Gauge-Higgs Unification

-ＬＨＣと暗黒物質-

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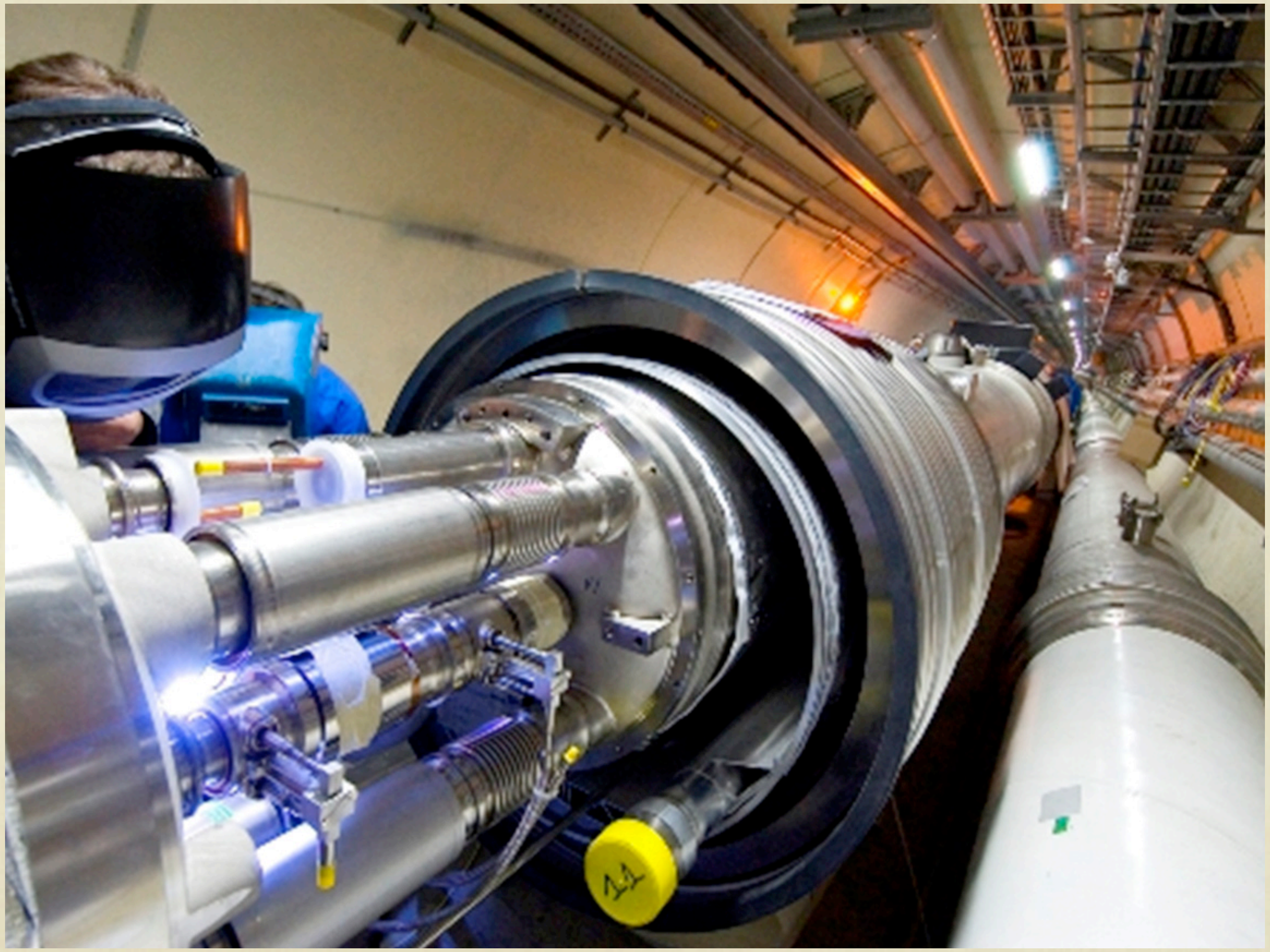
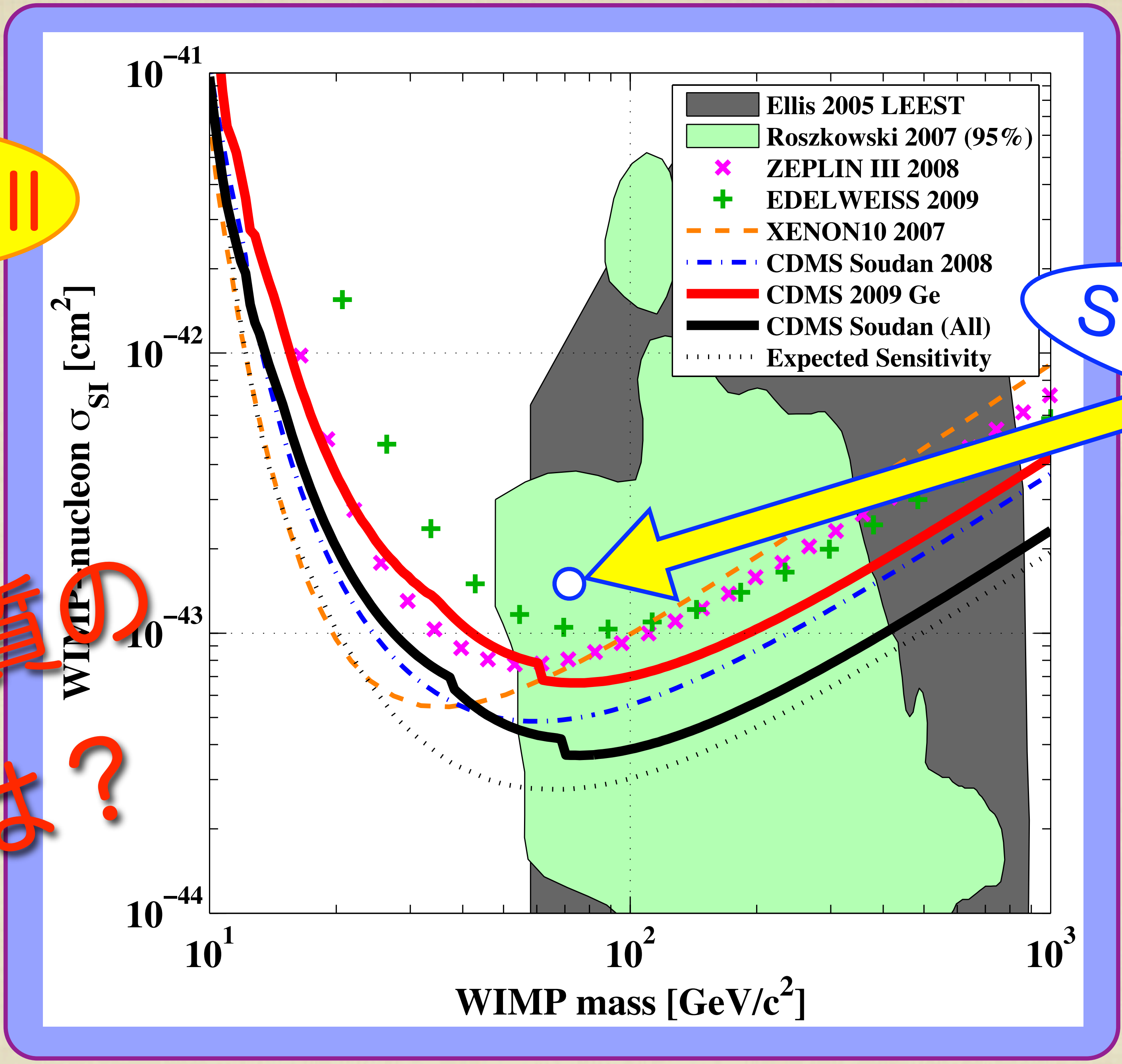
富山大学　12 February 2010

ＬＨＣで Higgs が見つかるか



- 暗黒物質が見えた？ -

CDMS II



Stable Higgs ?

