra dimensions

. . . but for simplicity discuss only two of them

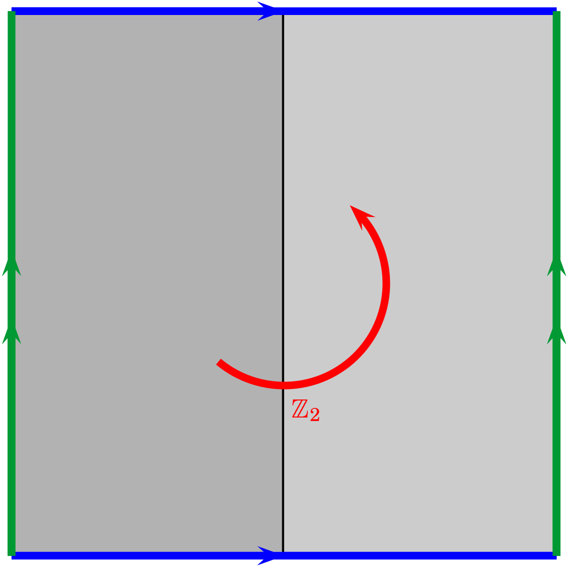
- Simple example: $\mathbb{Z}_2$ orbifold plane = $\mathbb{T}^2/\mathbb{Z}_2$



