Gauge-Higgs Unification from EW to GUT

Yutaka Hosotani

Physics
OSAKA UNIVERSITY

Funatsu, Hatanaka, YH, 1510.06550 (PRD)
YH, Yamatsu, 1504.03817 (PTEP), 1511.01674 (PoS)

Scalars 2015, Warsaw, 7 December 2015

In search of a Principle

for the 125 GeV Higgs scalar boson

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which

regulates Higgs couplings,

explains EW sym breaking,

solves the gauge-hierarchy prob.

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gauge theory A_M *in 5 dim.*

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4-dim. components A_μ

∪

4D gauge fields

γ , W , Z

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H

Aharonov-Bohm phase

θ_H

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Hosotani mechanism

EW symmetry breaking

SO(5)xU(1) gauge-Higgs unification

Agashe, Contino, Pomarol 2005
YH, Sakamura 2006
Medina, Shah, Wagner 2007
YH, Oda, Ohnuma, Sakamura 2008
YH, Noda, Uekusa 2009
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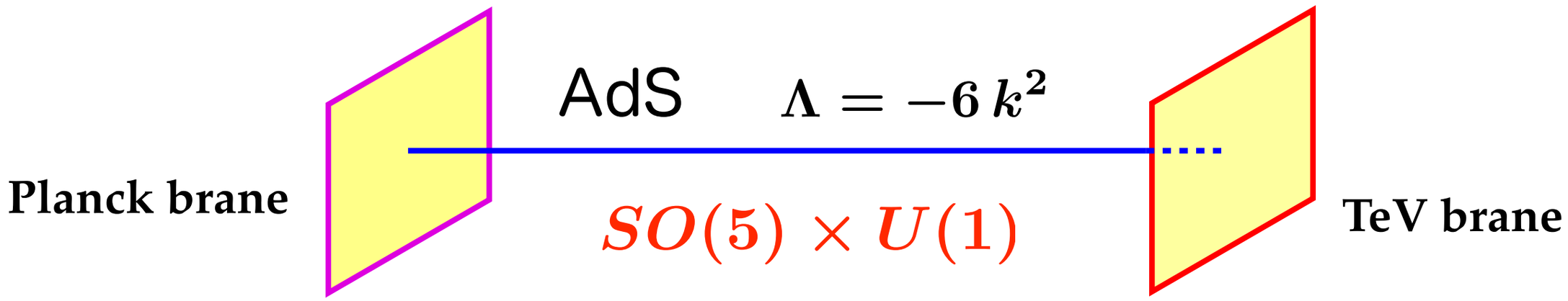

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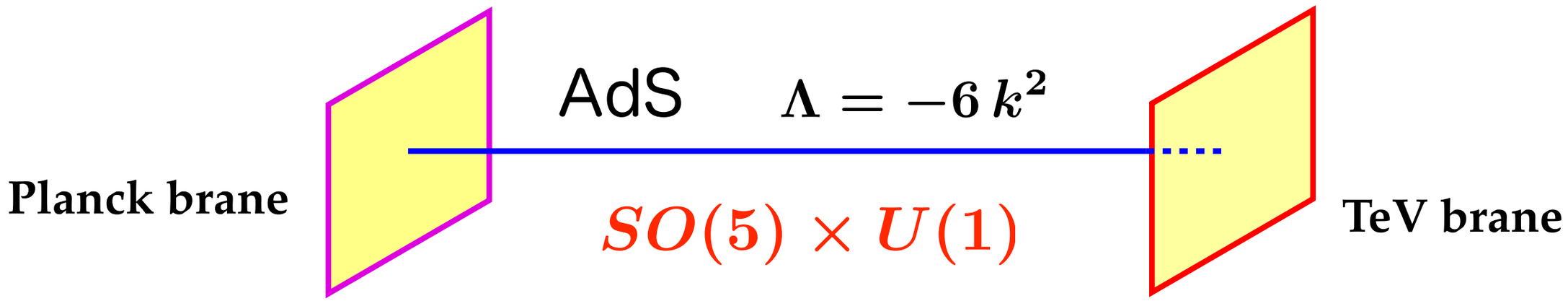

$$\begin{pmatrix} A_\mu \\ A_y \end{pmatrix}(x,-y) = P_0 \begin{pmatrix} A_\mu \\ -A_y \end{pmatrix}(x,y) P_0^\dagger$$

$$\begin{pmatrix} A_\mu \\ A_y \end{pmatrix}(x,\pi R - y) = P_1 \begin{pmatrix} A_\mu \\ -A_y \end{pmatrix}(x,\pi R + y) P_1^\dagger$$

Orbifold BC : P_0 , P_1

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4D gauge bosons and Higgs

Orbifold BC : P_0 , P_1

$$P_0 = P_1 = \begin{pmatrix} -1 & & & & \\ & -1 & & & \\ & & -1 & & \\ & & & -1 & \\ & & & & +1 \end{pmatrix}$$

$$SO(5) \to SO(4) \simeq SU(2)_L \times SU(2)_R$$

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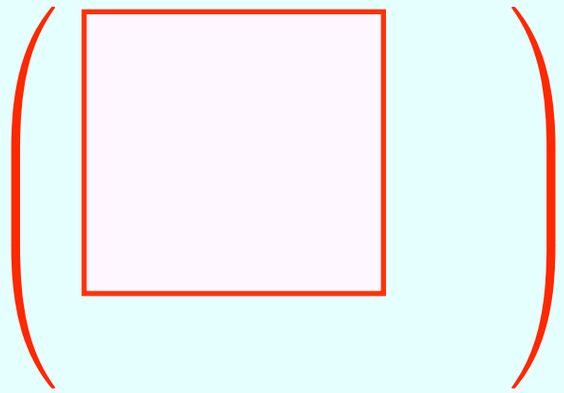
W Z γ

$A_\mu \sim$ 

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4D gauge bosons and Higgs

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$$A_\mu \sim \begin{pmatrix} \square & \\ & \end{pmatrix}$$

$$SO(5) \to SO(4) \simeq SU(2)_L \times SU(2)_R$$

Higgs

$$A_y \sim \begin{pmatrix} & \phi_1 \\ & \phi_2 \\ & \phi_3 \\ & \phi_4 \\ \square & \end{pmatrix} \qquad \Phi = \begin{bmatrix} \phi_1 + i\phi_2 \\ \phi_4 - i\phi_3 \end{bmatrix}$$

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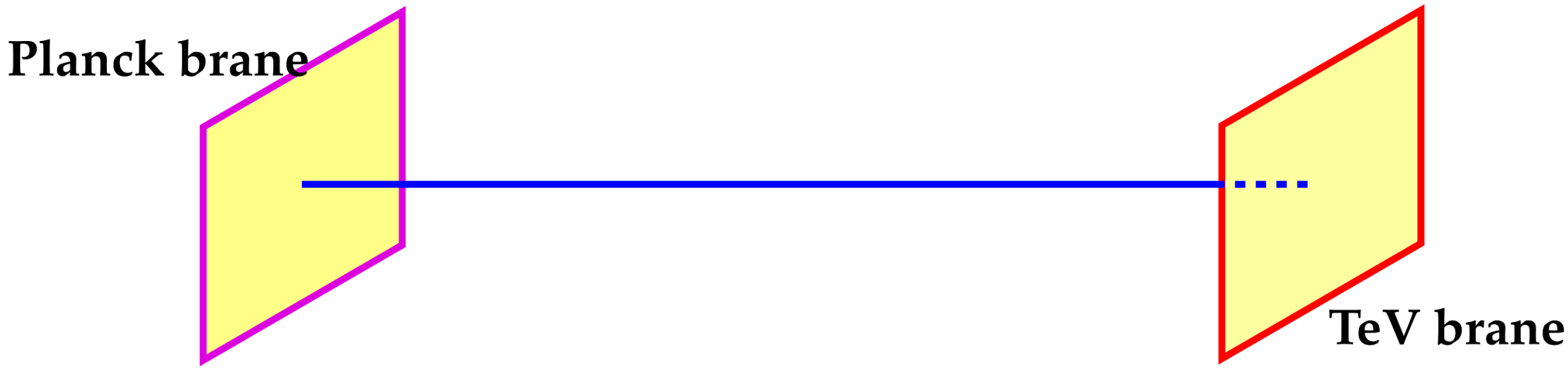
SO(5)xU(1) EW



