Chiral Asymmetry from a 5D Higgs Mechanism

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Based on
M. Shaposhnikov and A. S., arXiv:0707.2455

Chiral asymmetry and Higgs Mechanism in the SM

Higgs mechanism:

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

$U(1)_{em}$ generated by $Q_{em} = T^3 + Y$

$$\psi \sim (\mathbf{R_3}, \mathbf{R_2})_{\mathbf{Y}}$$

Unbroken gauge symmetry representations are **vector-like**
Spontaneously broken gauge symmetry representations are **chiral**

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SM fermion quantum numbers

$$Q_L \equiv \begin{pmatrix} u_L \\ d_L \end{pmatrix} \sim (\mathbf{3}, \mathbf{2})_{1/6}\,, \quad u_R \sim (\mathbf{3}, \mathbf{1})_{2/3}\,, \quad d_R \sim (\mathbf{3}, \mathbf{1})_{-1/3}\,,$$

$$L_L \equiv \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \sim (\mathbf{1}, \mathbf{2})_{-1/2}\,, \quad e_R \sim (\mathbf{1}, \mathbf{1})_{-1},$$

Chirality and extra dimensions

$$\Psi \quad \supset \quad \sum_{i,j} \psi_L^i \oplus \psi_R^j, \quad i = 1, ..., n_L, \; j = 1, ..., n_R$$

$$\gamma^5 \psi_L^i = \psi_L^i, \quad \gamma^5 \psi_R^j = -\psi_R^j$$

Before dimensional reduction $n_L = n_R$

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After dimensional reduction (D=4)
it can happen $n_L \neq n_R$ for $E \ll M_{KK}$; e. g. in both

- Old KK scenarios (with compact internal manifold)
  N. S. Manton (1981)
- Brane worlds (with infinite or compact internal manifold)
  V. A. Rubakov and M. E. Shaposhnikov (1983)

$\Rightarrow$Dynamical origin of chiral asymmetry

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Do the chiral asymmetry and the mass have a common origin?

Charged 5D fermion on domain walls

A very simple model:

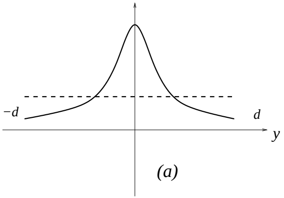
- a 5D spinor field $\Psi = \begin{pmatrix} \psi_L \\ \psi_R \end{pmatrix}$ $\quad n_L = 1, \; n_R = 1$
- a U(1) 5D gauge field A_M, $M = 0, 1, 2, 3, y$
- a domain wall configuration $\varphi = \varphi(y)$

Fermion action

$$S_F = \int d^5X \left(\overline{\Psi}\Gamma^M D_M \Psi + \varphi \overline{\Psi}\Psi\right), \quad \text{where} \quad D_M\Psi = (\partial_M + ie_f A_M)\,\Psi$$

The 4D fermion spectrum (masses and wave functions) depends on φ

S^1-compactification: $y \sim y + 2d$



Plot (a): 4D gauge field profile along y

- Dashed line: $v = 0$.
  The profile is constant
- Continuous line: $v \neq 0$

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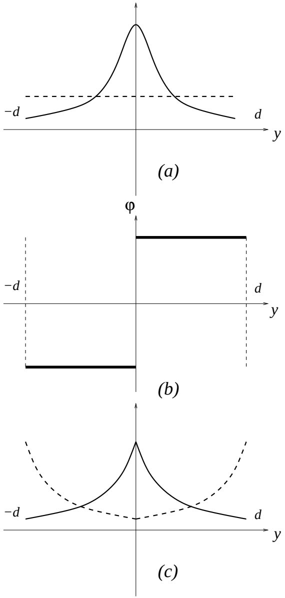

Plot (a): 4D gauge field profile along y

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Plot (b): Two domain wall configuration

$$\varphi(y) = h(2\theta(y) - 1), \quad \theta(y) = \begin{cases} 1, & \text{for } y > 0 \\ -1, & \text{for } y < 0 \end{cases}$$

Plot (c): Fermion 4D zero mode profiles

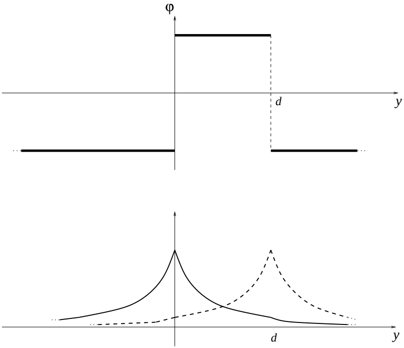
- Dashed line: right-handed fermion
- Continuous line: left-handed fermion