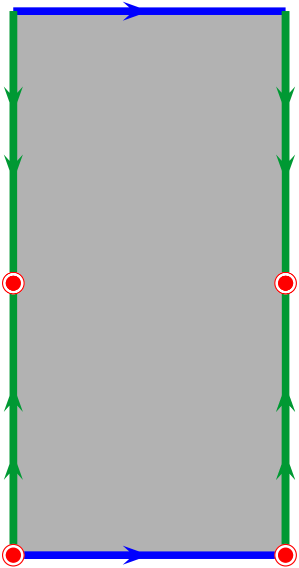
$\mathbb{Z}_2$ orbifold pillow



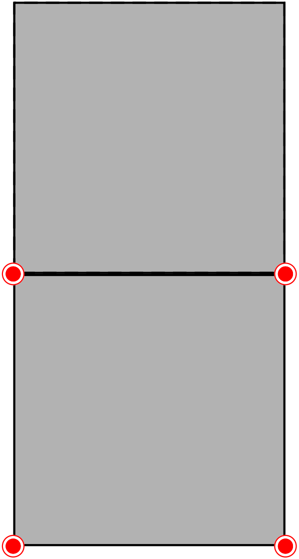
$\mathbb{Z}_2$ orbifold pillow



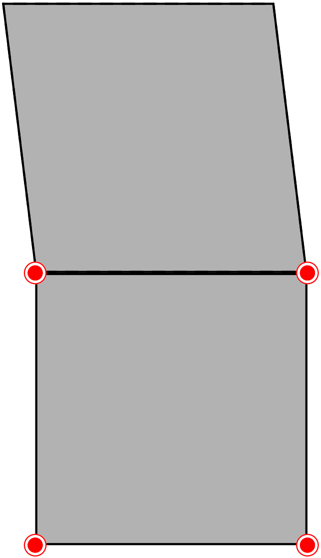
$\mathbb{Z}_2$ orbifold pillow



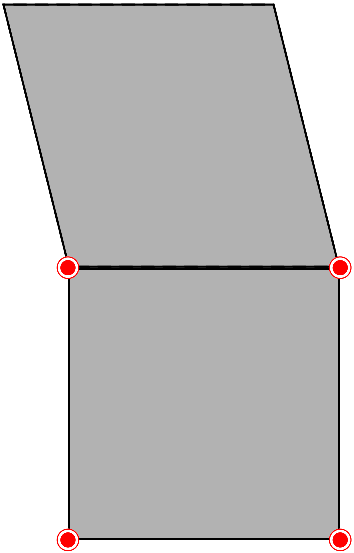
$\mathbb{Z}_2$ orbifold pillow



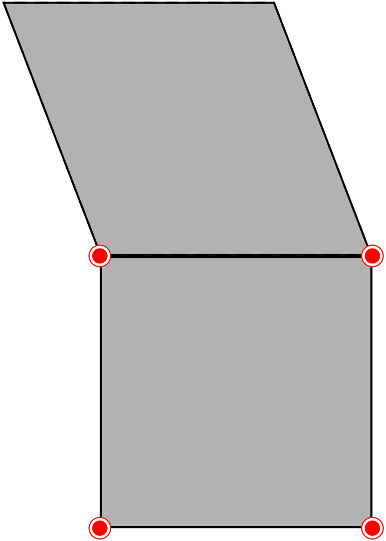
$\mathbb{Z}_2$ orbifold pillow



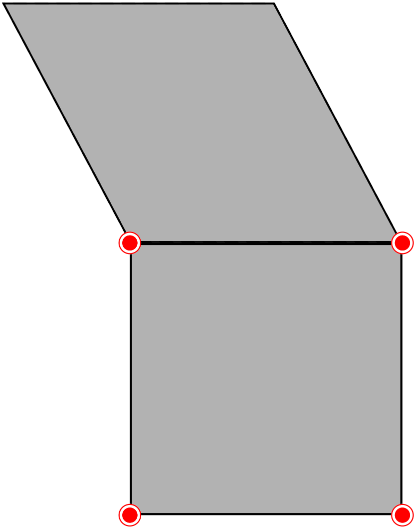
$\mathbb{Z}_2$ orbifold pillow



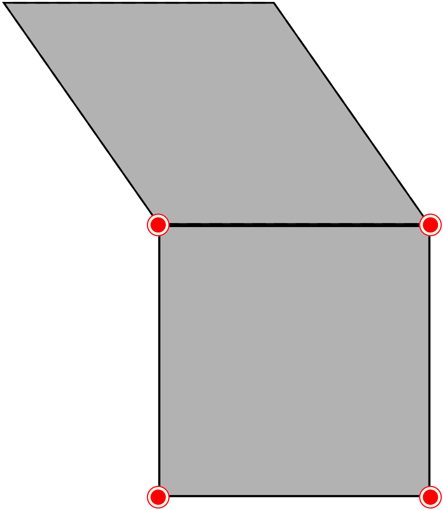
$\mathbb{Z}_2$ orbifold pillow



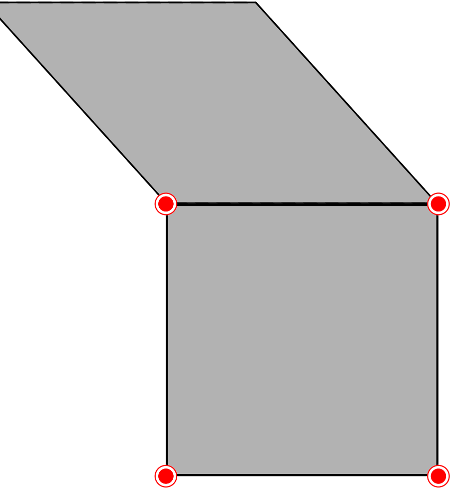
$\mathbb{Z}_2$ orbifold pillow



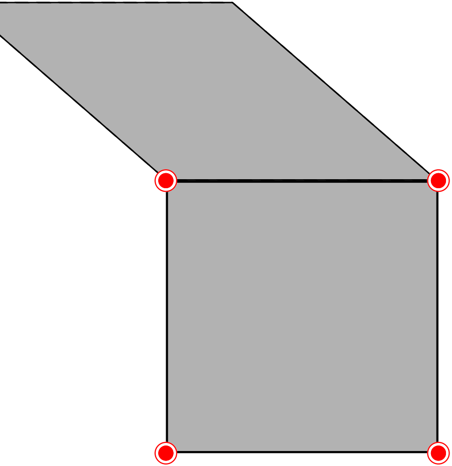
$\mathbb{Z}_2$ orbifold pillow



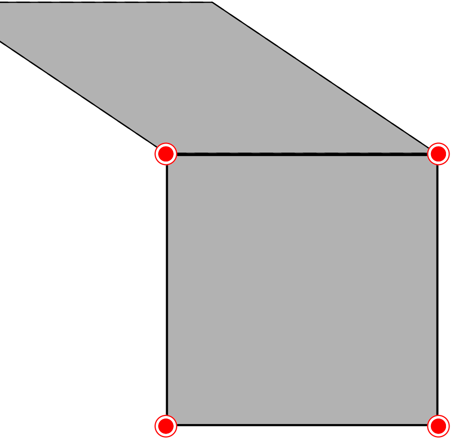
$\mathbb{Z}_2$ orbifold pillow



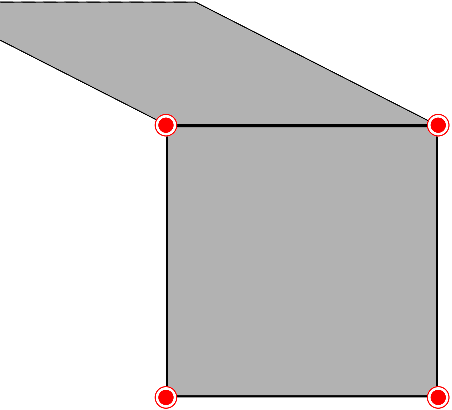
$\mathbb{Z}_2$ orbifold pillow



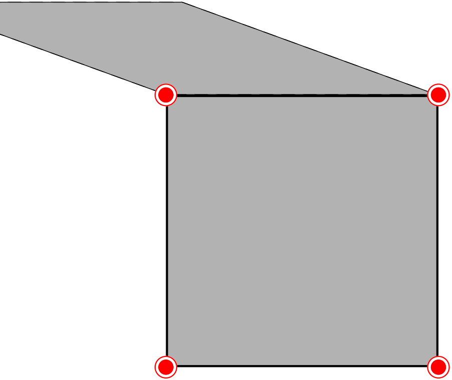
$\mathbb{Z}_2$ orbifold pillow



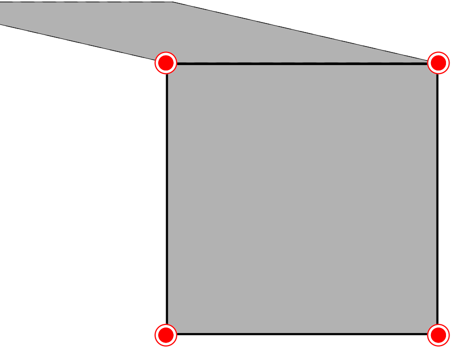
$\mathbb{Z}_2$ orbifold pillow



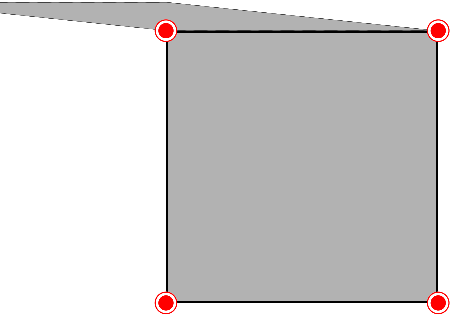
$\mathbb{Z}_2$ orbifold pillow



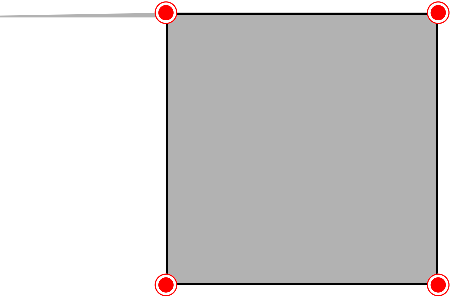
$\mathbb{Z}_2$ orbifold pillow



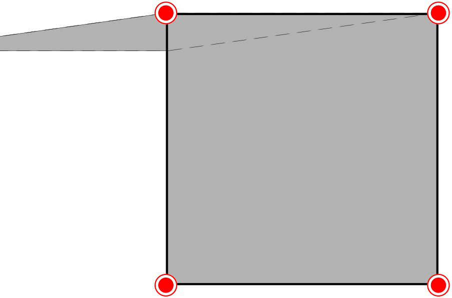
$\mathbb{Z}_2$ orbifold pillow



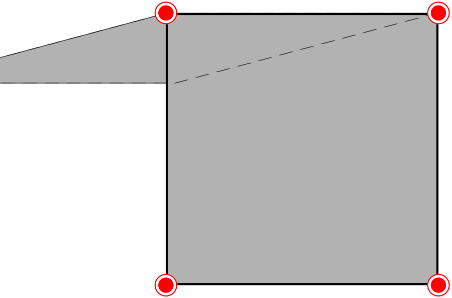
$\mathbb{Z}_2$ orbifold pillow



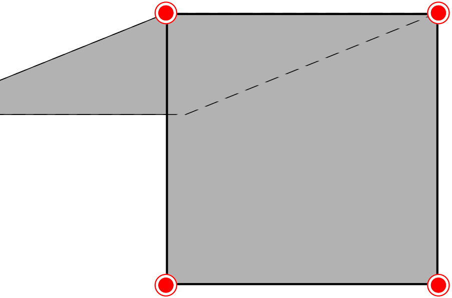
$\mathbb{Z}_2$ orbifold pillow



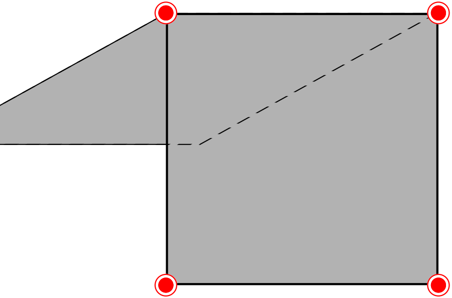
$\mathbb{Z}_2$ orbifold pillow



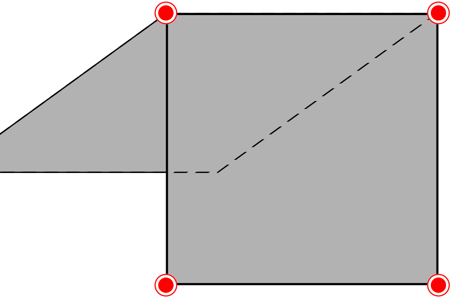
$\mathbb{Z}_2$ orbifold pillow



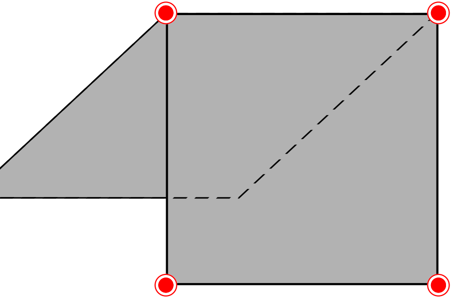
$\mathbb{Z}_2$ orbifold pillow



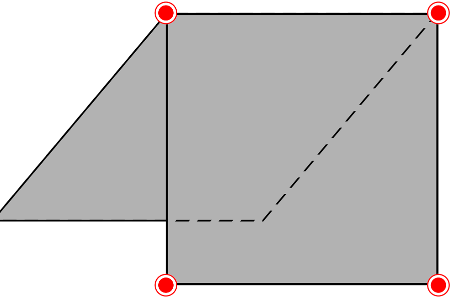
$\mathbb{Z}_2$ orbifold pillow



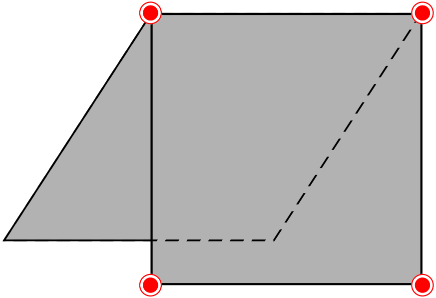
$\mathbb{Z}_2$ orbifold pillow



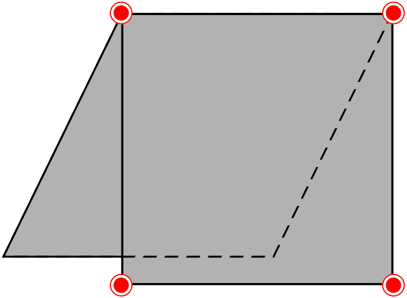
$\mathbb{Z}_2$ orbifold pillow



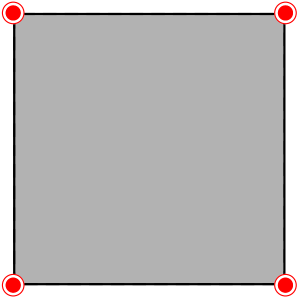
$\mathbb{Z}_2$ orbifold pillow



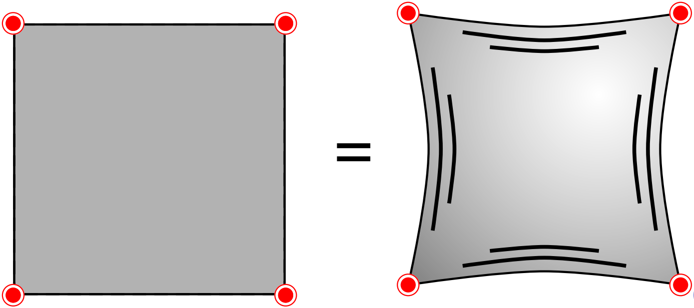
$\mathbb{Z}_2$ orbifold pillow



$\mathbb{Z}_2$ orbifold pillow

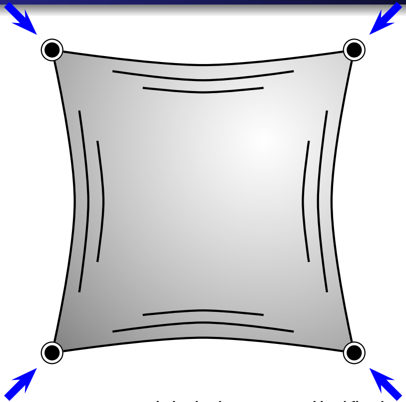


$\mathbb{Z}_2$ orbifold pillow



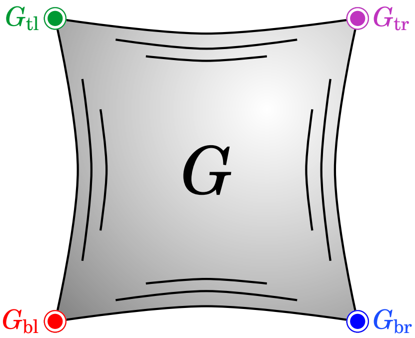
back

What is an orbifold?



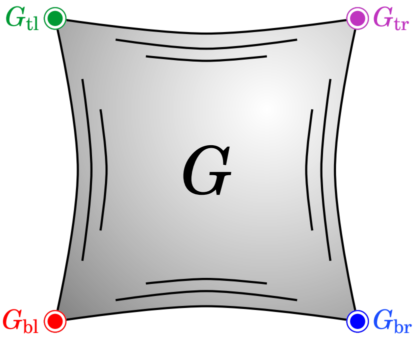
☞ An orbifold is a space which is smooth/flat everywhere except for special (orbifold fixed) points

What is an orbifold?



- An orbifold is a space which is smooth/flat everywhere except for special (orbifold fixed) points
- 'Bulk' gauge symmetry G is broken to (different) subgroups (local GUTs) at the fixed points

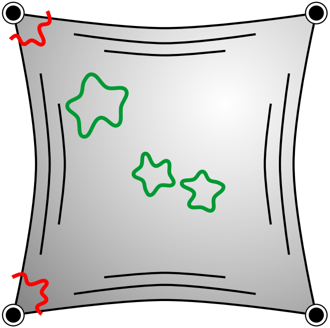
What is an orbifold?



- An orbifold is a space which is smooth/flat everywhere except for special (orbifold fixed) points
- 'Bulk' gauge symmetry G is broken to (different) subgroups (local GUTs) at the fixed points
- Low–energy gauge group : $G_{\mathrm{low-energy}} = G_{\mathrm{bl}} \cap G_{\mathrm{br}} \cap G_{\mathrm{tl}} \cap G_{\mathrm{tr}}$

What are the light states of an orbifold?

