Basics of Gauge-Higgs Unification

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Requested topics

(1) DM candidates in GHU
(arXiv:1704.04621, 1801.00686, 1803.01274)

(2) Calculations of Higgs mass
(arXiv:hep-ph/0603237 etc)

(3) GHU review
(Hosotani mechanism, finiteness of Higgs mass, SU(3) model etc)

(4) Higgs phenomenology@LHC in GHU (or future collider)

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(1) DM candidates in GHU ⇒ seminar
(arXiv:1704.04621, 1801.00686, 1803.01274)

(2) Calculations of Higgs mass ⇒ lecture
(arXiv:hep-ph/0603237 etc)

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(4) Higgs phenomenology@LHC in GHU (or future collider) ⇒ lecture

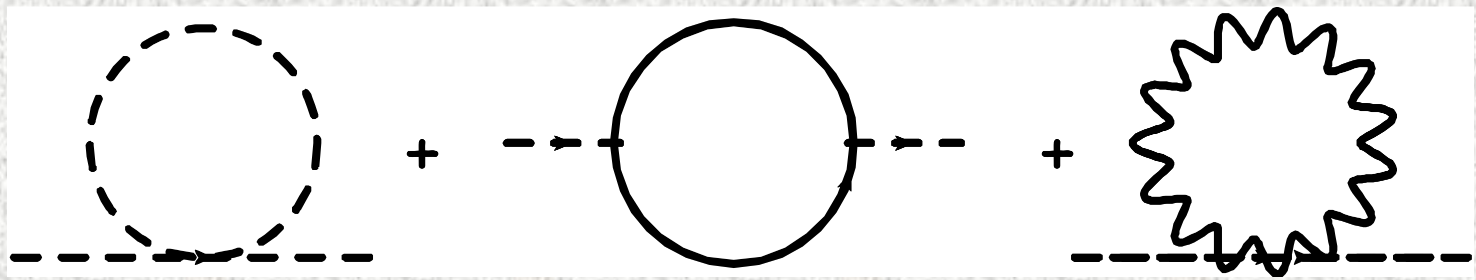
PLAN

- Introduction
- Higgs mass calculation
- Gauge-Higgs sector
- Matter content &
  Yukawa coupling
- EW symmetry breaking
- Summary

Introduction

One of the problems in the Standard Model:
Hierarchy Problem

Quantum corrections to the Higgs mass
is sensitive to the cutoff scale of the theory

$\delta m_H^2 =$  …

$$\delta m_H^2 \approx \frac{\Lambda^2}{16\pi^2}$$

Too large!!
(Natural cutoff scale is
Planck scale or GUT scale)

To get Higgs mass 125GeV,

an unnatural fine tuning of parameters are required

$$m_H^2 = m_0^2 + \delta m^2 \approx \mathcal{O}\left(\left(100GeV\right)^2\right)$$

classical　Quantum corrections

Naively, we have $m_0^2, \delta m^2 \approx \mathcal{O}\left(\left(10^{18}GeV\right)^2\right)$

32 digits of fine tuning

1.00000000000000000000000000000001

- 1.00000000000000000000000000000000 !!

Problem: We have NO symmetry forbidding the scalar mass

SUSY $\qquad \phi \leftrightarrow \psi$

Mass term is forbidden by chiral symmetry

Identified with Higgs in the SM

GHU $\qquad \mathcal{A}_5 \leftrightarrow \mathcal{A}_\mu$

Higher dimensional Lorentz invariance

Mass term is forbidden by the gauge symmetry

Higher dimensional gauge symmetry

Indeed, the (local) mass term A_5^2 can be forbidden by the gauge symmetry for 5th component of the gauge field

$$\because\ A_5 \to A_5 + \partial_5 \varepsilon(x,y) + i\left[\varepsilon(x,y), A_5\right]$$

In other words, no local counter term is allowed

⇒ No quadratic divergence, finite

This symmetry is very useful in the orbifold model since it is operative even on the branes $G \to H$

Gersdorff, Irges & Quiros (2002)

$$\because\ A_5 \to A_5 + \partial_5 \underbrace{\varepsilon_{G/H}(x,y)}_{Z_2\ \text{odd}} + i\left[\underbrace{\varepsilon_H(x,y)}_{Z_2\ \text{even}}, A_5\right]$$

No quadratic divergence from brane localized Higgs mass

Explicit calculations of Higgs mass

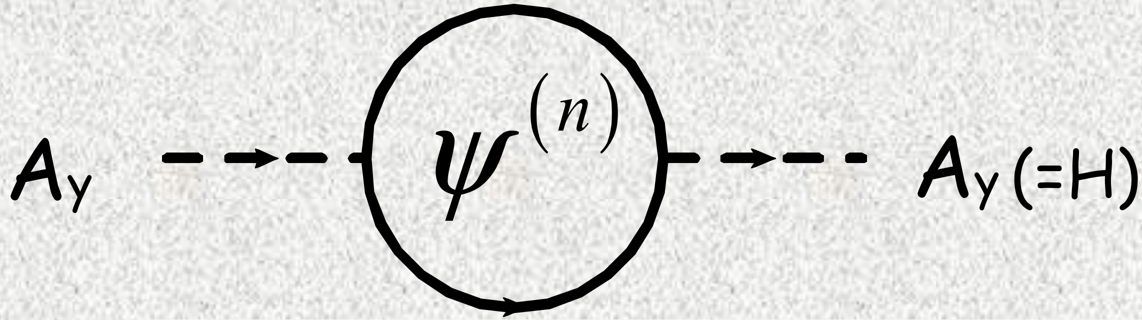
- D-dim QED on S^1@1-loop Hatanaka, Inami & Lim (1998)
- 5D Non-Abelian gauge theory on S^1/Z_2@1-loop
  Gersdorff, Irges & Quiros (2002)
- 6D Non-Abelian gauge theory on T^2@1-loop
  Antoniadis, Benakli & Quiros (2001)
- 6D Scalar QED on S^2@1-loop Lim, NM & Hasegawa (2006)
- 5D QED on S^1@2-loop
  NM & Yamashita (2006); Hosotani, NM, Takenaga & Yamashita (2007)
- 5D Gravity on S^1 (GGH) Hasegawa, Lim & NM (2004)

…

Higgs mass calculation

Consider (D+1)-dim QED on S^1

Hatanaka, Inami & Lim (1998)



$$m_H^2 = ie_D^2 \int \frac{d^D k}{(2\pi)^D} \sum_{n=-\infty}^{\infty} Tr\left[\gamma_y \frac{1}{\not{k}-m} \gamma^y \frac{1}{\not{k}-m}\right]$$

(No sum)

L=2πR

$$\xrightarrow{L\to\infty} \frac{i}{D+1} e_{D+1}^2 \int \frac{d^{D+1}k}{(2\pi)^{D+1}} Tr\left[\gamma_M \frac{1}{\not{k}-m} \gamma^M \frac{1}{\not{k}-m}\right] \left(M = 0,1,\cdots D\right)$$

$$= \frac{i}{D+1} e_{D+1}^2 2^{[(D+1)/2]} \int \frac{d^{D+1}k}{(2\pi)^{D+1}} \left[\frac{1-D}{k^2-m^2} - \frac{2m^2}{\left(k^2-m^2\right)^2}\right]$$

$$= \frac{i}{D+1} e_{D+1}^2 2^{[(D+1)/2]} \left(1-D+2m^2 \frac{\partial}{\partial m^2}\right) \int \frac{d^{D+1}k}{(2\pi)^{D+1}} \frac{1}{k^2-m^2}$$

$$= \frac{i}{D+1} e_{D+1}^2 2^{[(D+1)/2]} \frac{-i}{(4\pi)^{(D+1)/2}} \Gamma\left(\frac{1-D}{2}\right) \left(1-D+2m^2 \frac{\partial}{\partial m^2}\right) \left(m^2\right)^{(D-1)/2} = 0$$

Consider (D+1)-dim QED on S^1

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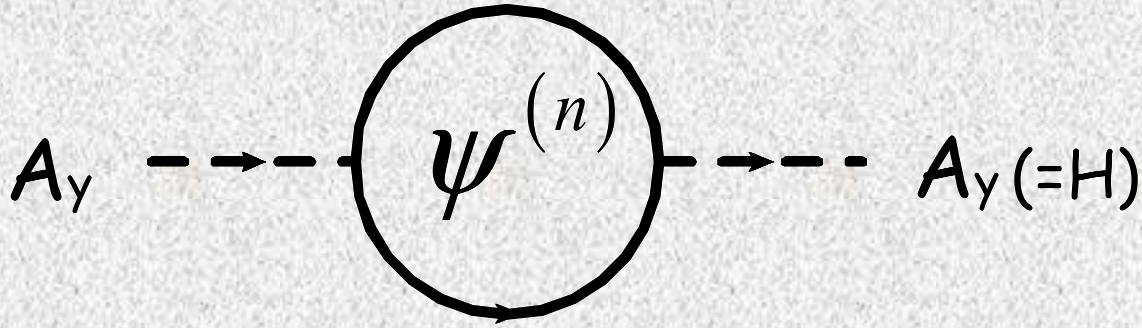


Boundary condition

$$\psi(x_\mu, y+L) = e^{i\alpha}\psi(x_\mu, y)$$

$$m_H^2 = ie_D^2 2^{[(D+1)/2]}\int \frac{d^Dk}{(2\pi)^D}\sum_{n=-\infty}^{\infty}\left[-\frac{1}{((2\pi n+\alpha)/L)^2+\rho^2}+\frac{2\rho^2}{\left[((2\pi n+\alpha)/L)^2+\rho^2\right]^2}\right]$$

$$= -ie_D^2 2^{[(D+1)/2]}\int \frac{d^Dk}{(2\pi)^D}\left(1+\rho\frac{\partial}{\partial\rho}\right)\left(\frac{L}{2\rho}\right)\frac{\sinh(\rho L)}{\cosh(\rho L)-\cos\alpha}$$

L=2πR

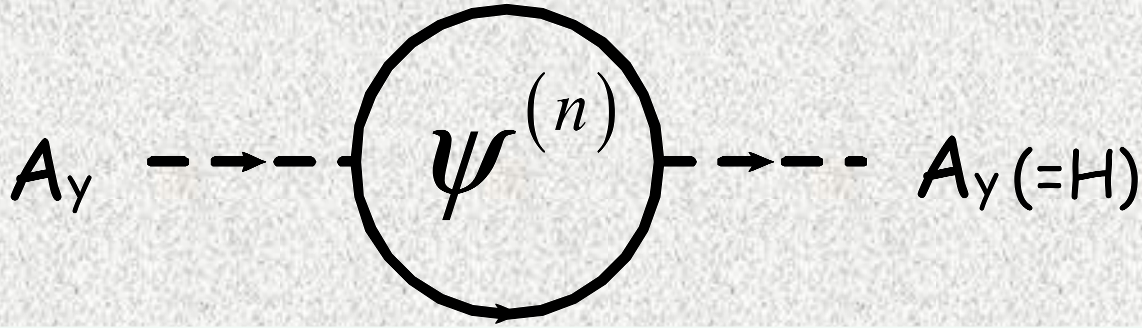
$$\rho^2 = -k^2 + m^2$$

$$\sum_n \frac{1}{\left(\frac{2\pi n+\alpha}{L}\right)^2+\rho^2} - L\int\frac{dk_y}{2\pi}\frac{1}{k_y^2+\rho^2} = \left(\frac{L}{2\rho}\right)\left[\frac{\sinh(\rho L)}{\cosh(\rho L)-\cos\alpha}-1\right]$$

Subtracting 0 in L→∞

Consider (D+1)-dim QED on S^1

Hatanaka, Inami & Lim (1998)



Boundary condition

$$\psi(x_\mu, y+L) = e^{i\alpha}\psi(x_\mu, y)$$

$$m_H^2 = ie_D^2\, 2^{[(D+1)/2]} \int \frac{d^D k}{(2\pi)^D} \sum_{n=-\infty}^{\infty} \left[-\frac{1}{((2\pi n+\alpha)/L)^2 + \rho^2} + \frac{2\rho^2}{\left[((2\pi n+\alpha)/L)^2 + \rho^2\right]^2} \right]$$

$$= -ie_D^2\, 2^{[(D+1)/2]} \int \frac{d^D k}{(2\pi)^D} \left(1+\rho\frac{\partial}{\partial\rho}\right)\left(\frac{L}{2\rho}\right) \frac{\sinh(\rho L)}{\cosh(\rho L) - \cos\alpha}$$

L=2πR

$$\rho^2 = -k^2 + m^2$$

$$= \frac{e_D^2 L^2}{2^{D-[(D+1)/2]}\pi^{D/2}\Gamma(D/2)} \int_0^\infty dk\; k_E^{D-1} \frac{1-\cosh\left(\sqrt{k_E^2+m^2}\,L\right)\cos\alpha}{\left[\cosh\left(\sqrt{k_E^2+m^2}\,L\right) - \cos\alpha\right]^2} < \infty$$

Superconvergent!!