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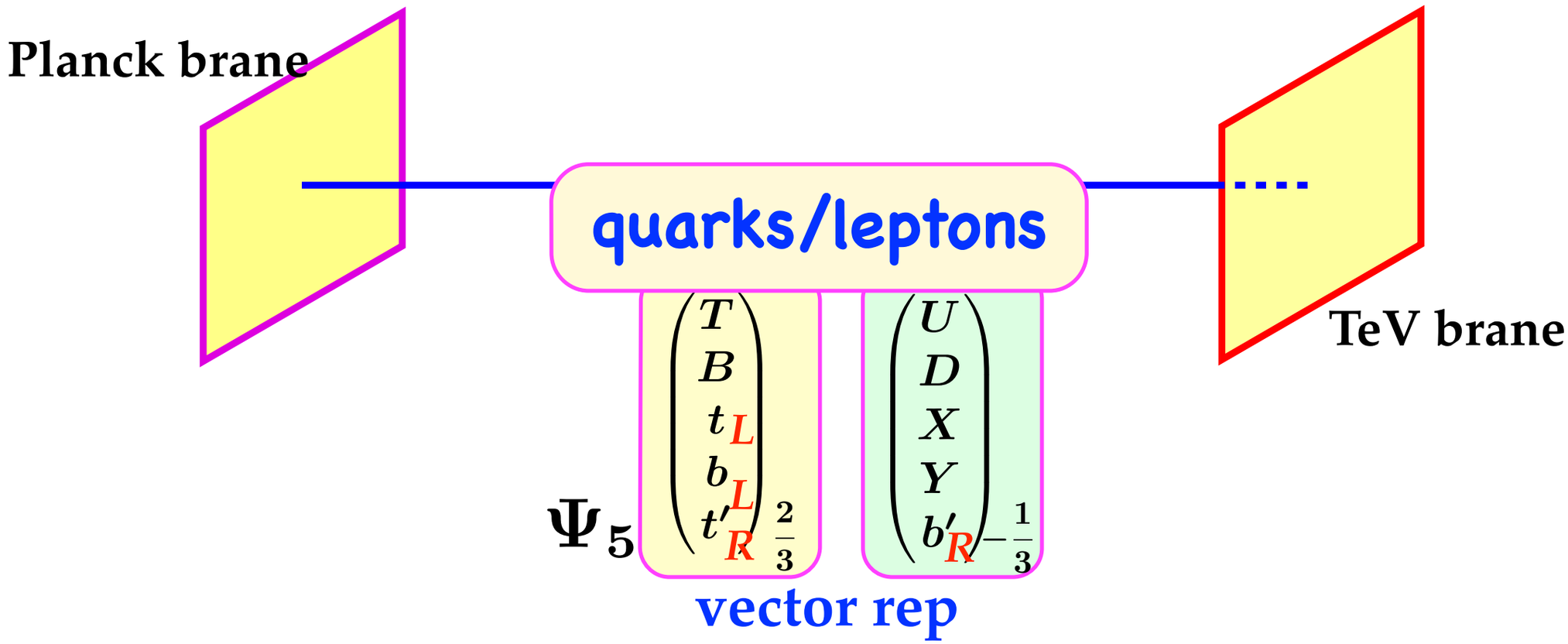
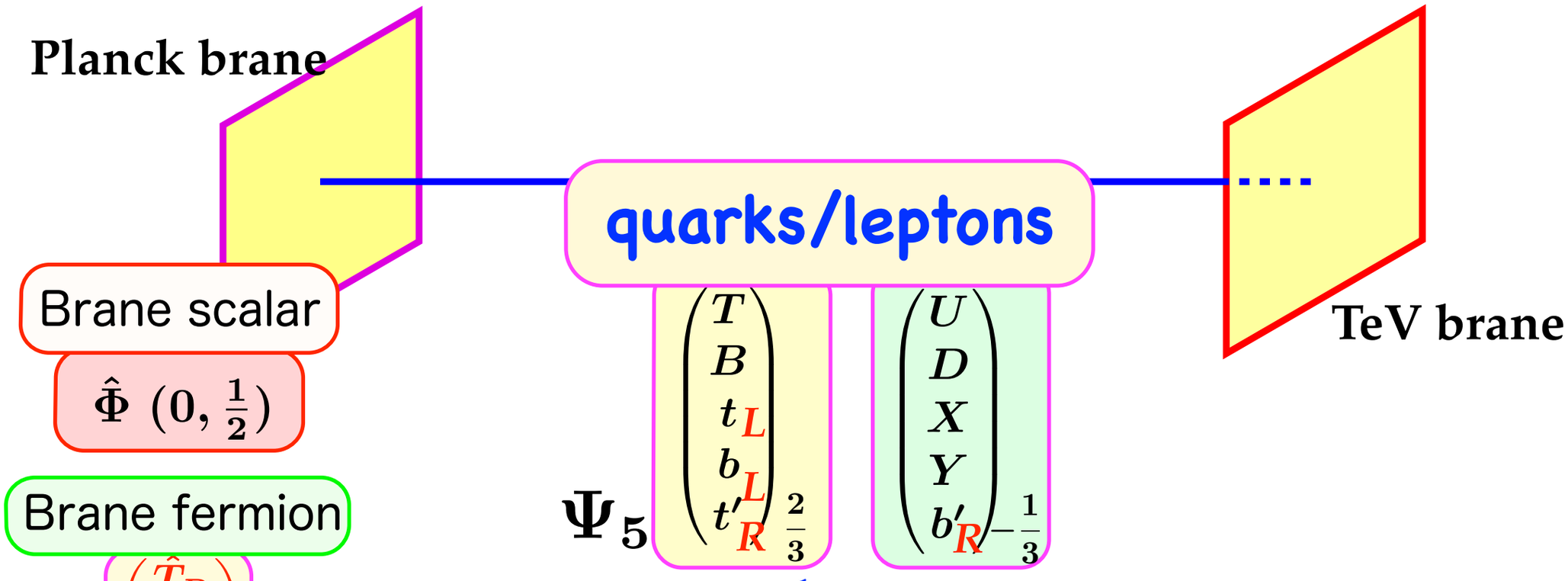

Planck brane
quarks/leptons
TeV brane
Ψ_5
$\begin{pmatrix} T \\ B \\ t_L \\ b_L \\ t'_R \end{pmatrix}_{\frac{2}{3}}$
$\begin{pmatrix} U \\ D \\ X \\ Y \\ b'_R \end{pmatrix}_{-\frac{1}{3}}$
vector rep

SO(5)xU(1) EW


Planck brane
TeV brane
quarks/leptons
Brane scalar
$\hat{\Phi}\ (0, \frac{1}{2})$
Brane fermion
$\begin{pmatrix} \hat{T}_R \\ \hat{B}_R \end{pmatrix}$
$\begin{pmatrix} \hat{U}_R \\ \hat{D}_R \end{pmatrix}$
$\begin{pmatrix} \hat{X}_R \\ \hat{Y}_R \end{pmatrix}$
$(\frac{1}{2}, 0)$
Ψ_5
$\begin{pmatrix} T \\ B \\ t_L \\ b_L \\ t'_R \end{pmatrix}_{\frac{2}{3}}$
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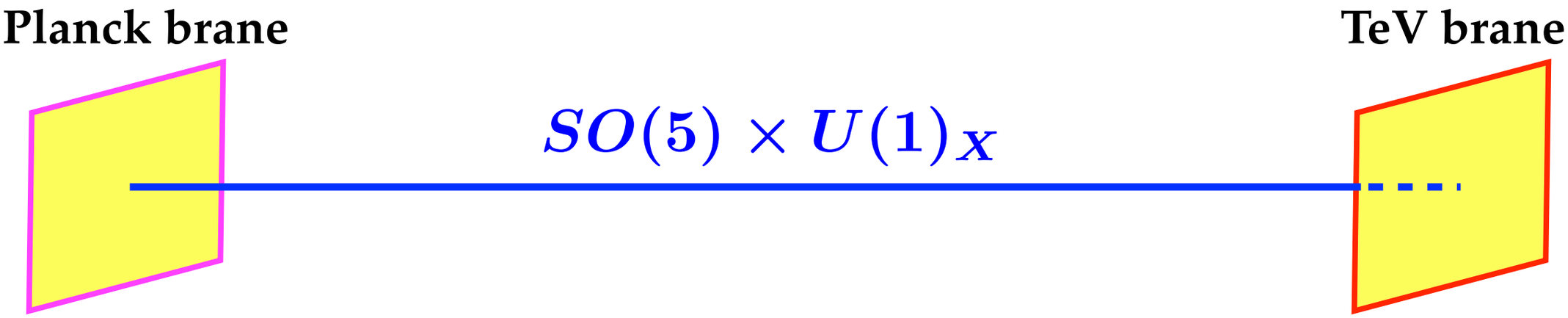
vector rep
dark fermions
Ψ_4 spinor rep


Planck brane
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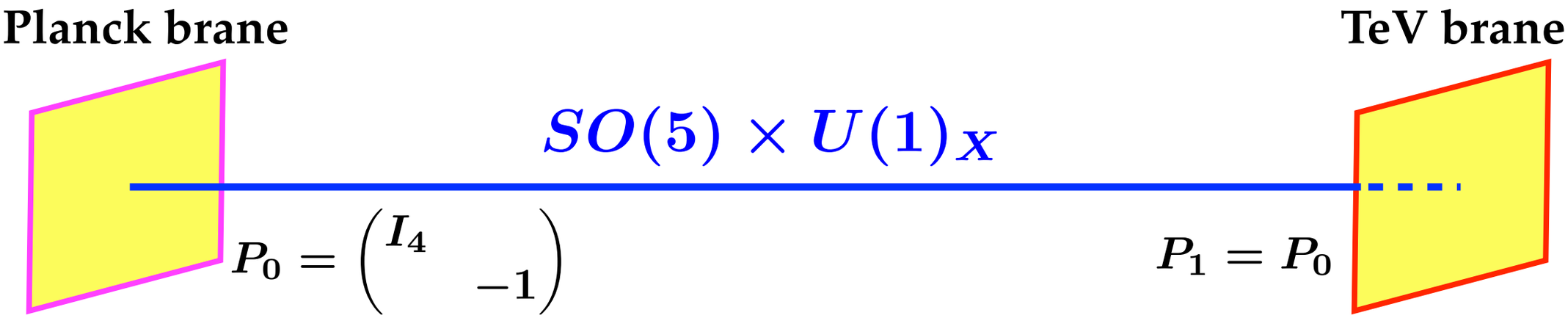
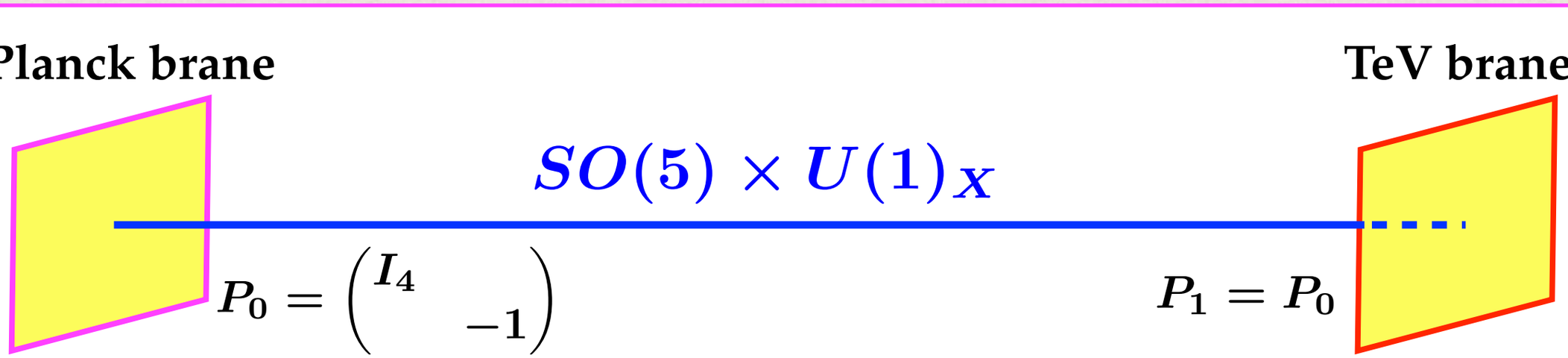
$SO(5) \times U(1)_X$

