余剰次元とGauge-Higgs 統一

大阪大学　　細谷　裕

「*LHC*での余剰次元研究」研究会

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1. Standard Model では

2. ゲージ・ヒッグス統一とは

3. ヒッグス場がゲージ場の一部になる

4. ヒッグス場はAB位相のゆらぎ

5. Effective Lagrangianでみる

6. Higgs couplings の予言 - SMからの大きなずれ

7. AB位相の量子効果でEW対称性が破れる

top quark がひきおこす

8. なんと $\theta_H = \frac{\pi}{2}$ が選ばれる

ZZH, Yukawa = 0 となる

9. ヒッグス粒子が安定になる

10. 暗黒物質　=　ヒッグス

11. WMAP からヒッグス質量が決まる

12. LHC, ILC でどう見るか

13. Weak universalityの破れ

14. まとめ

Standard Model では

$$|D_\mu \Phi|^2 \qquad y\, \bar{q}_L \Phi u_R \qquad V[\Phi]$$

$$\Phi \sim \frac{1}{\sqrt{2}} \begin{pmatrix} \\ v + H \end{pmatrix} \qquad m_W = \frac{1}{2} g v$$

Gauge sector : established.

Higgs sector : yet to be unveiled.

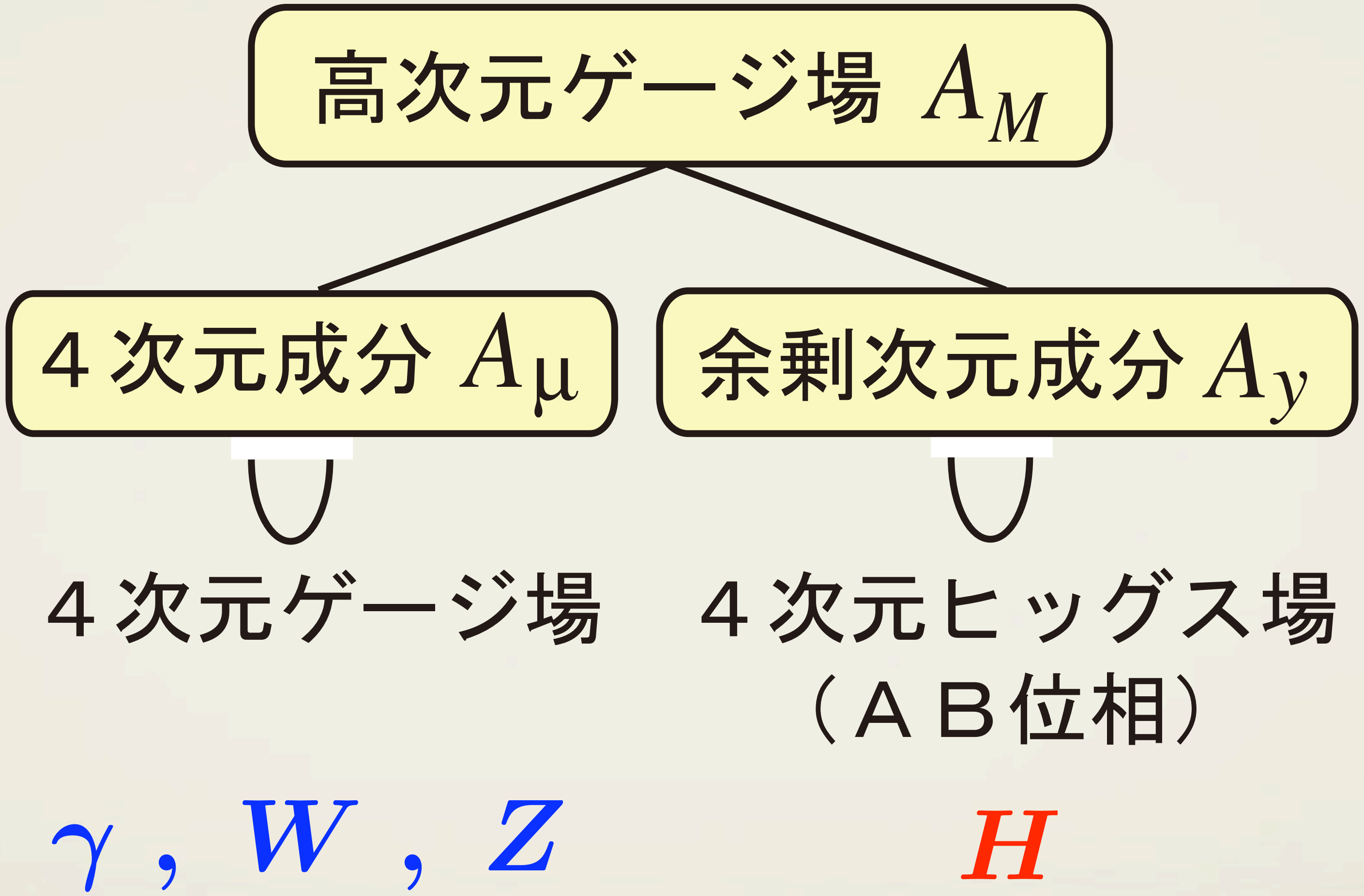
No principle

Many free parameters