Light states of effective field theory

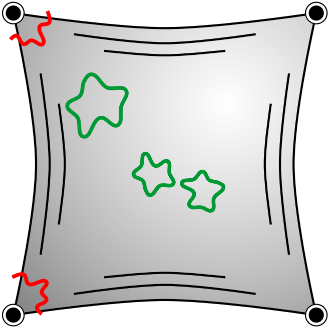


heterotic string	field theory
untwisted sector = strings closed on the torus	extra components of gauge fields
‘twisted’ sectors = strings which are only closed on the orbifold	‘brane fields’ (hard to understand in field–theoretical framework)

☞ (‘Brane’) Fields living at fixed point with a certain symmetry appear as complete multiplet of that symmetry

What are the light states of an orbifold?

Light states of effective field theory



heterotic string	field theory
untwisted sector = strings closed on the torus	extra components of gauge fields
'twisted' sectors = strings which are only closed on the orbifold	'brane fields' (hard to understand in field–theoretical framework)

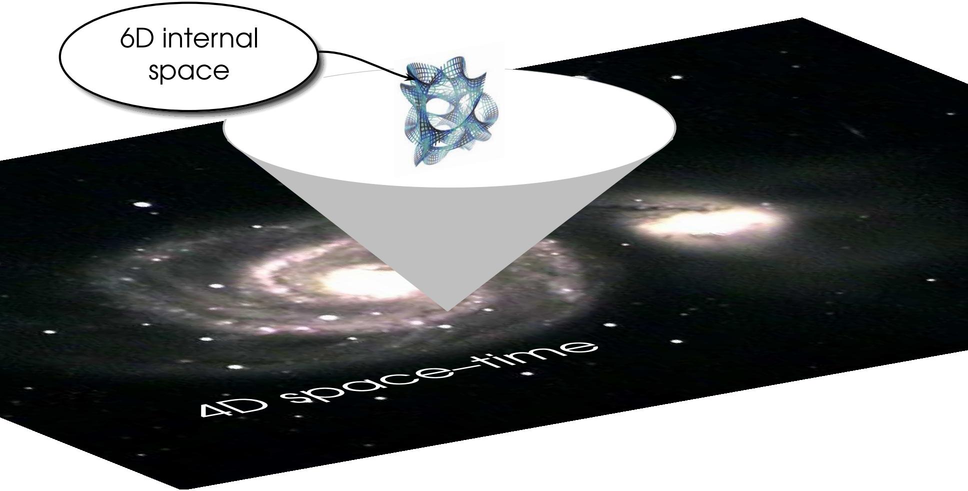
- ('Brane') Fields living at fixed point with a certain symmetry appear as complete multiplet of that symmetry
- E.g. if the electron lives at a point with SO(10) symmetry also u and d quarks live there

Orbifold compactification with local SO(10) GUT

Cartoon of heterotic orbifold compactification with local SO(10) GUT structures

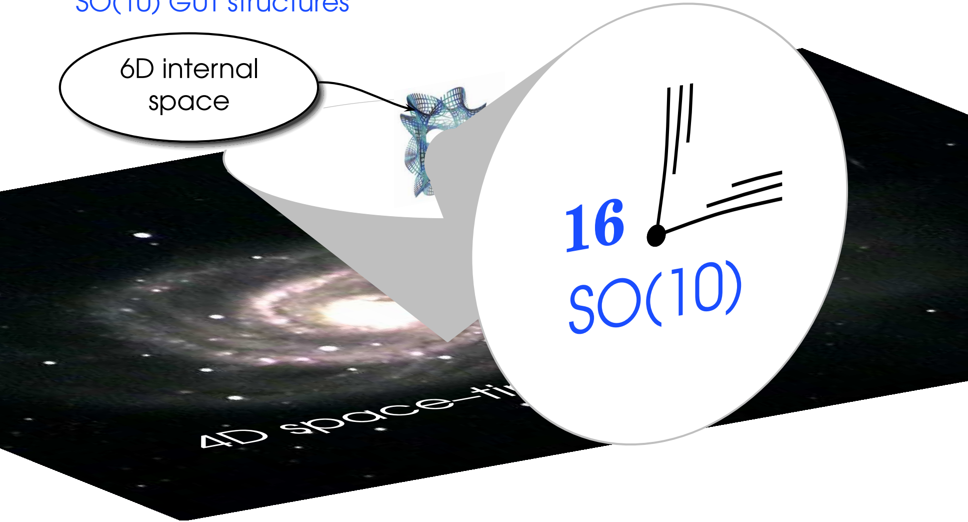
Orbifold compactification with local SO(10) GUT

Cartoon of heterotic orbifold compactification with local SO(10) GUT structures



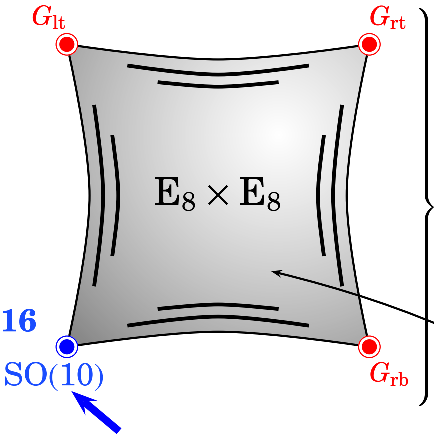
Orbifold compactification with local SO(10) GUT

Cartoon of heterotic orbifold compactification with local SO(10) GUT structures



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'

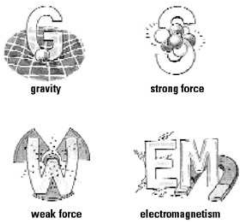
Results

① $3 \times \mathbf{16}$ + Higgs + nothing

No exotics

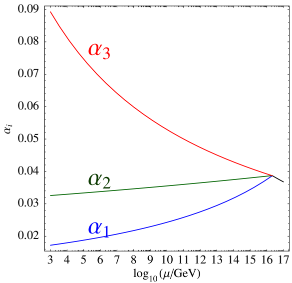
Results

1. $3 \times \mathbf{16}$ + Higgs + nothing
2. $\mathrm{SU}(3) \times \mathrm{SU}(2) \times \mathrm{U}(1)_Y \times G_{\mathrm{hid}}$

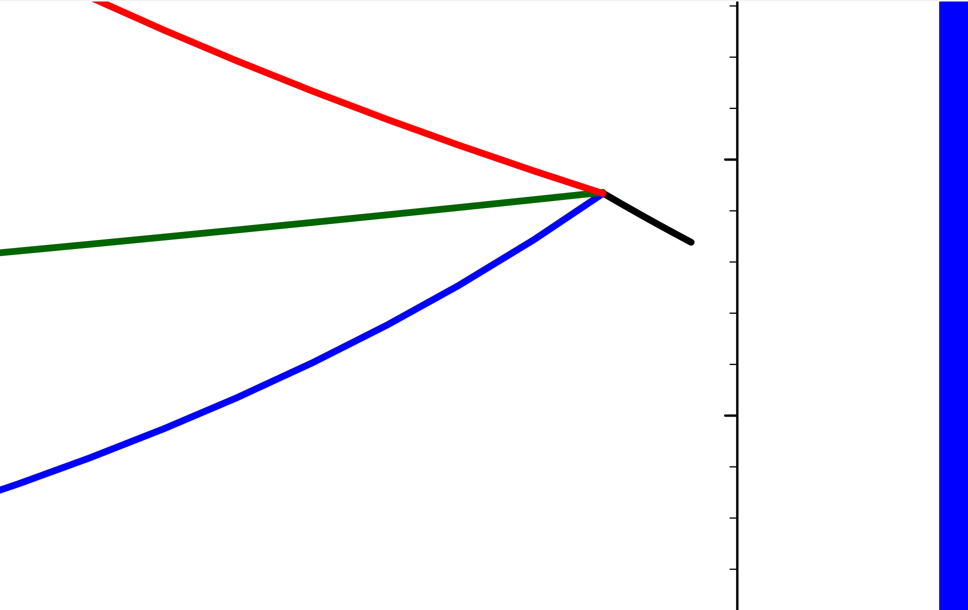


Results

1. $3 \times \mathbf{16}$ + Higgs + nothing
2. $\mathrm{SU}(3) \times \mathrm{SU}(2) \times \mathrm{U}(1)_Y \times G_{\mathrm{hid}}$
3. unification
   precision gauge unification (PGU) from non–local GUT breaking



Results



Results

1. $3 \times \mathbf{16}$ + Higgs + nothing
2. $\mathrm{SU}(3) \times \mathrm{SU}(2) \times \mathrm{U}(1)_Y \times G_{\mathrm{hid}}$
3. unification
4. R parity & $\mathbb{Z}_4^R$

$\cancel{\bar{u}\bar{d}\bar{d}}$ $\cancel{q\bar{d}\ell}$

$\cancel{\ell\ell\bar{e}}$ $\cancel{\ell H_u}$

$\curvearrowright$ proton long–lived

$\curvearrowright$ DM stable

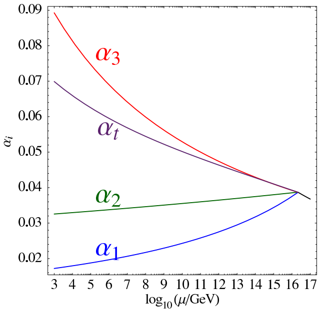
Results

1. $3 \times \mathbf{16}$ + Higgs + nothing
2. $\mathrm{SU}(3) \times \mathrm{SU}(2) \times \mathrm{U}(1)_Y \times G_{\mathrm{hid}}$
3. unification
4. R parity & $\mathbb{Z}_4^R$
5. see–saw

$\curvearrowright$ suppressed ν masses

Results

1. $3 \times \mathbf{16}$ + Higgs + nothing
2. $\mathrm{SU}(3) \times \mathrm{SU}(2) \times \mathrm{U}(1)_Y \times G_{\mathrm{hid}}$
3. unification
4. R parity & $\mathbb{Z}_4^R$
5. see–saw
6. $y_t \simeq g$ @ M_{GUT} & potentially realistic flavor structures à la Froggatt-Nielsen