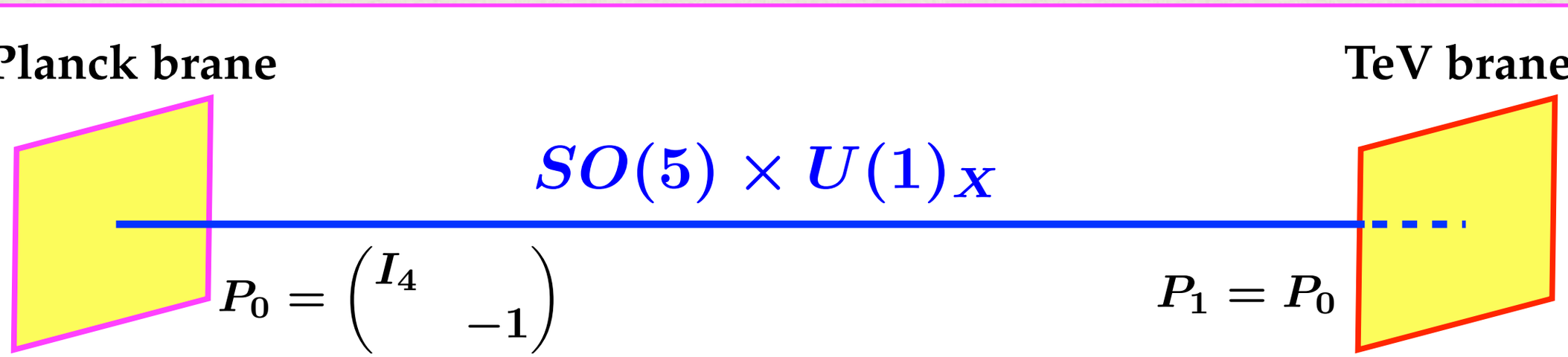


$\Rightarrow$ $SO(4) \times U(1)_X$

$B.C.$



$\xrightarrow{B.C.}$ $SO(4) \times U(1)_X$ $\xrightarrow{\langle \hat{\Phi} \rangle}$ $SU(2)_L \times U(1)_Y$



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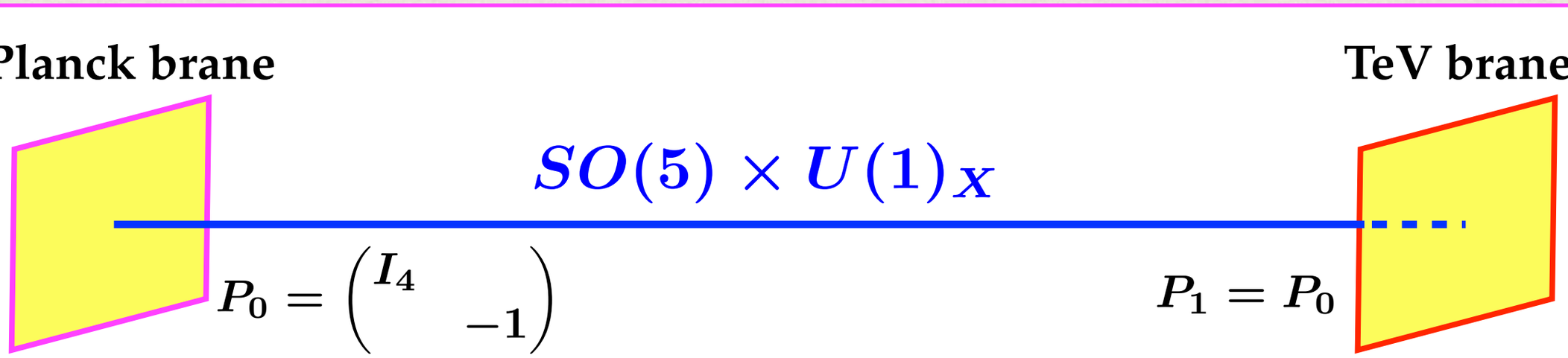
Higgs boson : AB phase $\hat{\theta}_H(x) = \theta_H + \dfrac{H(x)}{f_H}$

$$e^{i\hat{\theta}_H(x)} \sim \exp\left\{ ig \int dy\, A_y \right\}$$



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Hosotani mechanism $\Rightarrow U(1)_{EM}$

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"Almost" SM at low energies, 8TeV LHC

Higgs decay: $\mu \sim \mu_{\rm SM} \cdot \cos^2 \theta_H$

$$\theta_H < 0.1$$

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and predictions

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Universality in θ_H

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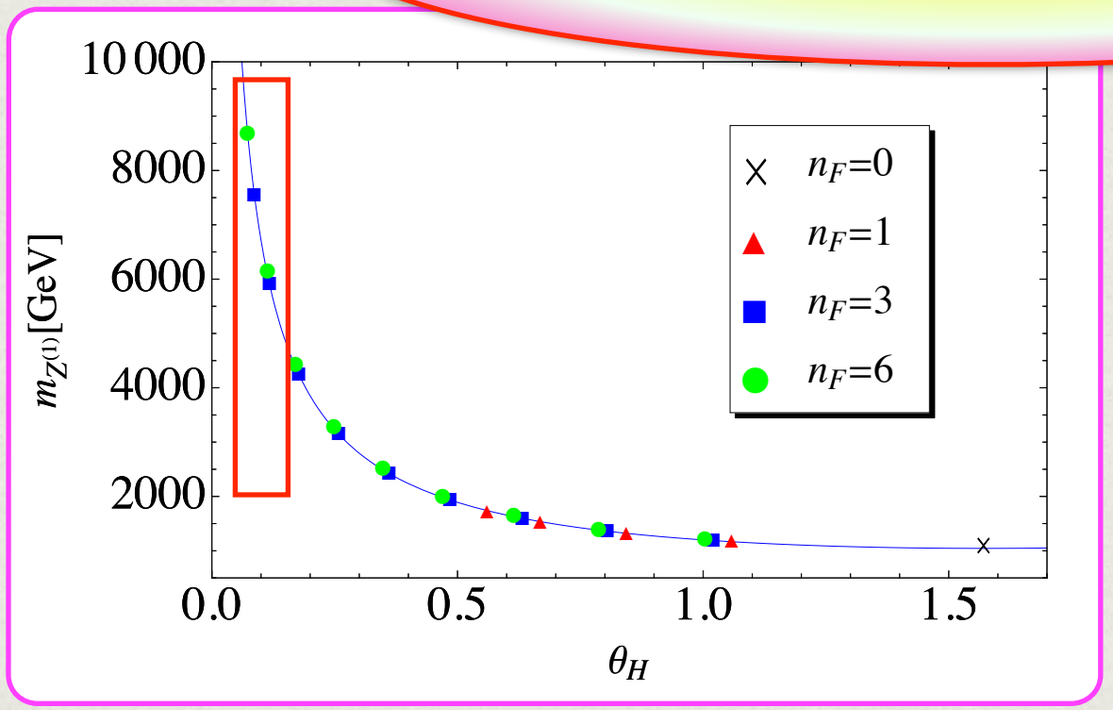
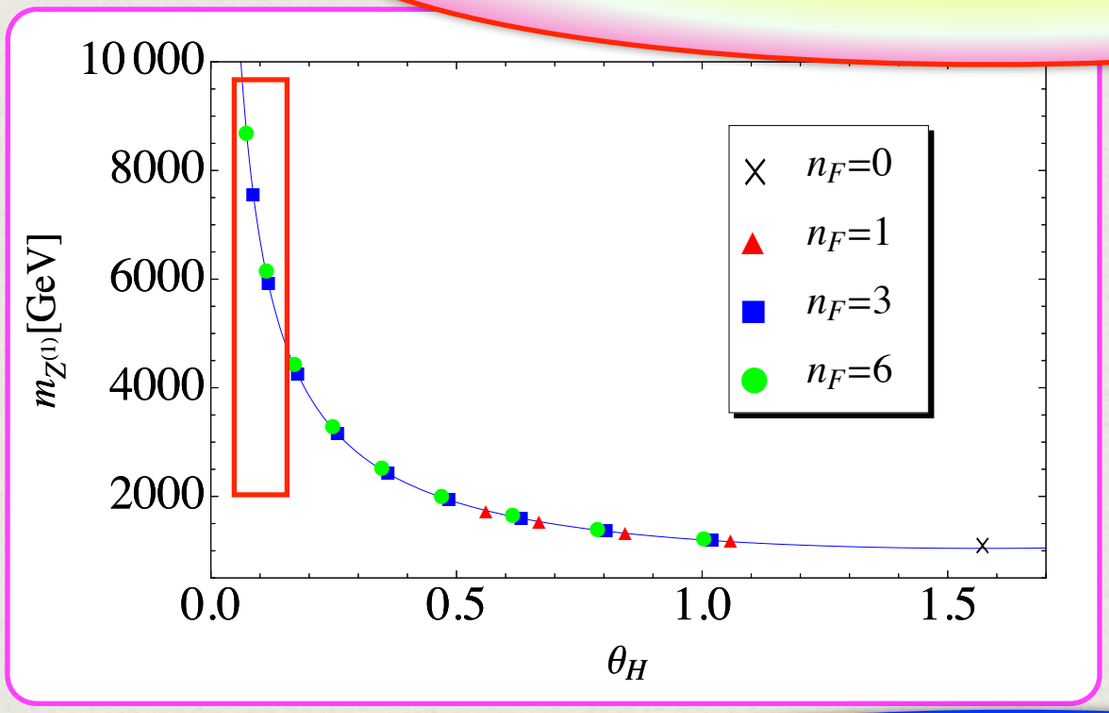


