Towards a unified description of Nature

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Unification of all forces

celestial movement

gravity

terrestrial movement
Towards a unified description of Nature

Unification of all forces

Magnetism
Electricity
Electro-magnetism

Celestial movement
Terrestrial movement
Gravity
Towards a unified description of Nature

Unification of all forces

magnetism — electro-magnetism — $v_{EW} \sim 100 \text{ GeV}$

electricity — electro-magnetism

weak interactions

celestial movement

terrestrial movement

gravity
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Unification of all forces

- magnetism
- electricity
- weak interactions
- strong interactions
- celestial movement
- terrestrial movement
- gravity

Experimentally confirmed

Electromagnetism

$\nu_{EW} \sim 100 \text{ GeV}
SU(2)_L \times U(1)_Y$

SU(3)$_C$

Standard model
Towards a unified description of Nature

Unification of all forces

- magnetism
- electricity
- weak interactions
- strong interactions
- celestial movement
- terrestrial movement

**Unification of all forces**

- Experimentally confirmed

- electromagnetism

- $v_{EW} \sim 100 \text{ GeV}$
- $SU(2)_L \times U(1)_Y$

- $M_{GUT} \approx 10^{16} \text{ GeV}$
- $SU(3)_C$

- Gravity
Towards a unified description of Nature

Unification of all forces

- magnetism
- electricity
- weak interactions
- strong interactions
- celestial movement
- terrestrial movement
- electro-magnetism

$v_{EW} \sim 100 \text{ GeV}
SU(2)_L \times U(1)_Y$

$M_{GUT} \approx 10^{16} \text{ GeV}$

$SU(3)_C$

$M_{Planck} \approx 10^{19} \text{ GeV}$

Speculations
The standard model of particle physics is extremely successful in describing observation.
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.
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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!
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

\[ G_{\text{SM}} = SU(3)_C \times SU(2)_L \times U(1)_Y \]
Gauge structure of the standard model

Interactions come from gauge symmetries

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

Matter multiplets: 3 copies of

\[ (3, 2)^{1/6} \oplus (3, 1)^{-2/3} \oplus (1, 1)_1 \oplus (3, 1)^{1/3} \oplus (1, 2)^{-1/2} \]

- left-handed quark doublets
- right-handed \( u \) type quarks
- right-handed \( d \) type quarks
- right-handed charged leptons
- left-handed lepton doublets

why 3 generations?
Towards a unified description of Nature

**Gauge structure of the standard model**

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- Hypercharge quantization: why?

- Stated differently: why are atoms neutral?

- Electric charge = hypercharge + weak isospin
Interactions come from gauge symmetries

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

\[
\begin{pmatrix}
\psi_q \\
\psi_q \\
\psi_q
\end{pmatrix}
\rightarrow
\begin{pmatrix}
* & * & * \\
* & * & * \\
* & * & *
\end{pmatrix}
\begin{pmatrix}
\psi_q \\
\psi_q \\
\psi_q
\end{pmatrix}
\]
Towards a unified description of Nature

**Grand unification**

**Concept**

Gauge structure of the standard model

Interactions come from gauge symmetries

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

\[
\begin{pmatrix}
\psi_{\nu} \\
\psi_e
\end{pmatrix}
\rightarrow
\begin{pmatrix}
* & * \\
* & *
\end{pmatrix}
\begin{pmatrix}
\psi_{\nu} \\
\psi_e
\end{pmatrix}
\]
Towards a unified description of Nature

Grand unification

Concept

Gauge structure of the standard model

- Interactions come from gauge symmetries
  \[ G_{\text{SM}} = SU(3)_C \times SU(2)_L \times U(1)_Y \subset SU(5) \]

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Local $SU(5)$ rotation

Georgi & Glashow (1974)
Towards a unified description of Nature

*Grand unification Concept*

Gauge structure of the standard model

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  \[ = 10 \quad \text{and} \quad = \overline{5} \]

Local SU(5) rotation

\[
\begin{pmatrix}
\psi_q \\
\psi_q \\
\psi_q \\
\psi_v \\
\psi_e
\end{pmatrix}
\rightarrow
\begin{pmatrix}
* & * & * & * & * \\
* & * & * & * & * \\
* & * & * & * & * \\
* & * & * & * & * \\
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Georgi & Glashow (1974)
Towards a unified description of Nature

