Orbifold stability of asymptotic GUTs

ANCA PREDA

Supervisor: Roman Pasechnik

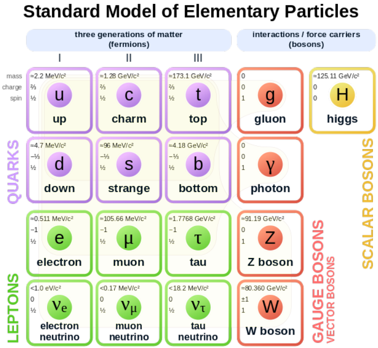
[arXiv:2409.16137]

G. Cacciapaglia, A. Cornell, A. Deandrea, W. Isnard, R. Pasechnik, AP, Z. Wang

LUND UNIVERSITY

Partikeldagarna 2024

The Standard Model (SM)



source: Wikipedia

Tested to high precision but...

leaves some open questions:

hierarchy problem, charge quantization

neutrino mass, dark matter, baryon asymmetry...

⇩

Beyond the Standard Model (BSM) physics

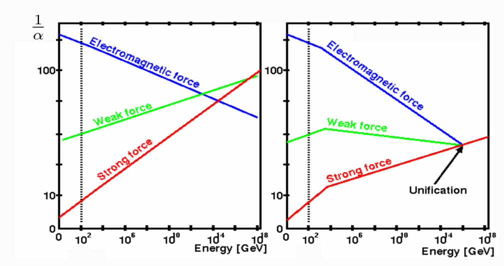
Beyond the Standard Model

There are many ways to include extensions

$\Rightarrow$ new particles, extra dimensions, grand unified theories (GUTs), supersymmetry...

$\Rightarrow$ our work: GUTs in higher dimensions $\equiv$ asymptotic GUTs[1]

Unification:



SM gauge couplings meet at some high scale

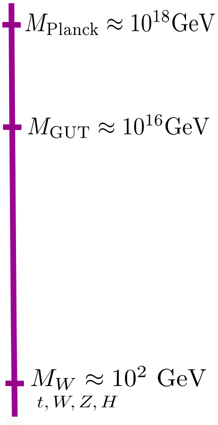
$\updownarrow$

Physics described by a **unified gauge group** $\mathcal{G} \supset \mathcal{G}_{\rm SM}$

e.g. $SU(5)$, $SO(10)$, E_6

[1] A. Hebecker, J. March-Russell, Nuclear Phys. B 625 (2002)

Beyond the Standard Model



Why Grand Unification? [2]

$\Rightarrow$ can explain some of the puzzles (neutrino mass, dark matter...) and more fundamental issues, e.g. charge quantization

...but, GUT scale is very high, orders of magnitude away from hadron colliders

[2] H. Georgi and S. Glashow, Phys. Rev. Lett., 438 (1974)

Asymptotic Grand Unified Theories (aGUTs)

What we do: standard picture of unification but in higher dimensions

GUTs defined on $\underbrace{\mathbb{R}^4}_{\text{4D Minkowski}} \times \underbrace{K}_{\delta \text{ extra dims}}$

Why we do it:

$\Longrightarrow$ lower GUT scale (no proton decay)

$\Longrightarrow$ less parameters/smaller representations

$\Longrightarrow$ solution to hierarchy problem

Introduction

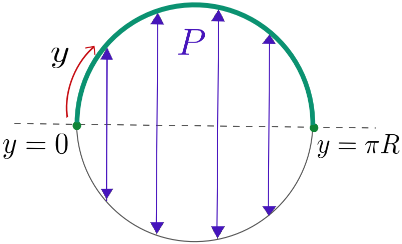
Asymptotic unification

Orbifold stability: results

Conclusions

Example: 5D case

- One extra dimension ($\delta = 1$) compactified on $K = \mathbb{S}^1/\mathbb{Z}_2 \times \mathbb{Z}'_2$:



