Proton stability in low-scale extra-dimensional grand unified theories

Mitsuru Kakizaki (University of Toyama)

August 6, 2013
YITP Workshop PPP2013

• MK, arXiv:1307.0535 [hep-ph]

1. Motivation

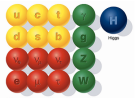
Standard Model (SM) and its problems

- July 4, 2012: Discovery of a new particle
  - Mass: 125GeV
  - Couplings to SM particles: consistent with the SM Higgs boson

➡ The SM is established as a low-energy effective theory

This is not the end of the story

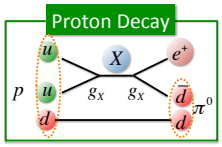
- Theoretical problems of the SM
  - Unexplained structure of the SM gauge bosons and fermions
  - Quantization of the electric charges



➡ More fundamental theory is needed

Grand Unified Theories (GUTs) and proton decay

- The SM gauge interactions are unified: $SU(3)_C \times SU(2)_L \times U(1)_Y \subset G$
- The SM fermions (quarks, leptons) are also unified:
  e.g.: $G = SU(5)$ $(Q, U^C, E^C) = 10$ $(D^C, L) = 5^*$ ➡ Charge quantization
- X-bosons are automatically introduced:
  $\begin{pmatrix} G & X \\ \bar{X} & W \end{pmatrix} \oplus B = 24$ ➡ Proton is unstable
- Proton lifetime: $\tau_p(p \to e^+\pi^0) > 8.2 \times 10^{33}\,yr$
  ➡ $M_X / g_X \geq 10^{15} GeV$
- Conventional GUTs: $g_X \sim 1$ $M_X \sim 10^{15} GeV$
  ➡ The GUT scale is beyond the reach of collider experiments



This work

- Localizing the X-bosons and fermions at different locations in extra dimensions ➡ $g_X \ll 1$

➡ The effects of GUT particles can be probed at colliders

3. Localizing X-bosons

- Idea: Kink background of an adjoint Higgs
  ➡ Different profiles in the same GUT multiplets

[MK,arXiv:1307:0535]

- Z_2-invariant real $\Sigma(24)$ terms in 5D SU(5) GUT Lagrangian:

$$\mathcal{L}_5 = \mathrm{tr}(\partial^M \Sigma)(\partial_M \Sigma) + \frac{M_\Sigma^2}{2}\mathrm{tr}\Sigma^2 - \frac{a}{4}(\mathrm{tr}\Sigma^2)^2 - \frac{b}{2}\mathrm{tr}\Sigma^4$$

➡ Domain wall solution:

$$\langle \Sigma \rangle = \begin{cases} V\,\mathrm{diag}(2,2,2,-3,-3), & x^5 \to \infty, \\ -V\,\mathrm{diag}(2,2,2,-3,-3), & x^5 \to -\infty, \end{cases}$$

Translational invariance along the extra dimension and SU(5) are simultaneously broken

- X-bosons: Localized with an exponential profile
- SM gauge bosons: Flat profle

➡ GUT relations are easily violated in the 4D viewpoint

[c.f. Hamada,Kobayashi,PTP128,903(2012)]

Applications

- Doublet Triplet Splitting [MK,Yamaguchi,PTP107,433(2002)]
- Realistic fermion masses, mixings and CP-phase [MK,Yamaguchi,IJMPA19,1715(2004)]

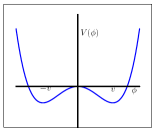
2. Localizing fermions in extra dimensions

- Idea:
  Chiral fermions are localized due to a kink in extra dimensions

[Jackiw,Rebbi,PRD13,3398(1976);Rubakov,Shaposhnikov,PLB125,139 (1983); Arkani-Hamed,Schmaltz,PRD61,033005(2000)]

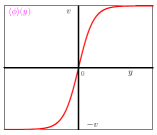
- Z_2-invariant real scalar theory in 5D space-time:

$$S = \int d^4x dy \left[\frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2}(\partial_y \phi)^2 - V(\phi)\right] \qquad x^M = (x^\mu, y)$$



➡ Domain wall solution: $\langle \phi \rangle (y \to \pm\infty) = \pm v$

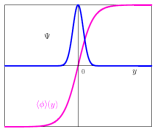
Translational invariance along the extra dimension broken



Profile of a fermion wave function

- 5D Fermion Ψ in the domain wall background:

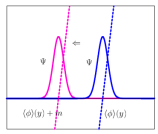
$$S = \int d^4x dy \bar{\Psi}\left[i\gamma^\mu \partial_\mu - \gamma^5 \partial_y + (\phi + m)\right]\Psi \qquad \langle \phi \rangle = 2\mu^2 y$$



➡ Left chiral zero mode in 4D:

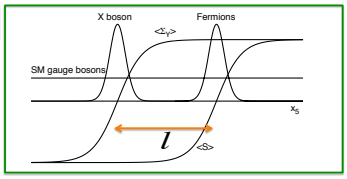
$$\Psi^0 \sim \sqrt{\mu}\exp\left[-\mu^2(y-l)^2\right]\psi_L(x), \quad l \equiv -\frac{m}{2\mu^2}$$

- The zero mode wave function is localized at the zero of $\langle \phi \rangle + m$ with a Gaussian profile
- m determines the position of Ψ^0
- The right-handed zero mode is killed



4. Small 4D coupling and proton stability

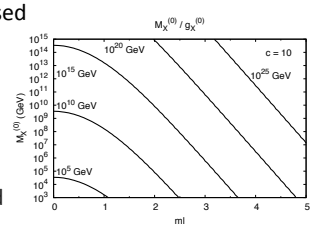
Profiles



[MK,arXiv:1307:0535]

➡ 4D $X^{(0)}$-coupling: $g_X^{(0)} = g_5 \int_\infty^\infty dx^5 \left[f_L^{(0)}(x^5)\right]^2 f_X^{(0)}(x^5)$

- Separation between the X-bosons and fermions
  ➡ g_X is exponentially suppressed
- $M_X^{(0)} / g_X^{(0)} > 10^{15} GeV$ is achieved with a smaller X-boson mass
- Contributions from higher KK X-bosons are also suppressed



5. Low GUT scale

- Non-observation of exotic colored particles
  ➡ Inverse of the size of the extra dimension: $L^{-1} \geq 1 TeV$
- To suppress proton decay: $4/m < l < L$ ➡ $M_X^{(0)} > 10 TeV$

➡ The effects of the X-bosons can be indirectly probed at the LHC and ILC

6. Summary

- Field localization in extra dimensions is a new approach to proton stability mediated by X-bosons
  - Exponentially small coupling constants are obtained by small overlaps of the wave functions in the extra dimension
  - Proton stability is explained even in low-scale extra dimensional GUTs without imposing symmetries
- The effects of the X-bosons can be indirectly probed at the LHC and ILC