$$m_{Z^{(1)}} \sim \frac{1044\,\mathrm{GeV}}{(\sin\theta_H)^{0.808}}$$

Universality in θ_H



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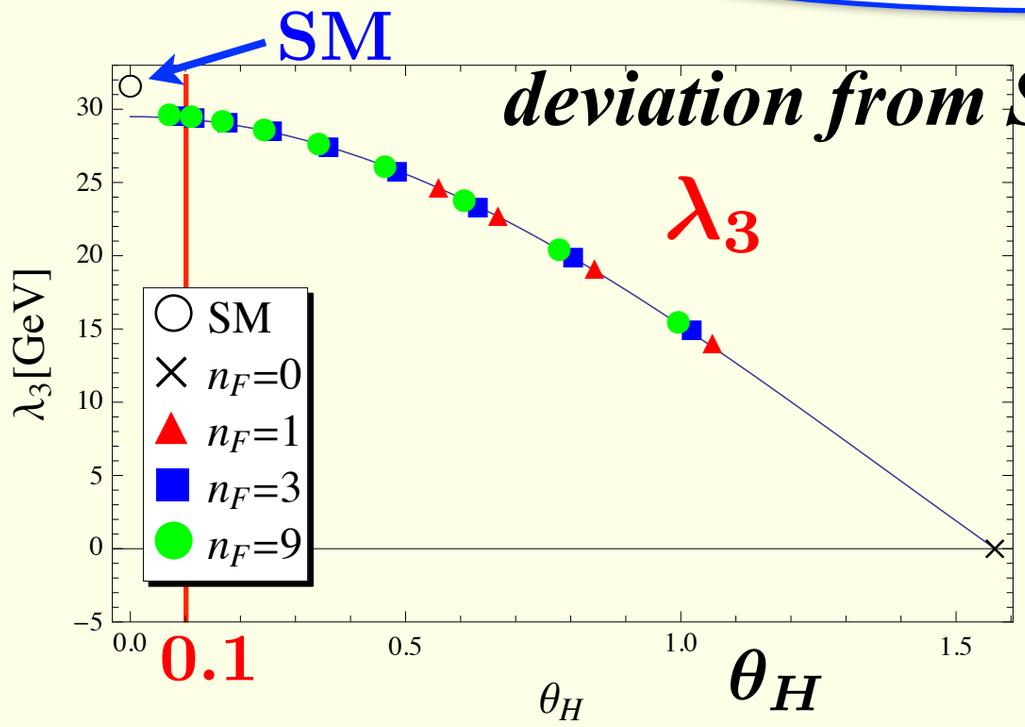
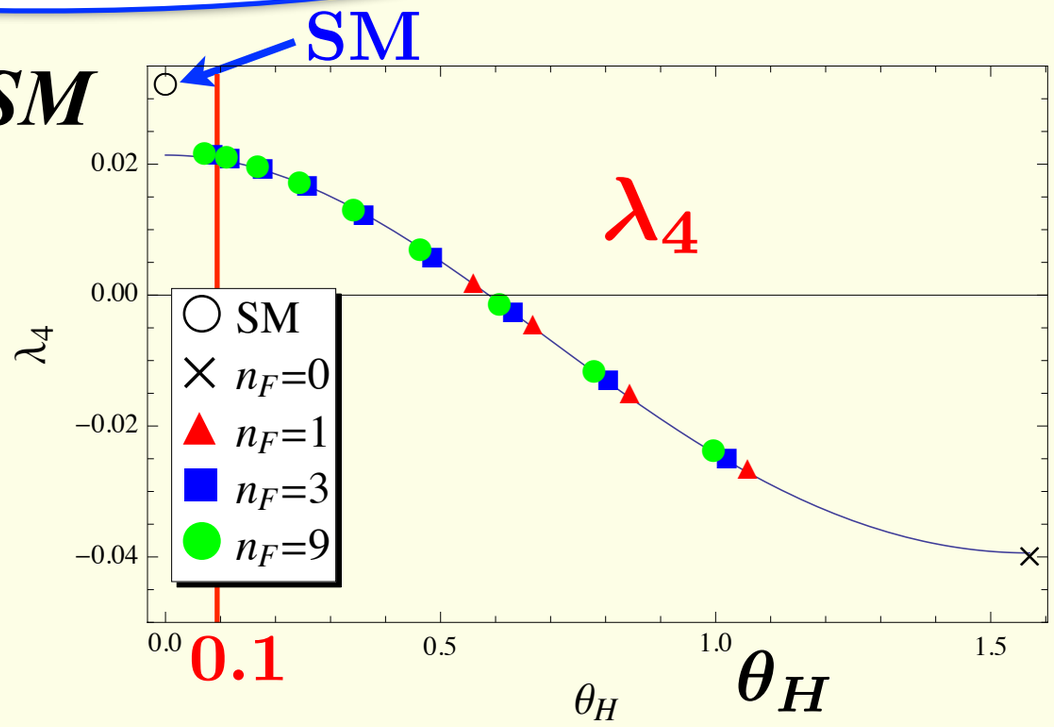
Higgs self-couplings





Loop corrections

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$V_{\rm eff}(\theta_H),\ m_H$

finite !

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$H \to \gamma\gamma\ ,\ Z\gamma$

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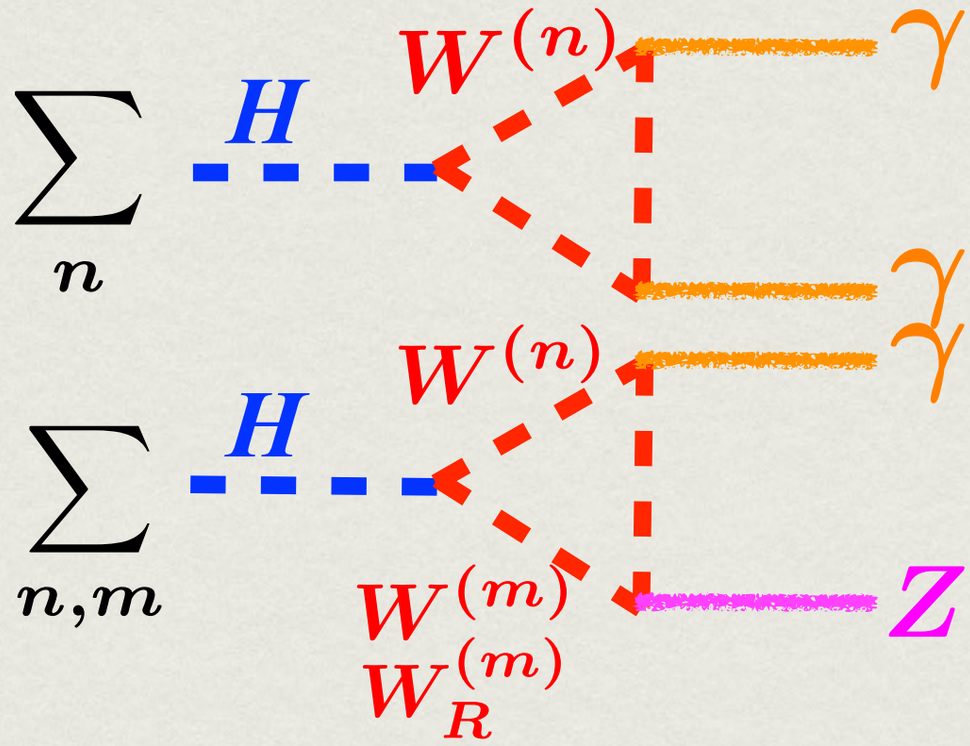

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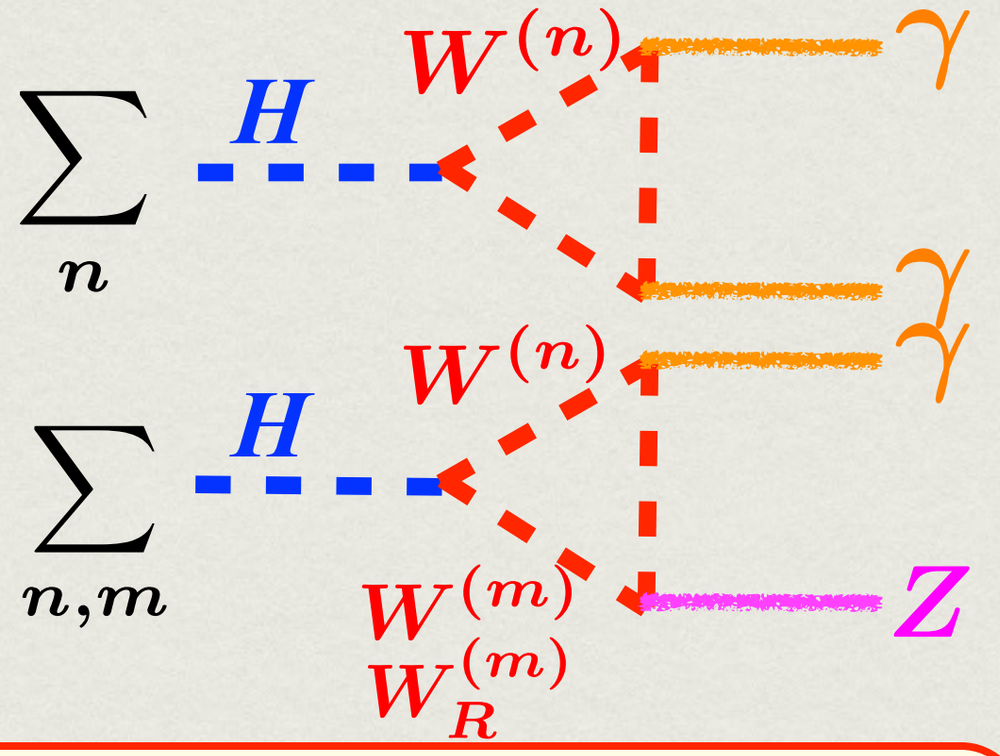