Example: 5D case

Introduction

Asymptotic unification

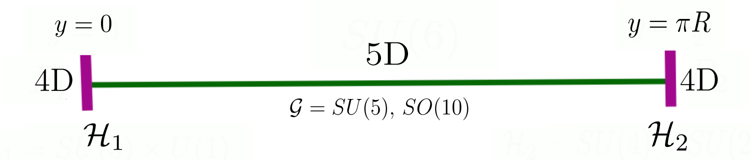
Orbifold stability: results

Conclusions

- One extra dimension ($\delta = 1$) compactified on $K = \mathbb{S}^1/\mathbb{Z}_2 \times \mathbb{Z}'_2$:

- The inverse radius R^{-1} sets the scale of compactification.

Example: 5D case



- The symmetry will be broken $\mathcal{G} \to \mathcal{H}_i$ on each boundary[3], such that

$$\mathcal{G}_{4\mathrm{D}} \equiv \mathcal{H}_i \cap \mathcal{H}_j$$

- Viable model must contain the Standard Model

$$\mathcal{G}_{4\mathrm{D}} \supset \mathcal{G}_{\mathrm{SM}}$$

[3] G. Cacciapaglia, arXiv:2309.10098 (2023)

Gauge-Higgs Unification[4] [5]

In asymptotic unification scenarios, a gauge field decomposes

⇓

$\underbrace{A_\mu(\mu = 1\dots4)}_{\text{4D}}$ and $\underbrace{A_5}_{\text{extra dimension}}$

gauge bosons **scalars**

[4] Y. Hosotani, Phys. Lett. B 126 (1983)
[5] R. Contino,et al, Nucl. Phys. B 671 (2003)

Gauge-Higgs Unification[4] [5]

In asymptotic unification scenarios, a gauge field decomposes

$$\underbrace{A_\mu(\mu = 1\ldots4)}_{\text{4D}} \quad \text{and} \quad \underbrace{A_5}_{\text{extra dimension}}$$

gauge bosons **scalars**

$A_5 \equiv$ **Higgs field**

[4] Y. Hosotani, Phys. Lett. B 126 (1983)
[5] R. Contino,et al, Nucl. Phys. B 671 (2003)

Gauge-Higgs Unification

$A_5 \equiv$ **scalar** embedded in the gauge fields

There will be a scalar potential for A_5!

...but gauge symmetry forbids the potential at tree level

⇩

one loop effective potential [6]

(dictates symmetry breaking, mass of the scalars etc.)

[6] I. Antoniadis, et al, New Journal of Physics 3 (2001)

One loop effective potential

Introduction

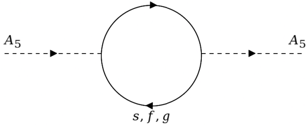
Asymptotic unification

Orbifold stability: results

Conclusions

Total potential given by:

$$V_{\text{eff}}^{\text{total}} = V_{\text{eff}}^{\text{gauge}} + V_{\text{eff}}^{\text{scalar}} + V_{\text{eff}}^{\text{fermionic}}$$



Global minimum of $V_{\text{eff}}^{\text{gauge}}$ must be at 0.

⇓

constraint on models in order to be viable

Orbifold stability [arXiv:2409.16137]

What we did:

Computed the effective potential for general $SU(N)$, $Sp(2N)$ and $SO(N)$ gauge theories

⇓

Imposed the global minimum constraint

⇓

Derived orbifold stability conditions based on this constraint

Minimal models

Minimal models that satisfy the **orbifold stability** criteria

Model	Breaking pattern	Fermions	Fixed point	Gauge-scalar
SM route (A)				
SU(5)	G_{SM}	✓	×	none
SU(6) (6A')	$G_{\mathrm{SM}} \times \mathrm{U}(1)$	✓	$n_g = 3$	$(3,1)_{-1/3}$
SU(6)	$G_{\mathrm{SM}} \times \mathrm{U}(1)$	×	–	$(3,2)_{-5/3}$
Sp(10)	$G_{\mathrm{SM}} \times \mathrm{U}(1)$	×	–	$(3,2)_y$
SO(10)	$G_{\mathrm{SM}} \times \mathrm{U}(1)$	×	–	$(3,2)_y$
PS route (B)				
SU(8)	$G_{\mathrm{PS}} \times \mathrm{U}(1)^2$	✓*	$n_g \leq 3$	$(4,1,2)$
SO(10)	G_{PS}	✓	$2 \leq n_g \leq 5$	none

The column **Fermions** indicates whether SM fermions can be embedded in the model, while **Fixed point** concerns the UV behaviour of the models.