Unnatural against radiative corrections

Hierarchy in fermion masses

ゲージ・ヒッグス統一とは



ヒッグス場はゲージ場の一部になる

Higgs mass

m_H dynamically generated

finite

Higgs couplings

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

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

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

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

all determined

Kaluza-Klein モード

$M^4 \times S^1$

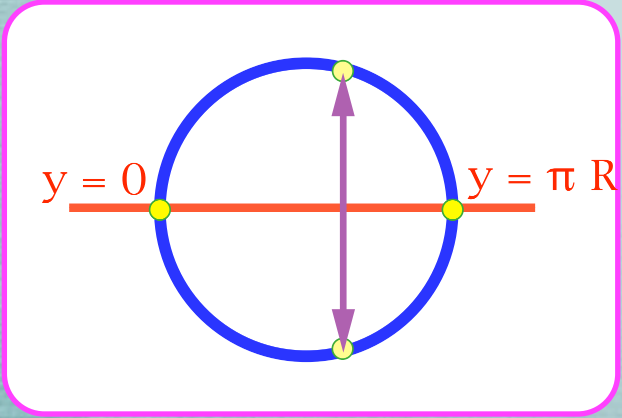
$$A_M(x,y) = \sum_n A_M^{(n)}(x)\, e^{iny/R}$$

KKモード $m_n = \dfrac{|n|}{R}$　KKスケール $m_{KK} = \dfrac{1}{R}$

$M^4 \times (S^1/Z_2)$

$$A_\mu(x,y) = \sum_{n=0}^{\infty} A_\mu^{(n)}(x) \cos\frac{ny}{R}$$

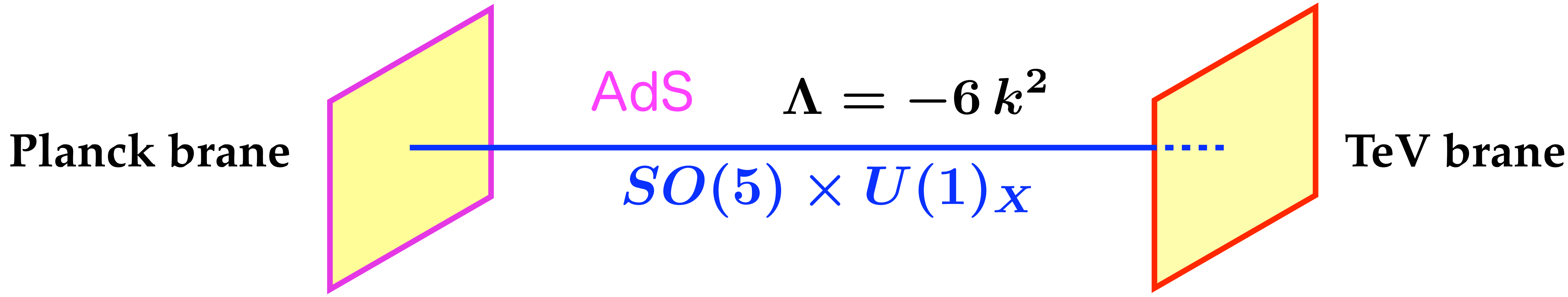
$$A_y(x,y) = \sum_{n=1}^{\infty} A_y^{(n)}(x) \sin\frac{ny}{R}$$