Ex. take D=4 (5 dimension case) & m=0,α=π

$$m_H^2 = \frac{e_D^2 L^2}{2^{D-[(D+1)/2]}\pi^{D/2}\Gamma(D/2)} \int_0^\infty dk\, k_E^{D-1} \frac{1-\cosh\left(\sqrt{k_E^2+m^2}\,L\right)\cos\alpha}{\left[\cosh\left(\sqrt{k_E^2+m^2}\,L\right)-\cos\alpha\right]^2}$$

$$= \frac{e_4^2}{4\pi^2}\frac{1}{(2\pi R)^2}\int_0^\infty ds s^3 \left.\frac{1-\cosh s\cos\alpha}{\left[\cosh s-\cos\alpha\right]^2}\right|_{\alpha=\pi}$$

$$= \frac{9e_4^2}{16\pi^4 R^2}\zeta(3) = \frac{9e_4^2}{16\pi^4}\underbrace{\zeta(3)}_{1.2} m_W^2$$

$m_W = \pi/R$

Higgs mass is too small

→ generic prediction of GHU

Way out to get 125 GeV Higgs mass

1: Realizing small Higgs VEV $a \ll 1$
by choosing appropriate matter content

$$m_H \sim m_W/(4\pi a) \quad (m_W = a/R)$$

Haba, Hosotani, Kawamura & Yamashita (2004)
Adachi, NM (2018)

2: $D > 5$ dimensions

F_{ij}^2 contains the Higgs quartic coupling $g^2[A_i, A_j]^2$
Higgs mass is generated at leading order
$m_H = 2m_W$ is predicted in 6D on T^2/Z_3 model

Scrucca, Serone, Silvestrini & Wulzer (2003)

3: Warped dimension (ex. Randall-Sundrum model)

Higgs mass is enhanced by curvature scale $k\pi R \sim 30$
Contino, Nomura & Pomarol (2003)

Gauge-Higgs sector

Model building of the gauge-Higgs unification

A_5 is an SU(2) adjoint originally, not SU(2) doublet
⇒ need to enlarge the gauge group

$G \to SU(2)_L \times U(1)_Y$
adj → doublet + other reps

Simplest G
SU(3)

Consider 5D SU(3) model on S^1/Z_2 with Parity: P = diag (-,-,+)

$$PA_\mu(x, y_i - y)P^\dagger = A_\mu(x, y_i + y),\ PA_5(x, y_i - y)P^\dagger = -A_5(x, y_i + y)$$

$$A_\mu = \begin{pmatrix} (+,+) & (+,+) & (-,-) \\ (+,+) & (+,+) & (-,-) \\ (-,-) & (-,-) & (+,+) \end{pmatrix},\ A_5 = \begin{pmatrix} (-,-) & (-,-) & (+,+) \\ (-,-) & (-,-) & (+,+) \\ (+,+) & (+,+) & (-,-) \end{pmatrix}$$

Only (+,+) mode has massless mode ("0 mode")

$$A_\mu^{(0)} = \frac{1}{2}\begin{pmatrix} W_\mu^3 + B_\mu^3/\sqrt{3} & \sqrt{2}W_\mu^+ & 0 \\ \sqrt{2}W_\mu^- & -W_\mu^3 + B_\mu^3/\sqrt{3} & 0 \\ 0 & 0 & -2B_\mu/\sqrt{3} \end{pmatrix}, A_5^{(0)} = \frac{1}{2}\begin{pmatrix} 0 & 0 & H^+ \\ 0 & 0 & H^0 \\ H^- & H^{0*} & 0 \end{pmatrix}$$

SU(2) x U(1) gauge fields

Higgs doublets

mode expansions

$$A_M^{(+,+)}(x,y) = \frac{1}{\sqrt{2\pi R}}\left[A_M^{(0)}(x) + \sqrt{2}\sum_{n=1}^{\infty} A_M^{(n)}(x)\cos\left(\frac{n}{R}y\right)\right]$$

$$A_M^{(-,-)}(x,y) = \frac{1}{\sqrt{\pi R}}\sum_{n=1}^{\infty} A_M^{(n)}(x)\sin\left(\frac{n}{R}y\right)$$

Gauge boson spectrum

$$M_{W_n} = \frac{n+a}{R}, M_{Z_n} = \frac{n+2a}{R}, M_{\gamma_n} = \frac{n}{R}, \left\langle A_5^{(0)}\right\rangle = \frac{a}{g_5 R}$$

$$M_{W_n} = \frac{n+a}{R}, M_{Z_n} = \frac{n+2a}{R}, M_{\gamma_n} = \frac{n}{R}, \left\langle A_5^{(0)} \right\rangle = \frac{a}{g_5 R}$$

- W, Z, γ are identified with zero modes:

  $M_W = a/R$, $M_Z = 2a/R$, $M_\gamma = 0$

  $SU(2) \times U(1) \rightarrow U(1)$ realized

- $M_Z = 2M_W \rightarrow \cos\theta_W = \frac{1}{2}$

  $(\sin^2\theta_W = \frac{3}{4} \gg 0.23)$

- Non-zero KK modes of A_5 are eaten by non-zero KK modes of A_μ

  ("Higgs mechanism")

Hypercharge of the doublet

Check the hypercharge of Higgs doublet

$$\delta_{U(1)} A_5^{(0)} = g\left[T^8, A_5^{(0)}\right] = \frac{g}{2\sqrt{3}}\left[\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -2 \end{pmatrix}, \begin{pmatrix} 0 & 0 & H^+ \\ 0 & 0 & H^0 \\ H^- & H^{0*} & 0 \end{pmatrix}\right]$$

$$= \frac{g}{2\sqrt{3}}\begin{pmatrix} 0 & 0 & H^+ \\ 0 & 0 & H^0 \\ -2H^- & -2H^{0*} & 0 \end{pmatrix} - \frac{g}{2\sqrt{3}}\begin{pmatrix} 0 & 0 & -2H^+ \\ 0 & 0 & -2H^0 \\ H^- & H^{0*} & 0 \end{pmatrix} = \frac{g\sqrt{3}}{2}\begin{pmatrix} 0 & 0 & H^+ \\ 0 & 0 & H^0 \\ -H^- & -H^{0*} & 0 \end{pmatrix}$$

$$\Rightarrow \quad \sin^2\theta_W = \frac{g_Y^2}{g^2 + g_Y^2} = \frac{\left(\sqrt{3}g\right)^2}{g^2 + \left(\sqrt{3}g\right)^2} = \frac{3}{4} \neq 0.23(\text{Exp})$$

Too Big!!

Well-known by Fairlie, Manton (6D on S^2 w/ monopole bkgd)

	G_2	SO(5)	SU(3)
$\mathrm{Sin}^2\Theta_W$	1/4	1/2	3/4

Way out to get a correct Θ_W

1: Additional U(1) $SU(3)\times U(1)' \rightarrow SU(2)_L \times U(1)_Y \times U(1)_X$

Scrucca, Serone & Silvestrini (2003)

$$\boxed{A_Y = \frac{g' A_8 + \sqrt{3} g A'}{\sqrt{3g^2 + g'^2}},\ A_X = \frac{\sqrt{3} g A_8 - g' A'}{\sqrt{3g^2 + g'^2}} \Rightarrow g_Y = \frac{\sqrt{3} g g'}{\sqrt{3g^2 + g'^2}}}$$

$$\because\ A_8 = \frac{g' A_Y + \sqrt{3} g A_X}{\sqrt{3g^2 + g'^2}} \Rightarrow g A_8 \supset \frac{g'}{\sqrt{3g^2 + g'^2}} g A_Y$$

$$\Rightarrow \quad \boxed{\sin^2\theta_W = \frac{g_Y^2}{g^2 + g_Y^2} = \frac{3}{4 + 3g^2/g'^2}}$$

Way out to get a correct Θ_W

2: Localized gauge kinetic terms

$$\mathcal{L} = -\frac{1}{2g_5^2} TrF_{MN}F^{MN} - \underbrace{\left[\frac{1}{2g_4^2}\delta(y) + \frac{1}{2g_4'^2}\delta(y-\pi R)\right] TrF_{\mu\nu}F^{\mu\nu}}_{\text{SU(2) x U(1) invariant}}$$

SU(3) invariant

SU(2) x U(1) invariant

4D effective Gauge coupling

$$\frac{1}{g_{eff}^2} = \frac{1}{g_5^2}\int_0^{\pi R} dy \left(f_{A_\mu}^{(0)}(y)\right)^2 + \frac{1}{g_4^2} + \frac{1}{g_4'^2}$$

By tuning g_4, g'_4, $\sin\Theta_W$ is adjustable

Matter Content
$
Yukawa Coupling

Quark & Lepton embedding

Consider a fundamental rep of SU(3)

$\mathbf{3}$ = $(q, q-1, 1-2q)^T$ (q: electric charge)

Putting q=2/3, we get

$\mathbf{3} = \mathbf{2}_{1/6} + \mathbf{1}_{-1/3} = (2/3, -1/3, -1/3)^T = (u_L, d_L, d_R)^T$

This can be obtained by Z_2 parity as

$$\psi(-y) = P\gamma_5\psi(y), \quad P = diag(-,-,+)$$

Only fundamental reps cannot incorporate right-handed up-type quarks as well as leptons

Quark & Lepton embedding

Only fundamental reps cannot incorporate right-handed up-type quarks as well as leptons

As one of the embeddings, tensor product is useful

$$\psi(-y)=(P\otimes P)\gamma_5\psi(y),\ \ \psi(-y)=(P\otimes P\otimes P)\gamma_5\psi(y)$$

2-rank sym: $\mathbf{6^*} = \begin{cases} \mathbf{3}_{L-1/3} + \mathbf{2}_{L1/6}\,(Q) + \mathbf{1}_{L2/3} \\ \mathbf{3}_{R-1/3} + \mathbf{2}_{R1/6} + \mathbf{1}_{R2/3}\,(u_R) \end{cases}$

3-rank sym: $\mathbf{10} = \begin{cases} \mathbf{4}_{L1/2} + \mathbf{3}_{L0} + \mathbf{2}_{L-1/2}\,(L) + \mathbf{1}_{L-1} \\ \mathbf{4}_{R1/2} + \mathbf{3}_{R0} + \mathbf{2}_{R-1/2} + \mathbf{1}_{R-1}\,(e_R) \end{cases}$

Many massless exotics ⇒ brane localized mass term

Big Hurdle

In the gauge-Higgs unification,

Yukawa coupling = gauge coupling

How can we get fermion mass hierarchy???

As will be shown below,
fermion masses except for top quark are relatively easy

1: Localizing fermions@different point in 5th direction

Yukawa ~ exponentially suppressed overlap integral

Arkani-Hamed & Schmaltz (1999)

2: Bulk fermions mixed with localized fermions
@the fixed points

Non-local Yukawa coupling

Csaki, Grojean & Murayama (2002)

1: Yukawa coupling from localizing fermions @different points

1: To localize fermions at different points along the 5th direction, bulk masses are introduced

2: To be consistent with Z2 orbifold, Z2 parity of bulk mass must be odd ⇒ kink mass

Consider a 5D fermion satisfying the following Dirac equation

$$0=\left[i\Gamma^M D_M - M\varepsilon(y)\right]\psi(x,y)$$

$$D_M=\partial_M - igA_M, \Gamma^M=\left(\gamma^\mu, i\gamma^5\right), (M=0,1,2,3,5), \varepsilon(y)=\begin{cases}1\ (y>0)\\ -1\ (y<0)\end{cases}$$

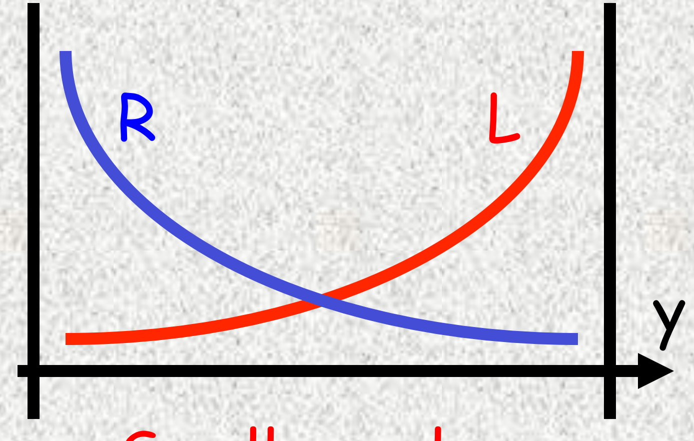
Focusing zero modes

$$\psi(x,y):\ \psi^{(0)}_{L(R)}(x)\, f^{(0)}_{L(R)}(y),\ \gamma^5\psi_{L(R)}=(-)\psi_{L(R)}$$

Zero mode wave functions

$$0=\left[\partial_y - M\varepsilon(y)\right]f_L^{(0)}(y) \to f_L^{(0)}(y)=\sqrt{\frac{M}{e^{2\pi MR}-1}}e^{M|y|}$$

$$0=\left[\partial_y + M\varepsilon(y)\right]f_R^{(0)}(y) \to f_R^{(0)}(y)=\sqrt{\frac{M}{1-e^{-2\pi MR}}}e^{-M|y|}$$



4D effective Yukawa coupling

$$Y=g_4\int_0^{\pi R} dy f_L^{(0)}(y) f_R^{(0)}(y) = g_4 \int_0^{\pi R} dy \sqrt{\frac{M^2}{\left(1-e^{-2\pi MR}\right)\left(e^{2\pi MR}-1\right)}}$$

$$\approx \pi MRg_4 e^{-\pi MR} \le g_4 \Leftrightarrow m_f \le m_W$$

$\pi MR \gg 1$

Fermion masses except top is easy, but top is hard
No need of unnatural fine-tuning for 5D parameters M,R

2: Mixing between bulk and boundary localized fermions

Csaki, Grojean & Murayama (2002)