$$\sum_{n=1}^{\infty} \sum_{j} \frac{a_{n,j}}{n} \quad = \text{finite !!!}$$

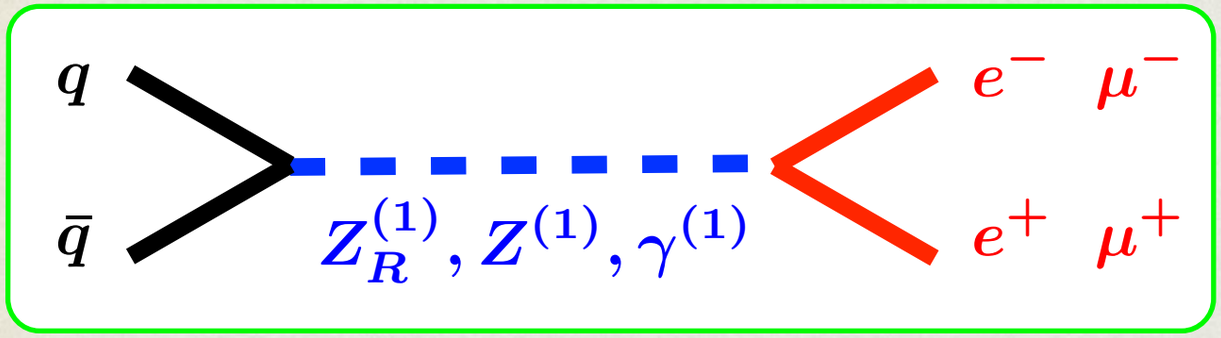
$$O(a_{n,j}) = 1$$

O(1%)
corrections to SM

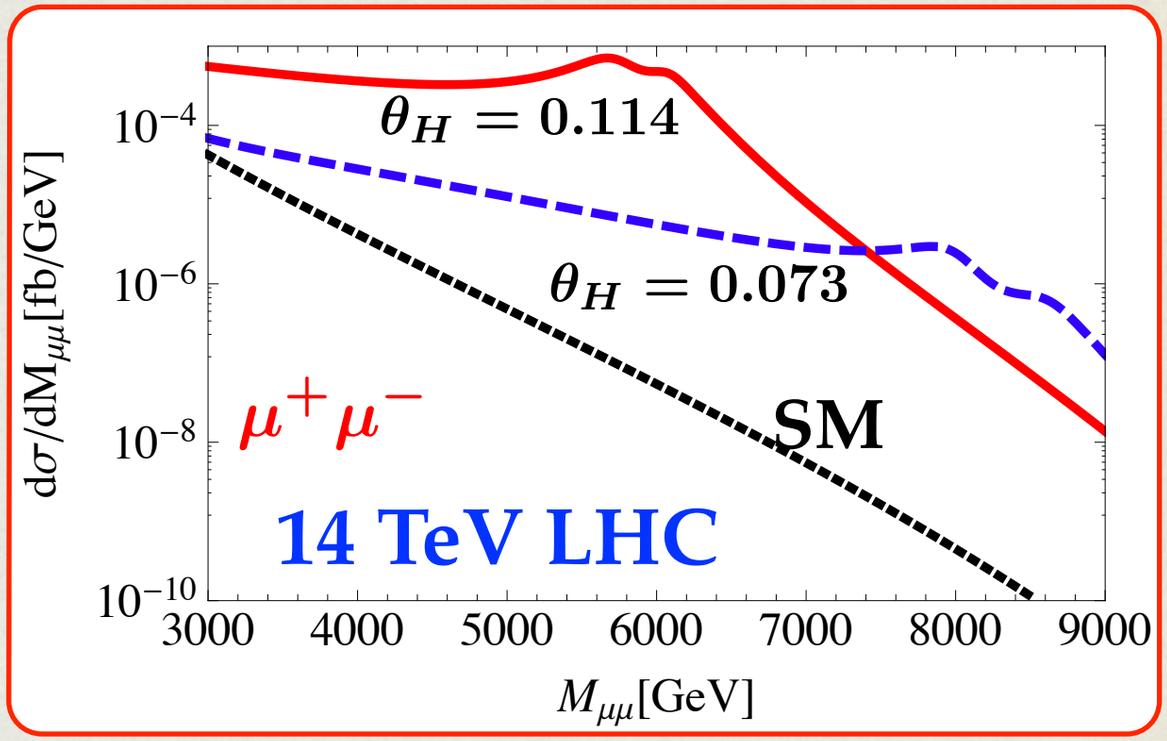
Z′ search

W′ search

Z′ search

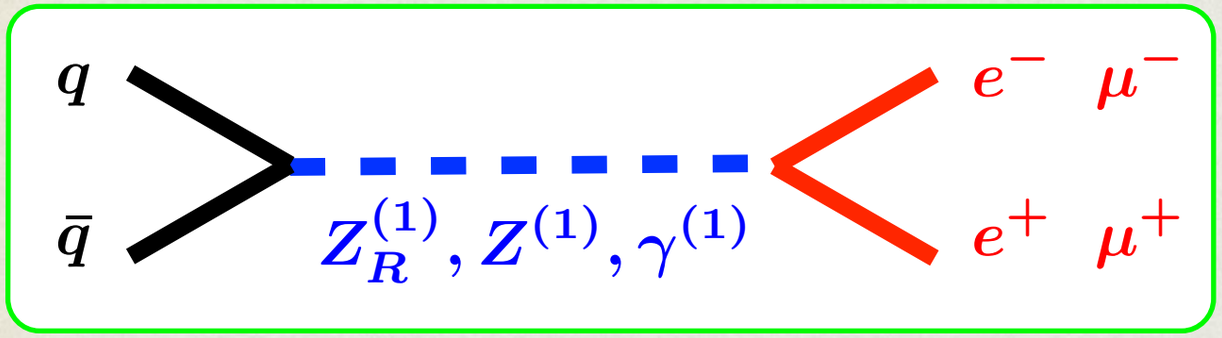


clear signals



W′ search

Z′ search



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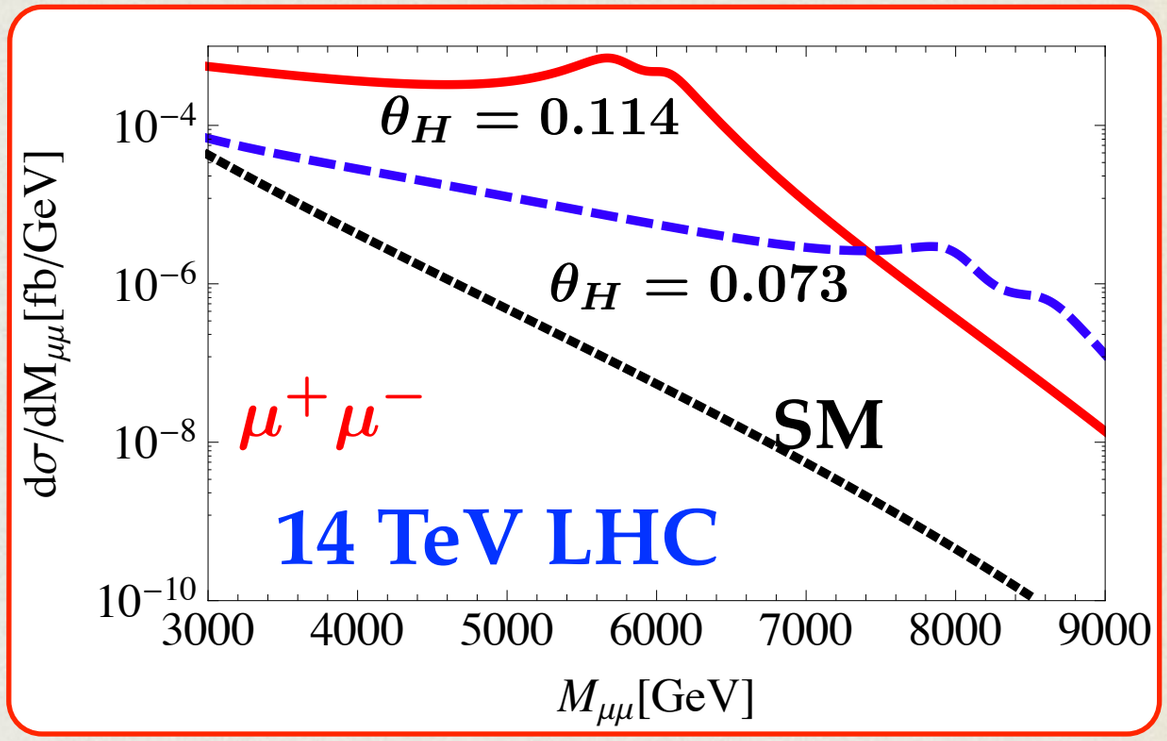
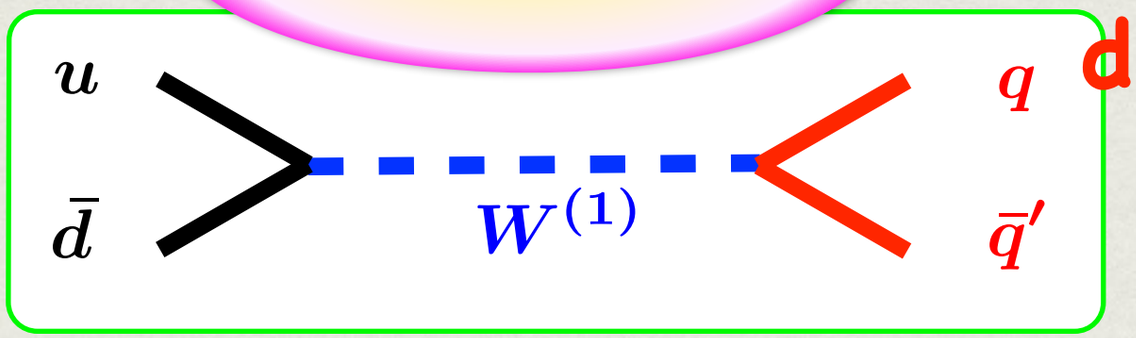
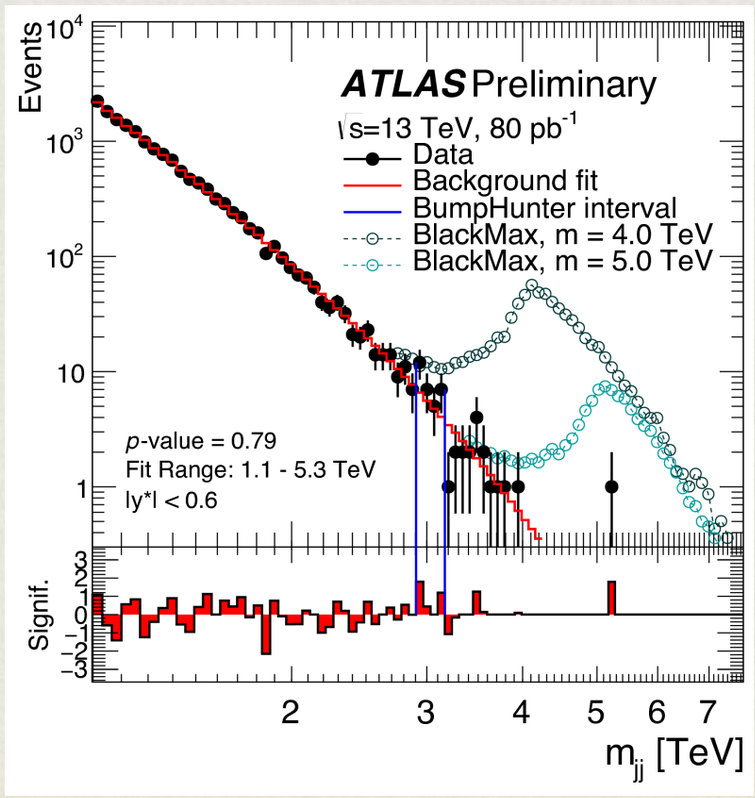


W′ search



di-jet



What is next?

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Gauge-Higgs Grand Unification

EM + Weak + Strong

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EM + Weak + Strong

$SO(5) \times U(1)$ GHU

?

Burdman, Nomura, NPB656 (2003)

Haba, YH, Kawamura, Yamashita, PRD70 (2004)

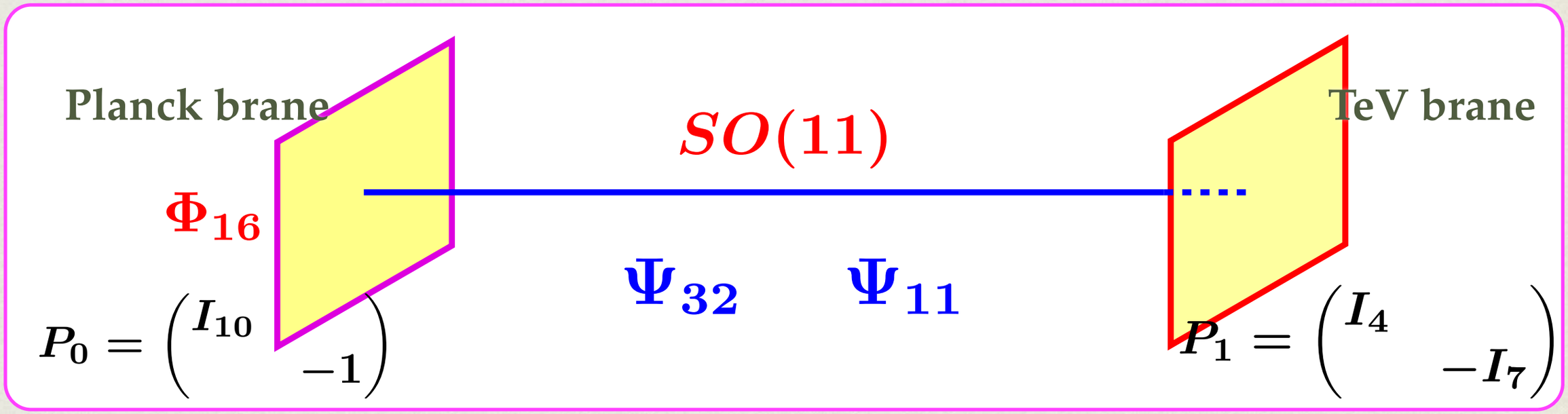
Lim, Maru, PLB653 (2007)