orbifold

A_μのみ零モード

Randall-Sundrum ワープ時空



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

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

Orbifold BC : P_0 , P_1

Origin of the Higgs doublet

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

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

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

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

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

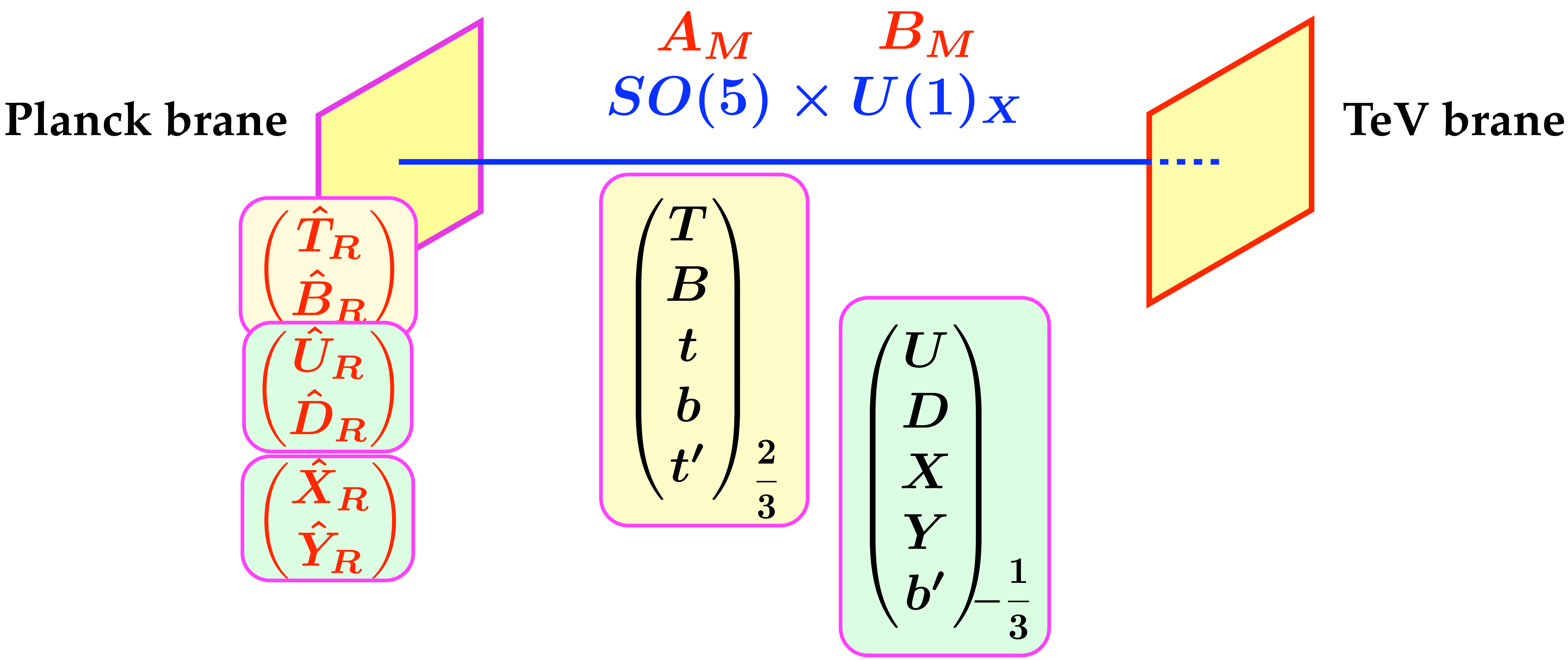
$A_\mu \sim \begin{pmatrix} \square & \\ & \end{pmatrix}$

Higgs

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

Model on RS

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

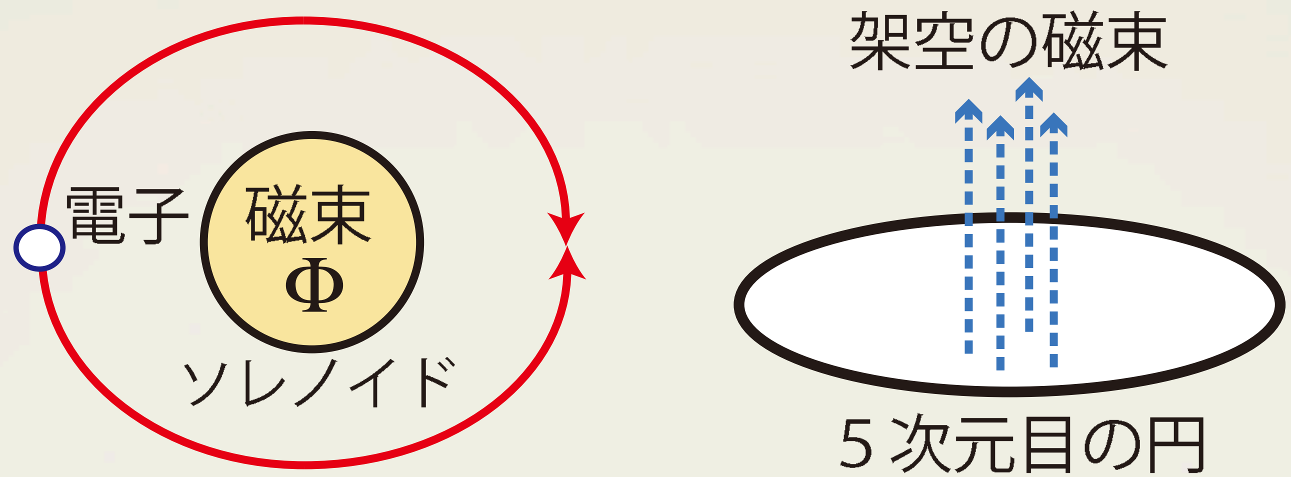


Anomaly-free

At low energies γ , W , Z $\begin{pmatrix} t_L \\ b_L \end{pmatrix}$ t'_R b'_R $\cdots$

H

ヒッグス場はAB位相のゆらぎ



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

$$\theta_H \sim \theta_H + 2\pi$$

Effective interactions

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

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

YH 1983

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

YH-Sakamura 2006, 2007

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

YH-Kobayashi 2008

$$\mathcal{L}_{\rm eff}(\hat{\theta}_H + 2\pi) = \mathcal{L}_{\rm eff}(\hat{\theta}_H)$$ *finite*

SO(5)xU(1) model	SM
$m_W(\hat\theta_H) \sim \frac{1}{2} g f_H \sin\hat\theta_H$	$\frac{1}{2} g(v+H)$
$m_Z(\hat\theta_H) \sim \frac{1}{2\cos\theta_W} g f_H \sin\hat\theta_H$	$\frac{1}{2\cos\theta_W} g(v+H)$
$m_f(\hat\theta_H) \sim \lambda_f \sin\hat\theta_H$	$y_f(v+H)$