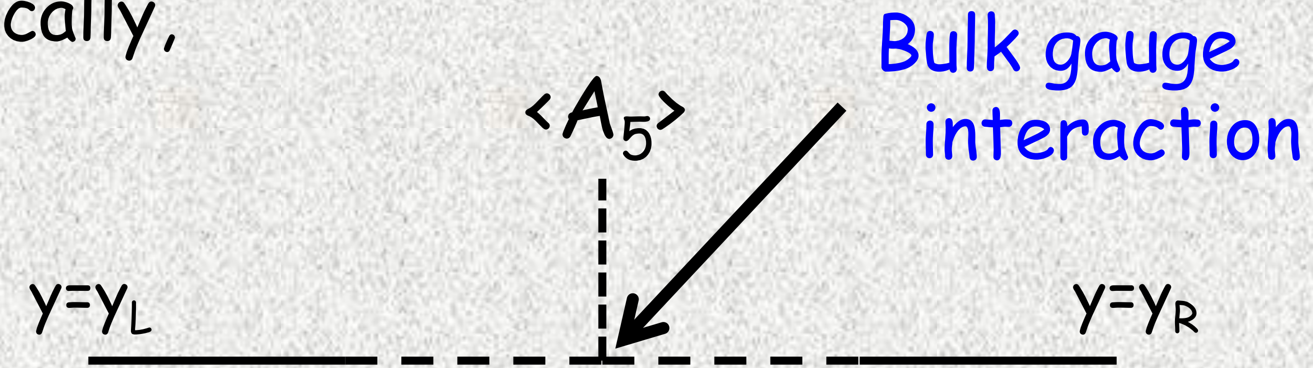
Consider the massive bulk fermion
coupling to SM fermions on the branes

$$\mathcal{L}_{Bulk} = \bar{\Psi} i \not{D} \Psi + \bar{\tilde{\Psi}} i \not{D} \tilde{\Psi} - M\left(\bar{\Psi}\tilde{\Psi} + \bar{\tilde{\Psi}}\Psi\right) \qquad \Psi \supset \psi^d, \chi^s$$

$$\mathcal{L}_{Brane} = \delta\left(y - y_L\right)\left[i\bar{Q}_L \bar{\sigma}^\mu \partial_\mu Q_L + \frac{\varepsilon_L}{\sqrt{\pi R}} \bar{\psi}^d Q_L + h.c. \right] + \delta\left(y - y_R\right)\left[i\bar{q}_L \bar{\sigma}^\mu \partial_\mu q_L + \frac{\varepsilon_R}{\sqrt{\pi R}} \bar{q}_R \chi^s + h.c. \right]$$

Mixing mass term between bulk & brane fermions

Schematically,



$$\frac{\varepsilon_L}{\sqrt{\pi R}} \bar{\psi}^d Q_L \qquad \bar{\psi}^d A_5 \chi^s \qquad \frac{\varepsilon_R}{\sqrt{\pi R}} \bar{q}_R \chi^s$$

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$$\mathcal{L}_{Brane} = \delta\left(y - y_L\right)\left[i\bar{Q}_L \bar{\sigma}^\mu \partial_\mu Q_L + \frac{\varepsilon_L}{\sqrt{\pi R}} \bar{\psi}^d Q_L + h.c. \right] + \delta\left(y - y_R\right)\left[i\bar{q}_L \bar{\sigma}^\mu \partial_\mu q_L + \frac{\varepsilon_R}{\sqrt{\pi R}} \bar{q}_R \chi^s + h.c. \right]$$

Mixing mass term between bulk & brane fermions

Integrating out massive fermion generates mass term as

$$\varepsilon_L \varepsilon_R \pi M R e^{-\pi M R} \bar{q}_R e^{ig\int_0^{\pi R} dy A_y} Q_L \Rightarrow m_f \propto \varepsilon_L \varepsilon_R \pi M R e^{-\pi M R} M_W$$

Exponentially suppressed coupling
$\Rightarrow$ easy to generate fermion masses except for top

How do we obtain top mass???

Top mass generation

Cacciapaglia, Csaki & Park (2005)

Consider large dimensional reps,
then an upper bound on fermion mass is modified as follows

$$m_t \leq \sqrt{n}\, m_W$$

(n: # of indices of rep)

For $m_t = 2m_W \Rightarrow$ need a **4-index** rep top is embedded
To saturate this bound, bulk mass should be zero

Simplest example: 

$(\mathbf{15^*})_{-2/3} \longrightarrow (\mathbf{1}, 2/3)(t_R) + (\mathbf{2}, 1/6)(t_L)$
$+ (\mathbf{3}, -1/3) + (\mathbf{4}, -5/6) + (\mathbf{5}, -4/3)$

$\sqrt{N}$ enhancement

Consider a rank N symmetric tensor of SU(3)

			...	

N boxes

Decompose it into SU(2) reps as 3 = 2 + 1

and make a singlet & a doublet

singlet	1	1	1	...	1	unique
doublet	1	1	2	...	1	etc N patterns

Canonical kinetic term ⇒ $1/\sqrt{N}$

$$\text{Yukawa} = 1_R\, 2_L\, 2_H \Rightarrow N \times 1/\sqrt{N} = \sqrt{N}$$

Fermion matter content

$3 = 2_{L1/6}(Q) + 1_{L-1/3}$
$\quad 2_{R1/6} + 1_{R-1/3}(d_R)$

Down quark sector

$6^* = 3_{L-1/3} + 2_{L1/6}(Q) + 1_{L2/3}$
$\quad 3_{R-1/3} + 2_{R1/6} + 1_{R2/3}(u_R)$

Up quark sector (except for top)

$10 = 4_{L1/2} + 3_{L0} + 2_{L-1/2}(L) + 1_{L-1}$
$\quad 4_{R1/2} + 3_{R0} + 2_{R-1/2} + 1_{R-1}(e_R)$

Charged lepton sector

$15^* = 5_{L-4/3} + 4_{L-5/6} + 3_{L-1/3} + 2_{L1/6}(Q) + 1_{L2/3}$
$\quad 5_{R-4/3} + 4_{R-5/6} + 3_{R-1/3} + 2_{R1/6} + 1_{R2/3}(t_R)$

Top quark

Unwanted massless exotics (blue reps) & two extra Qs must be massive by brane localized mass terms

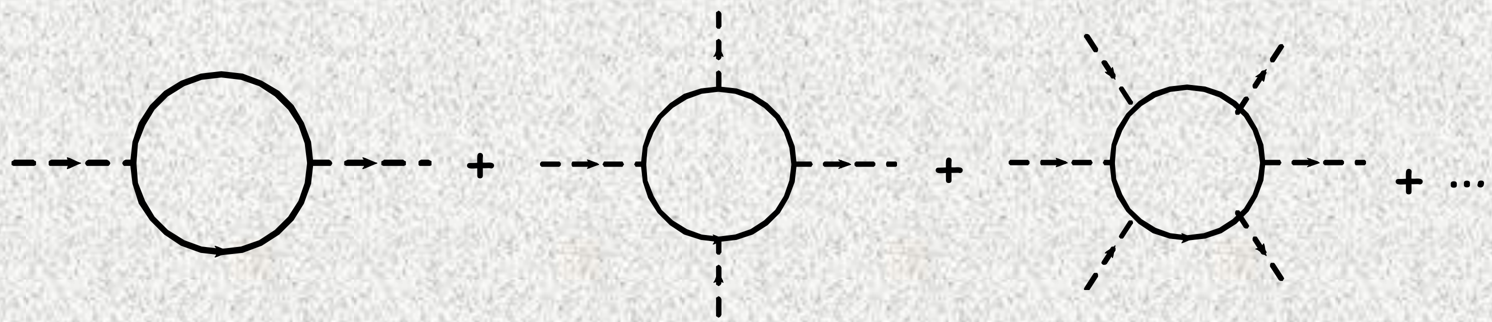
EW symmetry breaking

Electroweak symmetry breaking

In GHU, EW symmetry is dynamically broken
by the Hosotani mechanism Hosotani (1983,1989)

Higgs potential is radiatively generated
since the tree level potential is forbidden
by gauge invariance (Coleman-Weinberg potential)

$V(A_5)$ =



$$V(a) = (-1)^F \frac{(\mathrm{DOF})}{2} \int \frac{d^4 p_E}{(2\pi)^4} \frac{1}{2\pi R} \sum_n \log\left(p_E^2 + m_n^2\right)$$

KK mass

Calculation of the effective potential (Adj rep)

$$I(a) \equiv \int \frac{d^4 p}{(2\pi)^4} \sum_{n=-\infty}^{\infty} \log\left[p^2 + \left(\frac{n+a}{R}\right)^2 \right]$$

$$\frac{dI(a)}{da} = \frac{2}{R} \int \frac{d^4 p}{(2\pi)^4} \sum_{n=-\infty}^{\infty} \frac{\left(\frac{n+a}{R}\right)}{p^2 + \left(\frac{n+a}{R}\right)^2} = \frac{2}{R} \int \frac{d^4 p}{(2\pi)^4} \sum_{n=-\infty}^{\infty} \left(\frac{n+a}{R}\right) \int_0^{\infty} dt \exp\left[-\left\{ p^2 + \left(\frac{n+a}{R}\right)^2 \right\} t \right]$$

$$= \frac{2}{R} \sum_{n=-\infty}^{\infty} \frac{n+a}{R} \int_0^{\infty} dt \frac{1}{(4\pi t)^2} \exp\left[-\left(\frac{n+a}{R}\right)^2 t \right]$$

$$= \frac{2}{R} \frac{1}{(4\pi)^2} \int_0^{\infty} dt \frac{1}{t^2} \sum_{n=-\infty}^{\infty} R^2 \sqrt{\frac{\pi}{t^3}} i\pi n \exp\left[-\frac{(\pi R n)^2}{t} - 2\pi i n a \right] = \frac{3R}{16(\pi R)^5} \sum_{n=1}^{\infty} \frac{1}{n^4} \sin(2\pi n a)$$

$$\Rightarrow I(a) = -\frac{3R}{32\pi^6 R^5} \sum_{n=1}^{\infty} \frac{1}{n^5} \cos(2\pi n a) + (\text{a-independent})$$

Poisson resummation

$$\sum_{n=-\infty}^{\infty} \left(\frac{n+a}{R}\right) \exp\left[-\left(\frac{n+a}{R}\right)^2 t \right] = \sum_{m=-\infty}^{\infty} R^2 \sqrt{\frac{\pi}{t^3}} (i\pi m) \exp\left[-\frac{(\pi R m)^2}{t} - 2\pi i m a \right]$$

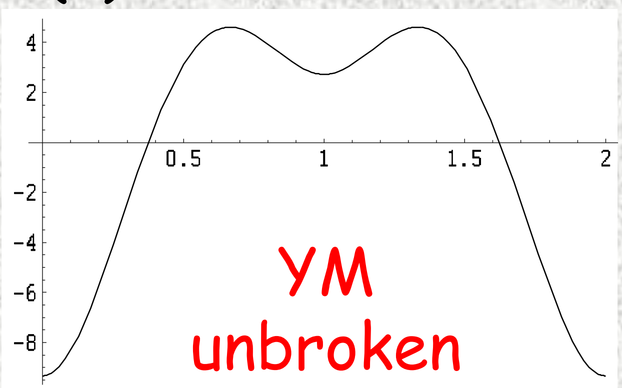
Ex. 5D SU(3) model on S^1/Z_2 with N_f fundamental & N_a adjoint fermions

Kubo, Lim & Yamashita (2002)

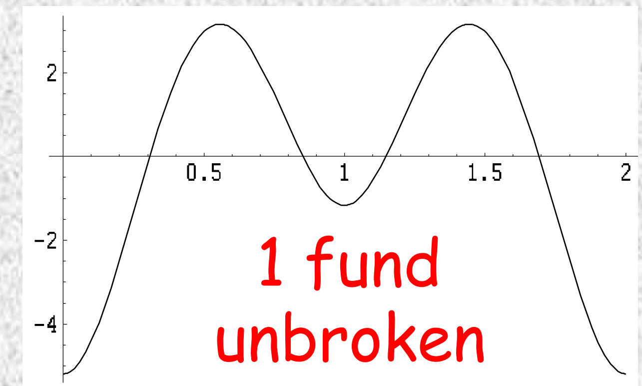
$$V(a)=\frac{3}{128\pi^7 R^5}\sum_{n=1}^{\infty}\frac{1}{n^5}\Big[(4N_a-3)\underbrace{\big(\cos[2\pi na]+2\cos[\pi na]\big)}_{\text{adjoint}}+4N_f\underbrace{\cos[\pi na]}_{\text{fund}}\Big]$$

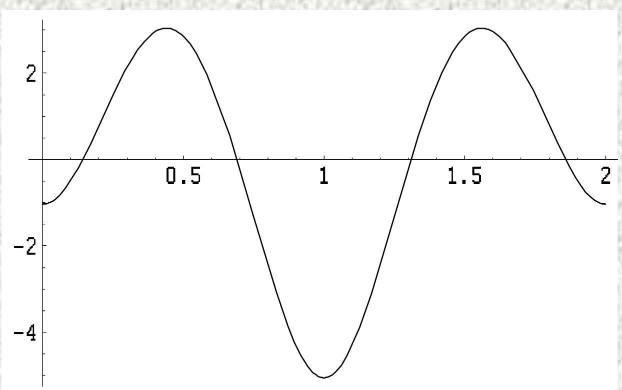
Gauge + ghost

V(a)