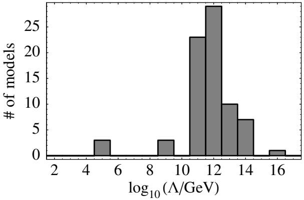


$\curvearrowright$ realistic top mass

Results

1. $3 \times \mathbf{16}$ + Higgs + nothing
2. $\mathrm{SU}(3) \times \mathrm{SU}(2) \times \mathrm{U}(1)_Y \times G_{\mathrm{hid}}$
3. unification
4. R parity & $\mathbb{Z}_4^R$
5. see–saw
6. $y_t \simeq g$ @ M_{GUT} & potentially realistic flavor structures à la Froggatt-Nielsen
7. ‘realistic’ hidden sector

   scale of hidden sector strong dynamics is consistent with TeV-scale soft masses and realistic gauge coupling



Results & "stringy surprises"

1. $3\times\mathbf{16}$ + Higgs + nothing
2. $\mathrm{SU}(3)\times\mathrm{SU}(2)\times\mathrm{U}(1)_Y\times G_{\mathrm{hid}}$
3. unification
4. R parity & $\mathbb{Z}_4^R$
5. see–saw
6. $y_t\simeq g$ @ M_{GUT} & potentially realistic flavor structures à la Froggatt-Nielsen
7. 'realistic' hidden sector
8. solution to the μ problem

$\mu\sim\langle\mathscr{W}\rangle$

$\langle\mathscr{W}\rangle\ll 1$ from approximate $\mathrm{U}(1)_R$ symmetries

$\curvearrowright$ light Higgs

Results & “stringy surprises”

1. $3 \times \mathbf{16}$ + Higgs + nothing
2. $\mathrm{SU}(3) \times \mathrm{SU}(2) \times \mathrm{U}(1)_Y \times G_{\mathrm{hid}}$
3. unification
4. R parity & $\mathbb{Z}_4^R$

} that's what we searched for. . .

5. see–saw
6. $y_t \simeq g$ @ M_{GUT} & potentially realistic flavor structures à la Froggatt-Nielsen
7. ‘realistic’ hidden sector
8. solution to the μ problem

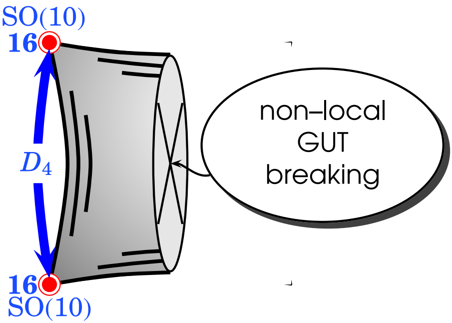
} . . . that's what we got ‘for free’

“stringy surprises”

2+1 family models

Structure of a class of successful models:

- Two families come from two equivalent fixed points and are related by a D_4 family symmetry
- 3^{rd} generation is a ‘patchwork family’
  i.e. different multiplets have different localization properties



Residual R symmetries

- Discrete R symmetries arise as remnants of the Lorentz symmetry of compact dimensions

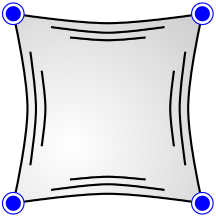
Residual R symmetries

- Discrete R symmetries arise as remnants of the Lorentz symmetry of compact dimensions
  and are arguably on the same footing as the fundamental symmetries C, P and T
- Superpartners transform differently under R symmetries

Residual R symmetries

- Discrete R symmetries arise as remnants of the Lorentz symmetry of compact dimensions
- Superpartners transform differently under R symmetries
- Example: order four discrete R symmetry $\mathbb{Z}_4^R$ from $\mathbb{Z}_2$ orbifold plane

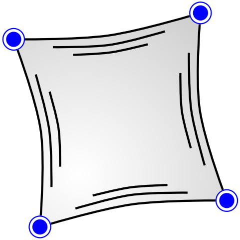
back



Residual R symmetries

- Discrete R symmetries arise as remnants of the Lorentz symmetry of compact dimensions
- Superpartners transform differently under R symmetries
- Example: order four discrete R symmetry $\mathbb{Z}_4^R$ from $\mathbb{Z}_2$ orbifold plane

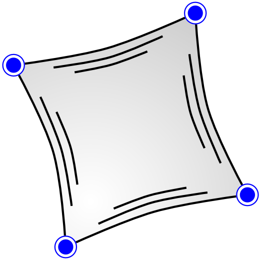
back



Residual R symmetries

- Discrete R symmetries arise as remnants of the Lorentz symmetry of compact dimensions
- Superpartners transform differently under R symmetries
- Example: order four discrete R symmetry $\mathbb{Z}_4^R$ from $\mathbb{Z}_2$ orbifold plane

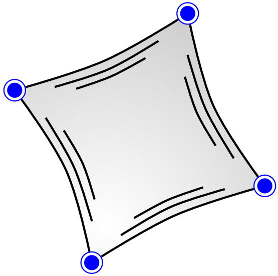
back



Residual R symmetries

- Discrete R symmetries arise as remnants of the Lorentz symmetry of compact dimensions
- Superpartners transform differently under R symmetries
- Example: order four discrete R symmetry $\mathbb{Z}_4^R$ from $\mathbb{Z}_2$ orbifold plane

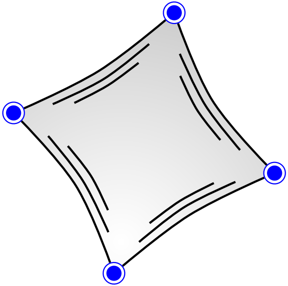
back



Residual R symmetries

- Discrete R symmetries arise as remnants of the Lorentz symmetry of compact dimensions
- Superpartners transform differently under R symmetries
- Example: order four discrete R symmetry $\mathbb{Z}_4^R$ from $\mathbb{Z}_2$ orbifold plane

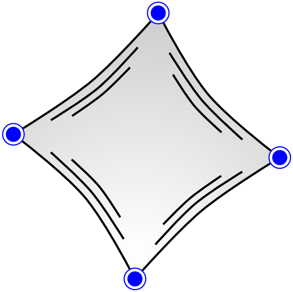
back



Residual R symmetries

- Discrete R symmetries arise as remnants of the Lorentz symmetry of compact dimensions
- Superpartners transform differently under R symmetries
- Example: order four discrete R symmetry $\mathbb{Z}_4^R$ from $\mathbb{Z}_2$ orbifold plane

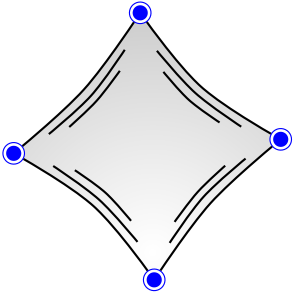
back



Residual R symmetries

- Discrete R symmetries arise as remnants of the Lorentz symmetry of compact dimensions
- Superpartners transform differently under R symmetries
- Example: order four discrete R symmetry $\mathbb{Z}_4^R$ from $\mathbb{Z}_2$ orbifold plane

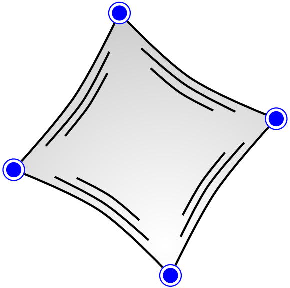
back



Residual R symmetries

- Discrete R symmetries arise as remnants of the Lorentz symmetry of compact dimensions
- Superpartners transform differently under R symmetries
- Example: order four discrete R symmetry $\mathbb{Z}_4^R$ from $\mathbb{Z}_2$ orbifold plane

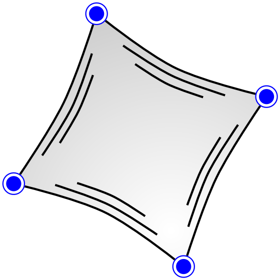
back



Residual R symmetries

- Discrete R symmetries arise as remnants of the Lorentz symmetry of compact dimensions
- Superpartners transform differently under R symmetries
- Example: order four discrete R symmetry $\mathbb{Z}_4^R$ from $\mathbb{Z}_2$ orbifold plane

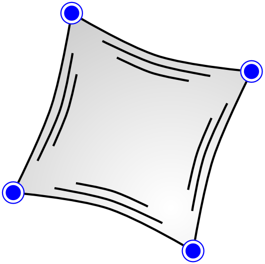
back



Residual R symmetries

- Discrete R symmetries arise as remnants of the Lorentz symmetry of compact dimensions
- Superpartners transform differently under R symmetries
- Example: order four discrete R symmetry $\mathbb{Z}_4^R$ from $\mathbb{Z}_2$ orbifold plane

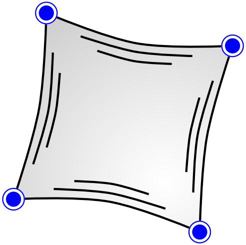
back



Residual R symmetries

- Discrete R symmetries arise as remnants of the Lorentz symmetry of compact dimensions
- Superpartners transform differently under R symmetries
- Example: order four discrete R symmetry $\mathbb{Z}_4^R$ from $\mathbb{Z}_2$ orbifold plane

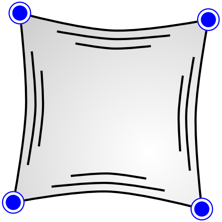
back



Residual R symmetries

- Discrete R symmetries arise as remnants of the Lorentz symmetry of compact dimensions
- Superpartners transform differently under R symmetries
- Example: order four discrete R symmetry $\mathbb{Z}_4^R$ from $\mathbb{Z}_2$ orbifold plane

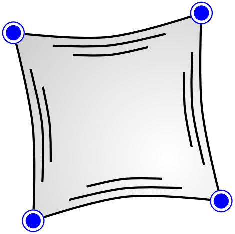
back



Residual R symmetries

- Discrete R symmetries arise as remnants of the Lorentz symmetry of compact dimensions
- Superpartners transform differently under R symmetries
- Example: order four discrete R symmetry $\mathbb{Z}_4^R$ from $\mathbb{Z}_2$ orbifold plane