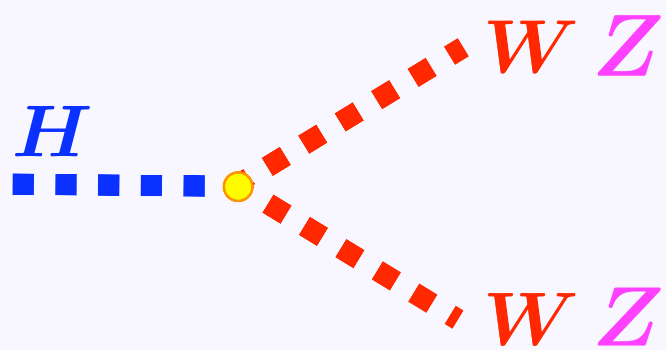
$$\hat\theta_H = \theta_H + \frac{H}{f_H}$$

周期性、非線形性

Prediction 1

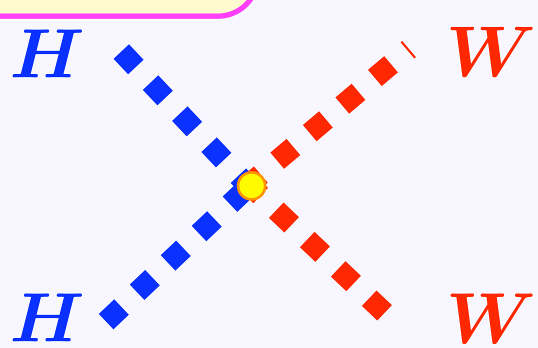
$$-m_W(\hat{\theta}_H)^2 W_\mu^\dagger W^\mu - \frac{1}{2} m_Z(\hat{\theta}_H)^2 Z_\mu Z^\mu$$

WWH
ZZH

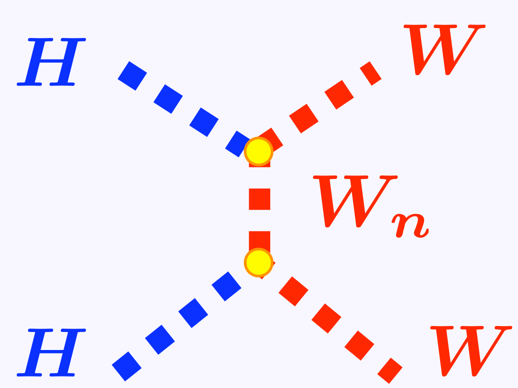


$$SM \times \cos\theta_H$$

WWHH
ZZHH



$$+\sum_n$$



$$SM \times \cos 2\theta_H$$

$$1 - \frac{2}{3}\sin^2\theta_H \qquad -\frac{4}{3}\sin^2\theta_H$$

4D gauge and Higgs couplings

$$ {F_{MN}}^2 \sim (\partial_\mu A_\nu - \partial_\nu A_\mu + g[A_\mu, A_\nu])^2 $$

WWZ
WWZZ
WWWW

Almost universal in RS

(Large deviation in flat space)