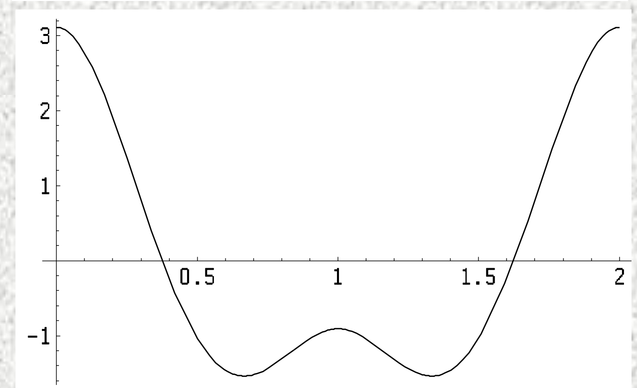
a





2 fund

SU(2)xU(1) -> U(1)xU(1)



1 adj

SU(2)xU(1) -> U(1)

Wilson line phase

$$W = \mathcal{P}\exp\left(ig\oint_{S^1} dy A_5\right) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos(\pi a) & i\sin(\pi a) \\ 0 & i\sin(\pi a) & \cos(\pi a) \end{pmatrix} \quad (a \bmod 2) = \begin{cases} SU(2)\times U(1) \text{ for a = 0} \\ U(1)' \times U(1) \text{ for a = 1} \\ U(1)_{em} \text{ for other cases} \end{cases}$$

$$\langle A_5 \rangle = \frac{a}{gR}\frac{T^6}{2} \equiv A_5^{6(0)}\frac{T^6}{2}$$

$$T^3 = diag(1,-1,0)$$

$$T^8 = diag(1,1,-2)/\sqrt{3}$$

$$a = 1 : W = diag(1,-1,-1) \Rightarrow \left[W, T^3\right] = \left[W, T^8\right] = 0$$

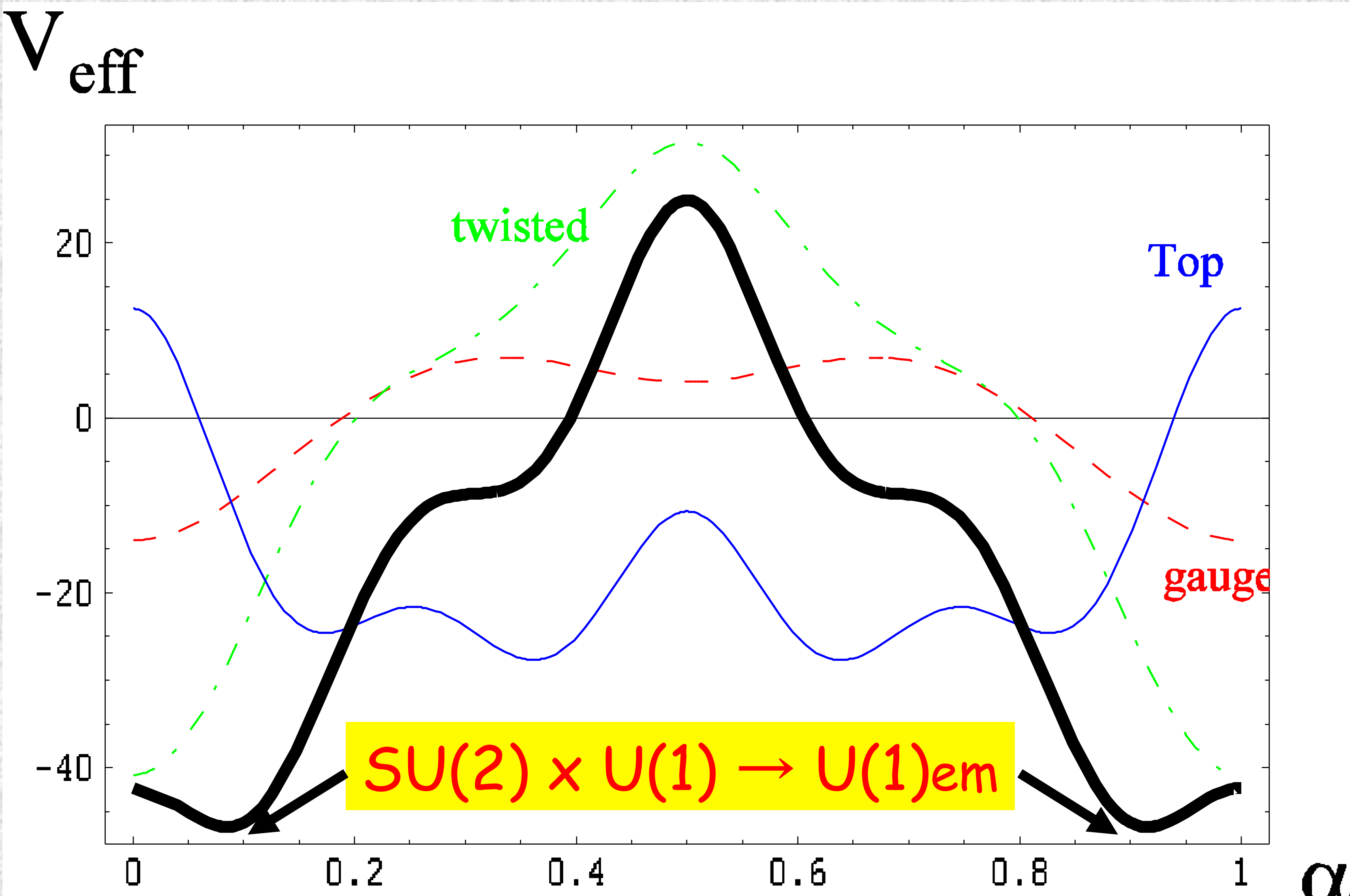
U(1) x U(1)' unbroken

$$0 < a < 1 : \left[W, \sqrt{3}T^3 + T^8\right] = \left[W, \sin\theta_W T^3 + \cos\theta_W T^8\right] = 0$$

U(1)em unbroken

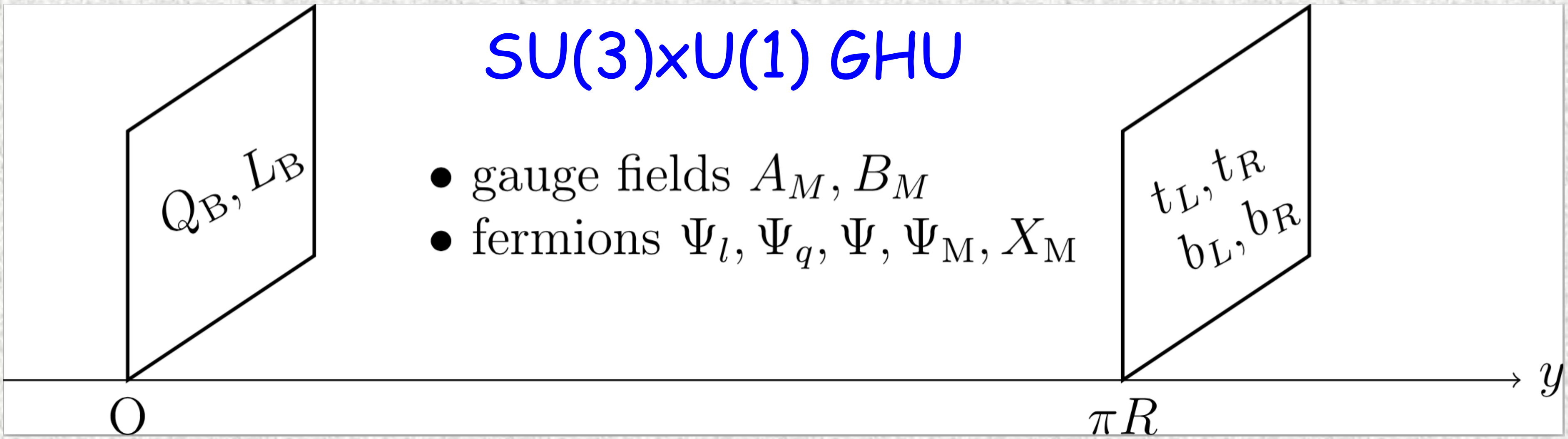
Higgs potential (top (15*) + bottom (3) + tau (10))

Cacciapaglia, Csaki & Park (2005)



Simplified model

Adachi &NM, PRD98 (2018) 015022



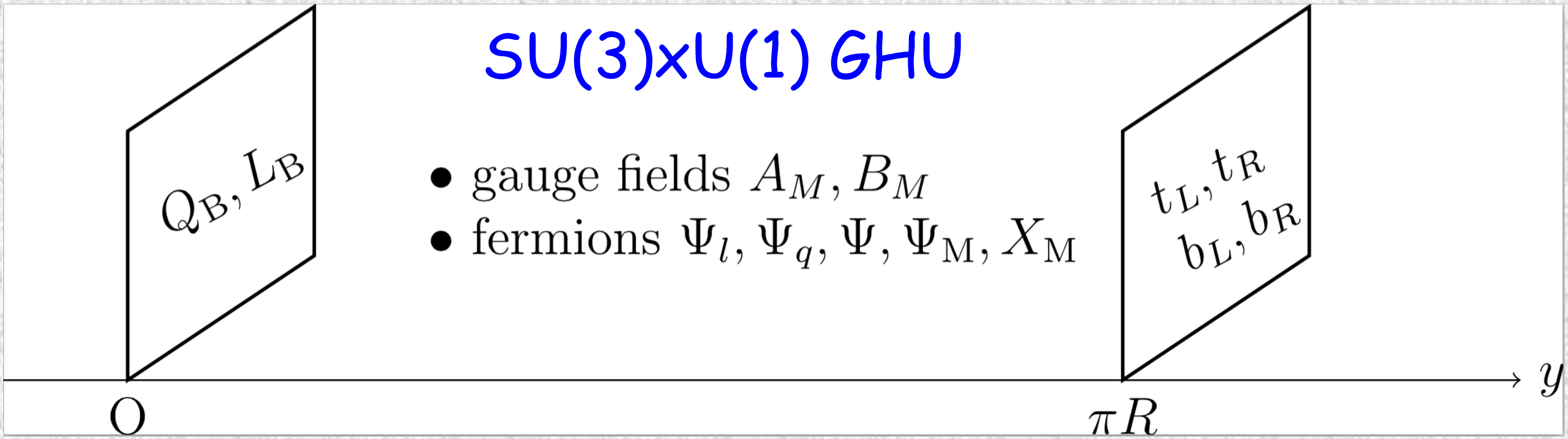
- 3rd generation quarks: $(t_L, b_L)^T$, t_R, b_R
  brane localized fermions@y=πR
- Messenger fermions: Ψ(3(b), 15*(t))

  linear combination of Q_{3R} & Q_{15^*R} couple to (t_L, b_L)

  B_{3L} & T_{15^*L} couple to b_R, & t_R

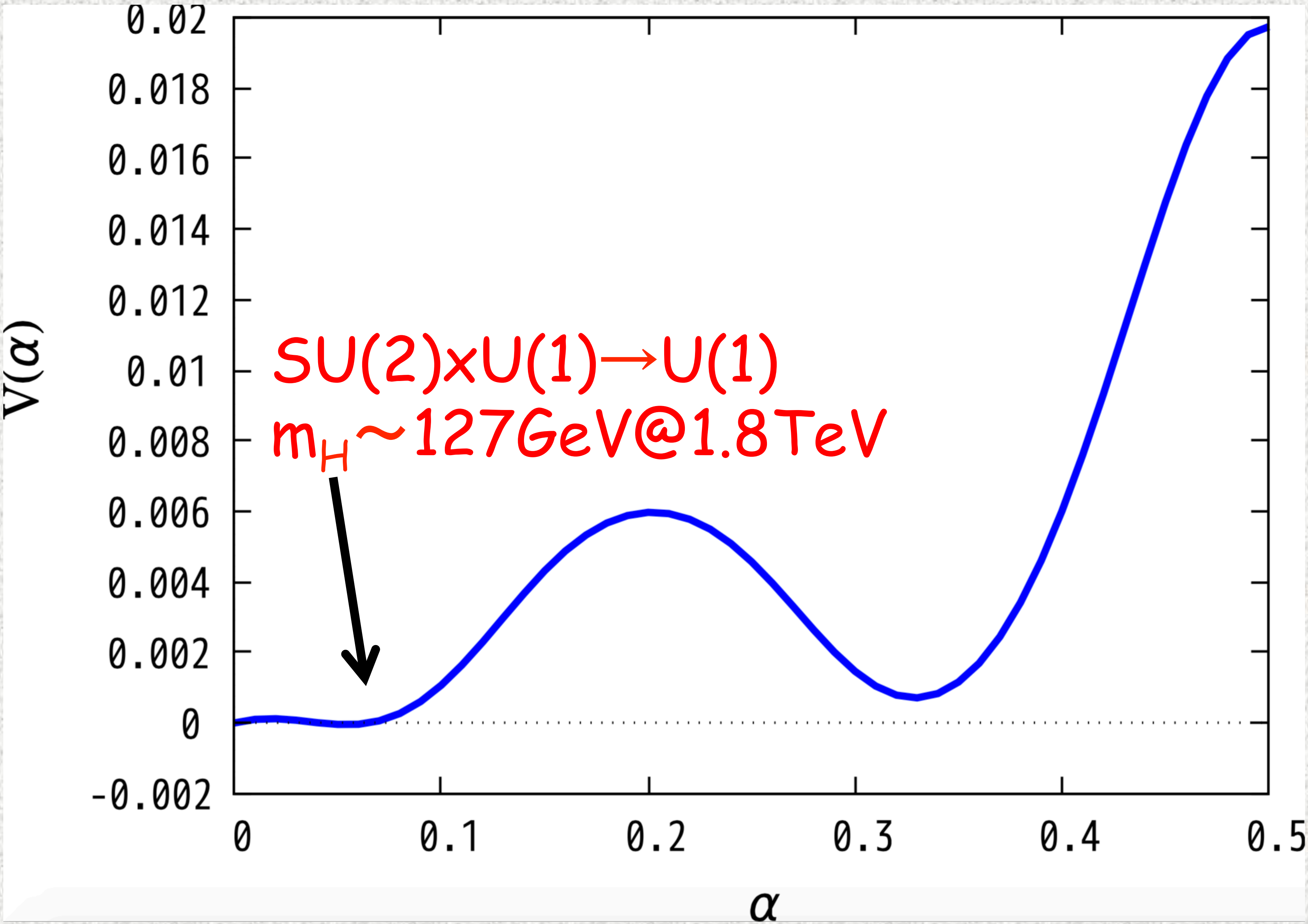
Simplified model

Adachi &NM, PRD98 (2018) 015022



- 1^{st} & 2^{nd} generations of q & l: bulk fields (3, 3*)
  3(Q, d_R), 3*(Q, u_R), 3(L, e_R), 3*(L, ν_R)
- Q_B, L_B: brane localized fermions@y=0
  to remove exotic SU(2) doublets
- Mirror fermions: Ψ_M, X_M (15*, 15*) for EWSB