Minimal models

Minimal models that satisfy the **orbifold stability** criteria

Model	Breaking pattern	Fermions	Fixed point	Gauge-scalar
SM route (A)				
SU(5)	G_{SM}	✓	×	none
SU(6) (6A')	$G_{\text{SM}} \times \text{U}(1)$	✓	$n_g = 3$	$(3,1)_{-1/3}$
SU(6)	$G_{\text{SM}} \times \text{U}(1)$	×	–	$(3,2)_{-5/3}$
Sp(10)	$G_{\text{SM}} \times \text{U}(1)$	×	–	$(3,2)_y$
SO(10)	$G_{\text{SM}} \times \text{U}(1)$	×	–	$(3,2)_y$
PS route (B)				
SU(8)	$G_{\text{PS}} \times \text{U}(1)^2$	✓*	$n_g \leq 3$	$(4,1,2)$
SO(10)	G_{PS}	✓	$2 \leq n_g \leq 5$	none

The column **Fermions** indicates whether SM fermions can be embedded in the model, while **Fixed point** concerns the UV behaviour of the models.

Conclusions

- aGUTs as an alternative to standard GUTs
- Viable models have to pass certain criteria $\Rightarrow$ **orbifold stability**
- The criteria of **orbifold stability** helps identify potentially interesting models ($SU(6)$, $SU(8)$, ...)
- **Systematic classification** that discards phenomenologically unrealistic scenarios

Back-up slides

Orbifold stability: $SU(N)$ results

For a general model based on the $SU(N)$ group (e.g $SU(5)$) we find:

$SU(N) \rightarrow SU(p) \times SU(q) \times U(1)$ ✅

$SU(N) \rightarrow SU(p) \times SU(q) \times SU(s) \times U(1)^2$ ✅ if $p \geq N/2$

$SU(N) \rightarrow SU(p) \times SU(q) \times SU(r) \times SU(s) \times U(1)^3$ ❌

... which tells us what symmetry breaking scenarios to consider.

Example: 5D case

For a given field $\Phi\left(x^\mu, y\right)$ we can do a **Kaluza-Klein decomposition**

⇓

Decomposition

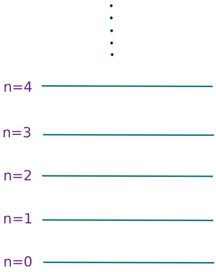
$$\Phi\left(x^\mu, y\right) = \underbrace{\sum_{n=0}^{\infty} \phi_+^{(n)}(x^\mu)\cos\left(\frac{ny}{R}\right)}_{\text{parity-even}} + \underbrace{\sum_{n=1}^{\infty} \phi_-^{(n)}(x^\mu)\sin\left(\frac{ny}{R}\right)}_{\text{parity-odd}}$$

- The 4D fields $\phi_\pm^{(n)} \equiv$ Kaluza-Klein (KK) modes with mass of n/R.
- The Standard Model fields are the massless zero modes of ϕ_+.
- For $E \ll 1/R$, the heavy Kaluza-Klein towers are integrated out.

⇓

4D effective field theory

Example: 5D case



Each 5D field $\equiv$ **infinite tower** of 4D fields

“ground state” (n=0) are the SM states

RGEs for the couplings get modified:

logarithmic $\rightarrow$ power-law dependence

⇩

couplings will flow **asymptotically** towards a UV fixed point