暗黒物質の
正体は？

arXiv:0912.3592 [astro-ph.CO]   18 Dec 2009

Two events in the signal region

何故 Higgs が必要か

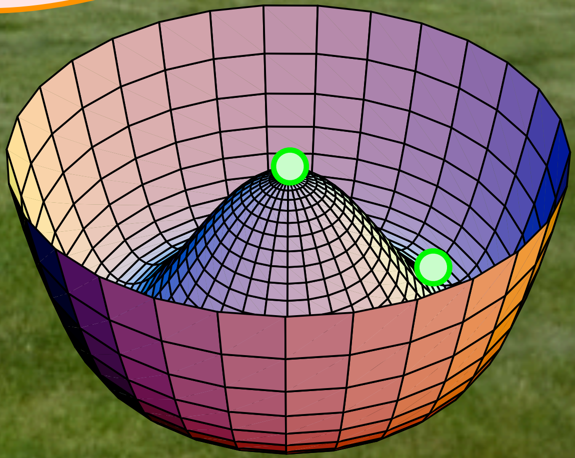
Idea of unification

Electroweak
$SU(2)_L \times U(1)_Y$

Unified theory
Large symmetry

Spontaneous
symmetry breaking

Higgs

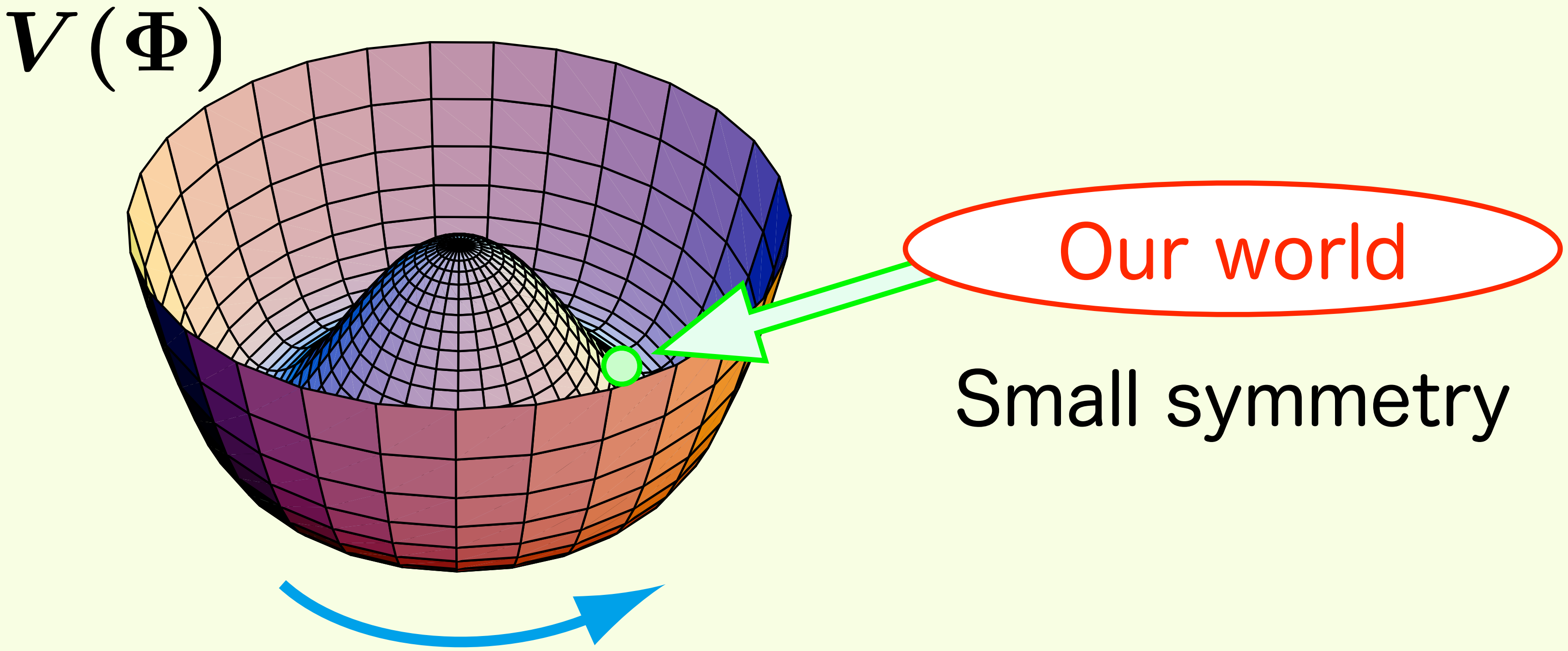


Our world
Small symmetry

$U(1)_{EM}$

標準理論での対称性の自発的破れ

ヒッグスのポテンシャル



Our world

Small symmetry

Is this scenario true?

今のところ
直接証拠なし

ヒッグス場の部分

原理の欠落

標準理論（SM）

超対称性理論（MSSM）

Little Higgs theory -- pseudo-NG boson

Higgsless theory -- 境界条件によるSB

ゲージ・ヒッグス統合理論

Gauge-Higgs unification in more than four dimensions

Kaluza-Klein's picture

1921, 1926

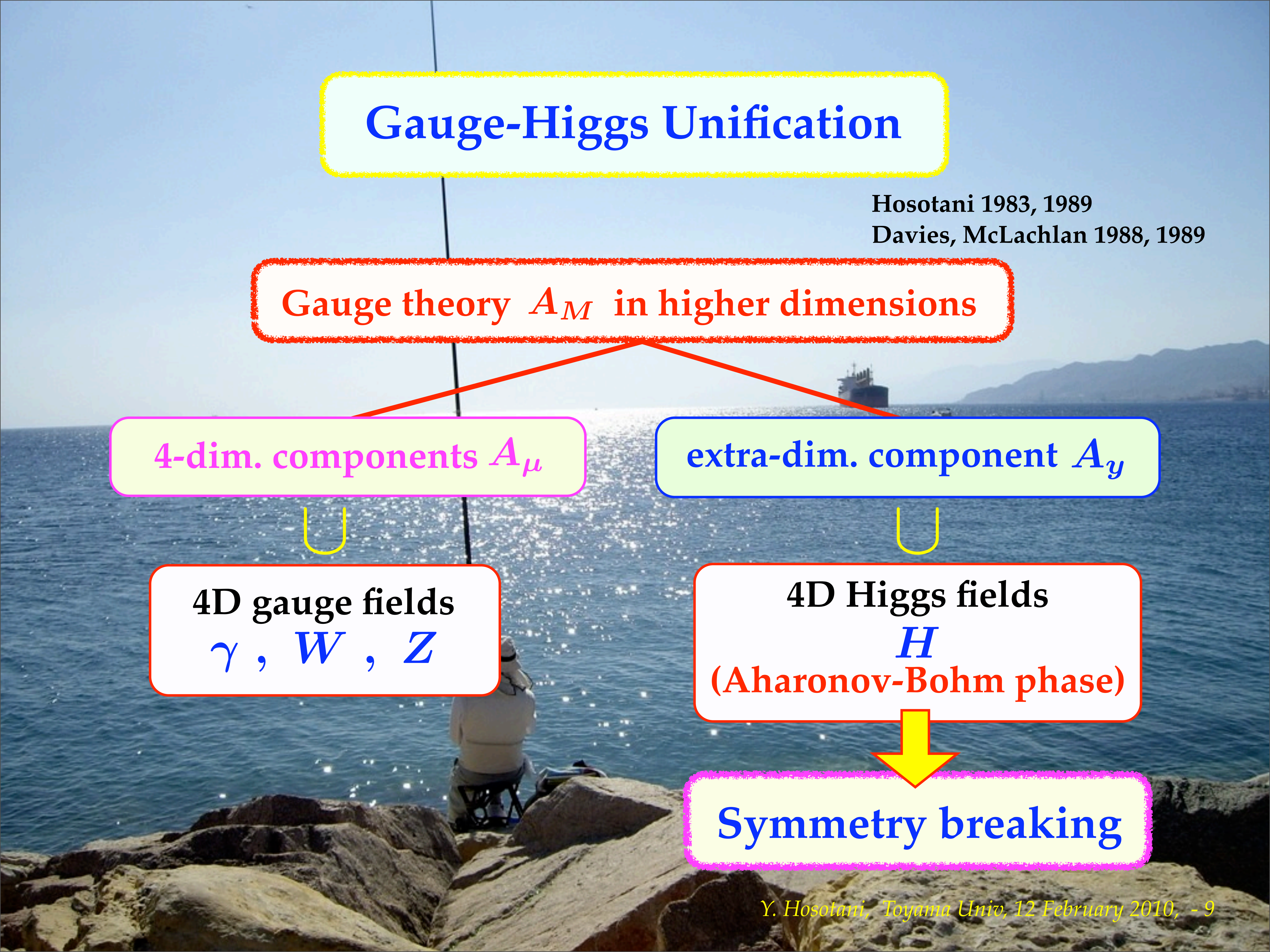
5D gravity

$M^4 \times S^1$ (circle)

$(t, \vec{x}, y)$

$$g_{MN} = \begin{pmatrix} \boxed{g_{\mu\nu}} & \boxed{A_\mu} \\ \boxed{A_\nu} & \boxed{\phi} \end{pmatrix}$$

Unification of 4D gravity and EM



Gauge-Higgs Unification

Hosotani 1983, 1989
Davies, McLachlan 1988, 1989

Gauge theory A_M in higher dimensions

4-dim. components A_μ

$\cup$

4D gauge fields
γ , W , Z

extra-dim. component A_y

$\cup$

4D Higgs fields
H
(Aharonov-Bohm phase)