EW symmetry breaking & Higgs mass



Summary

- Gauge-Higgs unification is a very attractive scenario beyond the SM alternative to SUSY

- Controlled by gauge principle & very predictive

  Higgs mass, potential → finite

- Yukawas except for top are easy,

  but top Yukawa is hard to generate

- EWSB @loop level

  Once the matter content is fixed,
  1/R is a unique free parameter in Higgs potential
  ⇒ very predictive contrary to SM case

Backup Slides

Sample points

α	$1/R$	f	m_H	m_t	m_t'
0.08	1 TeV	31% 42%	110 125 GeV	113 110 GeV	189 186 GeV
0.05	1.6 TeV	11% 14%	120 133 GeV	149 149 GeV	381 375 GeV
0.04	2 TeV	7% 9%	124 136 GeV	154 154 GeV	519 514 Gev
0.03	2.7 TeV	4% 5%	128 140 GeV	157 157 GeV	753 746 Gev
0.02	4 TeV	2% 2%	134 144 GeV	159 159 GeV	1224 1213 Gev

Fine-tuning required to obtain the potential minimum

Model A (top low)
Model B (bottom low)

Flavor Mixing

"Flavor Mixing in Gauge-Higgs Unification"
Adachi, Kurahashi, Lim and NM, JHEP1011 (2010) 015

"D^0-D^0bar Mixing in Gauge-Higgs Unification"
Adachi, Kurahashi, Lim and NM, JHEP1201 (2012) 047

"B^0-B^0bar Mixing in Gauge-Higgs Unification"
Adachi, Kurahashi, NM and Tanabe, PRD85 (2012) 096001

$$\mathcal{L} = -\frac{1}{4}F^{MN}F_{MN} - \frac{1}{4}B^{MN}B_{MN} - \frac{1}{4}G^{MN}G_{MN}$$
$$+\bar{\psi}_3^{1,2}\left(i\not{D} - M^{1,2}\varepsilon(y)\right)\psi_3^{1,2} + \bar{\psi}_{\bar{6}}^{1,2}\left(i\not{D} - M^{1,2}\varepsilon(y)\right)\psi_{\bar{6}}^{1,2}$$
$$+\bar{\psi}_3 i\not{D}\psi_3 + \bar{\psi}_{\overline{15}} i\not{D}\psi_{\overline{15}}$$
$$+\delta(y)\sqrt{2\pi R}\bar{Q}_R^i(x)\left[\eta_{ij}Q_{3L}^j(x,y) + \lambda_{ij}Q_L^j(x,y)\right](i,j=1,2,3)$$
$$+\text{brane mass terms for exotics} \qquad Q_L = \left(Q_{6L}^1, Q_{6L}^2, Q_{15L}\right)^T$$

- Brane mass matrices η, λ :
  off-diagonal elements ⇨ Flavor mixing
- Brane localized fields Q_R
- $M^3 = 0$ to avoid $m_\psi \sim M_W \exp[-\pi MR]$

$$\mathcal{L}_{\rm BM}^{\rm Q} \sim \delta(y)\bar{Q}_R\begin{bmatrix}\eta & \lambda\end{bmatrix}\begin{bmatrix}Q_3\\ Q\end{bmatrix}_L = \delta(y)\bar{Q}'_R\begin{bmatrix}m_{diag} & 0_{3\times3}\end{bmatrix}\begin{bmatrix}Q_H\\ Q_{SM}\end{bmatrix}_L$$

$$\begin{bmatrix}Q_3\\ Q\end{bmatrix}_L = \begin{bmatrix}U_1 & U_3\\ U_2 & U_4\end{bmatrix}\begin{bmatrix}Q_H\\ Q_{SM}\end{bmatrix}_L, \quad U^{\bar{Q}}Q_R = Q'_R$$

$$\mathcal{L}_{Yukawa} = g_5 A_y^6 \bar{d}^i Q_3^i + g_5 A_y^6 \bar{u}^i Q^i \leftarrow \text{Gauge interaction}$$

$$\rightarrow g_5\langle A_y^6\rangle\left(\bar{d}_R^{i(0)} Y_d^{ii} U_3^{ij} Q_{SM}^{j(0)} + \bar{u}_R^{i(0)} Y_u^{ii} U_4^{ij} Q_{SM}^{j(0)}\right)$$

$$Y^{ii} = \int_{-\pi R}^{\pi R} dy f_L^{i(0)} f_R^{i(0)} \approx 2\pi R M^i e^{-\pi R M^i}$$

Diagonalization

$$\begin{cases}\hat{Y}_d = V_{dR}^\dagger Y_d U_3 V_{dL}\\ \hat{Y}_u = V_{uR}^\dagger Y_u U_4 V_{uL}\end{cases} \quad V_{CKM} = V_{uL}^\dagger V_{dL} \quad \left(U_3^\dagger U_3 + U_4^\dagger U_4 = 1_{3\times3}\right)$$

$M_{3,6} \propto 1$ ($Y_{u,d} \propto 1$) case (flavor symmetry restored)

$$\begin{cases} \hat{Y}_d = V_{dR}^{\dagger} Y_d U_3 V_{dL} \to V_{dR}^{\dagger} U_3 V_{dL} \Rightarrow \hat{Y}_d^{\dagger} \hat{Y}_d = V_{dL}^{\dagger} U_3^{\dagger} U_3 V_{dL} \\ \hat{Y}_u = V_{uR}^{\dagger} Y_u U_4 V_{uL} \to V_{uR}^{\dagger} U_4 V_{uL} \Rightarrow \hat{Y}_u^{\dagger} \hat{Y}_u = V_{uL}^{\dagger} U_4^{\dagger} U_4 V_{uL} \end{cases}$$

$$\xrightarrow{U_3^{\dagger} U_3 + U_4^{\dagger} U_4 = 1} V_{uL} \propto V_{dL}$$

$$\Rightarrow V_{CKM} = V_{uL}^{\dagger} V_{dL} \propto V_{dL}^{\dagger} V_{dL} = 1 \left(\text{No mixing}\right)$$

Lesson

To get flavor mixing,
we need non-degenerate bulk masses
as well as the off-diagonal brane masses
(specific to gauge-Higgs unification)

Parametrization of Unitary matrices $U_{3,4}$ (CP violation ignored)

$$U_4 = R_u \begin{pmatrix} a_1 & 0 & 0 \\ 0 & a_2 & 0 \\ 0 & 0 & a_3 \end{pmatrix}, U_3 = R_d \begin{pmatrix} \sqrt{1-a_1^2} & 0 & 0 \\ 0 & \sqrt{1-a_2^2} & 0 \\ 0 & 0 & \sqrt{1-a_3^2} \end{pmatrix}$$

$$R_u = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_2' & \sin\theta_2' \\ 0 & \sin\theta_2' & \cos\theta_2' \end{pmatrix} \begin{pmatrix} \cos\theta_3' & 0 & \sin\theta_3' \\ 0 & 1 & 0 \\ -\sin\theta_3' & 0 & \cos\theta_3' \end{pmatrix} \begin{pmatrix} \cos\theta_1' & -\sin\theta_1' & 0 \\ \sin\theta_1' & \cos\theta_1' & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$R_d = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_2 & \sin\theta_2 \\ 0 & \sin\theta_2 & \cos\theta_2 \end{pmatrix} \begin{pmatrix} \cos\theta_3 & 0 & \sin\theta_3 \\ 0 & 1 & 0 \\ -\sin\theta_3 & 0 & \cos\theta_3 \end{pmatrix} \begin{pmatrix} \cos\theta_1 & -\sin\theta_1 & 0 \\ \sin\theta_1 & \cos\theta_1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Physical observables: 6 quark masses + 3 CKM angles

# of parameters: $a_{1,2,3}$, $b_{1,2,3} = I_{RL}^{1,2(00)}$, $\theta_{1,2,3}$, $\theta'_{1,2,3}$

⇒ 11-9=2 free parameters (6-5=1 for 2 generations)

Parameter fitting

Numerical results reproducing quark masses & mixings
(2 parameter scan technically hard
$\Rightarrow$ 3 angles fixed & m_t unfixed)

(i) No up-type mixing case

$$R_u = 1_{3\times3} : a_1^2 \approx 0.1023,\ b_1^2 \approx 4.335\times10^{-9},\ \sin\theta_1 \approx -2.587\times10^{-2}$$
$$a_2^2 \approx 0.9887,\ b_2^2 \approx 1.302\times10^{-4},\ \sin\theta_2 \approx 2.224\times10^{-2}$$
$$a_3^2 \approx 0.9966,\ \sin\theta_3 \approx 2.112\times10^{-4}$$

(ii) No down-type mixing case

$$R_d = 1_{3\times3} : a_1^2 \approx 0.0650,\ b_1^2 \approx 3.973\times10^{-9},\ \sin\theta_1' \approx 0.6704$$
$$a_2^2 \approx 0.9931,\ b_2^2 \approx 2.235\times10^{-4},\ \sin\theta_2' \approx -3.936\times10^{-2}$$
$$a_3^2 \approx 0.9966,\ \sin\theta_3' \approx 1.773\times10^{-2}$$

FCNC @tree level

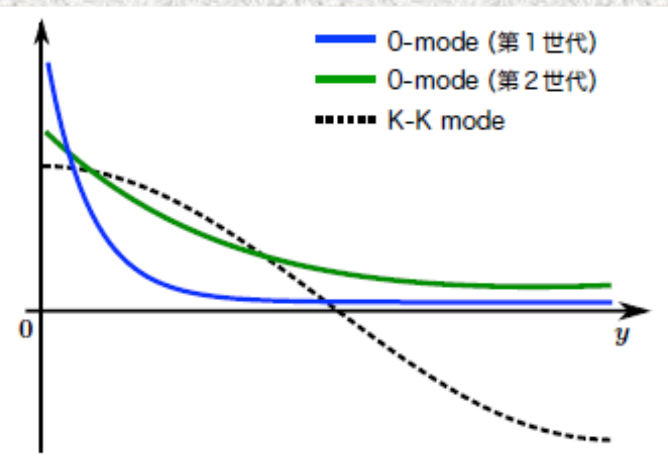
FCNC@tree level even in QCD sector

$$\mathcal{L}_{strong} \supset \frac{g_s}{\sqrt{2\pi R}} G_\mu^{(0)} \left(\bar{\psi}_R^{i(0)} \gamma^\mu \psi_R^{i(0)} + \bar{\psi}_L^{i(0)} \gamma^\mu \psi_L^{i(0)} \right)$$
$$+ g_s G_\mu^{(n)} \bar{\psi}_R^{i(0)} \gamma^\mu \psi_R^{j(0)} \left(V_{dR}^\dagger I_{RR}^{(0n0)} V_{dR} \right)_{ij}$$
$$+ g_s G_\mu^{(n)} \bar{\psi}_L^{i(0)} \gamma^\mu \psi_L^{j(0)} \left[V_{dL}^\dagger \left(U_3^\dagger I_{LL}^{(0n0)} U_3 + U_4^\dagger I_{LL}^{(0n0)} U_4 \right) V_{dL} \right]_{ij}$$

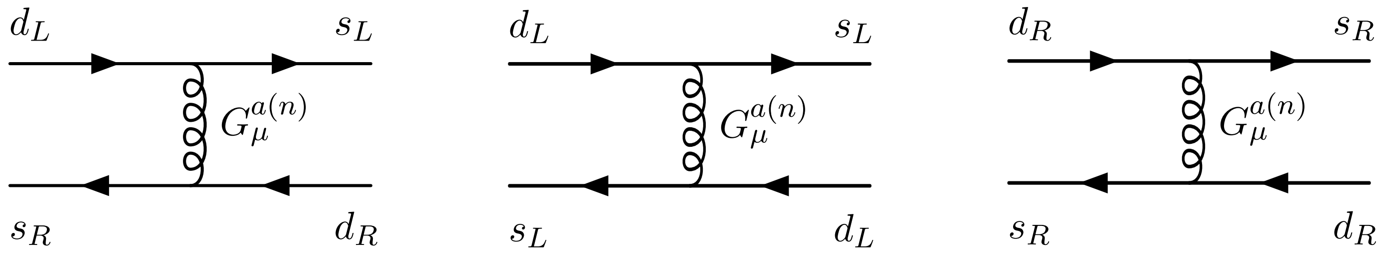
0 mode sector: No mixing O.K.