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\begin{align*}
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\end{align*}
\]

= 10

= 5

Local SU(5) rotation

extra X gauge bosons mediate transitions between quarks and leptons

Georgi & Glashow (1974)
Towards a unified description of Nature

**Gauge structure of the standard model**

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**Local SU(5) rotation**

Georgi & Glashow (1974)

\[
\begin{pmatrix}
\psi_q \\
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\end{pmatrix}
\rightarrow
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* & * & * & * & * \\
* & * & * & * & * \\
* & * & * & * & * \\
* & * & * & * & *
\end{pmatrix}
\begin{pmatrix}
\psi_q \\
\psi_q \\
\psi_q \\
\psi_y \\
\psi_e
\end{pmatrix}
\]

**bottom-line:**

All known (gauge) interactions can be unified!
\textbf{SU(5)}

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

\(\downarrow\) explains charge quantization

\(\uparrow\) simplifies matter content

\[
\text{SM generation} \ = \ 10 + 5
\]
**SU(5) and SO(10)**

**SU(5) grand unified theory (GUT) . . .**

- explains charge quantization
- simplifies matter content

SM generation = $10 + \bar{5}$

further simplification of matter sector

$$SO(10) \supset SU(5)$$

$$16 = 10 \oplus \bar{5} \oplus 1$$

= SM generation with ‘right–handed’ neutrino

Fritzsch & Minkowski (1975)
SU(5) and SO(10)

SU(5) grand unified theory (GUT) . . .

☞ explains charge quantization

☞ simplifies matter content

SM generation  =  10 + 5

Further simplification of matter sector

SO(10) ⊃ SU(5)

16  =  10 ⊕ 5 ⊕ 1

=  SM generation with ‘right-handed’ neutrino

☞ Once there is an electron, SO(10) tells us that there are also u and d quarks, i.e. protons and neutrons!
SU(5) and SO(10)

SU(5) grand unified theory (GUT) . . .
☞ explains charge quantization
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\[
\text{SM generation} = 10 + \bar{5}
\]

Further simplification of matter sector

\[
\text{SO(10)} \supset \text{SU(5)} \\
16 = 10 \oplus \bar{5} \oplus 1 \\
= \text{SM generation with ‘right–handed’ neutrino}
\]

⇒ Once there is an electron, 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 evolution in the SM: qualitatively nice: couplings run towards each other

However: couplings do not meet at a point
Towards a unified description of Nature

Grand unification

Support for grand unification

(Minimal) supersymmetric standard model

- Fermions
- Supersymmetry
- Bosons

SM particles

- Quarks
- Leptons
- Force particles

Superpartners

- Squarks
- Sleptons
- SUSY force particles
Towards a unified description of Nature

Grand unification

Support for grand unification

(Minimal) supersymmetric standard model

Supersymmetry

Fermions

Bosons

SM particles

R parity even

Quarks

Leptons

Force particles

superpartners

R parity odd

distinguish by $\mathbb{Z}_2^R$
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**Grand unification**

Support for grand unification

**(Minimal) supersymmetric standard model**

Supersymmetry

- Fermions
- Bosons

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

SM particles

- Quarks
- Leptons
- Force particles

superpartners

- $R$ parity even
- $R$ parity odd

$\tilde{\nu}_e, \tilde{\nu}_\mu, \tilde{\nu}_\tau, \tilde{e}, \tilde{\mu}, \tilde{\tau}, \tilde{W}$

$\bar{u}, \bar{c}, \bar{d}, \bar{s}, \bar{e}, \bar{\mu}, \bar{\tau}$
Towards a unified description of Nature

Gauge coupling unification in the MSSM

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

Dimopoulos, Raby & Wilczek (1981)

\[ \log_{10}(\mu/\text{GeV}) \]

\[ g_i \]

\[ g_1 \]

\[ g_2 \]

\[ g_3 \]
Towards a unified description of Nature

Grand unification

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

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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)

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

Unification scale ($M_{GUT}$)

Dimopoulos, Raby & Wilczek (1981)
Grand unification: virtues & predictions

- GUTs explain charge quantization
Grand unification: virtues & predictions

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- In SO(10): understanding of the structure of SM matter
Grand unification: virtues & predictions