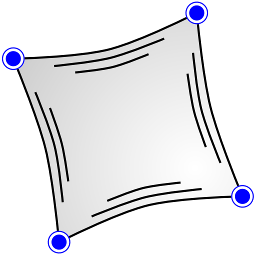
back



Residual R symmetries

- Discrete R symmetries arise as remnants of the Lorentz symmetry of compact dimensions
- Superpartners transform differently under R symmetries
- Example: order four discrete R symmetry $\mathbb{Z}_4^R$ from $\mathbb{Z}_2$ orbifold plane

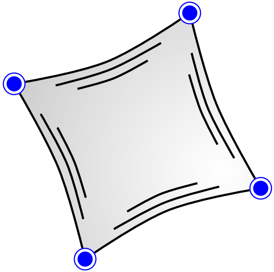
back



Residual R symmetries

- Discrete R symmetries arise as remnants of the Lorentz symmetry of compact dimensions
- Superpartners transform differently under R symmetries
- Example: order four discrete R symmetry $\mathbb{Z}_4^R$ from $\mathbb{Z}_2$ orbifold plane

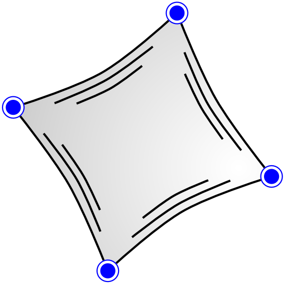
back



Residual R symmetries

- Discrete R symmetries arise as remnants of the Lorentz symmetry of compact dimensions
- Superpartners transform differently under R symmetries
- Example: order four discrete R symmetry $\mathbb{Z}_4^R$ from $\mathbb{Z}_2$ orbifold plane

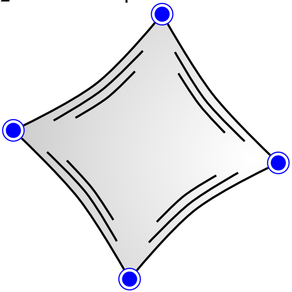
back



Residual R symmetries

- Discrete R symmetries arise as remnants of the Lorentz symmetry of compact dimensions
- Superpartners transform differently under R symmetries
- Example: order four discrete R symmetry $\mathbb{Z}_4^R$ from $\mathbb{Z}_2$ orbifold plane

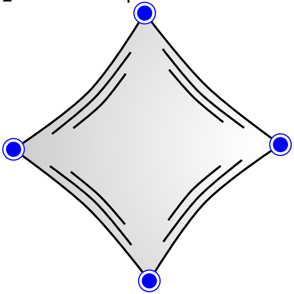
back



Residual R symmetries

- Discrete R symmetries arise as remnants of the Lorentz symmetry of compact dimensions
- Superpartners transform differently under R symmetries
- Example: order four discrete R symmetry $\mathbb{Z}_4^R$ from $\mathbb{Z}_2$ orbifold plane

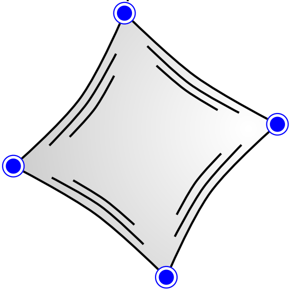
back



Residual R symmetries

- Discrete R symmetries arise as remnants of the Lorentz symmetry of compact dimensions
- Superpartners transform differently under R symmetries
- Example: order four discrete R symmetry $\mathbb{Z}_4^R$ from $\mathbb{Z}_2$ orbifold plane

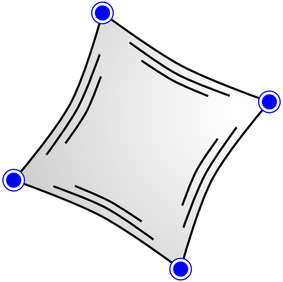
back



Residual R symmetries

- Discrete R symmetries arise as remnants of the Lorentz symmetry of compact dimensions
- Superpartners transform differently under R symmetries
- Example: order four discrete R symmetry $\mathbb{Z}_4^R$ from $\mathbb{Z}_2$ orbifold plane

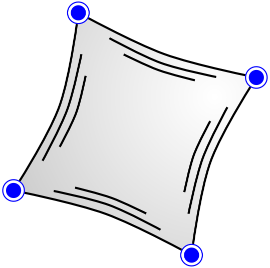
back



Residual R symmetries

- Discrete R symmetries arise as remnants of the Lorentz symmetry of compact dimensions
- Superpartners transform differently under R symmetries
- Example: order four discrete R symmetry $\mathbb{Z}_4^R$ from $\mathbb{Z}_2$ orbifold plane

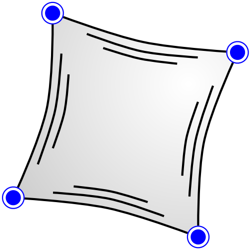
back



Residual R symmetries

- Discrete R symmetries arise as remnants of the Lorentz symmetry of compact dimensions
- Superpartners transform differently under R symmetries
- Example: order four discrete R symmetry $\mathbb{Z}_4^R$ from $\mathbb{Z}_2$ orbifold plane

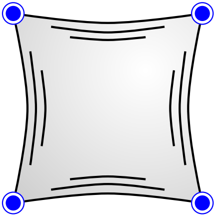
back



Residual R symmetries

- Discrete R symmetries arise as remnants of the Lorentz symmetry of compact dimensions
- Superpartners transform differently under R symmetries
- Example: order four discrete R symmetry $\mathbb{Z}_4^R$ from $\mathbb{Z}_2$ orbifold plane

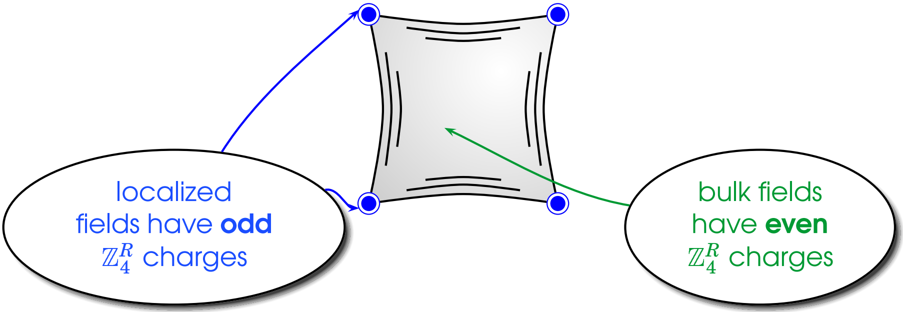
back



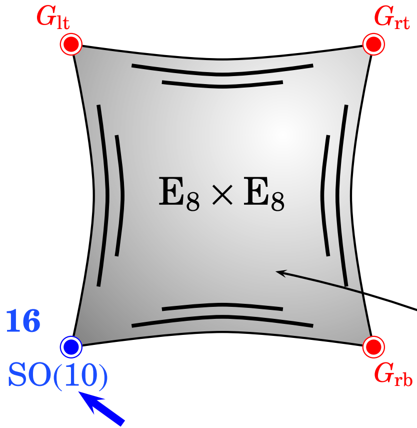
Residual R symmetries

- Discrete R symmetries arise as remnants of the Lorentz symmetry of compact dimensions
- Superpartners transform differently under R symmetries
- Example: order four discrete R symmetry $\mathbb{Z}_4^R$ from $\mathbb{Z}_2$ orbifold plane

back



Local grand unification & $\mathbb{Z}_4^R$



$\mathbb{Z}_4^R$ (bottom–up)

	$\mathbb{Z}_4^R$ charge
matter	1
Higgs	0

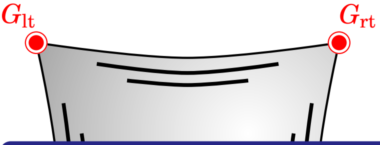
SM generation(s):

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

Higgs doublets:

live in the 'bulk'

Local grand unification & $\mathbb{Z}_4^R$



$\mathbb{Z}_4^R$ (bottom–up)

	$\mathbb{Z}_4^R$ charge
	1
	0

$\mathbf{16}$

SO

Virtues of $\mathbb{Z}_4^R$ include:

Babu, Gogoladze & Wang (2003); Lee, Raby, M.R., Ross, Schieren, et al. (2011)

- controls the Higgs mass
- consistent w/ $\mathrm{SO}(10)$
- satisfies consistency conditions (anomaly freedom etc.)
- guarantees longevity of the nucleon
- contains R parity ($\curvearrowright$ DM stable)

SM generation(s):

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

Higgs doublets:

live in the 'bulk'

Expectations

&

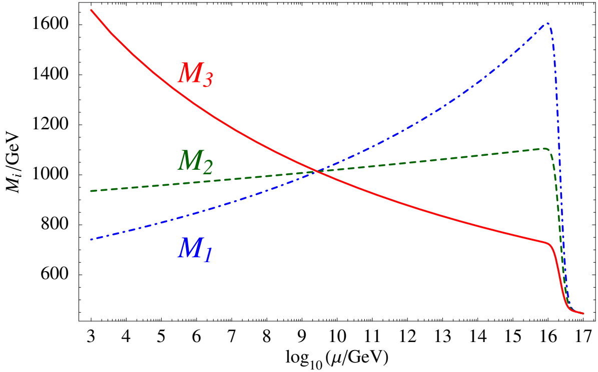
Experimental Tests

Pattern of soft supersymmetry breaking masses

☞ Scenario with ~~SUSY~~ by ‘matter field’ X + dilaton S

Pattern of soft supersymmetry breaking masses

- Scenario with ~~SUSY~~ by 'matter field' X + dilaton S
- ➥ Mirage pattern for gaugino masses + heavy sfermions



Pattern of soft supersymmetry breaking masses

- Scenario with ~~SUSY~~ by 'matter field' X + dilaton S
- Mirage pattern for gaugino masses + heavy sfermions
- Yields natural scenario for precision gauge unification (PGU)

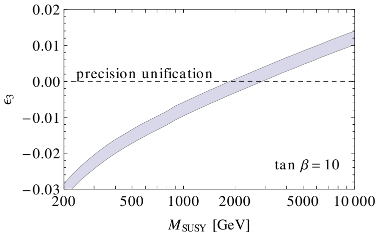
Carena, Clavelli, Matalliotakis, Nilles & Wagner (1993) ... Raby, M.R. & Schmidt-Hoberg (2010)
Krippendorf, Nilles, M.R. & Winkler (2013)