Kojima, Takenaga, Yamashita, PRD84 (2011)

Frigerio, Serra, Varagnolo, JHEP 1106 (2011)

YH, Yamatsu, 1504.03817 (PTEP), 1511.01674

SO(11) gauge-Higgs grand unification in RS



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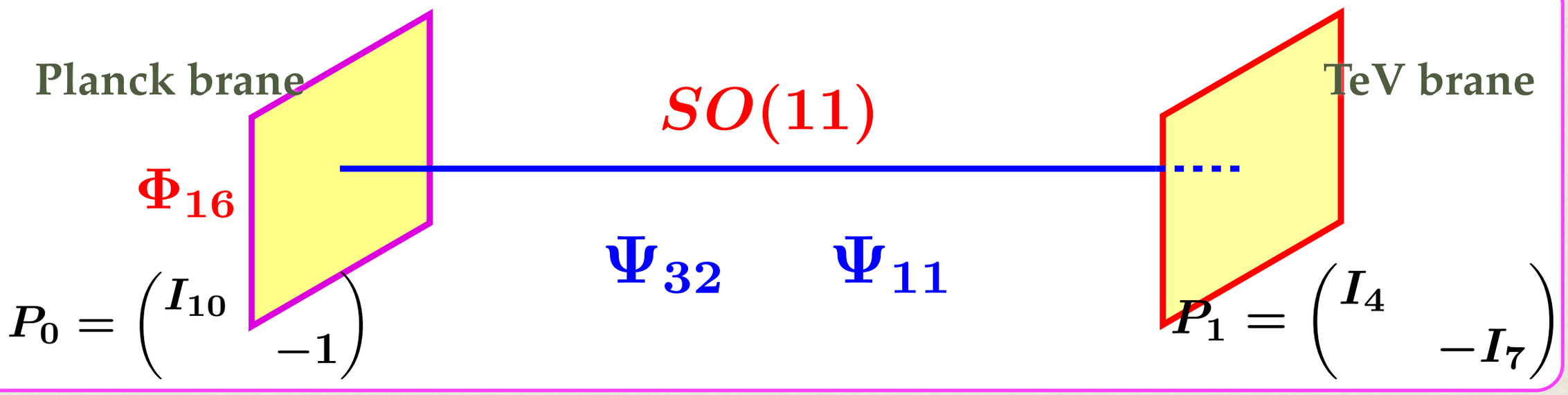

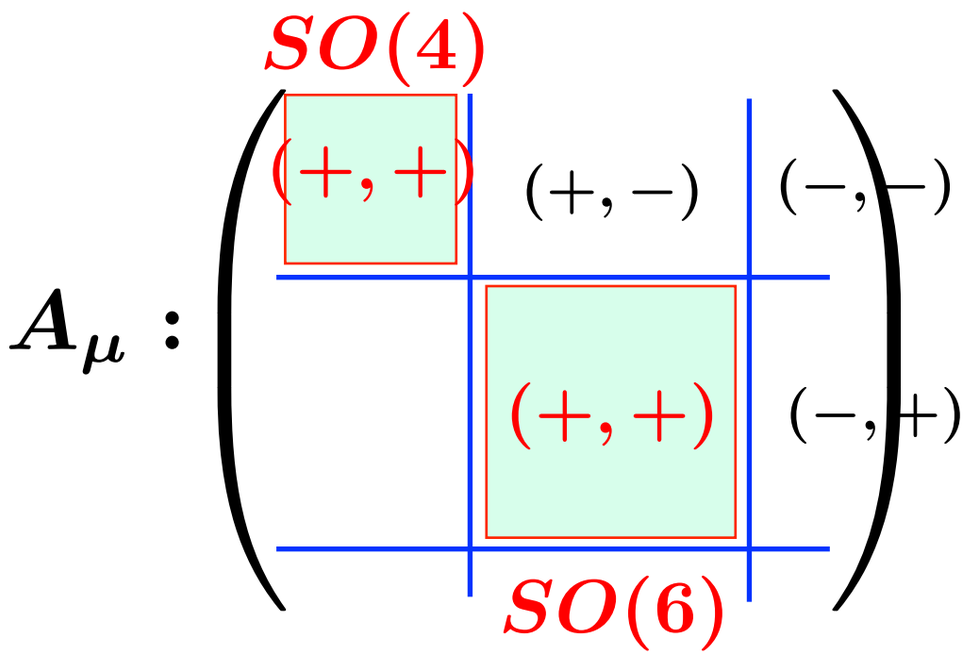

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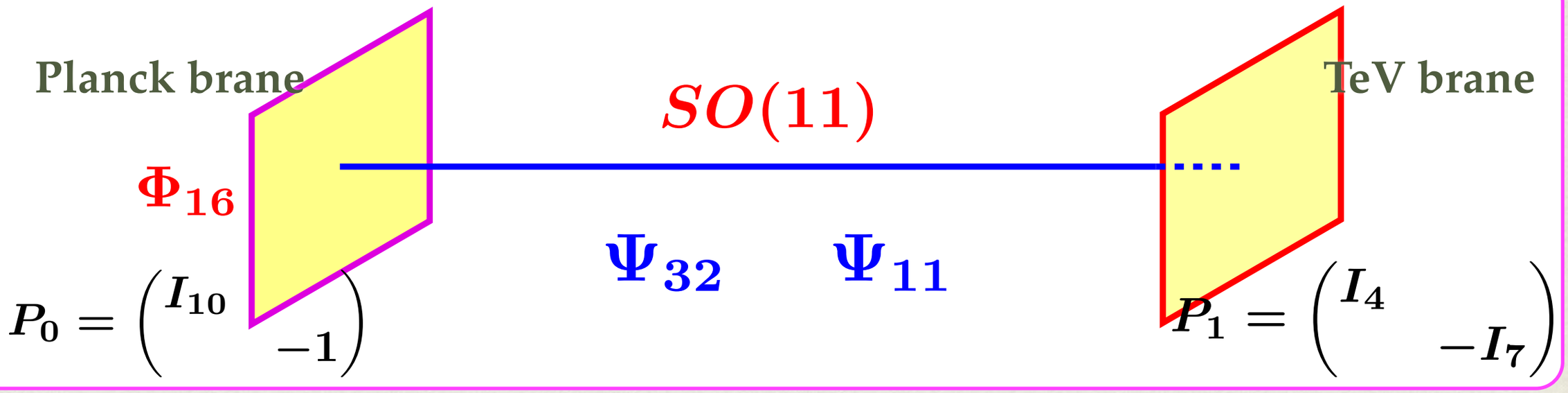
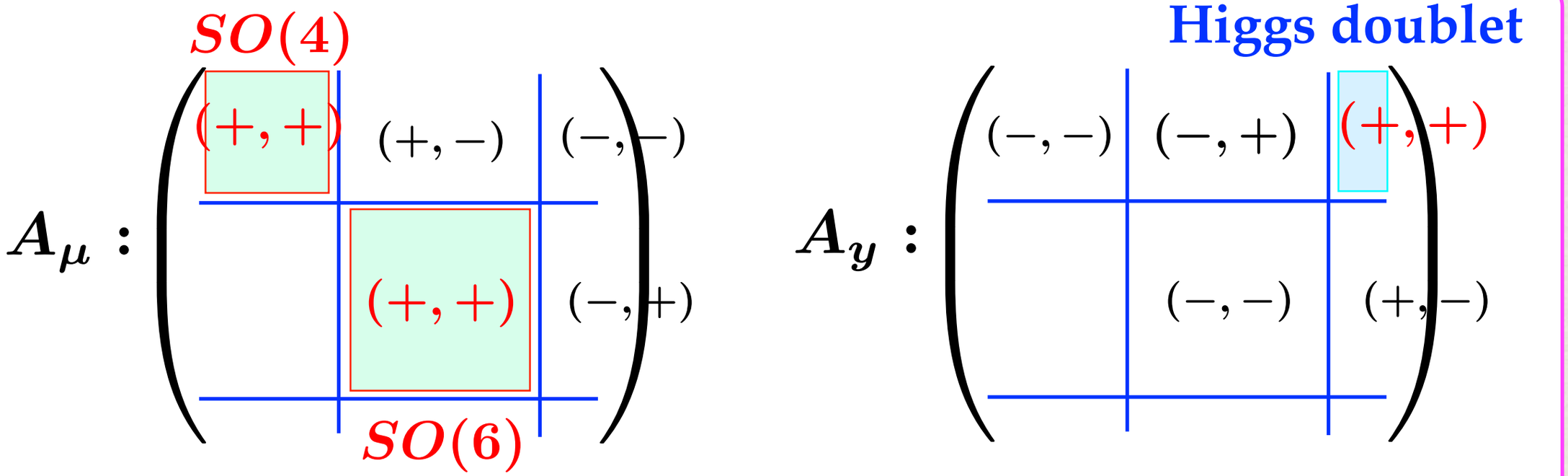
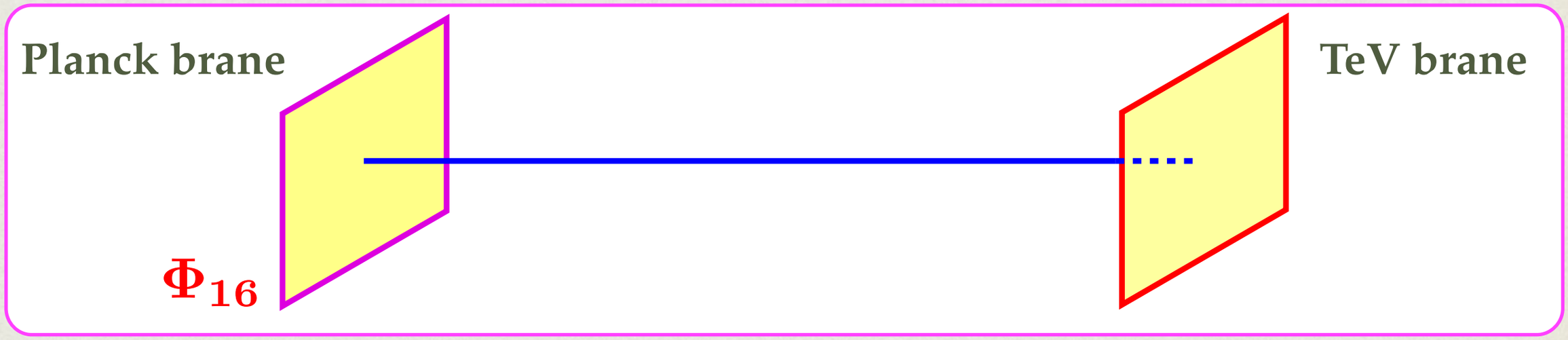




$$SO(4) \times SO(6) \to SU(2)_L \times SU(3)_C \times U(1)_Y$$



$$(D_\mu \Phi_{16})^\dagger D^\mu \Phi_{16}\, \delta(y) \to g^2 \langle \Phi_{16}^\dagger \rangle A^\mu A_\mu \langle \Phi_{16} \rangle\, \delta(y)$$