- GUTs explain charge quantization
- In $\text{SO}(10)$: understanding of the structure of SM matter
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Grand unification: virtues & predictions

- GUTs explain charge quantization

- In $\text{SO}(10)$: understanding of the structure of SM matter

- Gauge coupling unification (… with supersymmetry)

- Prediction: proton decay

\[
\begin{array}{c}
\text{p} \\
\text{u} \\
\text{d} \\
\text{X} \\
\text{e}^+ \\
\text{u} \\
\text{d} \\
\pi^0
\end{array}
\]
Grand unification: virtues & predictions

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

![Diagram showing proton decay process]

**main prediction of GUTs:** matter unstable
Grand unification: virtues & predictions

- GUTs explain **charge quantization**
- In **SO(10)**: understanding of the **structure of SM matter**
- **Gauge coupling unification** (with supersymmetry)
- Prediction: proton decay

![Diagram of proton decay](image)

**main prediction of GUTs:**

matter unstable \(\sim\) one day our universe will be ‘empty’
Towards a unified description of Nature

Grand unification

Disturbing aspects

Doublet–triplet splitting problem

GUTs also predict color triplets

smallest $\text{SO}(10)$ representation containing Higgs

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

doublets: needed

triplets: problematic
Towards a unified description of Nature

Grand unification

Disturbing aspects

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\[ 10^2 = 5 \oplus \overline{5} \rightarrow (1, 2)_{1/2} \oplus (1, 2)_{-1/2} \oplus (3, 1)_{-1/3} \oplus (\overline{3}, 1)_{1/3} \]

doublets: needed

triplets: problematic

Triplets

- spoil gauge coupling unification
- mediate proton decay
Doublet–triplet splitting in four dimensions

- Matter in complete multiplets
- Higgs in split multiplets

Why?
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)
- ...
Towards a unified description of Nature

Grand unification

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Doublet–triplet splitting in four dimensions

Why?

- matter in complete multiplets
- Higgs in split multiplets

☞ 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
Towards a unified description of Nature

Grand unification

Disturbing aspects

Doublet–triplet splitting in four dimensions

Why?

Higgs in split multiplets

matter in complete multiplets

☞ ‘Natural’ solution of the doublet–triplet splitting problem requires a symmetry that forbids Higgs mass $\mu$

According to ‘t Hooft’s ‘naturalness’ criteria: explaining a (supersymmetric) Higgs mass $\mu \ll M_{\text{GUT}}$ requires a symmetry that forbids $\mu$. 
Towards a unified description of Nature

Grand unification

Disturbing aspects

Doublet–triplet splitting in four dimensions

Why?

matter in complete multiplets

Higgs in split multiplets

☞ ‘Natural’ solution of the doublet–triplet splitting problem requires a symmetry that forbids Higgs mass $\mu$

☞ Only $R$ symmetries can do the job

Only $R$ symmetries can forbid the $\mu$ term in the MSSM

… and $R$ parity is not enough

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

Towards a unified description of Nature

Grand unification

Disturbing aspects

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 $\mu$

☞ 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 $G \supset SU(5)$
- spontaneous breaking
- finite number of fields

cannot have
exact MSSM spectrum & residual $R$ symmetries
(which are stronger than $R$ parity)
in four dimensions
Towards a unified description of Nature

Grand unification

Disturbing aspects

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 $\mu$

☞ 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
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 = $\mathbb{T}^2/\mathbb{Z}_2$
(Super-)String theory predicts six extra dimensions

... but for simplicity discuss only two of them

Simple example: $\mathbb{Z}_2$ orbifold plane = $\mathbb{T}^2/\mathbb{Z}_2$
Towards a unified description of Nature

$\mathbb{Z}_2$ orbifold pillow

GUTs from strings

What is an orbifold?
$\mathbb{Z}_2$ orbifold pillow
Towards a unified description of Nature

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$\mathbb{Z}_2$ orbifold pillow
Towards a unified description of Nature

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**GUTs from strings**

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Z_2 orbifold pillow
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Towards a unified description of Nature

GUTs from strings

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Towards a unified description of Nature

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Towards a unified description of Nature

$\mathbb{Z}_2$ orbifold pillow

GUTs from strings

What is an orbifold?
What is an orbifold?