D. B. Kaplan and M. Schmaltz (1996)

C. D. Fosco and R. C. Trinchero (1999)

Infinite fifth dimension

Again a two brane setup



$$\varphi(y) = h\theta(y)\left[1 - \theta(y - d)\right] - m$$

The lightest fermion mode is massive, but

- left-handed chirality on $y = 0$
- right-handed chirality on $y = d$

d: distance between the "left and right handed branes"

d large may lead to $g_L \gg g_R$ as well as with a compact fifth dimension

A simple bosonic completion

Some problems:

1. How can we dynamically obtain such a 4D gauge field profile?
2. Is there a chiral anomaly in $D = 4$?
3. In case, is it a gauge or a global anomaly?

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We introduce a *dynamical* 5D gauge field A_M and a charged scalar ϕ, and

$$S_B = \int d^5X \left\{ -\frac{\Delta(y)}{4} F_{MN}F^{MN} - \Delta_S(y) \left[(D_M\phi)^* D^M\phi + V(\phi) \right] \right\}$$

$$F_{MN} = \partial_M A_N - \partial_N A_M$$

$$D_M\phi = (\partial_M + ieA_M)\,\phi$$

$$V(\phi) = \lambda \left(|\phi|^2 - v^2 \right)^2, \ \lambda \text{ and } v \text{ real}, \ \lambda > 0$$

Gauge fixing and perturbations

$$\mathcal{L}_{GF} = -\frac{\Delta}{2}\left[\frac{1}{\Delta}\partial_M\left(\Delta A^M\right) + \sqrt{2}ev\frac{\Delta_S}{\Delta}\eta\right]^2$$

4D spin-1 and spin-0 sectors decouple

e.g.

$$\Delta(y) = \exp\left(-\frac{1}{2}\mathcal{M}^2 y^2\right), \qquad \Delta_S(y) = \frac{\delta^2}{8}y^2 \exp\left(-\frac{1}{2}\mathcal{M}^2 y^2\right)$$

$\mathcal{M}$ turns out to be the KK mass scale

Spin-1 sector

$A_\mu(x,y) = \sum_n A_\mu^{(n)}(x) f_n(y)$

$f_0(y) = N_0 \exp\left[-\frac{1}{4}\mathcal{M}^2\left(\sqrt{1+\epsilon^2}-1\right)y^2\right]$

$M_0^2 = \frac{1}{2}\mathcal{M}^2\left(\sqrt{1+\epsilon^2}-1\right)$

$$\epsilon^2 \equiv e^2 v^2 \delta^2/\mathcal{M}^4$$

$$\epsilon^2 \sim \frac{M_0^2}{\mathcal{M}^2} \ll 1$$

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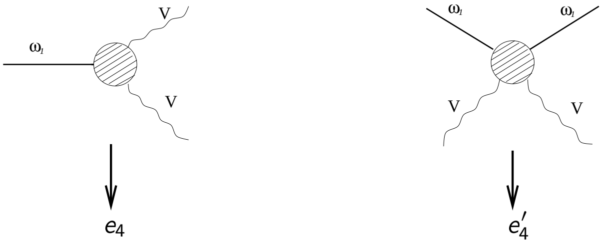
Low-energy degrees of freedom

- A vector field $V \equiv A^{(0)}$
- A physical Higgs field ω_1
- A would-be Goldstone boson ω_2

Small explicit breaking of gauge invariance

Two ways to measure the 4D gauge constant
(that should coincide in a gauge invariant theory)



In the tree-level approximation we have

$$\frac{e_4}{e_4'} = 1 + \mathcal{O}(\epsilon^2), \qquad \textbf{but remember} \qquad \epsilon^2 \sim \frac{M_0^2}{\mathcal{M}^2} \ll 1$$

Consequences

- No gauge symmetry in the 4D effective theory
- This mechanism cannot be described by a purely 4D gauge invariant language

Remarks

Summary

- We related the chiral asymmetry to the Higgs mechanism in a higher dimensional model
- In our model we found an (explicit but very small) breaking of the gauge invariance at low energies

Outlook

- Is there a chiral anomaly in the 4D effective theory?
- Extension to a realistic model
- Inclusion of gravity and dynamical origin for φ, Δ, Δ_S, ...