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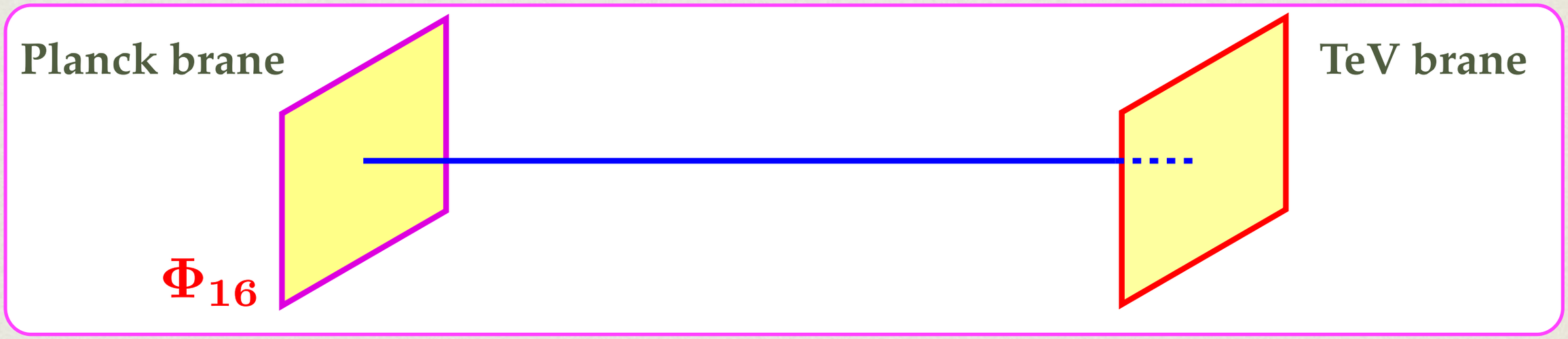

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$$Q_Y = \tfrac{1}{2}(T_{12} - T_{34}) - \tfrac{1}{3}(T_{56} + T_{78} + T_{9,10})$$

$$Q_{EM} = T_{12} - \tfrac{1}{3}(T_{56} + T_{78} + T_{9,10})$$

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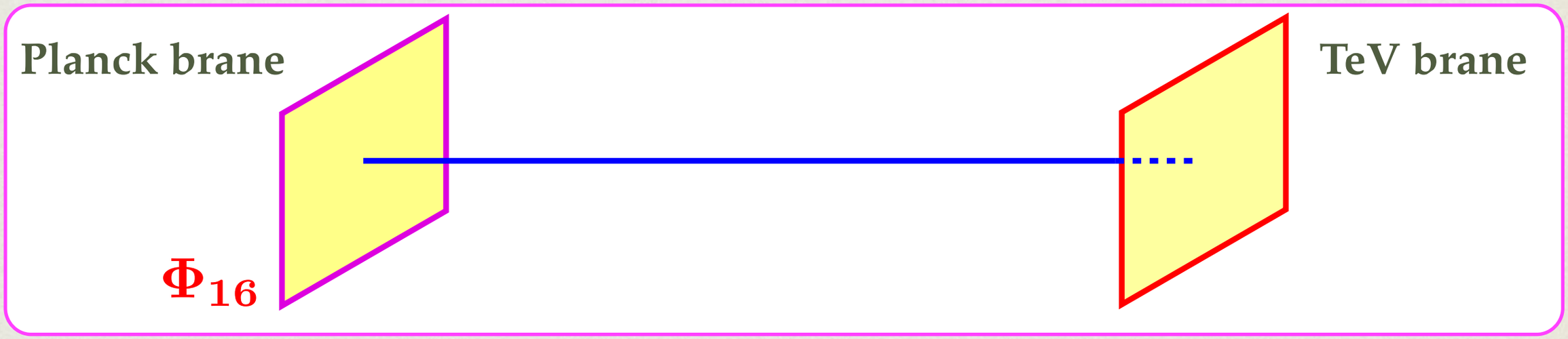

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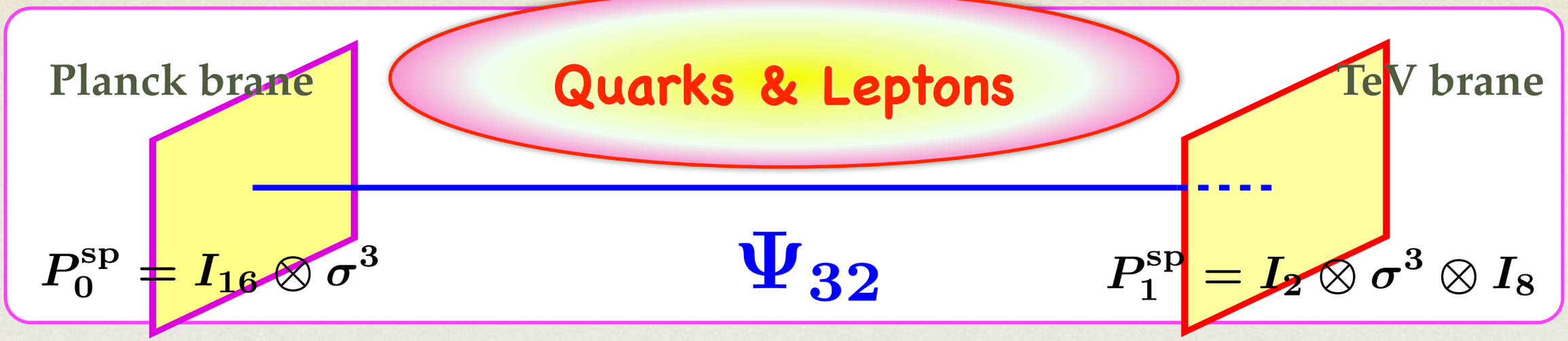
$$\Rightarrow \quad g'_Y = \sqrt{\frac{3}{5}}\, g_w \ , \ e = \sqrt{\frac{3}{8}}\, g_w \quad \Rightarrow \quad \sin^2 \theta_W = \frac{3}{8}$$


Planck brane
Quarks & Leptons
TeV brane
$P_0^{sp} = I_{16} \otimes \sigma^3$
Ψ_{32}
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Planck brane

Quarks & Leptons

TeV brane

$$P_0^{sp} = I_{16} \otimes \sigma^3$$

$$\Psi_{32}$$

$$P_1^{sp} = I_2 \otimes \sigma^3 \otimes I_8$$

$$\Psi_{32} = \begin{pmatrix} \Psi_{16} \\ \Psi_{\overline{16}} \end{pmatrix}$$

$$\Psi_{16} = \begin{pmatrix} \nu \\ e \\ \tilde{d}_1 \\ \tilde{u}_1 \\ u_3 \\ d_3 \\ \tilde{d}_2 \\ \tilde{u}_2 \\ u_1 \\ d_1 \\ \tilde{e} \\ \tilde{\nu} \\ u_2 \\ d_2 \\ \tilde{d}_3 \\ \tilde{u}_3 \end{pmatrix}$$

$$\Psi_{\overline{16}} = \begin{pmatrix} \tilde{d}'_3 \\ \tilde{u}'_3 \\ u'_2 \\ d'_2 \\ \tilde{e}' \\ \tilde{\nu}' \\ u'_1 \\ d'_1 \\ \tilde{d}'_2 \\ \tilde{u}'_2 \\ u'_3 \\ d'_3 \\ \tilde{d}'_1 \\ \tilde{u}'_1 \\ \nu' \\ e' \end{pmatrix}$$

Quarks & Leptons

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Ψ_{32}

$P_1^{sp} = I_2 \otimes \sigma^3 \otimes I_8$

$$\Psi_{32} = \begin{pmatrix} \Psi_{16} \\ \Psi_{\overline{16}} \end{pmatrix}$$

$$\Psi_{16} = \begin{pmatrix} \nu \\ e \\ \tilde{d}_1 \\ \tilde{u}_1 \\ u_3 \\ d_3 \\ \tilde{d}_2 \\ \tilde{u}_2 \\ u_1 \\ d_1 \\ \tilde{e} \\ \tilde{\nu} \\ u_2 \\ d_2 \\ \tilde{d}_3 \\ \tilde{u}_3 \end{pmatrix} \begin{matrix} \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \\ \\ \text{zero modes} \\ \\ \begin{pmatrix} u_{3L} \\ d_{3L} \end{pmatrix} \\ \\ \\ \\ \begin{pmatrix} u_{1L} \\ d_{1L} \end{pmatrix} \\ \\ \\ \\ \begin{pmatrix} u_{2L} \\ d_{2L} \end{pmatrix} \\ \\ \end{matrix}$$

$$\Psi_{\overline{16}} = \begin{pmatrix} \tilde{d}'_3 \\ \tilde{u}'_3 \\ u'_2 \\ d'_2 \\ \tilde{e}' \\ \tilde{\nu}' \\ u'_1 \\ d'_1 \\ \tilde{d}'_2 \\ \tilde{u}'_2 \\ u'_3 \\ d'_3 \\ \tilde{d}'_1 \\ \tilde{u}'_1 \\ \nu' \\ e' \end{pmatrix} \begin{matrix} \text{zero modes} \\ \\ \begin{pmatrix} u_{2R} \\ d_{2R} \end{pmatrix} \\ \\ \\ \\ \begin{pmatrix} u_{1R} \\ d_{1R} \end{pmatrix} \\ \\ \\ \\ \begin{pmatrix} u_{3R} \\ d_{3R} \end{pmatrix} \\ \\ \\ \\ \begin{pmatrix} \nu_R \\ e_R \end{pmatrix} \end{matrix}$$

Fits well.