An orbifold is a space which is smooth/flat everywhere except for special \textit{(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
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 : $G_{\text{low–energy}} = G_{bl} \cap G_{br} \cap G_{tl} \cap G_{tr}$
What are the light states of an orbifold?

Light states of effective field theory

<table>
<thead>
<tr>
<th>Heterotic String</th>
<th>Field Theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>Untwisted sector = strings closed on the torus</td>
<td>Extra components of gauge fields</td>
</tr>
<tr>
<td>‘twisted’ sectors = strings which are only closed on the orbifold</td>
<td>‘brane fields’</td>
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</tbody>
</table>

(‘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?

- **Heterotic string**
  - **Untwisted sector** = strings closed on the torus
  - **Twisted sectors** = strings which are only closed on the orbifold

- **Field theory**
  - Extra components of gauge fields
  - **‘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.
Towards a unified description of Nature

Orbifold compactification with local SO(10) GUT structures

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

6D internal space

4D space-time
Orbifold compactification with local SO(10) GUT

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

6D internal space

4D space–time

SO(10)

16
Local grand unification (using small extra dimensions)

- Idea of ‘local grand unification’

\[ G_{rb}, G_{rt}, G_{lt} \]

E\(_8 \times E_8\)

- ‘low-energy’ effective theory
- as an intersection of \(G_{rb}, G_{rt}, G_{lt}\) & \(SO(10)\) in \(G\)

**SM generation(s):** localized in region with \(SO(10)\) symmetry

**Higgs doublets:** live in the ‘bulk’
Results

1. $3 \times 16 + \text{Higgs} + \text{nothing}$

No exotics
Results

1. $3 \times 16 + \text{Higgs} + \text{nothing}$

2. $\text{SU}(3) \times \text{SU}(2) \times \text{U}(1)_Y \times G_{\text{hid}}$
Results

1. $3 \times 16 + \text{Higgs} + \text{nothing}$

2. $\text{SU}(3) \times \text{SU}(2) \times \text{U}(1)_Y \times G_{\text{hid}}$

3. unification
   precision gauge unification (PGU) from non–local GUT breaking
Results

1. $3 \times 16 + \text{Higgs} + \text{nothing}$

2. $\text{SU}(3) \times \text{SU}(2) \times \text{U}(1)_Y \times G_{\text{hid}}$

3. unification

4. $R$ parity & $\mathbb{Z}_4$

$\bar{u} \bar{d} \bar{d}$, $q \bar{d} \ell$, $\ell \ell \ell$, $\ell H_u$

$\sim$ proton long-lived

$\sim$ DM stable
Towards a unified description of Nature

GUTs from strings

Results & “stringy surprises”

Results

1. $3 \times 16 + \text{Higgs} + \text{nothing}$

2. $\text{SU}(3) \times \text{SU}(2) \times \text{U}(1)_Y \times G_{\text{hid}}$

3. unification

4. $R$ parity & $\mathbb{Z}_4^R$

5. see–saw

$\sim$ suppressed $\nu$ masses
Results

1. $3 \times 16 + \text{Higgs} + \text{nothing}$

2. $\text{SU}(3) \times \text{SU}(2) \times \text{U}(1)_Y \times G_{\text{hid}}$

3. unification

4. $R$ parity $\& \mathbb{Z}_4^R$

5. see–saw

6. $y_t \simeq g \ @ \ M_{\text{GUT}}$ $&$ potentially realistic flavor structures à la Froggatt-Nielsen

\[ \sim \text{realistic top mass} \]
Results

1. $3 \times 16 + \text{Higgs} + \text{nothing}$

2. $SU(3) \times SU(2) \times U(1)_Y \times G_{\text{hid}}$

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6. $y_t \simeq g \ @ M_{\text{GUT}}$ & 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”

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8. solution to the $\mu$ problem

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

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

$\sim$ light Higgs
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that’s what we searched for...

$\ldots$ that’s what we got ‘for free’

“stringy surprises”
Structure of a class of successful models:

- Two families come from two equivalent fixed points and are related by a $D_4$ family symmetry.
- 3rd 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

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Localized fields have odd $\mathbb{Z}_4^R$ charges.