Symmetry breaking

ヒッグス場はゲージ場の一部になる

ヒッグス粒子の質量

m_H 量子補正で有限に予言

Higgs couplings

$H^3 \ , \ H^4 \ , \ \cdots$

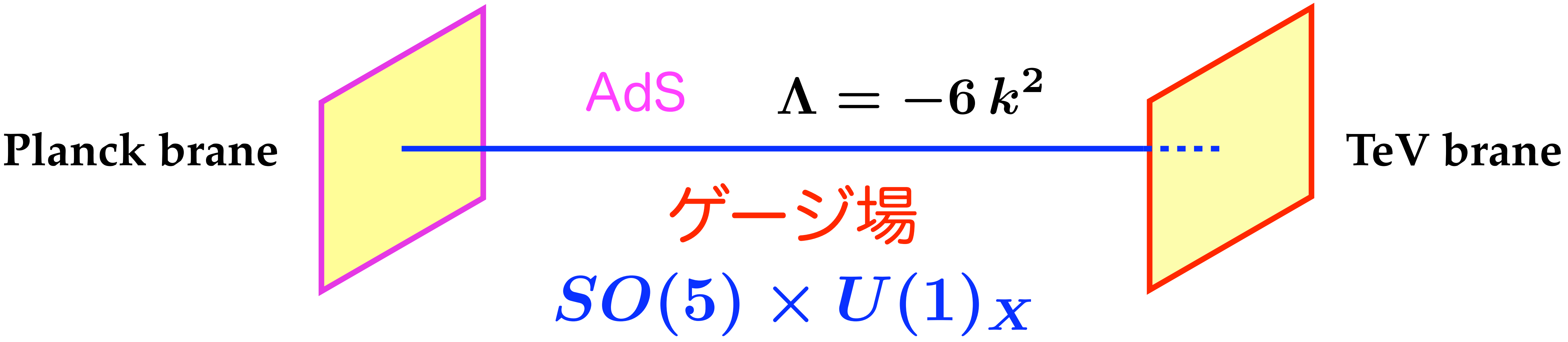
$WWH \ , \ WWH^2 \ , \ \cdots$

$ZZH \ , \ ZZH^2 \ , \ \cdots$

全て決まる

$\bar{\Psi}\Psi H \ , \ \cdots$

Randall-Sundrum ワープ時空上の SO(5)xU(1)ゲージ理論

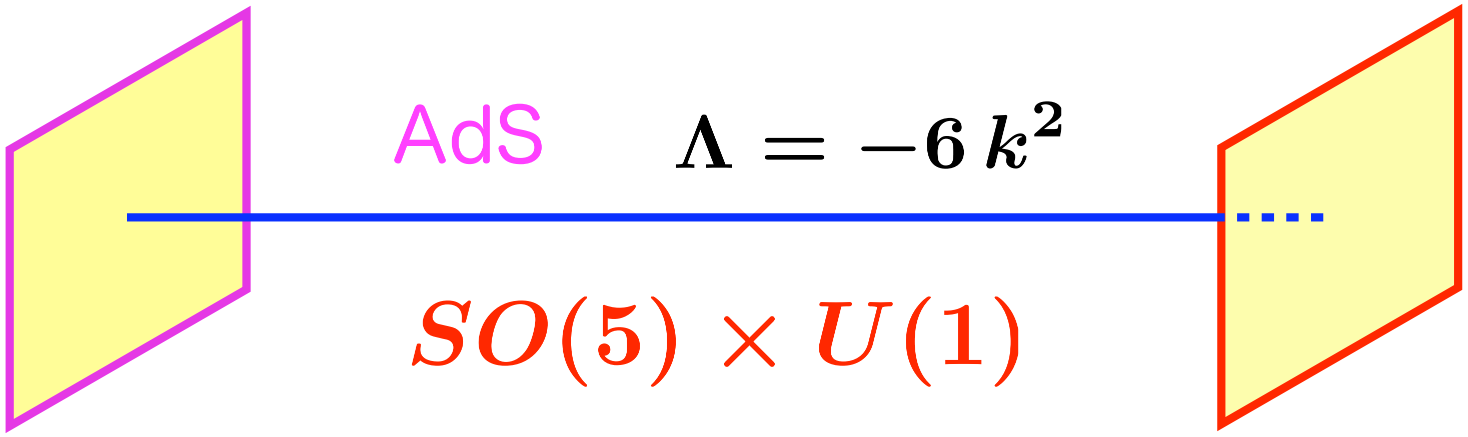


Agashe, Contino, Pomarol 2005
Hosotani, Sakamura 2006
Medina, Shah, Wagner 2007

クォーク・レプトン

YH, Oda, Ohnuma, Sakamura 2008
YH, Noda, Uekusa 2009

Gauge fields on RS

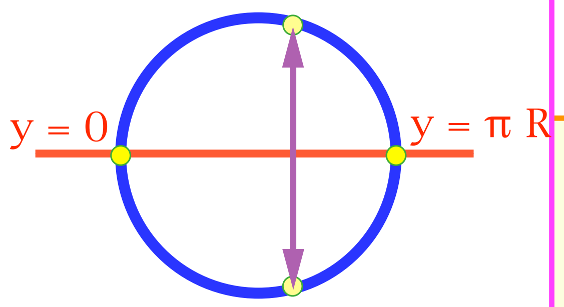


Planck brane

AdS $\Lambda = -6\,k^2$

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

TeV brane



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

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

Orbifold BC : $P_0 \, , \; P_1$

Origin of the Higgs doublet

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

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

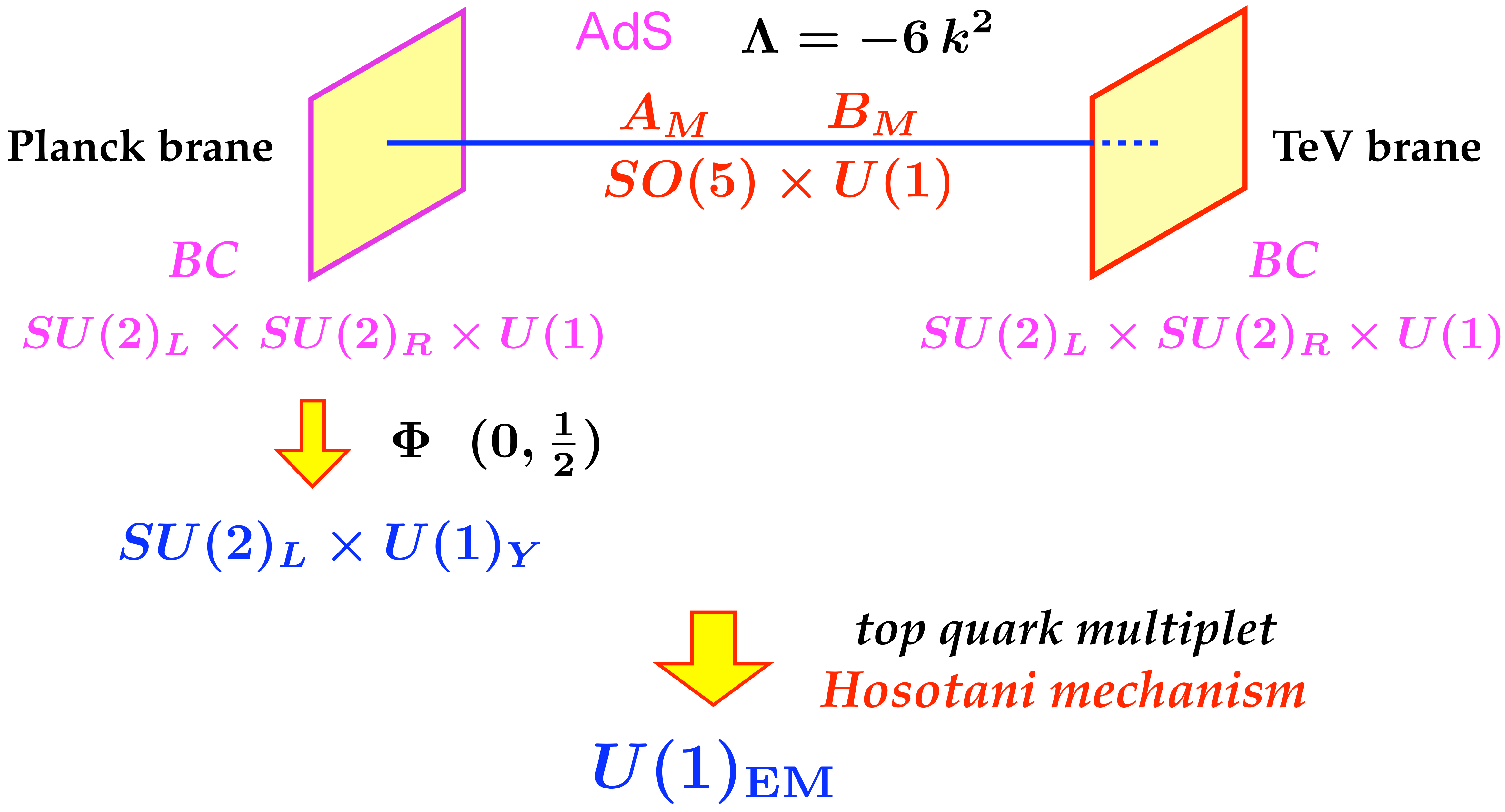
$W \;\; Z \;\; \gamma$

$$A_\mu \sim \begin{pmatrix} \boxed{\phantom{\begin{matrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{matrix}}} & \\ & \end{pmatrix}$$