Scales

Scales

Size of 5th dim $\dfrac{\pi}{L}$ *fully 5-dim.*

Weak scale $m_{\rm EW}$

Scales

Size of 5th dim $\dfrac{\pi}{L}$ *fully 5-dim.*

KK scale $m_{\mathrm{KK}} = \pi k e^{-kL} \sim \dfrac{\sqrt{kL}}{\sin\theta_H} m_W > 4\,\mathrm{TeV}$

Weak scale m_{EW}

Physics OSAKA UNIVERSITY

Scales

Size of 5th dim $\dfrac{\pi}{L}$ *fully 5-dim.*

GUT scale $m_{\rm GUT}$ *coupling unification ?*

KK scale $m_{\rm KK} = \pi k e^{-kL} \sim \dfrac{\sqrt{kL}}{\sin\theta_H} m_W > 4\,{\rm TeV}$

Weak scale $m_{\rm EW}$

QCD scale: $\Lambda_{\rm QCD}$

Size of 5th dim $\dfrac{\pi}{L}$

GUT scale m_{GUT}

KK scale m_{KK}

Weak scale m_{EW}

QCD scale: Λ_{QCD}

Physics
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Size of 5th dim $\dfrac{\pi}{L}$

GUT scale m_{GUT}

KK scale m_{KK}

GUT structure above m_{KK}

Weak scale m_{EW}

QCD scale: Λ_{QCD}

Size of 5th dim $\dfrac{\pi}{L}$

GUT scale m_{GUT}

KK scale m_{KK}

RGE (Yamatsu)

$\alpha_1, \alpha_2, \alpha_3 \to 0$ **rapidly**

$m_{\mathrm{GUT}} \sim 100\, m_{\mathrm{KK}}$ **almost**

GUT structure above m_{KK}

Weak scale m_{EW}

QCD scale: Λ_{QCD}

Physics
OSAKA UNIVERSITY

Size of 5th dim $\dfrac{\pi}{L}$

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$\alpha_1, \alpha_2, \alpha_3 \to 0$ **rapidly**

$m_{\mathrm{GUT}} \sim 100\, m_{\mathrm{KK}}$ **almost**

GUT structure above m_{KK}

Proton decay ?

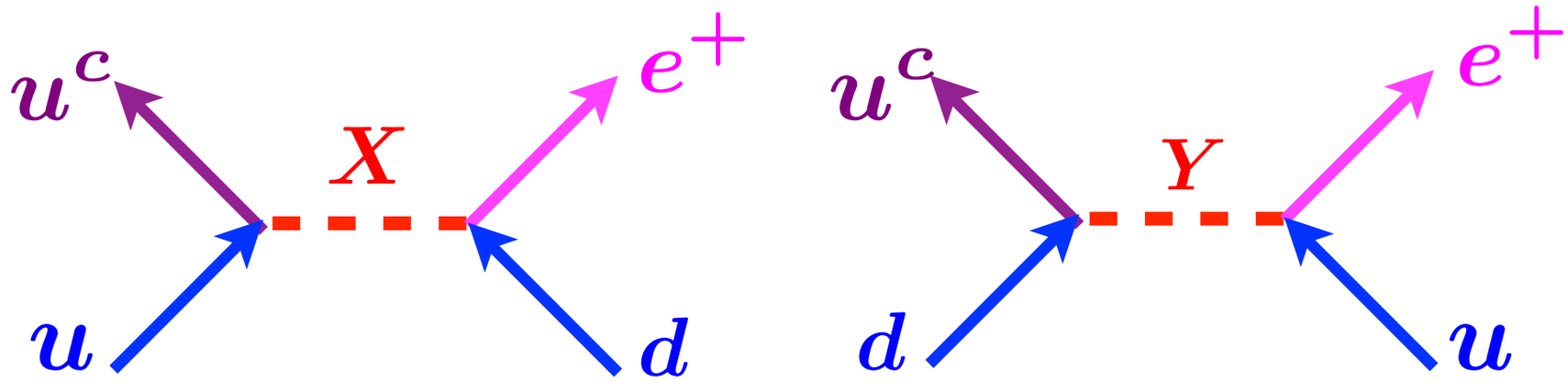
Proton decay in 4D GUT

4D SU(5) GUT

$$\overline{5} \quad \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \quad d_L^c$$

$$10 \quad \begin{pmatrix} u_L \\ d_L \end{pmatrix} \quad u_L^c \quad e_L^c$$

4D SO(10) GUT $\quad 16 = 1 + \overline{5} + 10$



$$p \to \pi^0 \, e^+$$

Proton decay - forbidden

$$\Psi_{32} = \begin{pmatrix} \Psi_{16} \\ \Psi_{\overline{16}} \end{pmatrix}$$

$$\Psi_{16} = \begin{pmatrix} \nu \\ e \\ \tilde{d}_1 \\ \tilde{u}_1 \\ u_3 \\ d_3 \\ \tilde{d}_2 \\ \tilde{u}_2 \\ u_1 \\ d_1 \\ \tilde{e} \\ \tilde{\nu} \\ u_2 \\ d_2 \\ \tilde{d}_3 \\ \tilde{u}_3 \end{pmatrix} \quad \begin{matrix} \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \\ \\ \\ \\ \begin{pmatrix} u_{3L} \\ d_{3L} \end{pmatrix} \\ \\ \\ \\ \begin{pmatrix} u_{1L} \\ d_{1L} \end{pmatrix} \\ \\ \\ \\ \begin{pmatrix} u_{2L} \\ d_{2L} \end{pmatrix} \\ \\ \\ \end{matrix}$$

$$\Psi_{\overline{16}} = \begin{pmatrix} \tilde{d}'_3 \\ \tilde{u}'_3 \\ u'_2 \\ d'_2 \\ \tilde{e}' \\ \tilde{\nu}' \\ u'_1 \\ d'_1 \\ \tilde{d}'_2 \\ \tilde{u}'_2 \\ u'_3 \\ d'_3 \\ \tilde{d}'_1 \\ \tilde{u}'_1 \\ \nu' \\ e' \end{pmatrix} \quad \begin{matrix} \\ \\ \begin{pmatrix} u_{2R} \\ d_{2R} \end{pmatrix} \\ \\ \\ \\ \begin{pmatrix} u_{1R} \\ d_{1R} \end{pmatrix} \\ \\ \\ \\ \begin{pmatrix} u_{3R} \\ d_{3R} \end{pmatrix} \\ \\ \\ \\ \begin{pmatrix} \nu_R \\ e_R \end{pmatrix} \end{matrix}$$

Proton decay - forbidden

$$\Psi_{16} = \begin{pmatrix} \nu \\ e \\ \tilde{d}_1 \\ \tilde{u}_1 \\ u_3 \\ d_3 \\ \tilde{d}_2 \\ \tilde{u}_2 \\ u_1 \\ d_1 \\ \tilde{e} \\ \tilde{\nu} \\ u_2 \\ d_2 \\ \tilde{d}_3 \\ \tilde{u}_3 \end{pmatrix} \begin{matrix} \\ \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \\ \\ \\ \\ \begin{pmatrix} u_{3L} \\ d_{3L} \end{pmatrix} \\ \\ \\ \begin{pmatrix} u_{1L} \\ d_{1L} \end{pmatrix} \\ \\ \\ \begin{pmatrix} u_{2L} \\ d_{2L} \end{pmatrix} \\ \\ \end{matrix} \qquad \Psi_{\overline{16}} = \begin{pmatrix} \tilde{d}'_3 \\ \tilde{u}'_3 \\ u'_2 \\ d'_2 \\ \tilde{e}' \\ \tilde{\nu}' \\ u'_1 \\ d'_1 \\ \tilde{d}'_2 \\ \tilde{u}'_2 \\ u'_3 \\ d'_3 \\ \tilde{d}'_1 \\ \tilde{u}'_1 \\ \nu' \\ e' \end{pmatrix} \begin{matrix} \\ \\ \begin{pmatrix} u_{2R} \\ d_{2R} \end{pmatrix} \\ \\ \\ \\ \begin{pmatrix} u_{1R} \\ d_{1R} \end{pmatrix} \\ \\ \\ \\ \begin{pmatrix} u_{3R} \\ d_{3R} \end{pmatrix} \\ \\ \\ \\ \begin{pmatrix} \nu_R \\ e_R \end{pmatrix} \end{matrix}$$

$$\Psi_{32} = \begin{pmatrix} \Psi_{16} \\ \Psi_{\overline{16}} \end{pmatrix}$$

N_Ψ conservation

$$p \to \pi^0 \; e^+$$

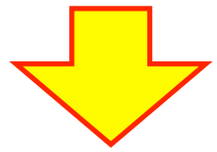
$$N_\Psi = 3 \qquad N_\Psi = -1$$

Proton decay - forbidden

$$\Psi_{16} = \begin{pmatrix} \nu \\ e \\ \tilde{d}_1 \\ \tilde{u}_1 \\ u_3 \\ d_3 \\ \tilde{d}_2 \\ \tilde{u}_2 \\ u_1 \\ d_1 \\ \tilde{e} \\ \tilde{\nu} \\ u_2 \\ d_2 \\ \tilde{d}_3 \\ \tilde{u}_3 \end{pmatrix} \begin{matrix} \\ \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \\ \\ \\ \\ \begin{pmatrix} u_{3L} \\ d_{3L} \end{pmatrix} \\ \\ \\ \\ \begin{pmatrix} u_{1L} \\ d_{1L} \end{pmatrix} \\ \\ \\ \\ \begin{pmatrix} u_{2L} \\ d_{2L} \end{pmatrix} \\ \\ \end{matrix} \qquad \Psi_{\overline{16}} = \begin{pmatrix} \tilde{d}'_3 \\ \tilde{u}'_3 \\ u'_2 \\ d'_2 \\ \tilde{e}' \\ \tilde{\nu}' \\ u'_1 \\ d'_1 \\ \tilde{d}'_2 \\ \tilde{u}'_2 \\ u'_3 \\ d'_3 \\ \tilde{d}'_1 \\ \tilde{u}'_1 \\ \nu' \\ e' \end{pmatrix} \begin{matrix} \\ \\ \begin{pmatrix} u_{2R} \\ d_{2R} \end{pmatrix} \\ \\ \\ \\ \begin{pmatrix} u_{1R} \\ d_{1R} \end{pmatrix} \\ \\ \\ \\ \begin{pmatrix} u_{3R} \\ d_{3R} \end{pmatrix} \\ \\ \\ \\ \begin{pmatrix} \nu_R \\ e_R \end{pmatrix} \end{matrix}$$

$$\Psi_{32} = \begin{pmatrix} \Psi_{16} \\ \Psi_{\overline{16}} \end{pmatrix}$$

N_Ψ conservation



no proton decay

$$p \not\to \pi^0 \; e^+$$

$N_\Psi = 3 \quad N_\Psi = -1$

Summary

SO(5)xU(1) Gauge-Higgs EW Unification

SO(11) Gauge-Higgs Grand Unification

Summary

SO(5)xU(1) Gauge-Higgs EW Unification

Dynamical EW sym breaking

Consistent at low energies

Predictions for 14 TeV LHC

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SO(11) Gauge-Higgs Grand Unification

SO(11) structure above $m_{\rm KK}$

Proton decay naturally forbidden