Bulk fields have even $\mathbb{Z}_4^R$ charges.
Local grand unification & $\mathbb{Z}_4^R$ (bottom–up)

<table>
<thead>
<tr>
<th>$\mathbb{Z}_4^R$ charge</th>
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<th>Higgs</th>
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<tbody>
<tr>
<td></td>
<td>1</td>
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$E_8 \times E_8$

SM generation(s):
localized in region with $SO(10)$ symmetry

Higgs doublets:
live in the ‘bulk’
Towards a unified description of Nature

GUTs from strings

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

$G_{lt}$

$G_{rt}$

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

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


SM generation(s):

localized in region with SO(10) symmetry

Higgs doublets:

live in the ‘bulk’

$\mathbb{Z}_4^R$ (bottom–up)

charge

<table>
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Expectations
&
Experimental Tests
Pattern of soft supersymmetry breaking masses

Scenario with SUSY by ‘matter field’ $X +$ dilaton $S$
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Mirage pattern for gaugino masses $+$ heavy sfermions
Towards a unified description of Nature

Expectations & Tests

Implications for the LHC & future colliders

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)

Krippendorf, Nilles, M.R. & Winkler (2013)

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

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

effective SUSY mass

$X_{\text{sfermion}} \sim 1$
PGU implies a superpartner mass scale $\sim 2$ TeV

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precision unification

$\tan \beta = 10$
PGU implies a superpartner mass scale \( \sim 2 \text{ TeV} \)

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

\( H_u, Q_L \) & \( t_R \) bulk fields

Coinciding boundary conditions at high scale

‘Focus point’

Feng, Matchev & Moroi (2000)
PGU implies a superpartner mass scale $\sim 2$ TeV

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

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


Krippendorf, Nilles, M.R. & Winkler (2013)
Towards a unified description of Nature

Results from a more detailed analysis

Running of the soft masses

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

$m_{3/2} = 20 \text{ TeV}, \alpha = 10, \tan \beta = 10$

$\mu = 150 \text{ GeV}, m_A = 2000 \text{ GeV}$

$c_m = 250, c_{m_3} = 23, a_3 = 6$
Results from a more detailed analysis

Sample spectrum

Baer, Barger, Savoy, Serce & Tata (2017)
Results from a more detailed analysis

- Sample spectrum

- Amazingly low fine-tuning: $\Delta_{EW} < 20$ possible
Results from a more detailed analysis

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

Baer, Barger, Savoy, Serce & Tata (2017)
Towards a unified description of Nature

Proton decay

Mütter, M.R. & Vaudrevange (2016)

\[ \mathbb{Z}_4^R \text{ symmetry:} \]

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

**$\mathbb{Z}_4^R$ symmetry:**
- no dimension 4 proton decay
- dimension 5 proton decay negligible

**non-local GUT breaking:**
no dimension 6 proton decay!

\[
\begin{align*}
\bar{d}^{(1)}_{\text{red}} & \sim \bar{d}^{(1)}_{\text{red}} - d^{(2)}_{\text{red}} \\
\bar{d}^{(1)}_{\text{green}} & \sim \bar{d}^{(1)}_{\text{green}} - d^{(2)}_{\text{green}} \\
\bar{d}^{(1)}_{\text{blue}} & \sim \bar{d}^{(1)}_{\text{blue}} - d^{(2)}_{\text{blue}} \\
\ell^{(1)} & \sim \ell^{(1)} + \ell^{(2)} \\
\ell^{(2)} & \sim \ell^{(2)} + \ell^{(2)}
\end{align*}
\]
**Proton decay**

**$\mathbb{Z}_4^R$ 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
Models with local GUT breaking: proton decay from GUT gauge boson exchange

\[ \tau(p \rightarrow e^+\pi^0) \sim 10^{35\pm1} \text{ yr} \]

Uncertainties: matrix elements, \( \alpha_3(m_Z) \), precise value of \( m_{\text{Unification}} \) etc.
Summary
The quest for unification of all forces requires new physics beyond the standard model such as supersymmetry, extra dimensions & strings.
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Stringy completions of the standard model allow us to answer some of the basic questions:

- Family as a $16$-plet of $\text{SO}(10)$
- 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
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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 have cheese!
Backup slides
Neutrino masses in grand unification: see–saw

\[ m_\nu \sim \frac{v_{EW}^2}{m_\bar{\nu}} \]