$$ +(\partial_\mu A_y - \partial_y A_\mu + g[A_\mu, A_y])^2 $$

WWH
ZZH
WWHH
ZZHH

significant θ_H -dependence

Sakamura-Hosotani 2006

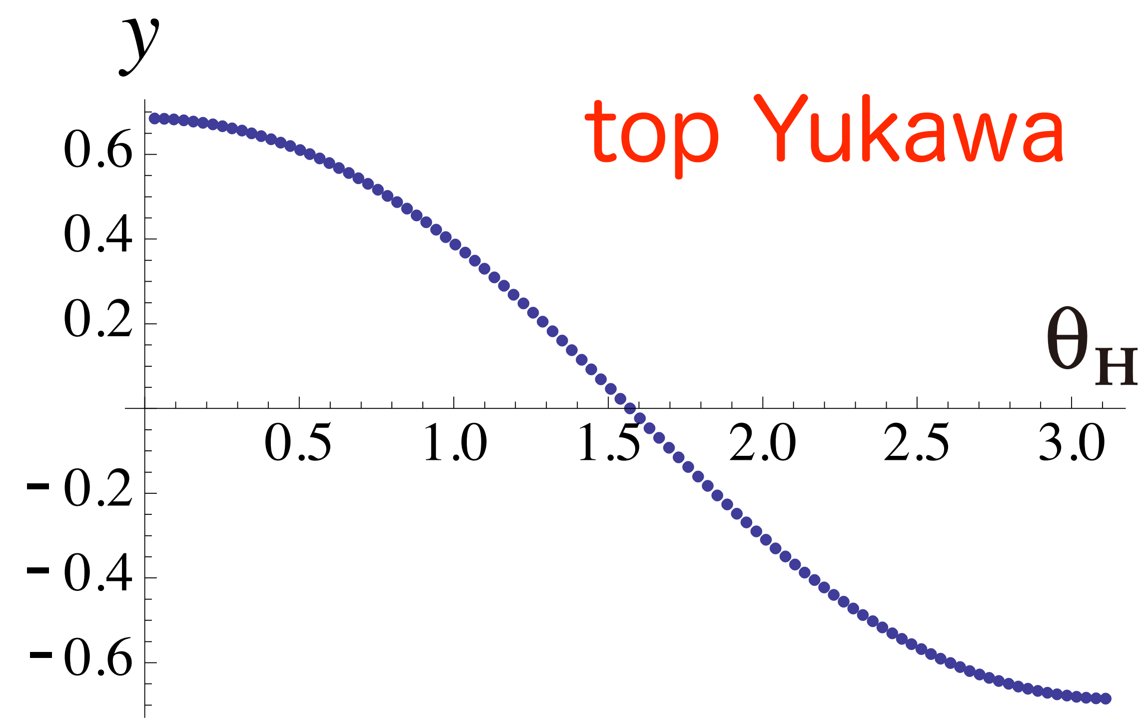
Prediction 2

Yukawa couplings

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

$$m_f \sim \lambda_f \sin\theta_H$$

$$y_f \sim \frac{\lambda_f}{f_H}\cos\theta_H$$

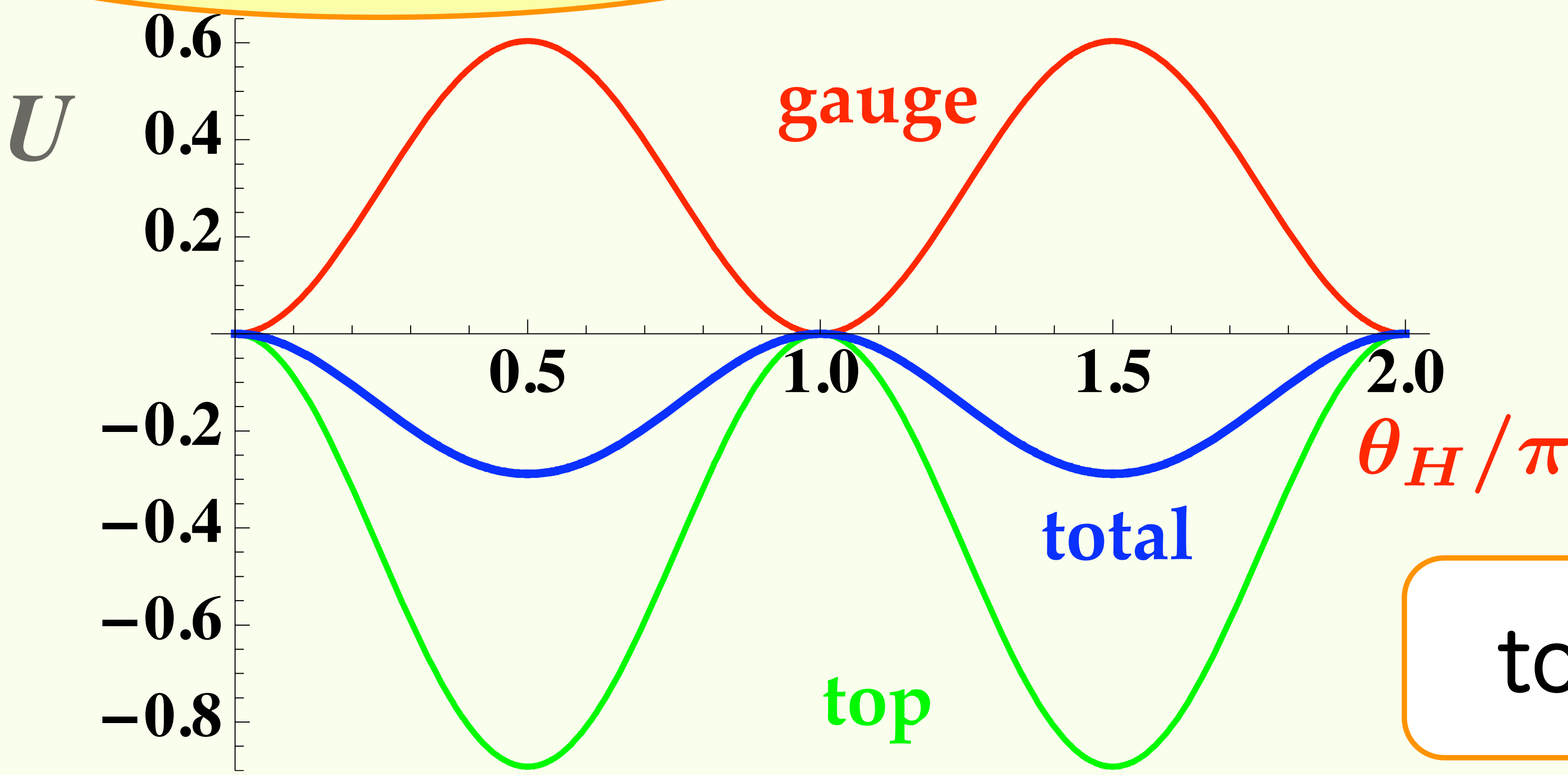


Prediction 3

AB位相の量子効果でEW対称性が破れる

Hosotani mechanism 1983

Effective potential



top quark がひきおこす

このモデルでは

$m_H \sim 50\,\mathrm{GeV}$!