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

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

effective SUSY mass

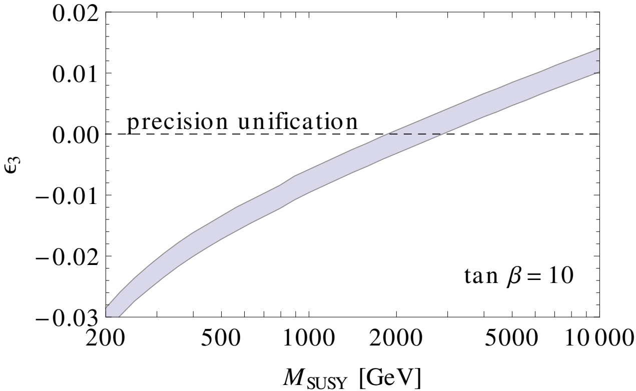
$X_{\text{sfermion}} \sim 1$



Implications for the LHC and future colliders

☞ PGU implies a superpartner mass scale $\sim 2\,\mathrm{TeV}$

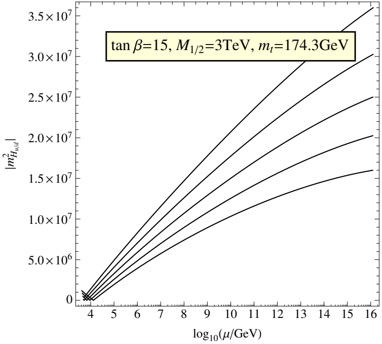
$$\epsilon_3 = \frac{g_3^2(M_{\mathrm{GUT}}) - g_{1,2}^2(M_{\mathrm{GUT}})}{g_{1,2}^2(M_{\mathrm{GUT}})} \quad \& \quad M_{\mathrm{SUSY}} = \frac{m_{\widetilde{W}}^{32/19}\, m_{\widetilde{h}}^{12/19}\, m_H^{3/19}}{m_{\widetilde{g}}^{28/19}} X_{\mathrm{sfermion}}$$



Implications for the LHC and future colliders

- PGU implies a superpartner mass scale $\sim 2\,\mathrm{TeV}$
- Geometric properties of ingredients of top–Yukawa coupling entail 'focus point'

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

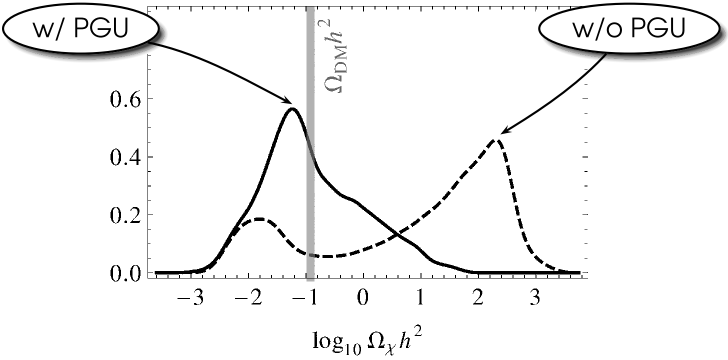


  - H_u, Q_L & t_R bulk fields
  - ➥ Coinciding boundary conditions at high scale
  - ➥ 'Focus point'

Feng, Matchev & Moroi (2000)

Implications for the LHC and future colliders

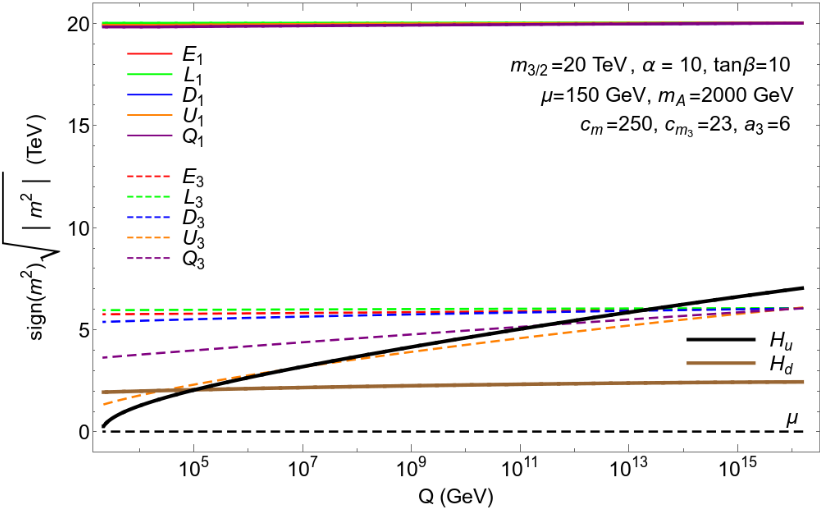
- PGU implies a superpartner mass scale $\sim 2\,\mathrm{TeV}$
- Geometric properties of ingredients of top–Yukawa coupling entail ‘focus point’ Krippendorf, Nilles, M.R. & Winkler (2012)
- PGU leads to naturally to a relic density of WIMPs which is consistent with observed CDM Krippendorf, Nilles, M.R. & Winkler (2013)



Results from a more detailed analysis

Baer, Barger, Savoy, Serce & Tata (2017)

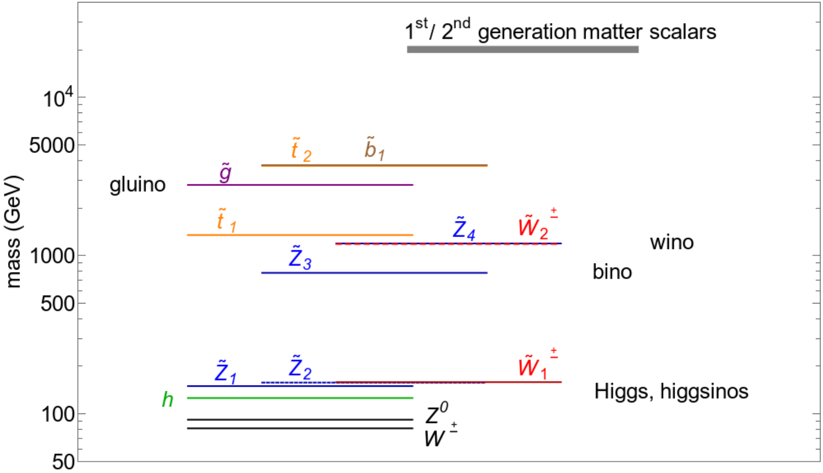
- Running of the soft masses



Results from a more detailed analysis

☞ Sample spectrum

Baer, Barger, Savoy, Serce & Tata (2017)



Results from a more detailed analysis

Baer, Barger, Savoy, Serce & Tata (2017)

- Sample spectrum
- Amazingly low fine–tunig: $\Delta_{\mathrm{EW}} < 20$ possible

Results from a more detailed analysis

Baer, Barger, Savoy, Serce & Tata (2017)

- Sample spectrum
- Amazingly low fine–tunig: $\Delta_{\mathrm{EW}} < 20$ possible
- Perhaps hard to verify at the LHC

Proton decay

Mütter, M.R. & Vaudrevange (2016)

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

- no dimension 4 proton decay
- dimension 5 proton decay negligible

Proton decay

Mütter, M.R. & Vaudrevange (2016)

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

- no dimension 4 proton decay
- dimension 5 proton decay negligible

non–local GUT breaking:

no dimension 6 proton decay!

$$\begin{array}{cc} \bar{d}^{(1)}_{\mathrm{red}} & \bar{d}^{(2)}_{\mathrm{red}} \\ \bar{d}^{(1)}_{\mathrm{green}} & \bar{d}^{(2)}_{\mathrm{green}} \\ \bar{d}^{(1)}_{\mathrm{blue}} & \bar{d}^{(2)}_{\mathrm{blue}} \\ \ell^{(1)}_{\uparrow} & \ell^{(2)}_{\uparrow} \\ \ell^{(1)}_{\downarrow} & \ell^{(2)}_{\downarrow} \end{array}$$

$$\begin{array}{rcl} \bar{d}^{\mathrm{phys}}_{\mathrm{red}} & \sim & \bar{d}^{(1)}_{\mathrm{red}} - \bar{d}^{(2)}_{\mathrm{red}} \\ \bar{d}^{\mathrm{phys}}_{\mathrm{green}} & \sim & \bar{d}^{(1)}_{\mathrm{green}} - \bar{d}^{(2)}_{\mathrm{green}} \\ \bar{d}^{\mathrm{phys}}_{\mathrm{blue}} & \sim & \bar{d}^{(1)}_{\mathrm{blue}} - \bar{d}^{(2)}_{\mathrm{blue}} \\ \ell^{\mathrm{phys}}_{\uparrow} & \sim & \ell^{(1)}_{\uparrow} + \ell^{(2)}_{\uparrow} \\ \ell^{\mathrm{phys}}_{\downarrow} & \sim & \ell^{(1)}_{\downarrow} + \ell^{(2)}_{\downarrow} \end{array}$$

Proton decay

Mütter, M.R. & Vaudrevange (2016)

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

- no dimension 4 proton decay
- dimension 5 proton decay negligible

non–local GUT breaking:

no dimension 6 proton decay!

combined:

almost no proton decay

$$\begin{array}{cc}
\bar{d}^{(1)}_{\mathrm{red}} & \bar{d}^{(2)}_{\mathrm{red}} \\
\bar{d}^{(1)}_{\mathrm{green}} & \bar{d}^{(2)}_{\mathrm{green}} \\
\bar{d}^{(1)}_{\mathrm{blue}} & \bar{d}^{(2)}_{\mathrm{blue}} \\
\ell^{(1)}_{\uparrow} & \ell^{(2)}_{\uparrow} \\
\ell^{(1)}_{\downarrow} & \ell^{(2)}_{\downarrow}
\end{array}$$

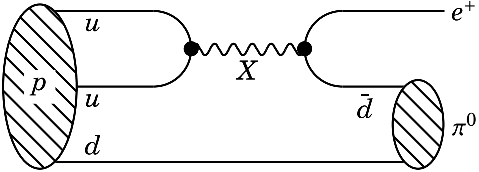
$$\begin{aligned}
\bar{d}^{\mathrm{phys}}_{\mathrm{red}} &\sim \bar{d}^{(1)}_{\mathrm{red}} - \bar{d}^{(2)}_{\mathrm{red}} \\
\bar{d}^{\mathrm{phys}}_{\mathrm{green}} &\sim \bar{d}^{(1)}_{\mathrm{green}} - \bar{d}^{(2)}_{\mathrm{green}} \\
\bar{d}^{\mathrm{phys}}_{\mathrm{blue}} &\sim \bar{d}^{(1)}_{\mathrm{blue}} - \bar{d}^{(2)}_{\mathrm{blue}} \\
\ell^{\mathrm{phys}}_{\uparrow} &\sim \ell^{(1)}_{\uparrow} + \ell^{(2)}_{\uparrow} \\
\ell^{\mathrm{phys}}_{\downarrow} &\sim \ell^{(1)}_{\downarrow} + \ell^{(2)}_{\downarrow}
\end{aligned}$$

Proton decay (cont'd)

- Models with local GUT breaking: proton decay from GUT gauge boson exchange

$$\tau(p \to e^+\pi^0) \;\sim\; 10^{35\pm1}\,\mathrm{yr}$$

Uncertainties: matrix elements, $\alpha_3(m_Z)$, precise value of $m_{\mathrm{Unification}}$ etc.