Higgs

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

Symmetry reduction



AdS $\Lambda = -6\,k^2$

Planck brane

A_M B_M

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

TeV brane

BC

$SU(2)_L \times SU(2)_R \times U(1)$

BC

$SU(2)_L \times SU(2)_R \times U(1)$

$\Phi \quad (0, \frac{1}{2})$

$SU(2)_L \times U(1)_Y$

top quark multiplet

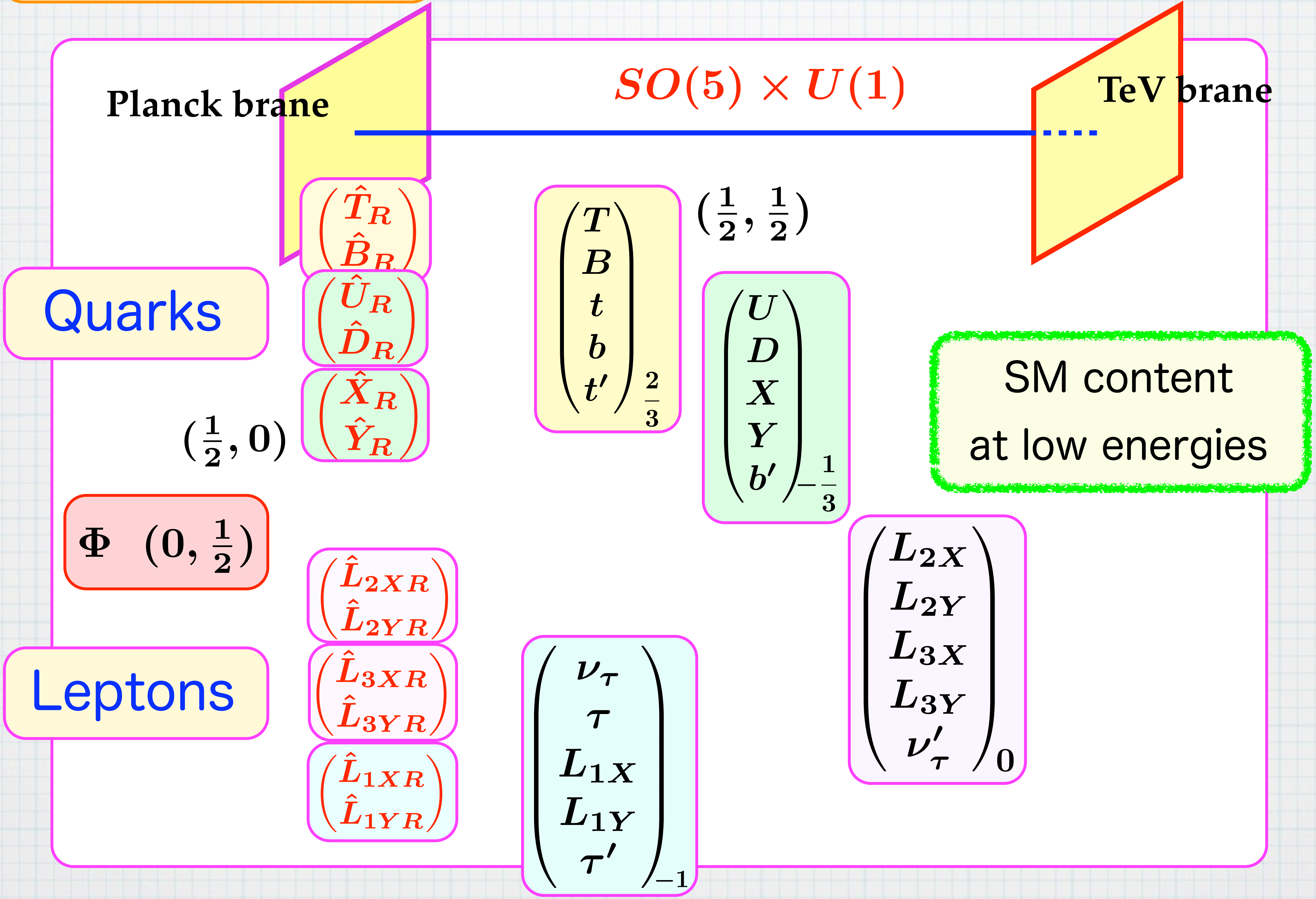
Hosotani mechanism

$U(1)_{\mathrm{EM}}$

Matter content

YH, Noda, Uekusa 2009

(YH, Oda, Ohnuma, Sakamura 2008)



Planck brane

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

TeV brane

Quarks

$(\frac{1}{2}, 0)$

$\begin{pmatrix} \hat{T}_R \\ \hat{B}_R \end{pmatrix}$ $\begin{pmatrix} \hat{U}_R \\ \hat{D}_R \end{pmatrix}$ $\begin{pmatrix} \hat{X}_R \\ \hat{Y}_R \end{pmatrix}$

$(\frac{1}{2}, \frac{1}{2})$

$\begin{pmatrix} T \\ B \\ t \\ b \\ t' \end{pmatrix}_{\frac{2}{3}}$ $\begin{pmatrix} U \\ D \\ X \\ Y \\ b' \end{pmatrix}_{-\frac{1}{3}}$

$\Phi \quad (0, \frac{1}{2})$

Leptons

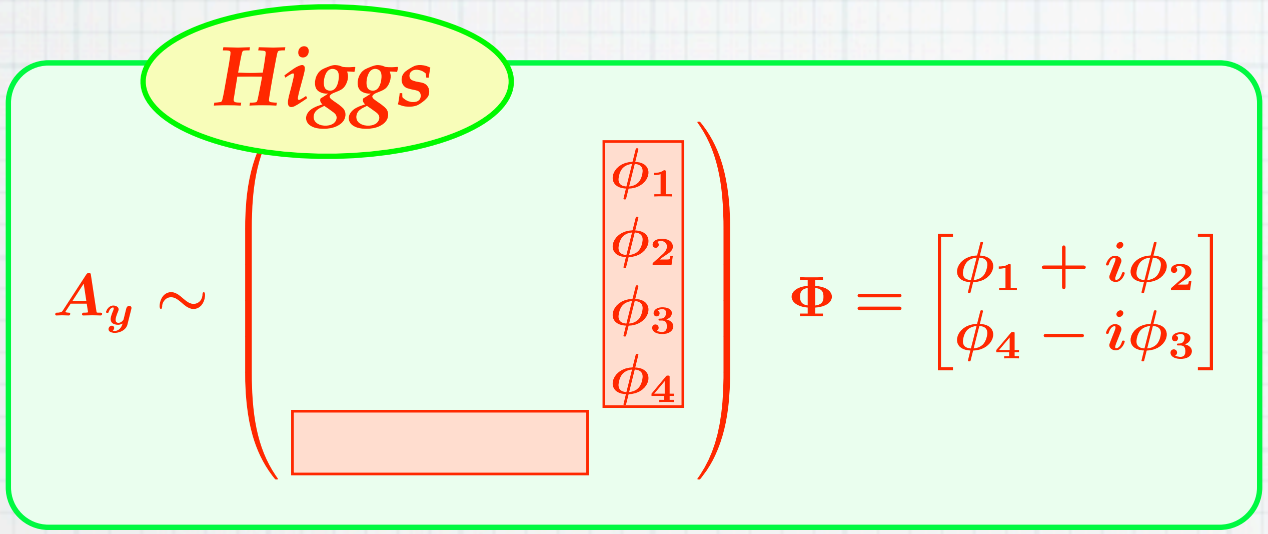
$\begin{pmatrix} \hat{L}_{2XR} \\ \hat{L}_{2YR} \end{pmatrix}$ $\begin{pmatrix} \hat{L}_{3XR} \\ \hat{L}_{3YR} \end{pmatrix}$ $\begin{pmatrix} \hat{L}_{1XR} \\ \hat{L}_{1YR} \end{pmatrix}$

$\begin{pmatrix} \nu_\tau \\ \tau \\ L_{1X} \\ L_{1Y} \\ \tau' \end{pmatrix}_{-1}$ $\begin{pmatrix} L_{2X} \\ L_{2Y} \\ L_{3X} \\ L_{3Y} \\ \nu'_\tau \end{pmatrix}_0$