\( v_{EW} \sim 100 \text{ GeV} \)
\( \nu = \text{‘left–handed’ neutrino} \)
\( \bar{\nu} = \text{‘right–handed’ neutrino} \)
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Minkowski (1977)
Gell-Mann, Ramond & Slansky (1979)
Yanagida (1979)
Neutrino masses in grand unification: see-saw

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

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Experiments: \( \sqrt{\Delta m^2_{\text{atm}}} \approx 0.04 \text{ eV} \) & \( \sqrt{\Delta m^2_{\text{sol}}} \approx 0.008 \text{ eV} \)
Neutralino masses in grand unification: see–saw

Naive expectation: $m_{\tilde{\nu}} \sim M_{\text{GUT}}$

$\nu \sim (100 \text{ GeV})^2 / 10^{16} \text{ GeV} \sim 10^{-3} \text{ eV}$

Experiments: $\sqrt{\Delta m^2_{\text{atm}}} \approx 0.04 \text{ eV}$ & $\sqrt{\Delta m^2_{\text{sol}}} \approx 0.008 \text{ eV}$

Rough (although not perfect) agreement
Dimension five proton decay

\[ q_i \quad 3_H \quad 3_H \quad q_\ell \]

Integrating out Higgs(ino) triplets

\[ q_i \quad q_\ell \quad q_j \quad q_\ell \quad q_j \quad \ell_k \quad \ell_k \]
Dimension five proton decay

Towards a unified description of Nature

Sakai & Yanagida (1982)
Dimension five proton decay

Sakai & Yanagida (1982)

Integrating out Higgs(ino) triplets

\[ q_i \quad 3_H \quad 3_H \quad q_\ell \]

for 'reasonable' soft masses:

\[ \tau(p \rightarrow K^+ + \bar{\nu}) \gtrsim 3 \times 10^{33} \text{ y} \]

\[ \sim m_{\text{triplet}} \gtrsim 10^{19} \text{ GeV} \]
SO(10) breaking by Higgs mechanism

\[ \text{SO}(10) \xrightarrow{54, 210} \text{SU}(4) \times \text{SU}(2) \times \text{SU}(2) \times \mathbb{Z}_2 \]

\[ \text{SU}(4) \times \text{SU}(2) \times \text{SU}(2) \]

\[ \text{SU}(4) \times \text{SU}(2) \times \text{SU}(2) \]

\[ \text{SU}(3) \times \text{SU}(2) \times \text{U}(1) \times \mathbb{Z}_2^R \]

\[ \text{SU}(3) \times \text{SU}(2) \times \text{U}(1) \]

GUT breaking by Higgs: need large Higgs representations
\((54, 126, 210) \sim \text{lot of } \text{`junk'}\) (which, however, can be paired up)
What are the light states of an orbifold?

Light states of effective field theory

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

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

$\Leftrightarrow \{ \text{unique solution: discrete } \mathbb{Z}_4^R \text{ symmetry} \}$

Lee, Raby, M.R., Ross, Schieren, et al. (2011)
Unique $\mathbb{Z}_4^R$ symmetry for the MSSM

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\begin{align*}
\mathbb{Z}_4^R &
\begin{cases}
\text{forbids } \mu \text{ term perturbatively} \\
\text{forbids dimension 5 proton decay perturbatively} \\
\text{contains matter/}R \text{ parity} \\
\text{charge assignment: } \begin{cases}
\text{matter: 1} \\
\text{Higgs: 0}
\end{cases}
\end{cases}
\end{align*}

\begin{align*}
\text{unique solution: discrete } \mathbb{Z}_4^R \text{ symmetry}
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Towards a unified description of Nature

Backup slides

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

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

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$\mathbb{Z}_4^R$

- forbids $\mu$ term perturbatively
- forbids dimension 5 proton decay perturbatively
- contains matter/$R$ parity
- charge assignment:
  - matter: 1
  - Higgs: 0

$\mathcal{W}^{\text{non-pert eff}} \supset \mu_{\text{eff}} H_u H_d + \kappa_{ijk\ell} Q_i Q_j Q_j L_\ell$

$\sim m_{3/2} \sim \text{TeV}$

$\sim m_{3/2}/M_P^2 \sim 10^{-15}/M_P$
References I


