Grand unification in extra dimensions

ANCA PREDA

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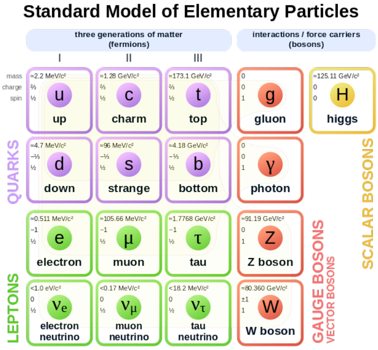
Outline

The Standard Model (SM)



source: Wikipedia

Tested to high precision but…

leaves some open questions:

hierarchy problem, strong CP

neutrino mass, dark matter, baryon asymmetry…

Beyond the Standard Model (BSM) physics

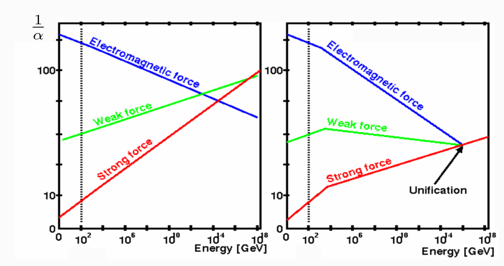
Beyond the Standard Model

There are many ways to include extensions

⇒ new particles, extra dimensions, grand unified theories (GUTs), supersymmetry...

⇒ our work: GUTs in higher dimensions ≡ asymptotic GUTs[1]

Unification:



SM gauge couplings meet at some high scale

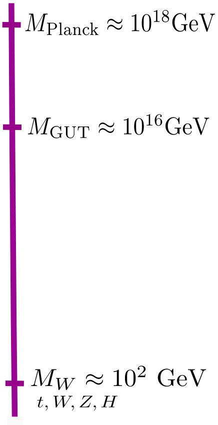
↕

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

⬇

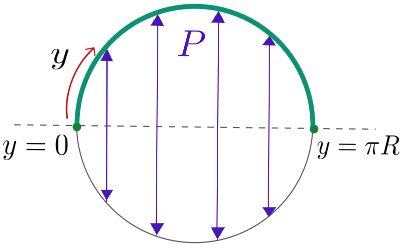
GUTs defined on $\mathbb{R}^4 \times K$, where $\mathbb{R}^4$ is the usual 4-dimensional Minkowski space and K defines δ *compact* extra dimensions .

Motivation:

- lower GUT scale
- less parameters/smaller representations
- solution to hierarchy problem

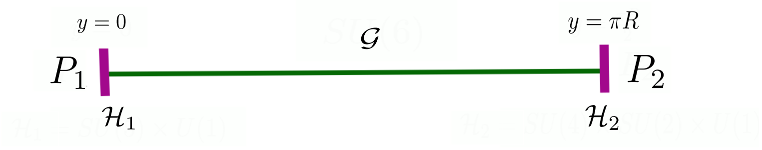
Example: 5D case

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



Example: 5D case

- Each intrinsic $\mathbb{Z}_2$ transformation is specified by a parity matrix P acting on the fields [3]



- Each P_i will break $\mathcal{G} \to \mathcal{H}_i$ on one boundary, such that

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

- Viable model must contain the Standard Model

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

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

Gauge-Higgs Unification[4] [5]

Assume a 5D gauge theory and A_M $(M = 1, \ldots, 5)$ a gauge field

⬇

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

⬇

A_5 behaves as a scalar field in 4D

$\equiv$ **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 ≡**gauge-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

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 phenomenologically relevant

Orbifold stability

G. Cacciapaglia, A. Deandrea, A. Cornell, W. Isnard, R. Pasechnik, A. Preda and Z. Wang [in preparation]

What we did:

1. Computed the effective potential for general $SU(N)$, $Sp(2N)$ and $SO(N)$ gauge theories
2. Imposed the global minimum constraint
3. Derived orbifold stability conditions based on this constraint

Orbifold stability: $SU(N)$ results

- All breaking patterns of the form

$$SU(N) \to SU(a) \times SU(N-a) \times U(1)$$

satisfy the constraint.

- Breaking patterns of the form

$$SU(N) \to SU(p) \times SU(q) \times SU(s) \times U(1)^2$$

satisfy the constraint only if $p \geq N/2$.

- For breaking patterns of the form

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

the constraint is never satisfied.

Orbifold stability: $SU(N)$ results

Examples:

$$SU(5) \to SU(3) \times SU(2) \times U(1)$$
$$SU(6) \to SU(3) \times SU(2) \times U(1)^2 \qquad \text{satisfy } p \geq N/2 \; ✅$$
$$SU(8) \to SU(4) \times SU(2) \times SU(2)$$

whereas

$$SU(7) \to SU(3) \times SU(3) \times U(1)^2 \qquad \text{has } p \leq N/2 \; ❌$$

$\Rightarrow$ Analysis was extended to $Sp(2N)$ and $SO(N)$: more group theory needed, but results follow in a similar way

$\Rightarrow$ Next: derive similar constraints for exceptional groups E_6, E_8

Conclusions

- aGUTs as an alternative to standard GUTs
- Viable models have to pass certain criteria $\Rightarrow$ **orbifold stability**
- For $SU(N)$: two-blocks and three-blocks with $p \geq N/2$ are stable, while four-blocks are not
- The criteria of **orbifold stability** helps identify potentially interesting models
- **Systematic classification** that discards phenomenologically unrealistic scenarios

Back-up slides

Example: 5D case

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

⬇

Decomposition

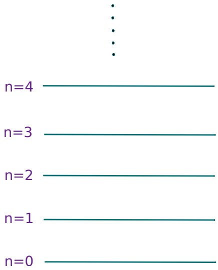
$$\Phi\left(x^{\mu}, y\right) = \underbrace{\sum_{n=0}^{\infty} \phi_{+}^{(n)}\left(x^{\mu}\right) \cos\left(\frac{ny}{R}\right)}_{\text{parity-even}} + \underbrace{\sum_{n=1}^{\infty} \phi_{-}^{(n)}\left(x^{\mu}\right) \sin\left(\frac{ny}{R}\right)}_{\text{parity-odd}}$$

- 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