SM content

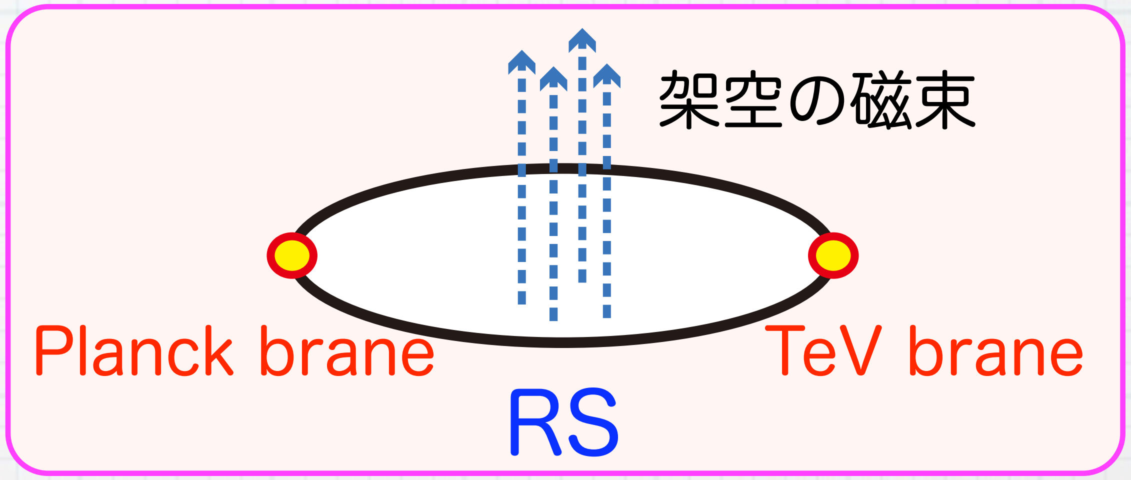
at low energies

ヒッグス場は余剰次元AB位相のゆらぎ



$$A_y \sim \begin{pmatrix} & \begin{matrix}\phi_1\\ \phi_2\\ \phi_3\\ \phi_4\end{matrix} \\ \square & \end{pmatrix}$$

$$\Phi = \begin{bmatrix} \phi_1 + i\phi_2 \\ \phi_4 - i\phi_3 \end{bmatrix}$$



$$A_y^{45}(x,y) = h_0(y)\left\{ \theta_H + \frac{H(x)}{f_H} \right\}$$

$$\boxed{\theta_H \sim \theta_H + 2\pi}$$

Effective interactions

AB phase $$\hat{\theta}_H = \theta_H + \frac{H}{f_H} \qquad f_H = \frac{2}{\sqrt{kL}}\frac{m_{KK}}{\pi g}$$

~246 GeV

0.8 ~1.5 TeV

$$\mathcal{L}_{\rm eff} \sim -V_{\rm eff}(\hat{\theta}_H)$$

YH 1983, Oda-Weiler 2005

$$-m_W(\hat{\theta}_H)^2 W_\mu^\dagger W^\mu - \frac{1}{2} m_Z(\hat{\theta}_H)^2 Z_\mu Z^\mu$$

YH-Sakamura 2006, 2007

$$-m_f(\hat{\theta}_H)\,\overline{\psi}_f \psi_f$$

YH-Kobayashi 2008

Gauge-Higgs	**SM**
$m_W(\hat\theta_H) \sim \frac{1}{2} g \underline{\underline{f_H \sin\hat\theta_H}}$	$\frac{1}{2} g(\underline{\underline{v+H}})$
$m_Z(\hat\theta_H) \sim \frac{1}{2\cos\theta_W} g \underline{\underline{f_H \sin\hat\theta_H}}$	$\frac{1}{2\cos\theta_W} g(\underline{\underline{v+H}})$
$m_f(\hat\theta_H) \sim y_f \underline{\underline{f_H \sin\hat\theta_H}}$	$y_f(\underline{\underline{v+H}})$

periodic
nonlinear

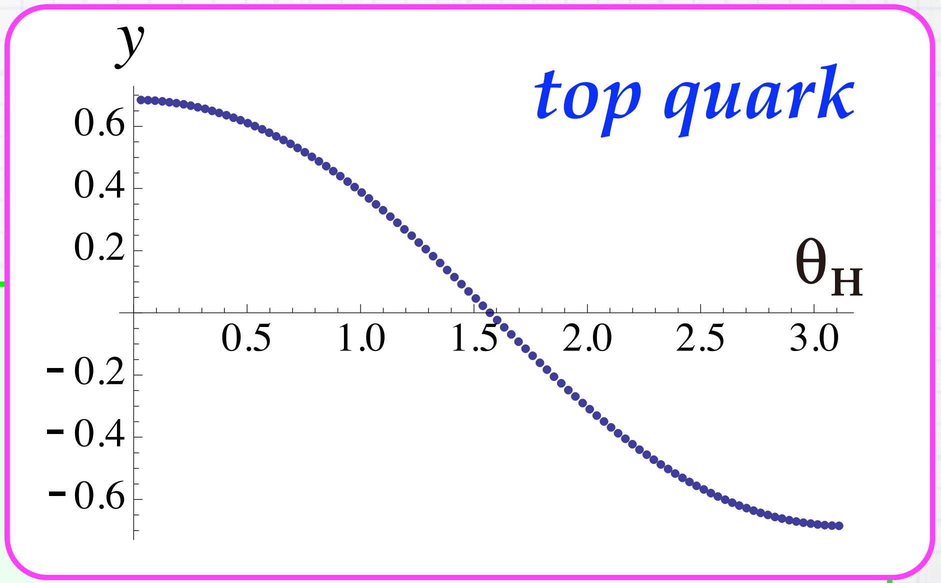
$$\hat\theta_H = \theta_H + \frac{H}{f_H}$$

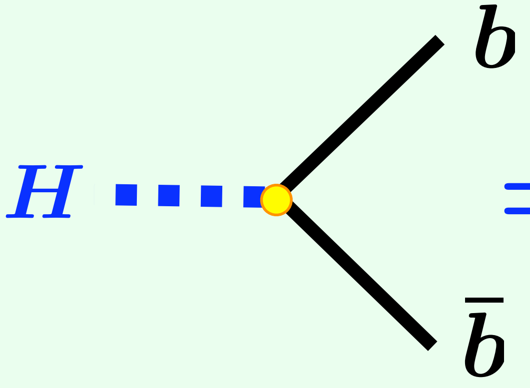
⇒

WWH
ZZH
Yukawa
= *SM* $\times \cos\theta_H$

WWHH
ZZHH
= *SM* $\times \cos 2\theta_H$

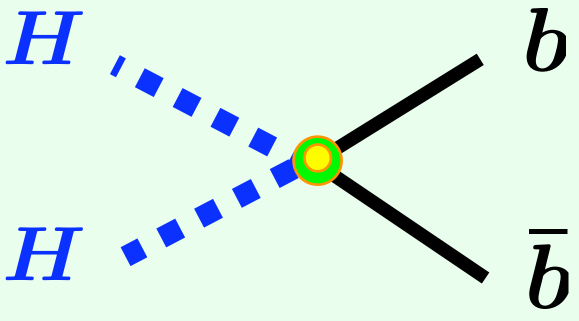
$\cos\theta_H = 0$ at $\theta_H = \frac{\pi}{2}$