Nonzero KK gluon couplings induce nontrivial flavor mixing

⇒ flavor mixing@tree level

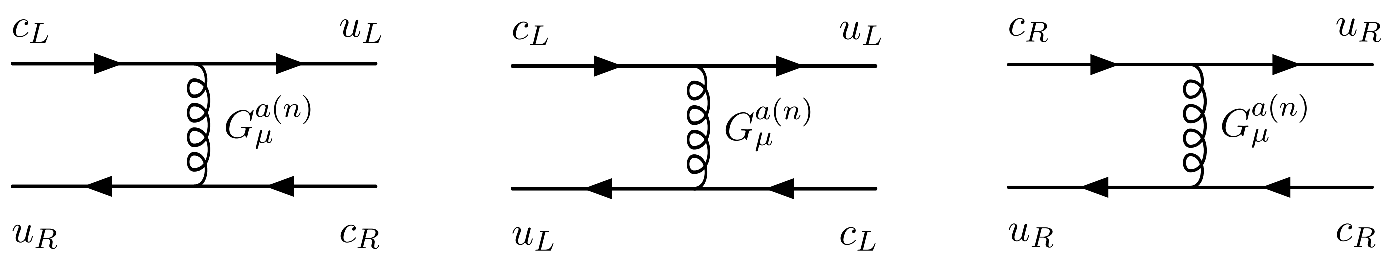


$K^0 - \bar{K}^0$



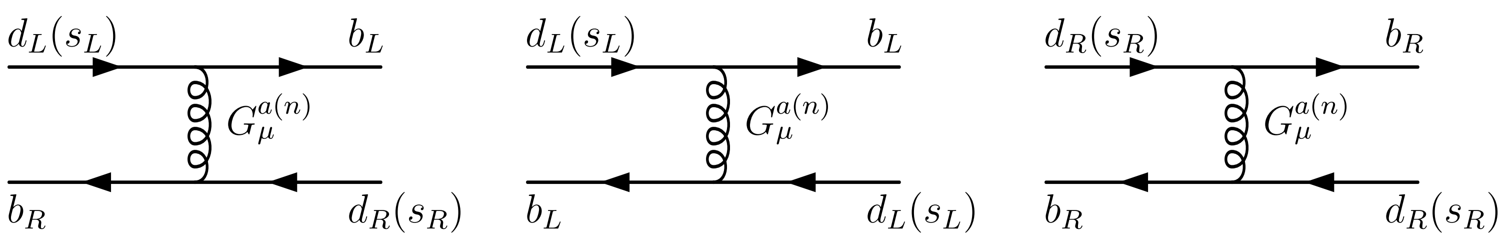
(i) LR type (ii) LL type (iii) RR type

$D^0 - \bar{D}^0$



(i) LR type (ii) LL type (iii) RR type

$B_d^0 - \bar{B}_d^0$
&
$B_s^0 - \bar{B}_s^0$



(i) LR type (ii) LL type (iii) RR type

KL-KS mass difference

$$\Delta m_K(\mathrm{KK}) = 2\langle \bar{K} | \mathcal{L}_{eff}^{\Delta S=2} | K \rangle \approx \alpha_S C B_1 R^2 f_K^2 m_K \sum_n \frac{1}{n^2}\left[I_{RR}^{1(0n0)} - I_{RR}^{2(0n0)} \right]^2$$

$$I_{RR}^{i(0n0)} = \frac{1}{\sqrt{\pi R}} \int_{-\pi R}^{\pi R} \left(f_R^{(0)}(y) \right)^2 \cos\left(\frac{n}{R} y \right)$$

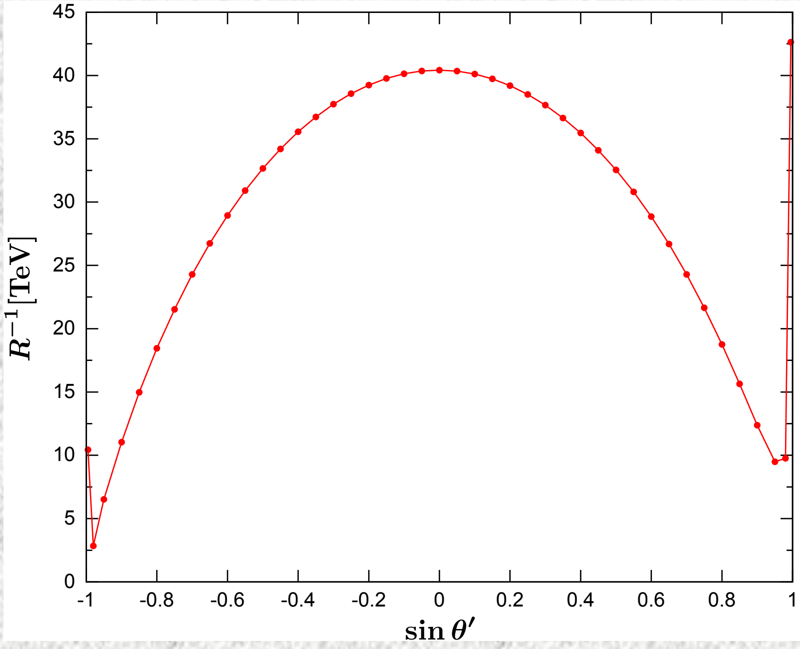
Bag parameter: B1=0.57, f_K ~1.23f_π, m_K~497MeV

Mode sum is finite

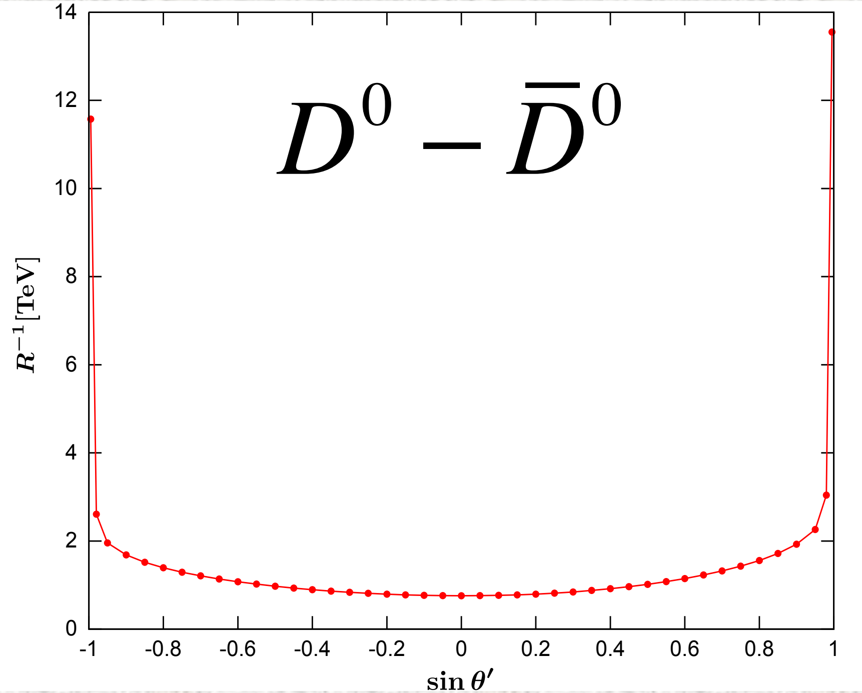
Exp. constraint:

$$\left| \Delta m_K(NP) \right| < 3.48 \times 10^{-12}\, MeV$$

$$R^{-1} \geq 2.8 TeV \sim 43 TeV$$



Similar analysis applied to D & B systems



$$B^0 - \bar{B}^0$$

$$R_u = 1_{3\times3} : R^{-1} \geq 1.71 TeV \left(B_d^0 - \bar{B}_d^0 \right)$$

$$R^{-1} \geq 2.54 TeV \left(B_s^0 - \bar{B}_s^0 \right)$$

$$R_d = 1_{3\times3} : R^{-1} \geq 0.92 TeV \left(B_d^0 - \bar{B}_d^0 \right)$$

$$R^{-1} \geq 1.79 TeV \left(B_s^0 - \bar{B}_s^0 \right)$$

Lower bounds for compactification scale

$$R^{-1} \geq 0.8 TeV \sim 14 TeV$$

Results

$$K^0 - \bar{K}^0 : \mathcal{O}(10)\,TeV$$

$$D^0 - \bar{D}^0 : \mathcal{O}(1)\,TeV$$

$$B_d^0 - \bar{B}_d^0, B_s^0 - \bar{B}_s^0 : \mathcal{O}(1)\,TeV$$

"GIM-like" mechanism

The above results is smaller than
that from naïve order estimate

$$\frac{1}{M_{KK}^2}\bar{\psi}\psi\bar{\psi}\psi \Rightarrow \begin{cases} M_{KK} \geq 1000 TeV \left(K^0-\bar{K}^0, D^0-\bar{D}^0\right) \\ M_{KK} \geq 400 TeV \left(B_d^0-\bar{B}_d^0\right) \\ M_{KK} \geq 70 TeV \left(B_s^0-\bar{B}_s^0\right) \end{cases}$$

This apparent discrepancy can be understood
since the "GIM-like" mechanism works in GHU

i.e. FCNC processes are automatically suppressed
for 1st & 2nd generation of quarks

In the large bulk mass limit, the KK mode sum can be approximated as follows

$$S_{KK}^{LR} = \pi R \sum_{n=1}^{\infty} \frac{(-1)^n}{n^2} \left(I_{RR}^{1(0n0)} - I_{RR}^{2(0n0)} \right)^2$$

$$\simeq -\frac{\pi^2}{2} \left(e^{-2\pi R M^1} + e^{-2\pi R M^2} \right)$$

$$-\frac{\pi}{2R} \frac{(M^1)^2 - M^1 M^2 + (M^2)^2}{M^1 M^2 (M^1 - M^2)} \left(e^{-2\pi R M^1} - e^{-2\pi R M^2} \right) \quad (\pi R M^i \gg 1)$$

exponential suppression!!

$$e^{-2\pi R M^i} \Leftrightarrow \frac{m_{q^i}^2}{m_W^2}$$

similar to GIM suppression

$$\frac{m_c^2 - m_u^2}{m_W^2}$$

$$S_{KK}^{LL(RR)} = \pi R \sum_{n=1}^{\infty} \frac{1}{n^2} \left(I_{RR}^{1(0n0)} - I_{RR}^{2(0n0)} \right)^2 \simeq \frac{\pi}{8R} \frac{(M^1 - M^2)^2}{M^1 M^2 (M^1 + M^2)}$$

Power suppression

More intuitive understanding of "GIM-like" suppression

FCNC is controlled by the factor

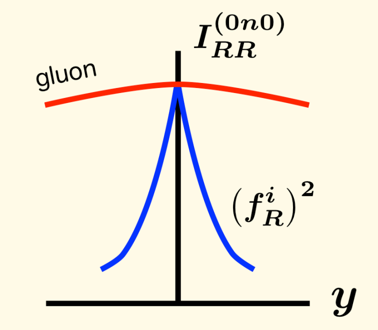
$$\left(I_{RR}^{1(0n0)} - I_{RR}^{2(0n0)}\right)^2$$

$$I_{RR}^{i(0n0)} = \frac{1}{\sqrt{\pi R}} \int_{-\pi R}^{\pi R} dy \frac{M^i}{e^{2\pi R M^i} - 1} e^{2M^i y} \cos\left(\frac{n}{R} y\right)$$

In πMR >> 1 limit & for small mode index n

Width "1/M" of 0 mode function = Period 2πR/n of KK gluon mode function

Almost flat KK gluon mode function for fast exponential dumping 0 mode fermions



⇨ Almost flavor universal
(similar to 0 mode sector)