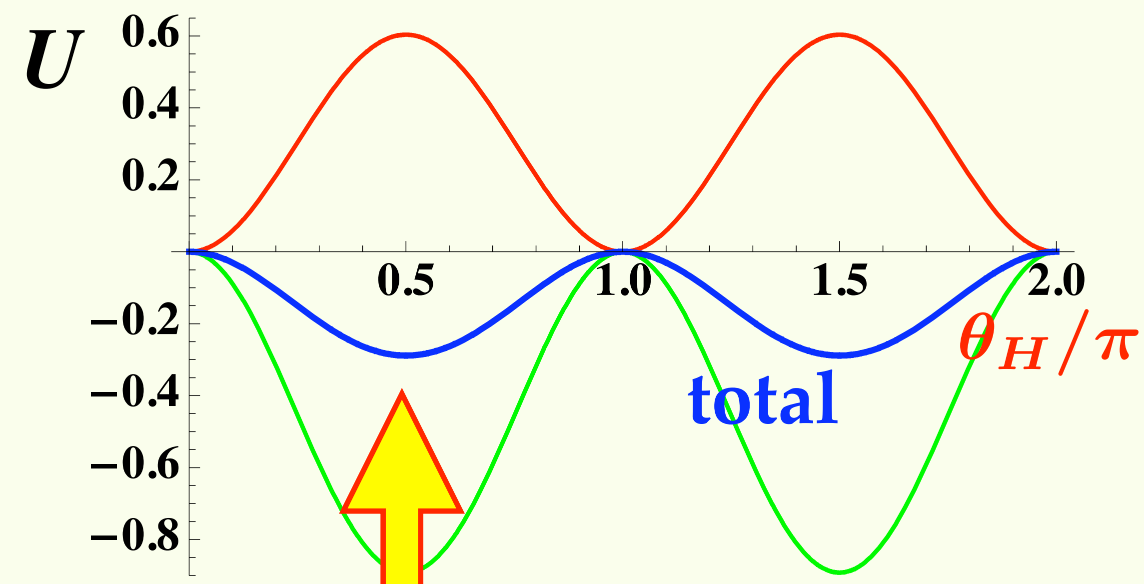
Prediction 4

$z_L = e^{kL}$	k (GeV)	m_{KK}(TeV)	c	m_H(GeV)
$\mathbf{10^{17}}$	$\mathbf{5.0 \times 10^{19}}$	1.58	0.435	54.4
$\mathbf{10^{15}}$	$\mathbf{4.7 \times 10^{17}}$	1.48	0.426	50.8
$\mathbf{10^{13}}$	$\mathbf{4.4 \times 10^{15}}$	1.38	0.413	47.0
$\mathbf{10^{10}}$	$\mathbf{3.9 \times 10^{12}}$	1.21	0.384	40.6
$\mathbf{1.30 \times 10^{4}}$	$\mathbf{3.2 \times 10^{6}}$	0.78	0.	24.5

$$m_{KK} \sim \mathbf{1.5\ TeV}$$

Light Higgs

(Its value depends on details of the model.)

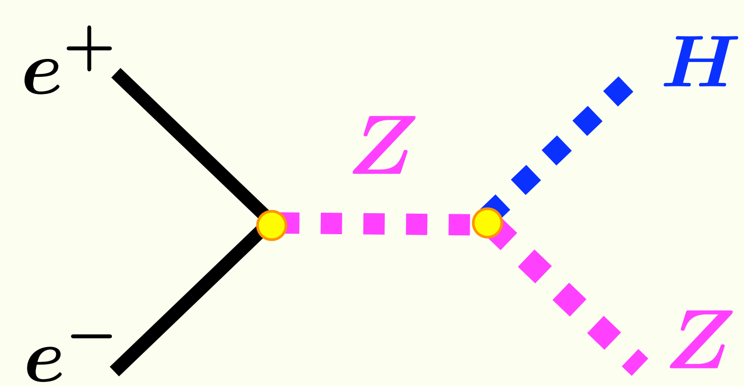


Minima at

$$\theta_H = \frac{\pi}{2}$$

$$\theta_H = \frac{\pi}{2}$$ が選ばれる

WWH, ZZH, Yukawa = 0 となる！



$= 0$

LEP2 bound is evaded.

安定なヒッグスボゾン

Under certain conditions, Higgs bosons become absolutely stable to all orders.

$$“\ \theta_H = \frac{\pi}{2}\ ”$$

SO(5)xU(1) ゲージ・ヒッグス統合理論の対称性

YH, P. Ko, M. Tanaka, arXiv:0908.0212 (PLB)

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

条件: all bulk fermions は SO(5)のvector rep.