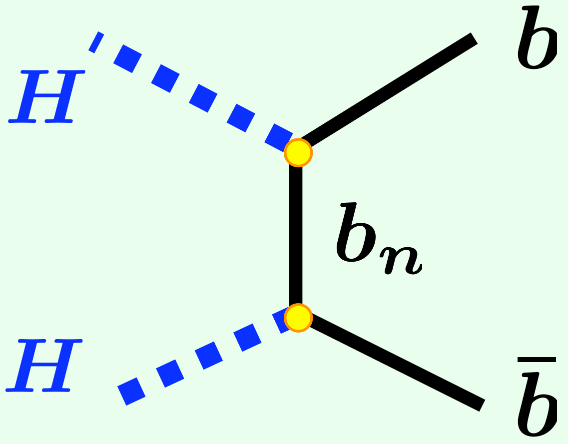


$= 0$

Yukawa = 0



$= \sum_n$

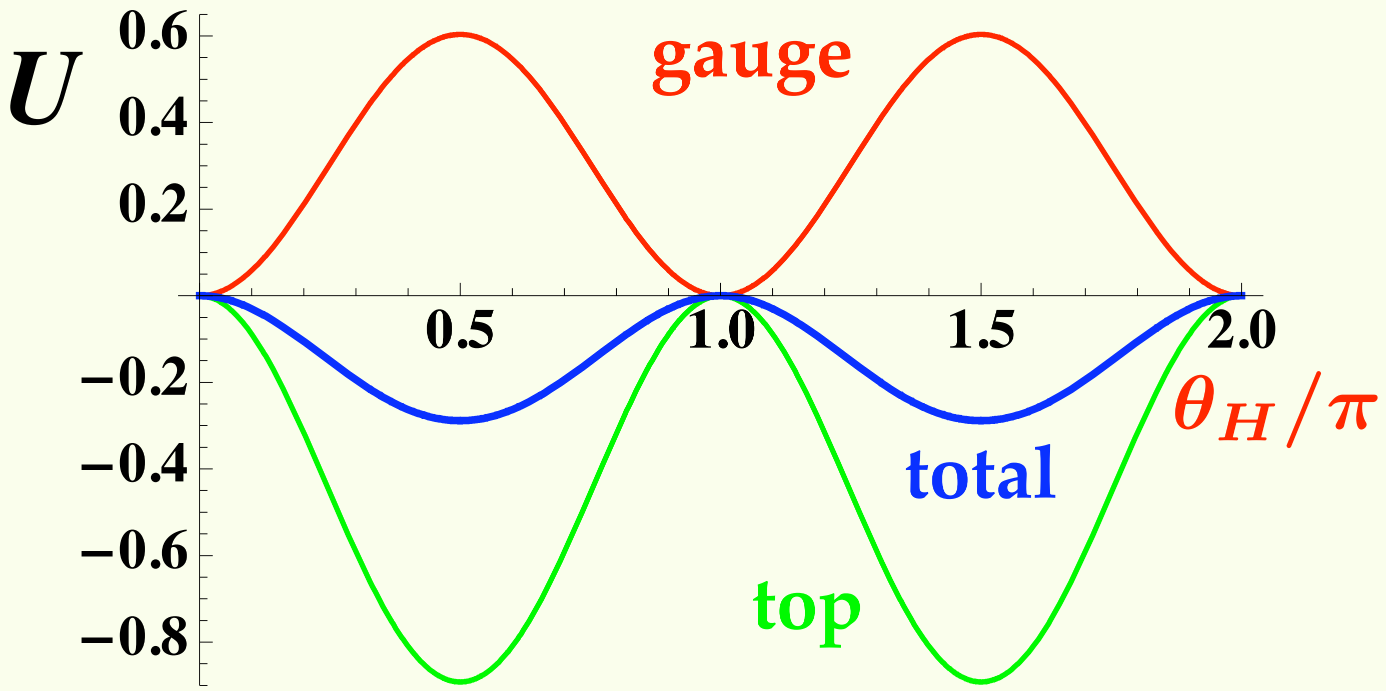


$$= \frac{m_b}{2f_H^2} H^2 \bar{b} b$$

AB位相の量子効果でEW対称性が破れる

Hosotani mechanism 1983

$\theta_H = \dfrac{\pi}{2}$ でエネルギーが最小になる



$z_L = 10^5 \sim 10^{17}$

⇨ $m_H = 70 \sim 140\,\mathrm{GeV}$

YH, Noda, Sakamura, Tanaka, Uekusa

WWH, ZZH, Yukawa = 0

LEP2 bound is evaded.

宇宙は暗黒物質で満ちている

その正体は？

ヒッグスボゾンは安定になり
暗黒物質になる

WMAPデータから
ヒッグス質量が
決まる

Hosotani, Ko, Tanaka
0908.0212 [hep-ph]

In the SO(5) x U(1) gauge-Higgs unification

Mirror reflection symmetry

$$(x^\mu, y) \to (x^\mu, -y)$$
$$(A_\mu, A_y) \to (A_\mu, -A_y) \ , \ \Psi \to \pm\gamma^5\Psi$$

invariant under $\hat\theta_H = \theta_H + \dfrac{H}{f_H} \to -\hat\theta_H$

Enhanced gauge symmetry

If all bulk fermions belong to vector rep. of SO(5)

invariant under $\hat\theta_H \to \hat\theta_H + \pi$

top quark ⇒ $\theta_H = \frac{\pi}{2}$

$\frac{\pi}{2} + \frac{H}{f_H}$ ⇔ $-\frac{\pi}{2} - \frac{H}{f_H}$ ⇔ $\frac{\pi}{2} - \frac{H}{f_H}$