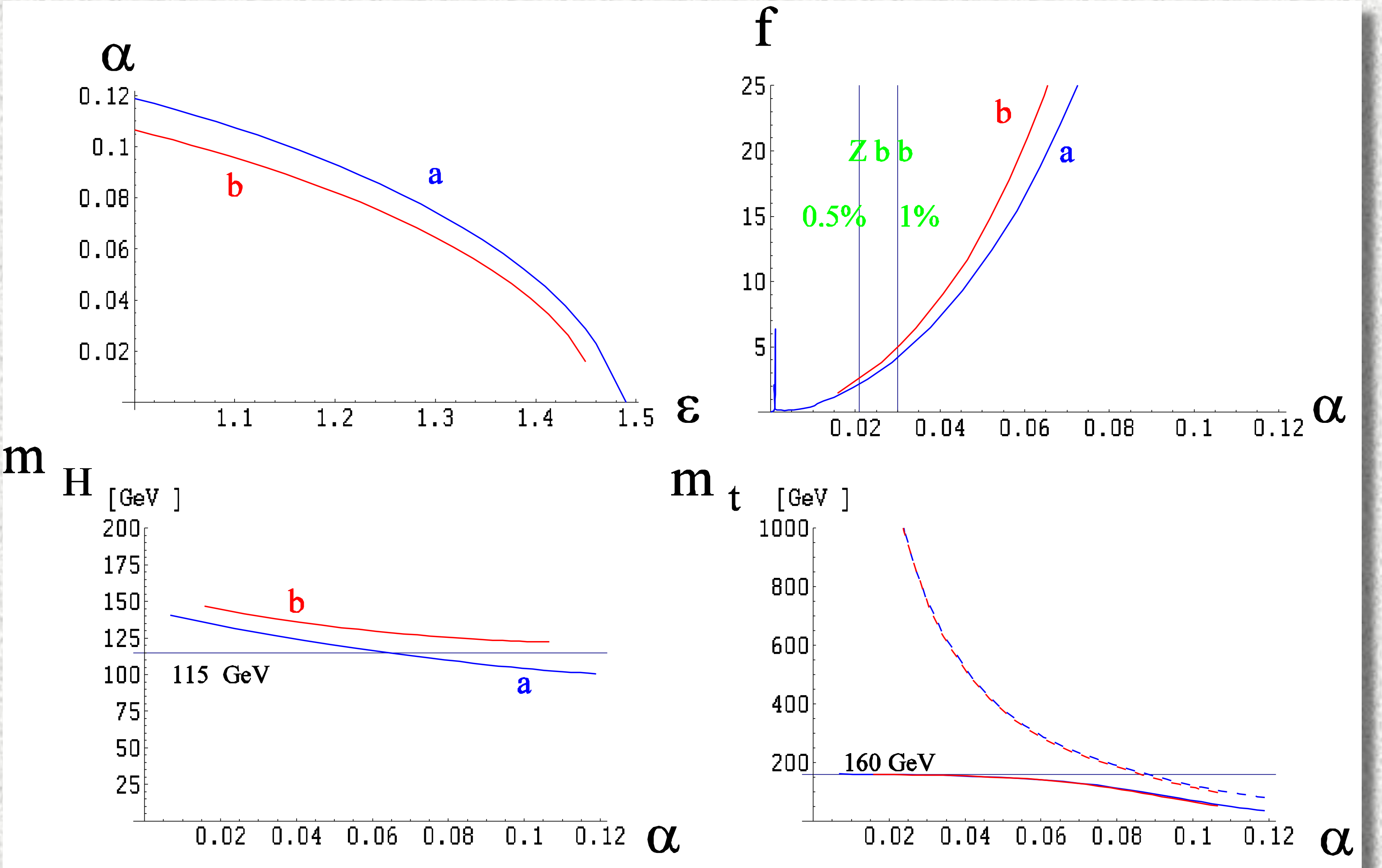
As for the 3rd generation,
GIM-like mechanism does not work

∵ $M^3=0$ for top mass

↓

Suppressed FCNC due to small mixing between 1-3 & 2-3 generations

Higgs mass, top mass,...etc



top

Model a: b(3), τ(10)   Model b: b(6), τ(3)

Calculation of the effective potential (Adj rep)

$$I(a) \equiv \int \frac{d^4p}{(2\pi)^4} \sum_{n=-\infty}^{\infty} \log\left[p^2 + \left(\frac{n+a}{R}\right)^2\right]$$

$$\frac{dI(a)}{da} = \frac{2}{R}\int \frac{d^4p}{(2\pi)^4} \sum_{n=-\infty}^{\infty} \frac{\left(\frac{n+a}{R}\right)}{p^2 + \left(\frac{n+a}{R}\right)^2} = \frac{2}{R}\int \frac{d^4p}{(2\pi)^4} \sum_{n=-\infty}^{\infty} \left(\frac{n+a}{R}\right)\int_0^\infty dt \exp\left[-\left\{p^2 + \left(\frac{n+a}{R}\right)^2\right\}t\right]$$

$$= \frac{2}{R}\sum_{n=-\infty}^{\infty} \frac{n+a}{R}\int_0^\infty dt \frac{1}{(4\pi t)^2} \exp\left[-\left(\frac{n+a}{R}\right)^2 t\right]$$

$$= \frac{2}{R}\frac{1}{(4\pi)^2}\int_0^\infty dt \frac{1}{t^2}\sum_{n=-\infty}^{\infty} R^2\sqrt{\frac{\pi}{t^3}}\, i\pi n \exp\left[-\frac{(\pi R n)^2}{t} - 2\pi i n a\right] = \frac{3R}{16(\pi R)^5}\sum_{n=1}^{\infty}\frac{1}{n^4}\sin(2\pi n a)$$

$$\Rightarrow I(a) = -\frac{3R}{32\pi^6 R^5}\sum_{n=1}^{\infty}\frac{1}{n^5}\cos(2\pi n a) + (\text{a-independent})$$

Poisson resummation

We have investigated the structure of divergence for 1-loop contributions to S & T parameters in the gauge-Higgs unification

Results:

In 5D case, S & T are both finite
In more than 5D case, both divergent
⇒ Natural from the power counting argument

However, the gauge-Higgs unification predicts

$S - 4\cos\theta_W\, T$ becomes finite in 6D cases

because S & T are related by the higher dim. gauge inv.

Substituting KK mode expansions

$$A_{\mu,5}^{(+,+)}(x,y)=\frac{1}{\sqrt{2\pi R}}\left[A_{\mu,5}^{(0)}(x)+\sqrt{2}\sum_{n=1}^{\infty}A_{\mu,5}^{(n)}\cos\left(\frac{n}{R}y\right)\right],$$

$$A_{\mu,5}^{(-,-)}(x,y)=\frac{1}{\sqrt{\pi R}}\sum_{n=1}^{\infty}A_{\mu,5}^{(n)}\sin\left(\frac{n}{R}y\right),$$

$$\Psi_{1L,2L,3R}^{(+,+)}(x,y)=\frac{1}{\sqrt{2\pi R}}\left[\psi_{1L,2L,3R}^{(0)}(x)+\sqrt{2}\sum_{n=1}^{\infty}\psi_{1L,2L,3R}^{(n)}\cos\left(\frac{n}{R}y\right)\right],$$

$$\Psi_{1R,2R,3L}^{(-,-)}(x,y)=\frac{1}{\sqrt{\pi R}}\sum_{n=1}^{\infty}\psi_{1R,2R,3L}^{(n)}\sin\left(\frac{n}{R}y\right)$$

and integrating out 5th coordinate "y",
making a chiral rotation $\psi_{1,2,3}\to e^{-i\pi\gamma_5/4}\psi_{1,2,3}$ to remove $i\gamma_5$,

we obtain 4D effective Lagrangian

$$
\begin{aligned}
\mathrm{L}^{(4\mathrm{D})}_{\text{fermion}} = \sum_{n=1}^{\infty} \Bigg[& i\left(\bar{\psi}_1^{(n)}, \bar{\psi}_2^{(n)}, \bar{\psi}_3^{(n)}\right) \gamma^\mu \partial_\mu \begin{pmatrix} \psi_1^{(n)} \\ \psi_2^{(n)} \\ \psi_3^{(n)} \end{pmatrix} \\
& + \frac{g}{2}\left(\bar{\psi}_1^{(n)}, \bar{\psi}_2^{(n)}, \bar{\psi}_3^{(n)}\right) \begin{pmatrix} W_\mu^3 + \frac{B_\mu}{\sqrt{3}} & \sqrt{2}W_\mu^+ & 0 \\ \sqrt{2}W_\mu^- & -W_\mu^3 + \frac{B_\mu}{\sqrt{3}} & 0 \\ 0 & 0 & -\frac{2}{\sqrt{3}}B_\mu \end{pmatrix} \gamma^\mu \begin{pmatrix} \psi_1^{(n)} \\ \psi_2^{(n)} \\ \psi_3^{(n)} \end{pmatrix} \\
& - \left(\bar{\psi}_1^{(n)}, \bar{\psi}_2^{(n)}, \bar{\psi}_3^{(n)}\right) \begin{pmatrix} m_n & 0 & 0 \\ 0 & m_n & -m \\ 0 & -m & m_n \end{pmatrix} \begin{pmatrix} \psi_1^{(n)} \\ \psi_2^{(n)} \\ \psi_3^{(n)} \end{pmatrix} \Bigg] \\
& + i\bar{t}_L \gamma^\mu \partial_\mu t_L + \bar{b}\left(i\gamma^\mu \partial_\mu - m\right)b + \frac{g}{\sqrt{2}}\left(\bar{t}\gamma^\mu L b W_\mu^+ + \bar{b}\gamma^\mu L t W_\mu^-\right) + \frac{g}{2}\left(\bar{t}\gamma^\mu L t + \bar{b}\gamma^\mu L b\right) W_\mu^3 \\
& + \frac{\sqrt{3}g}{6}\left(\bar{t}\gamma^\mu L t + \bar{b}\gamma^\mu L b - 2\bar{b}\gamma^\mu R b\right) B_\mu
\end{aligned}
$$

$$
L \equiv \frac{1}{2}(1-\gamma_5),\ R \equiv \frac{1}{2}(1+\gamma_5),\ m_n = \frac{n}{R},\ g = \frac{g_5}{\sqrt{2\pi R}},\ m = \frac{1}{2} g v \,(= M_W)
$$

Mixing occurs between SU(2) doublet component
& singlet component

Each of mass eigenvalues has a **periodicity** with respect to m

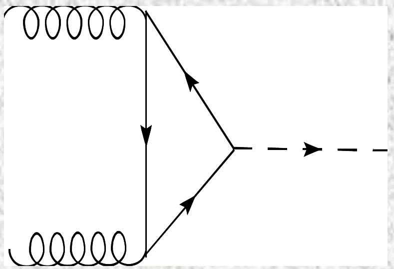
$$m_n \pm \left(m + \frac{1}{R} \right) = m_{n\pm 1} \pm m$$

Characteristic feature of gauge-Higgs unification

(c.f. $\sqrt{m_n^2 + m^2}$ for UED)

SM contributions

gg -> H

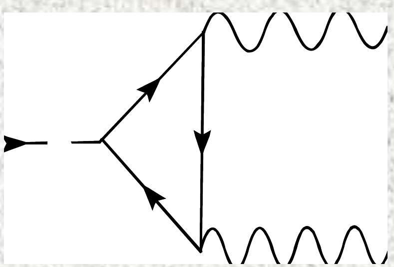


$$\mathrm{L}_{eff} = C^{SM}_{glue} h G^{a\mu\nu} G^{a}_{\mu\nu}$$

$$C^{SM}_{glue} = -\frac{m_t}{v} \times \frac{\alpha_S F_{1/2}\left(4m_t^2/m_h^2\right)}{8\pi m_t} \times \frac{1}{2}$$

$$F_{1/2}(x) = -2x\left[1+(1-x)\left(\sin^{-1}\left(1/\sqrt{x}\right)\right)^2\right] \rightarrow -\frac{4}{3}(x\ ?\ 1)$$

H -> γγ



$$\mathrm{L}_{eff} = C^{SM}_{\gamma} h G^{a\mu\nu} G^{a}_{\mu\nu}$$

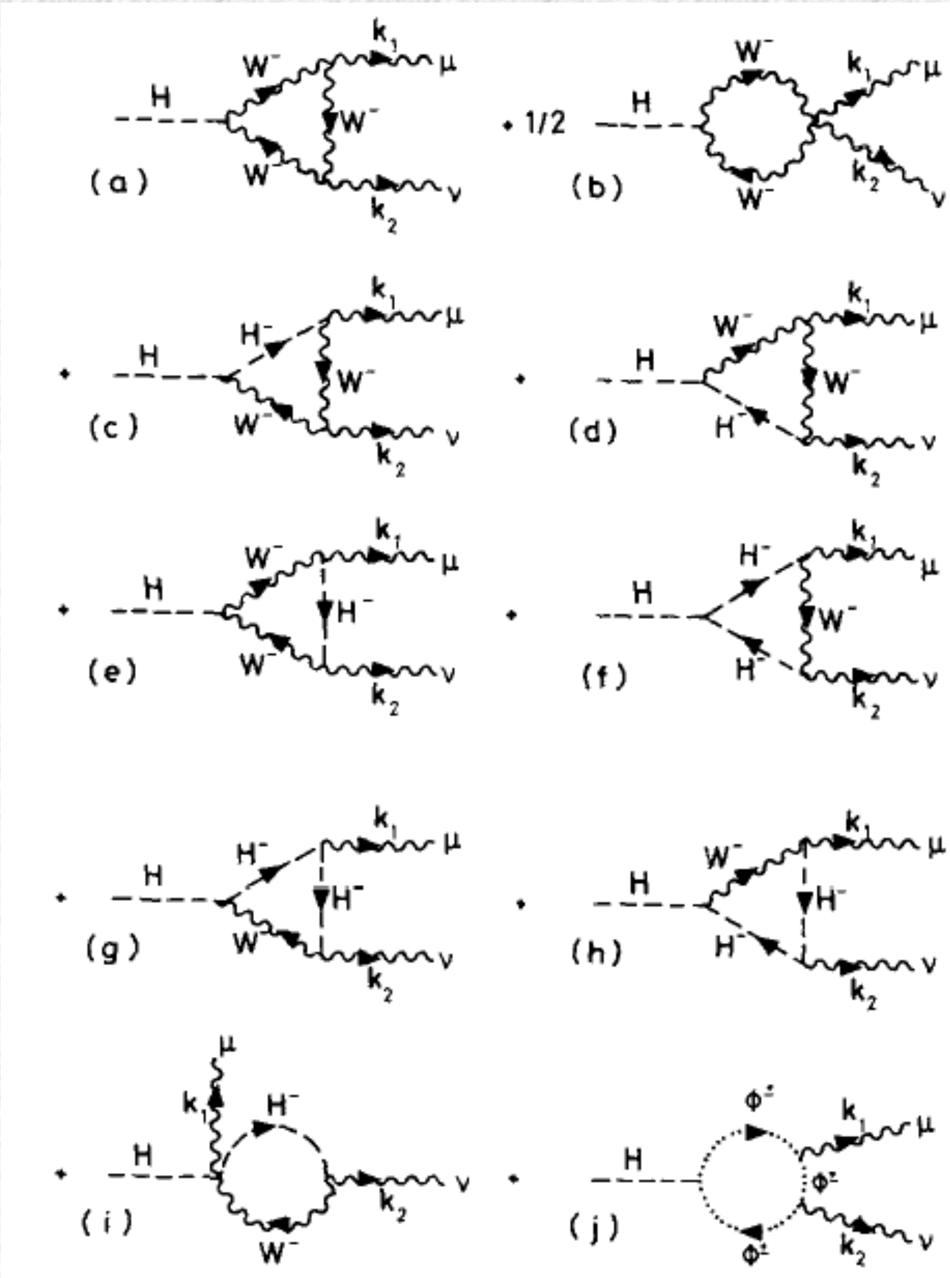
$$C^{SM}_{\gamma} = C^{t}_{\gamma} + C^{W}_{\gamma}$$