Summary

Summary

- ☞ The quest for unification of all forces requires new physics beyond the standard model such as supersymmetry, extra dimensions & strings

Summary

- ☞ The quest for unification of all forces requires new physics beyond the standard model such as supersymmetry, extra dimensions & strings
- ☞ Stringy completions of the standard model allow us to answer some of the basic questions:
  - Family as a $\mathbf{16}$–plet of $\mathrm{SO}(10)$
  - Repetition of families from extra dimensions
  - Discrete remnants of the Lorentz group of compact space explain the longevity of the nucleon and the stability of dark matter

Summary

☞ The quest for unification of all forces requires new physics beyond the standard model such as supersymmetry, extra dimensions & strings

☞ Stringy completions of the standard model allow us to answer some of the basic questions:

- Family as a $\mathbf{16}$–plet of $\mathrm{SO}(10)$
- Repetition of families from extra dimensions
- Discrete remnants of the Lorentz group of compact space explain the longevity of the nucleon and the stability of dark matter

☞ Testable predictions for the scale of superpartner masses, the nature of dark matter and proton decay

Thank you very much for your attention!

Let's **H**ave **C**heese!

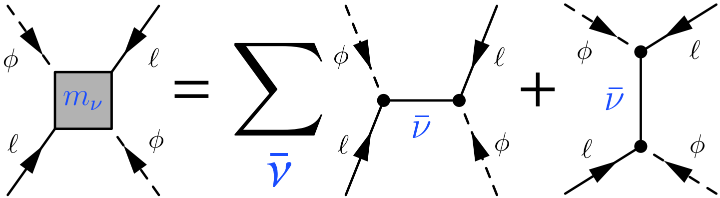
Backup slides

Neutrino masses in grand unification: see–saw

Minkowski (1977)
Gell-Mann, Ramond & Slansky (1979)
Yanagida (1979)

$$m_\nu \sim \frac{v_{\rm EW}^2}{m_{\bar{\nu}}}$$

$v_{\rm EW} \sim 100\,{\rm GeV}$
ν = ‘left–handed’ neutrino
$\bar{\nu}$ = ‘right–handed’ neutrino

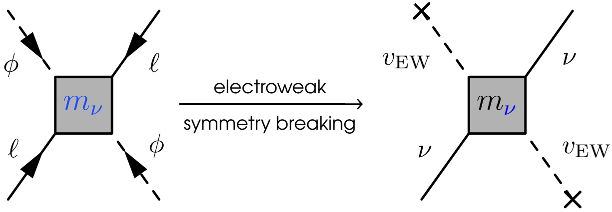


Neutrino masses in grand unification: see–saw

Minkowski (1977)
Gell-Mann, Ramond & Slansky (1979)
Yanagida (1979)

$$m_\nu \sim \frac{v_{\rm EW}^2}{m_{\bar\nu}}$$

$v_{\rm EW} \sim 100\,{\rm GeV}$
ν = 'left–handed' neutrino
$\bar{\nu}$ = 'right–handed' neutrino



Neutrino masses in grand unification: see–saw

Minkowski (1977)
Gell-Mann, Ramond & Slansky (1979)
Yanagida (1979)

$$m_\nu \sim \frac{v_{\rm EW}^2}{m_{\bar{\nu}}}$$

$v_{\rm EW} \sim 100\,{\rm GeV}$
ν = ‘left–handed’ neutrino
$\bar{\nu}$ = ‘right–handed’ neutrino

- Naive expectation: $m_{\bar{\nu}} \sim M_{\rm GUT}$
  $m_\nu \sim (100\,{\rm GeV})^2/10^{16}\,{\rm GeV} \sim 10^{-3}\,{\rm eV}$

Neutrino masses in grand unification: see–saw

Minkowski (1977)
Gell-Mann, Ramond & Slansky (1979)
Yanagida (1979)

$$m_\nu \sim \frac{v_{\mathrm{EW}}^2}{m_{\bar{\nu}}}$$

$v_{\mathrm{EW}} \sim 100\,\mathrm{GeV}$
ν = 'left–handed' neutrino
$\bar{\nu}$ = 'right–handed' neutrino

➥ Naive expectation: $m_{\bar{\nu}} \sim M_{\mathrm{GUT}}$
$m_\nu \sim (100\,\mathrm{GeV})^2/10^{16}\,\mathrm{GeV} \sim 10^{-3}\,\mathrm{eV}$

☞ Experiments: $\sqrt{\Delta m^2_{\mathrm{atm}}} \simeq 0.04\,\mathrm{eV}$ & $\sqrt{\Delta m^2_{\mathrm{sol}}} \simeq 0.008\,\mathrm{eV}$

Neutrino masses in grand unification: see–saw

Minkowski (1977)
Gell-Mann, Ramond & Slansky (1979)
Yanagida (1979)

$$m_\nu \sim \frac{v_{\mathrm{EW}}^2}{m_{\bar{\nu}}}$$

$v_{\mathrm{EW}} \sim 100\,\mathrm{GeV}$
ν = 'left–handed' neutrino
$\bar{\nu}$ = 'right–handed' neutrino

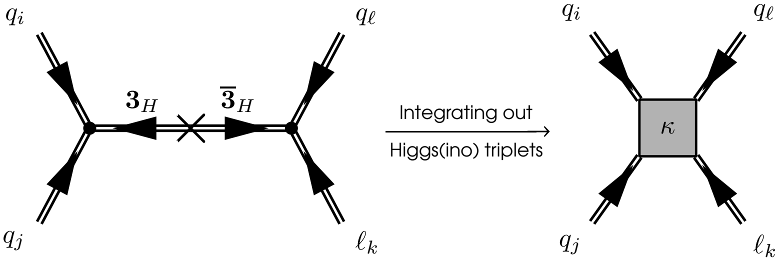
- Naive expectation: $m_{\bar{\nu}} \sim M_{\mathrm{GUT}}$
  $m_\nu \sim (100\,\mathrm{GeV})^2/10^{16}\,\mathrm{GeV} \sim 10^{-3}\,\mathrm{eV}$

- Experiments: $\sqrt{\Delta m^2_{\mathrm{atm}}} \simeq 0.04\,\mathrm{eV}$ & $\sqrt{\Delta m^2_{\mathrm{sol}}} \simeq 0.008\,\mathrm{eV}$

- Rough (although not perfect) agreement

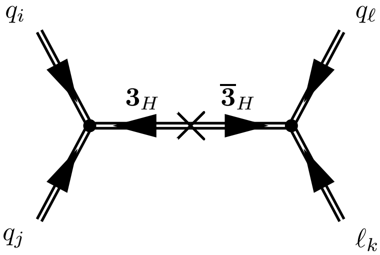
Dimension five proton decay

Sakai & Yanagida (1982)

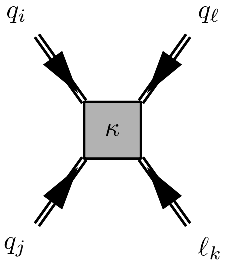


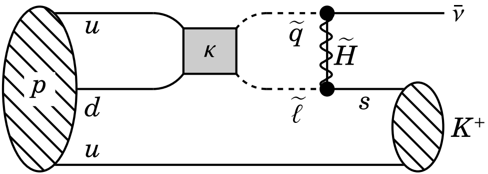
Dimension five proton decay

Sakai & Yanagida (1982)



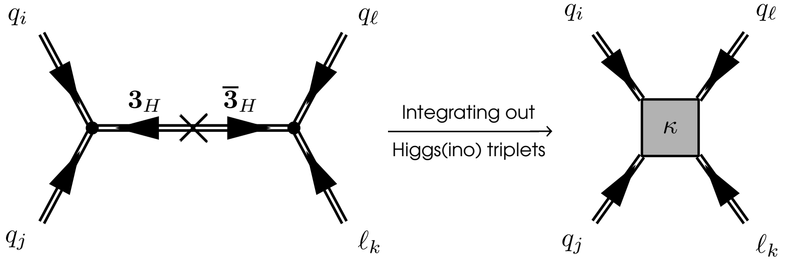
Integrating out $\longrightarrow$ Higgs(ino) triplets



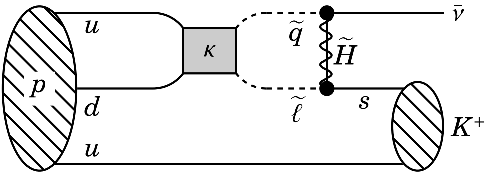


Dimension five proton decay

Sakai & Yanagida (1982)



e.g. Dermíšek, Mafi & Raby (2001)