Invariant under $H \rightarrow -H$

H-parity

$H : -$

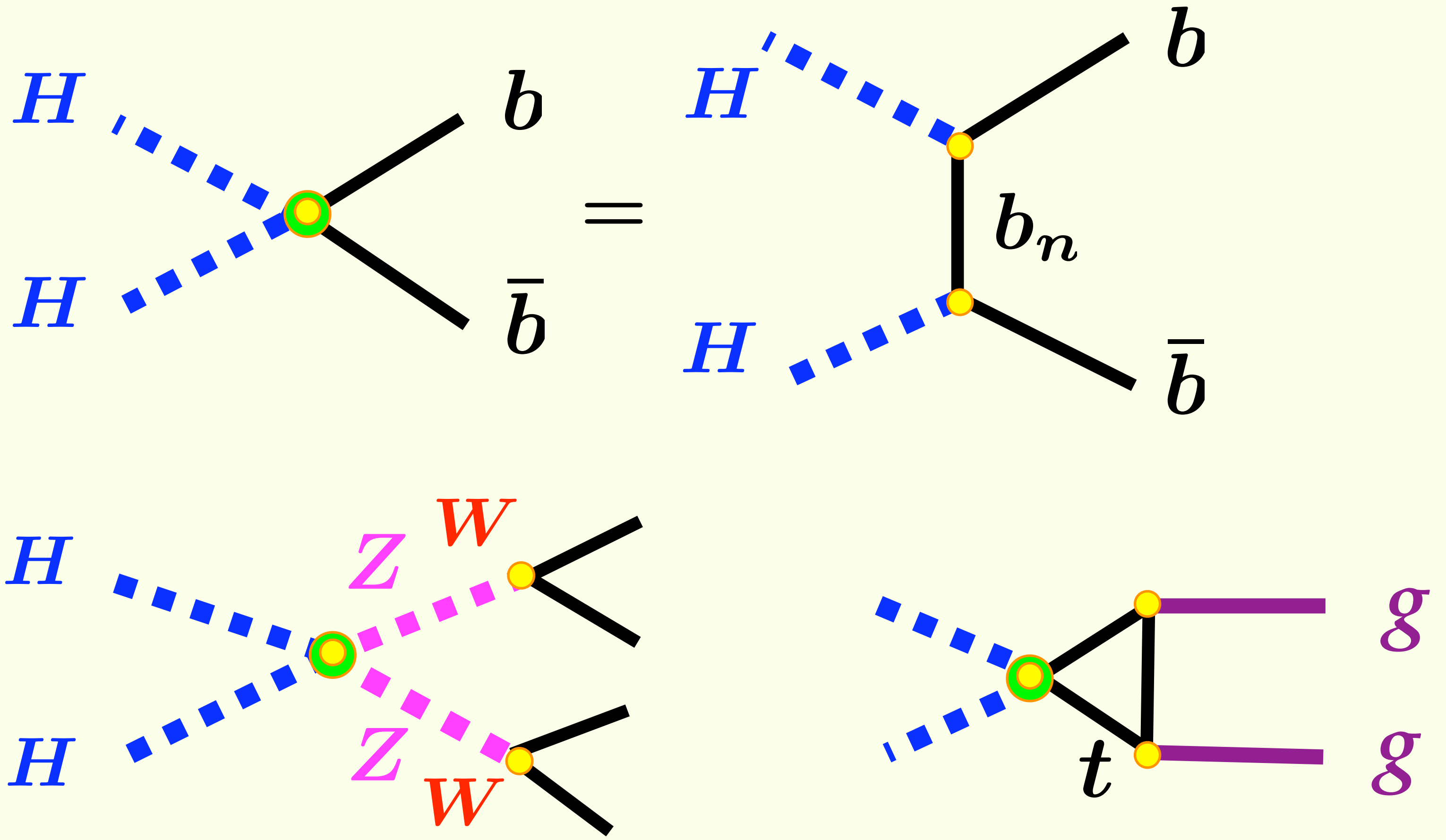
all other SM particles : $+$

⇒ **Higgs bosons become absolutely stable.**

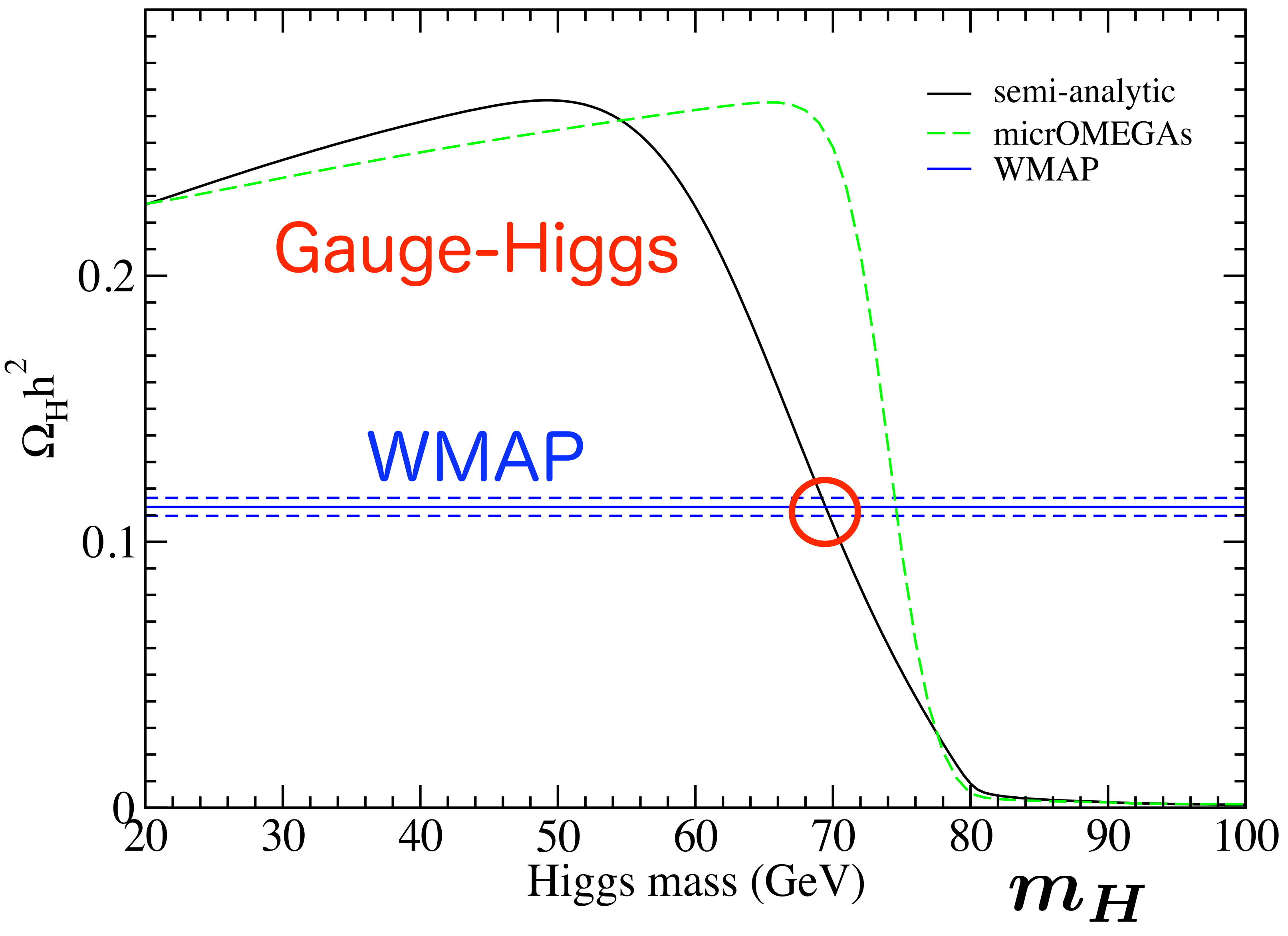
WWH, ZZH, Yukawa = 0

暗黒物質 = ヒッグス

Annihilation



$\Omega_H h^2$ Relic abundance



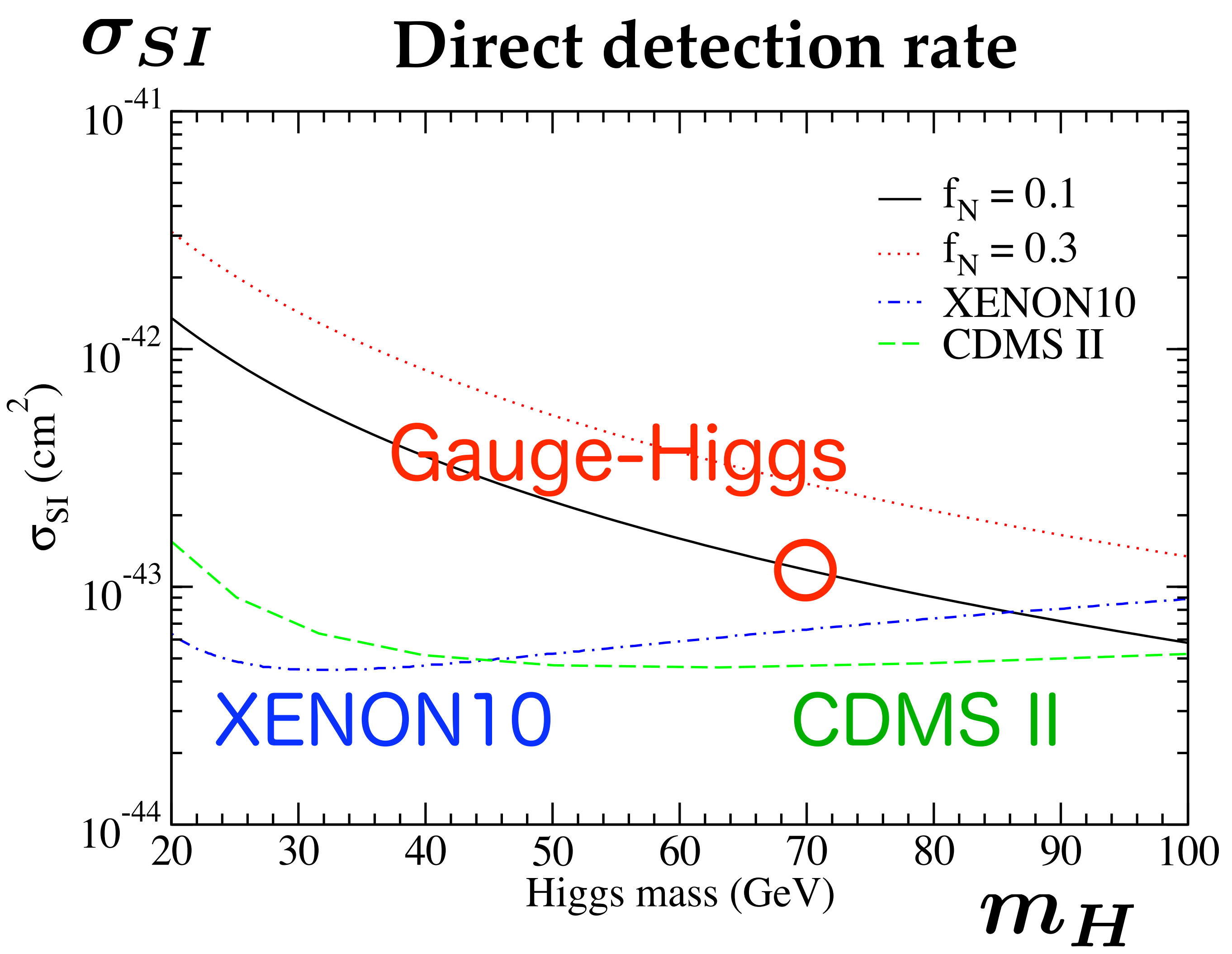
WMAP data ⇒ $m_H \sim 70\,\text{GeV}$

$T_f \sim 3\,\text{GeV}$

$HH \to b\bar{b}$ 34%

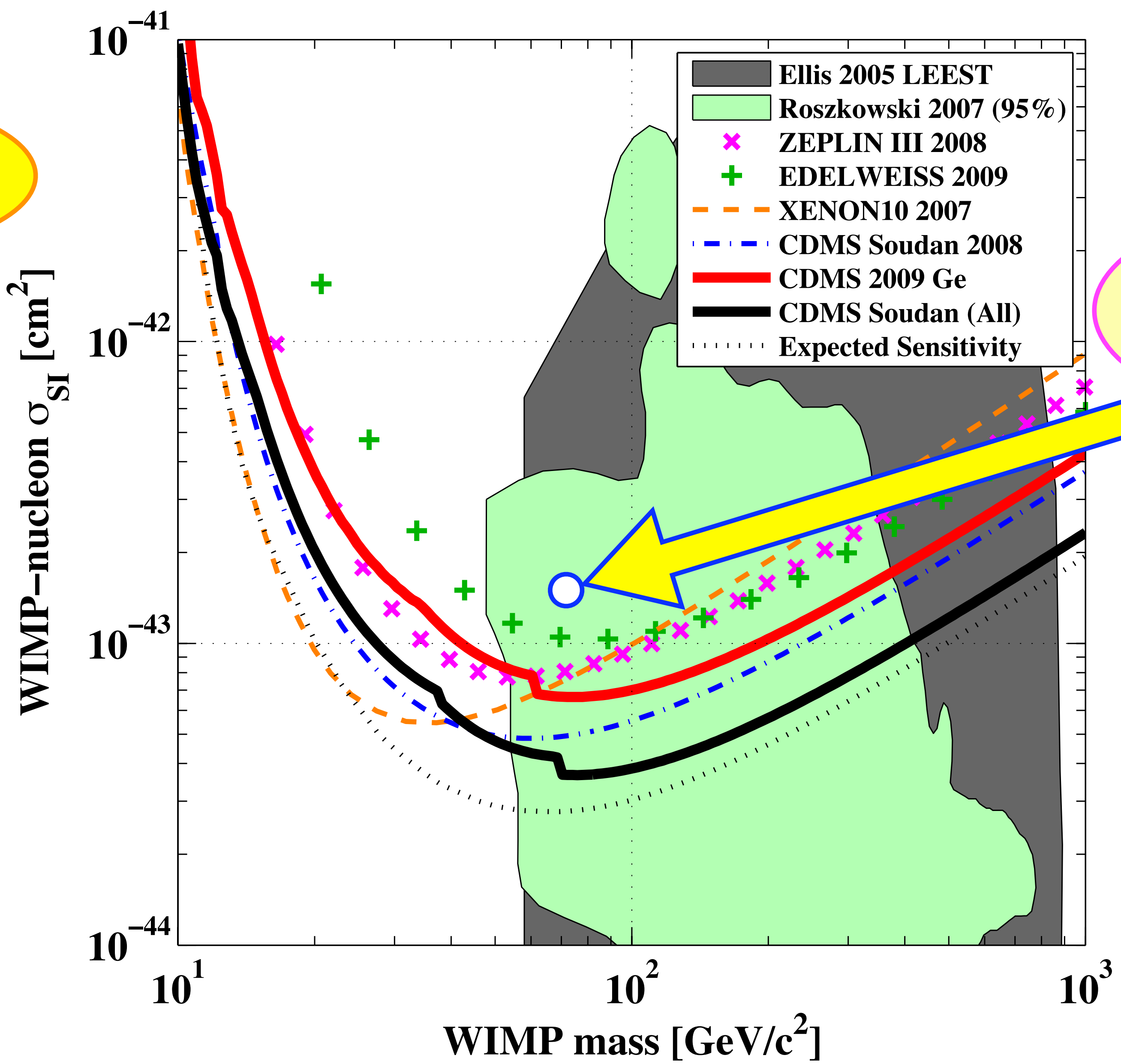
$\to WW$ 61%

Higgs-nucleon 弾性散乱



多くの不定性（強い相互作用の効果、DMの分布）
CDMS II, XENON10 で除外されたとは言えない。

CDMS II



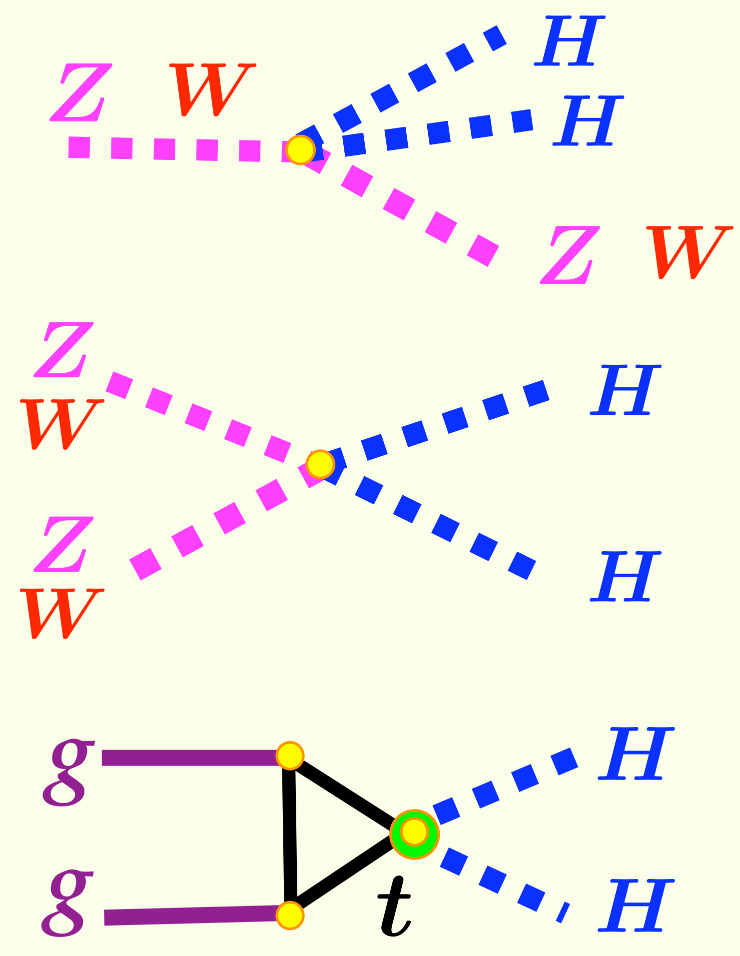
GHU
stable Higgs

arXiv:0912.3592 [astro-ph.CO]   18 Dec 2009

Two events in the signal region

LHC, ILC でヒッグスをどうみるか

Production:



だが、ヒッグスは安定

ヒッグス粒子

=

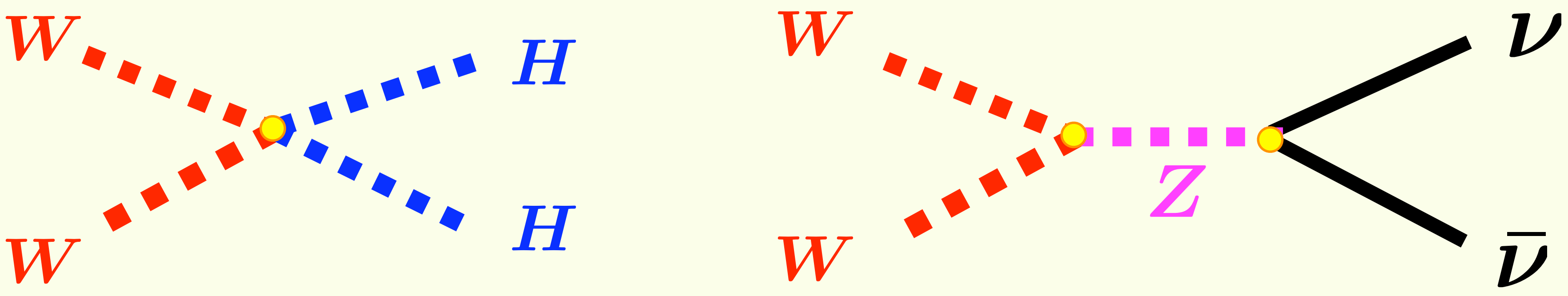
missing energy,

missing momentum

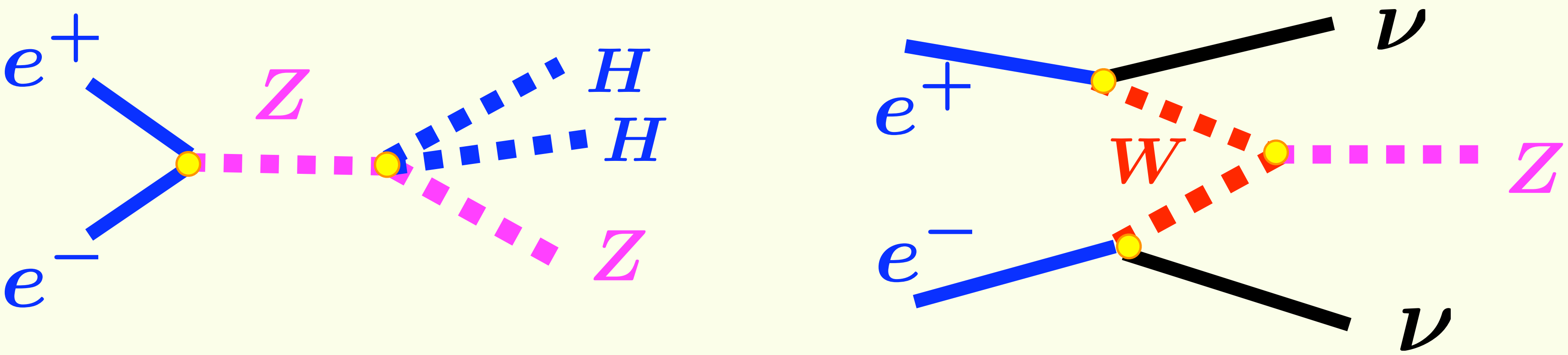
実験のやり方を変える必要あり

LHC, ILC でヒッグスをどうみるか

LHC



ILC



Z : neutral currents

YH, Noda, Uekusa, 0912.1173 [hep-ph]

$$\frac{1}{\cos\theta_W} Z_\mu \Big\{ g_{tL}^{(Z)} \bar{t}_L \gamma^\mu t_L + g_{tR}^{(Z)} \bar{t}_R \gamma^\mu t_R + g_{bL}^{(Z)} \bar{b}_L \gamma^\mu b_L + g_{bR}^{(Z)} \bar{b}_R \gamma^\mu b_R \Big\}$$