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

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

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

理論は$H \to -H$で不変

H-parity

$H : -$

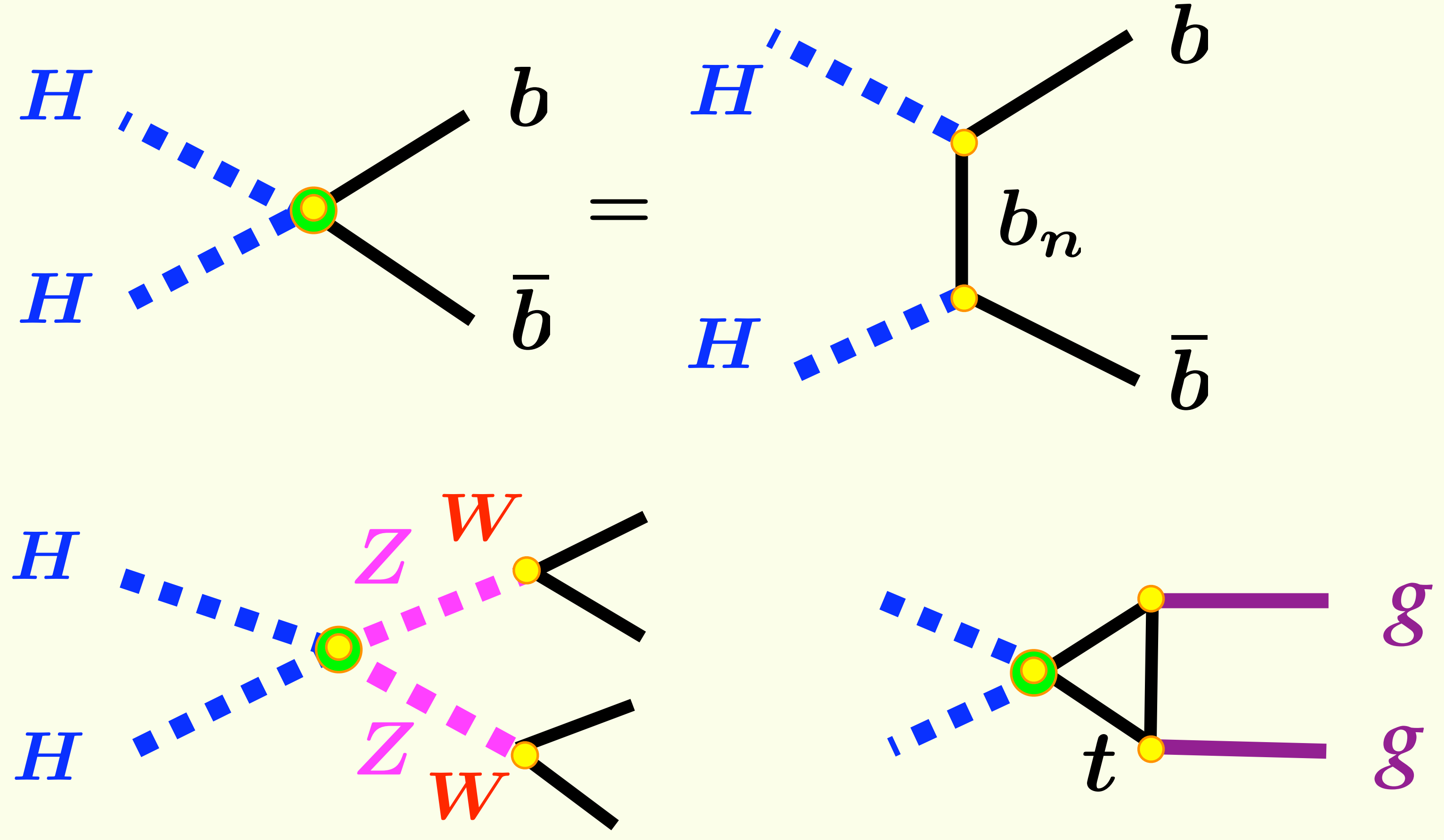
$\text{all other SM particles} : +$

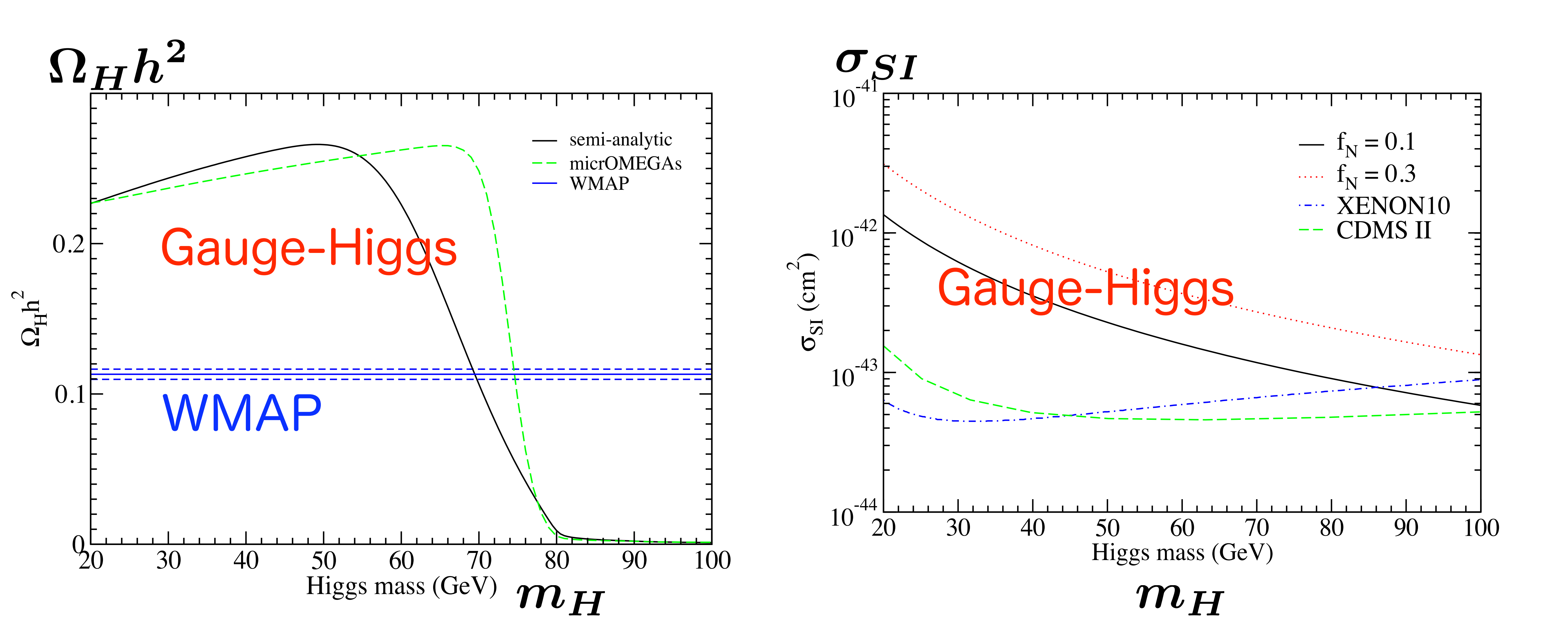
⇒ Higgs bosons become absolutely stable.

WWH, ZZH, Yukawa = 0

暗黒物質 = ヒッグス

Annihilation



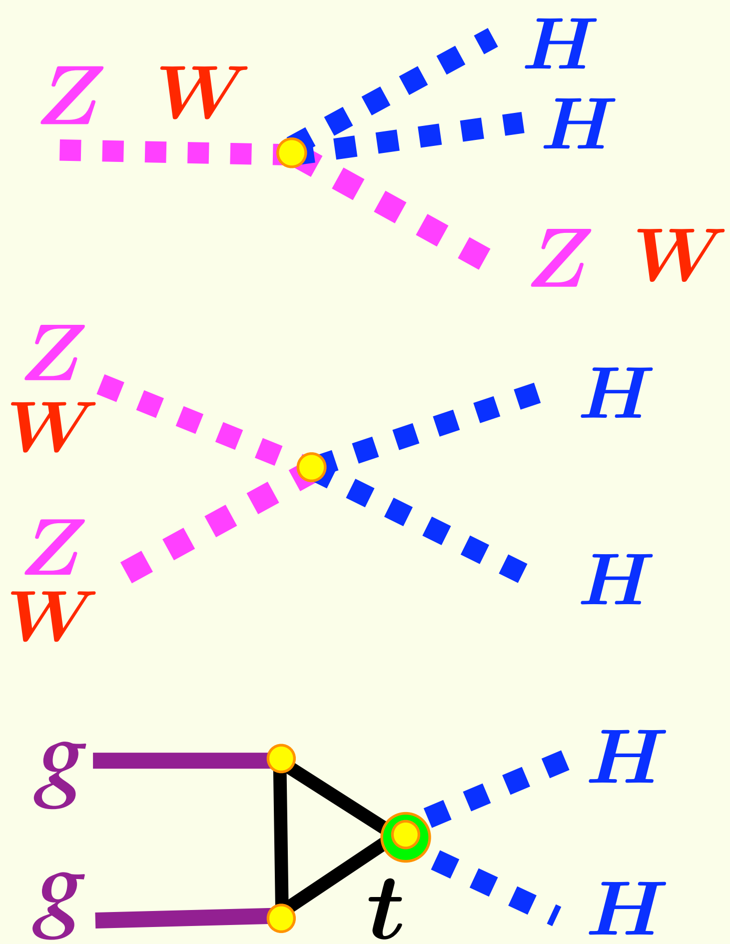


WMAP data ⇨ $m_H \sim 70\,\mathrm{GeV}$

With many uncertainties it is premature to exclude the Higgs DM scenario from the CDMS II and XENON10 bounds.

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

KK モード？

g_n

W_n , Z_n , γ_n

Weak universality の破れ

WWZ coupling ~ 0.2 %

μ-e , τ-e , t-e universality violation

2×10^{-8} 5×10^{-6} 4×10^{-2}

Summary

ゲージ・ヒッグス統一では

Higgs couplings がSMより大きくずれる

安定なヒッグス粒子

暗黒物質＝ヒッグス　$m_H \sim 70\,\mathrm{GeV}$

新しい可能性

ヒッグス＝missing energy, momentum