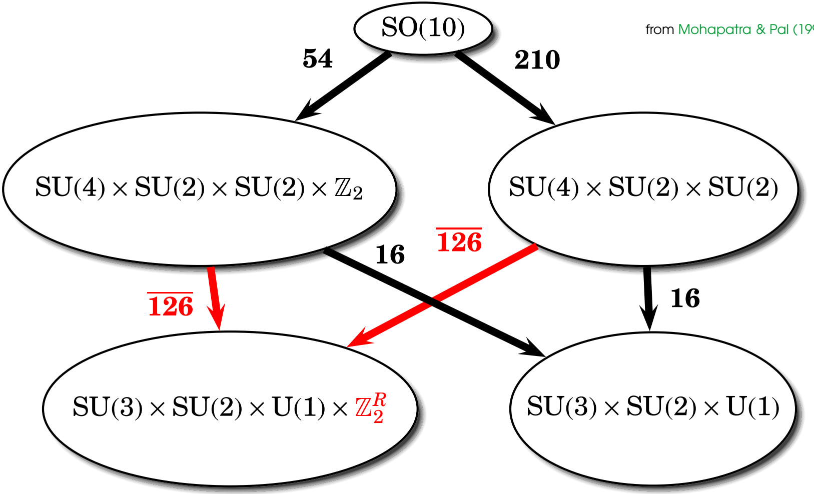
for 'reasonable' soft masses:

$\tau(p \to K^+ + \bar{\nu}) \gtrsim 3 \times 10^{33}\,\mathrm{y}$

$\curvearrowright\ m_{\mathrm{triplet}} \gtrsim 10^{19}\,\mathrm{GeV}$

SO(10) breaking by Higgs mechanism

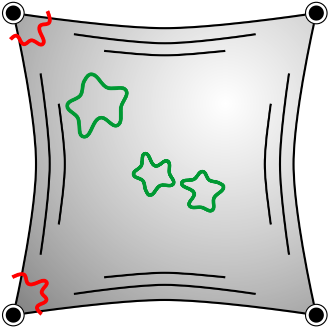
from Mohapatra & Pal (1991)



- GUT breaking by Higgs: need large Higgs representations $(\mathbf{54}, \overline{\mathbf{126}}, \mathbf{210})$ $\curvearrowright$ lot of 'junk' (which, however, can be paired up)

What are the light states of an orbifold?

Light states of effective field theory

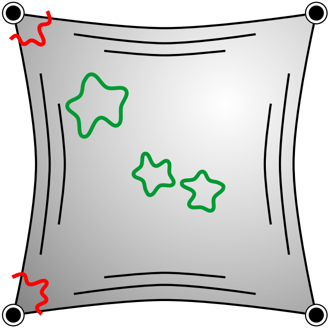


heterotic string	field theory
untwisted sector = strings closed on the torus	extra components of gauge fields
'twisted' sectors = strings which are only closed on the orbifold	'brane fields' (hard to understand in field–theoretical framework)

☞ ('Brane') Fields living at fixed point with a certain symmetry appear as complete multiplet of that symmetry

What are the light states of an orbifold?

Light states of effective field theory



heterotic string	field theory
untwisted sector = strings closed on the torus	extra components of gauge fields
'twisted' sectors = strings which are only closed on the orbifold	'brane fields' (hard to understand in field–theoretical framework)

- ('Brane') Fields living at fixed point with a certain symmetry appear as complete multiplet of that symmetry
- E.g. if the electron lives at a point with SO(10) symmetry also u and d quarks live there

Unique $\mathbb{Z}_4^R$ symmetry for the MSSM

Lee, Raby, M.R., Ross, Schieren, et al. (2011)

- anomaly freedom
- forbid μ term
- fermion masses (Yukawa couplings & neutrino mass operator)
- consistency with SO(10)

$\curvearrowright$ **unique** solution: discrete $\mathbb{Z}_4^R$ symmetry

Unique $\mathbb{Z}_4^R$ symmetry for the MSSM

Lee, Raby, M.R., Ross, Schieren, et al. (2011)

- anomaly freedom
- forbid μ term
- fermion masses (Yukawa couplings & neutrino mass operator)
- consistency with SO(10)

$\curvearrowright$ **unique** solution: discrete $\mathbb{Z}_4^R$ symmetry

$\mathbb{Z}_4^R$

- forbids μ term perturbatively
- forbids dimension 5 proton decay perturbatively
- contains matter/R parity
- charge assignment: matter: 1, Higgs: 0

Unique $\mathbb{Z}_4^R$ symmetry for the MSSM

Lee, Raby, M.R., Ross, Schieren, et al. (2011)

- anomaly freedom
- forbid μ term
- fermion masses
  (Yukawa couplings &
  neutrino mass operator)
- consistency with SO(10)

$\curvearrowright$ **unique** solution: discrete $\mathbb{Z}_4^R$ symmetry

$\mathbb{Z}_4^R$

- forbids μ term perturbatively
- forbids dimension 5 proton decay perturbatively
- contains matter/R parity
- charge assignment: matter: 1, Higgs: 0

$$\mathscr{W}_{\mathrm{eff}}^{\mathrm{non-pert}} \supset \mu_{\mathrm{eff}}\, H_u\, H_d + \kappa_{ijk\ell}\, Q_i\, Q_j\, Q_j\, L_\ell$$

$\mu_{\mathrm{eff}} \sim m_{3/2} \sim$TeV

$\kappa_{ijk\ell} \sim m_{3/2}/M_{\mathrm{P}}^2 \sim 10^{-15}/M_{\mathrm{P}}$

References I

K.S. Babu, Ilia Gogoladze & Kai Wang. Natural R parity, mu term & fermion mass hierarchy from discrete gauge symmetries. *Nucl. Phys.*, B660:322–342, 2003. doi: 10.1016/S0550-3213(03)00258-X.

Howard Baer, Vernon Barger, Michael Savoy, Hasan Serce & Xerxes Tata. Superparticle phenomenology from the natural mini-landscape. *JHEP*, 06:101, 2017. doi: 10.1007/JHEP06(2017)101.

Marcela S. Carena, L. Clavelli, D. Matalliotakis, Hans Peter Nilles & C.E.M. Wagner. Light gluinos & unification of couplings. *Phys. Lett.*, B317:346–353, 1993. doi: 10.1016/0370-2693(93)91006-9.

Mu-Chun Chen, Maximilian Fallbacher & Michael Ratz. Supersymmetric unification & R symmetries. *Mod.Phys. Lett.*, A27:1230044, 2012. doi: 10.1063/1.4807363,10.1142/S0217732312300443.

References II

Radovan Dermíšek, Arash Mafi & Stuart Raby. Susy guts under siege: Proton decay. *Phys. Rev.*, D63:035001, 2001.

S. Dimopoulos & Frank Wilczek. Incomplete multiplets in supersymmetric unified models. 1981. Santa Barbara Print-81-0600.

S. Dimopoulos, S. Raby & Frank Wilczek. Supersymmetry & the scale of unification. *Phys. Rev.*, D24:1681–1683, 1981.

Maximilian Fallbacher, Michael Ratz & Patrick K.S. Vaudrevange. No-go theorems for R symmetries in four-dimensional GUTs. *Phys. Lett.*, B705:503–506, 2011. doi: 10.1016/j.physletb.2011.10.063.

Jonathan L. Feng, Konstantin T. Matchev & Takeo Moroi. Multi - TeV scalars are natural in minimal supergravity. *Phys. Rev. Lett.*, 84:2322–2325, 2000. doi: 10.1103/PhysRevLett.84.2322.

Harald Fritzsch & Peter Minkowski. Unified interactions of leptons & hadrons. *Ann. Phys.*, 93:193–266, 1975.

References III

Murray Gell-Mann, Pierre Ramond & Richard Slansky. Complex spinors & unified theories. In P. van Nieuwenhuizen & D. Z. Freedman, editors, *Supergravity*, page 315. North Holland, Amsterdam, 1979.

H. Georgi & S. L. Glashow. Unity of all elementary particle forces. *Phys. Rev. Lett.*, 32:438–441, 1974.

Lawrence J. Hall, Yasunori Nomura & Aaron Pierce. R symmetry & the mu problem. *Phys. Lett.*, B538:359–365, 2002. doi: 10.1016/S0370-2693(02)02043-9.

Sven Krippendorf, Hans Peter Nilles, Michael Ratz & Martin Wolfgang Winkler. The heterotic string yields natural supersymmetry. *Phys. Lett.*, B712:87–92, 2012. doi: 10.1016/j.physletb.2012.04.043.

References IV

Sven Krippendorf, Hans Peter Nilles, Michael Ratz & Martin Wolfgang Winkler. Hidden SUSY from precision gauge unification. *Phys. Rev.*, D88:035022, 2013. doi: 10.1103/PhysRevD.88.035022.

Hyun Min Lee, Stuart Raby, Michael Ratz, Graham G. Ross, Roland Schieren, et al. A unique Z_4^R symmetry for the MSSM. *Phys. Lett.*, B694:491–495, 2011. doi: 10.1016/j.physletb.2010.10.038.

A. Masiero, Dimitri V. Nanopoulos, K. Tamvakis & T. Yanagida. Naturally massless higgs doublets in supersymmetric SU(5). *Phys. Lett.*, B115:380, 1982.

Peter Minkowski. mu → e gamma at a Rate of One Out of 1-Billion Muon Decays? *Phys. Lett.*, B67:421, 1977. doi: 10.1016/0370-2693(77)90435-X.

Andreas Mütter, Michael Ratz & Patrick K. S. Vaudrevange. Grand Unification without Proton Decay. 2016.

References V

Stuart Raby, Michael Ratz & Kai Schmidt-Hoberg. Precision gauge unification in the MSSM. *Phys. Lett.*, B687:342–348, 2010. doi: 10.1016/j.physletb.2010.03.060.

N. Sakai & Tsutomu Yanagida. Proton decay in a class of supersymmetric grand unified models. *Nucl. Phys.*, B197:533, 1982.

T. Yanagida. Horizontal gauge symmetry & masses of neutrinos. In O. Sawada & A. Sugamoto, editors, *Proceedings of the Workshop on The Unified Theory & the Baryon Number in the Universe*, page 95. KEK, Tsukuba, Japan, 1979.