$$g_{fL}'^{(Z)} = \frac{g_{fL}^{(Z)}}{g_{\nu e L}^{(W)}} \qquad \left(\frac{g_{fL}'^{(Z)}}{g_{SM}^{(Z)}} - 1 \right)$$

$z_L = 10^{15}$, $k = 4.7 \times 10^{17}$ GeV

f	u	c	t	SM
$g_{fL}'^{(Z)}$	0.34642 $(+1.6438 \times 10^{-3})$	0.3464 $(+1.640 \times 10^{-3})$	0.32039 (-7.3614×10^{-2})	0.345853
$g_{fR}'^{(Z)}$	-0.15559 $(+9.37 \times 10^{-3})$	-0.15555 $(+9.1000 \times 10^{-3})$	-0.18234 $(+0.18292)$	-0.154147

f	d	s	b	SM
$g_{fL}'^{(Z)}$	-0.42362 $(+1.6438 \times 10^{-3})$	-0.42362 $(+1.6438 \times 10^{-3})$	-0.424 $(+2.775 \times 10^{-3})$	-0.422927
$g_{fR}'^{(Z)}$	0.077795 $(+9.37 \times 10^{-3})$	0.077774 $(+9.0925 \times 10^{-3})$	0.077751 $(+8.7864 \times 10^{-3})$	0.0770733

Forward-backward asymmetry

$$e^+ + e^- \to Z \to f + \bar{f}$$

Uekusa 0912.1218 [hep-ph]

	Exp.	Gauge-Higgs (at tree level)	Standard Model
A^b_{FB}	0.0992 ± 0.0016	0.09952	0.1033 ± 0.0007
A^c_{FB}	0.0707 ± 0.0035	0.07073	0.0738 ± 0.0006

$$z_L = 10^{15}\ ,\ k = 4.7 \times 10^{17}\ \text{GeV}$$

Summary

Gauge-Higgs unification

Gauge couplings ~ ほぼ SM.

Higgs couplings ~ SMから大きくずれる.

⇩

自然にヒッグスボソンが安定になる

実験のやり方を変える必要

暗黒物質＝ヒッグス　$m_H \sim 70\,\mathrm{GeV}$