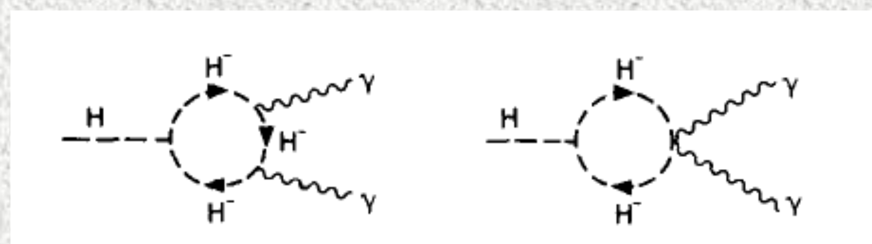
$$C^{t}_{\gamma} = -\frac{m_t}{v} \times \frac{\alpha_{em} F_{1/2}\left(4m_t^2/m_h^2\right)}{8\pi m_t} \times \frac{4}{3},\ C^{W}_{\gamma} = -\frac{m_t}{v} \times \frac{\alpha_{em} F_{1}\left(4m_W^2/m_h^2\right)}{8\pi m_t}$$

$$F_1(x) = 2+3x+3x(2-x)\left(\sin^{-1}\left(1/\sqrt{x}\right)\right)^2 \rightarrow 7\,(x\ ?\ 1)$$

W-boson loop effects of 2 photon decay in SM

Ellis, Gaillard & Nanopoulos, NPB106 (1976) 292





Collider Physics in Gauge-Higgs Unification

Nobuhito Maru
(Osaka City University
& NITEP)

2019/06/07 Lecture@E-ken

References

- 125 GeV Higgs Boson and TeV Scale Colored Fermions in Gauge-Higgs Unification, arXiv:1310.3348
- Diphoton and Z photon Decays of Higgs Boson in Gauge-Higgs Unification: A Snowmass white paper arXiv: 1307:8181
- $H \rightarrow Z\gamma$ in Gauge-Higgs Unification, PRD88 037701 (2013)
- Diphoton Decay Excess and 125 GeV Higgs Mass in Gauge-Higgs Unification, PRD87 095019 (2013)
- Gauge-Higgs Unification at CERN LHC, PRD77 055010 (2008)

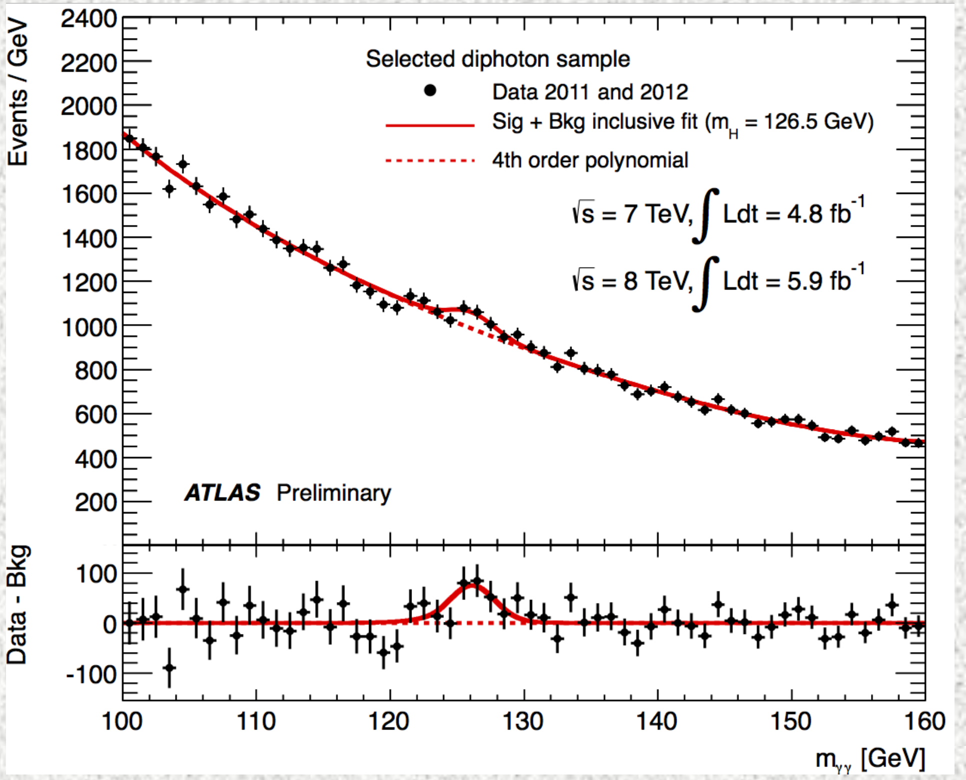
All papers with Nobuchika Okada

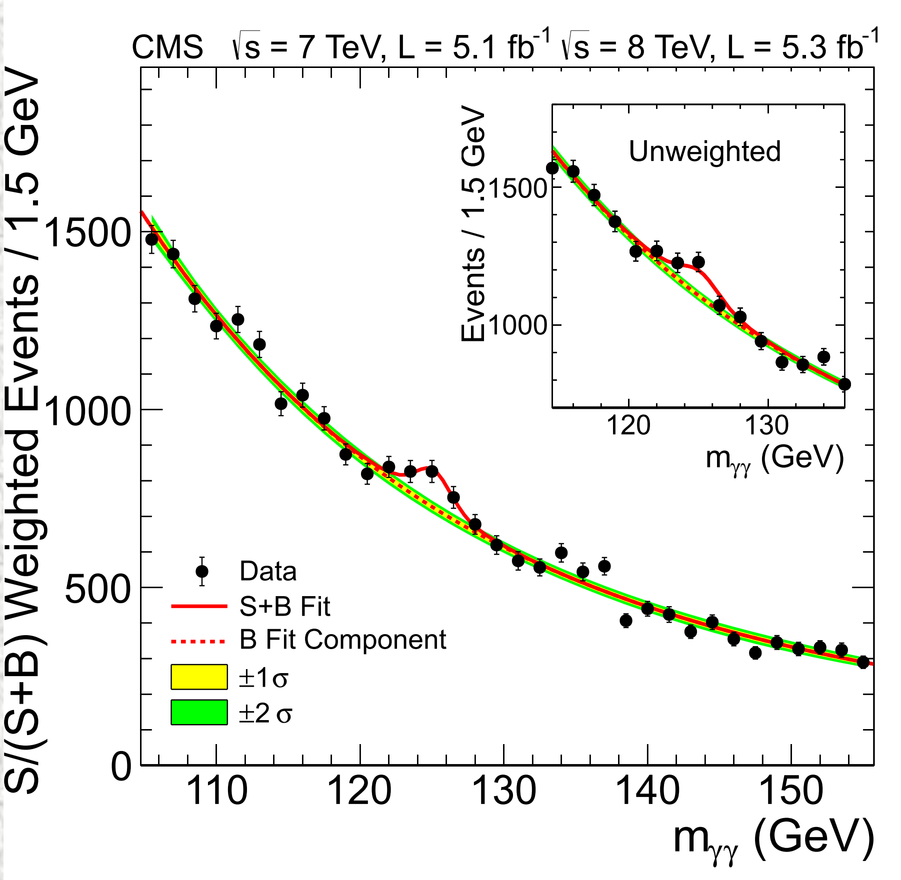
PLAN

- Introduction
- A Model of GHU
- $gg \to H$ & $H \to \gamma\gamma$ in GHU
- $H \to Z\gamma$
- Summary

Introduction

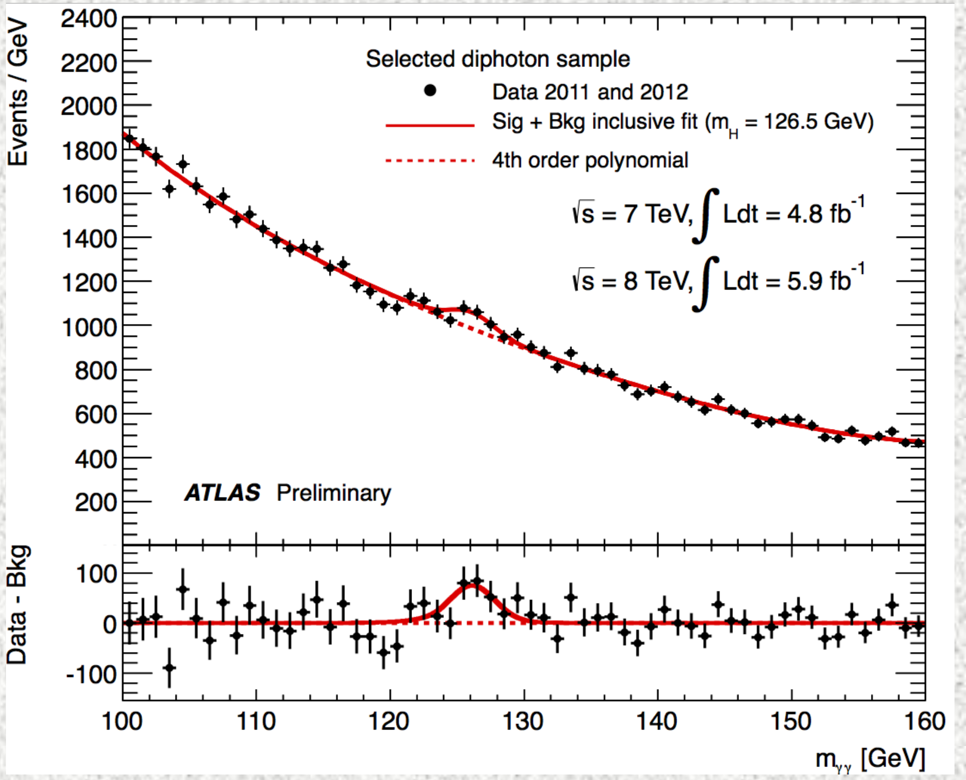
A Higgs boson was discovered!!

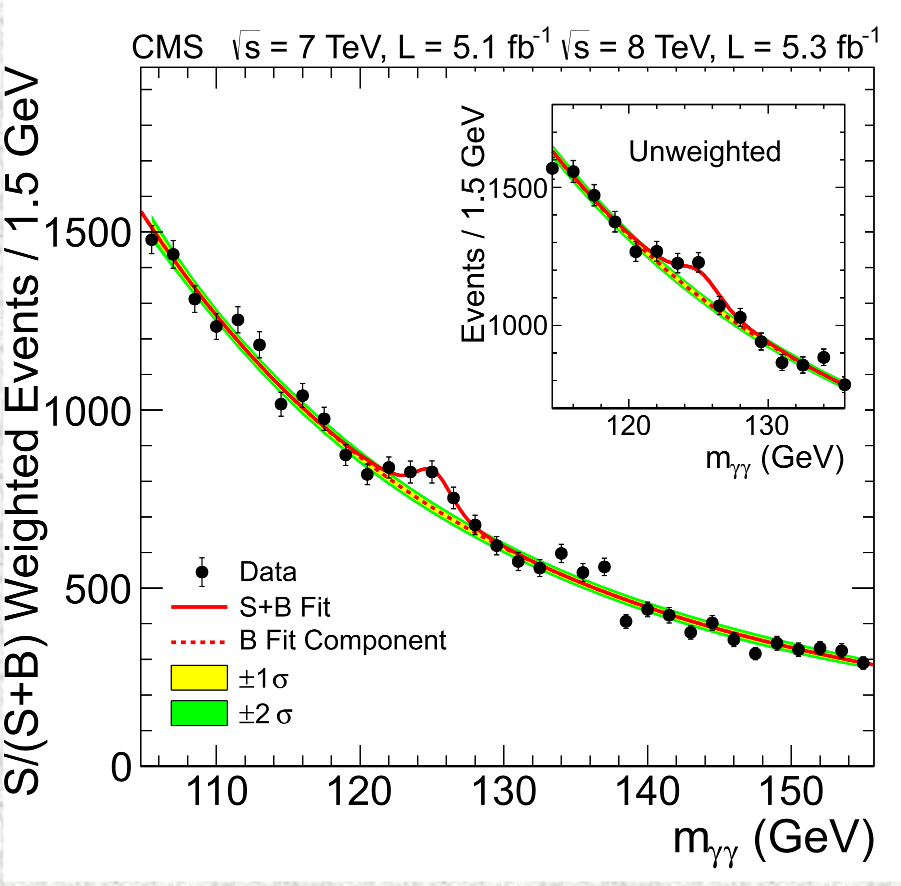


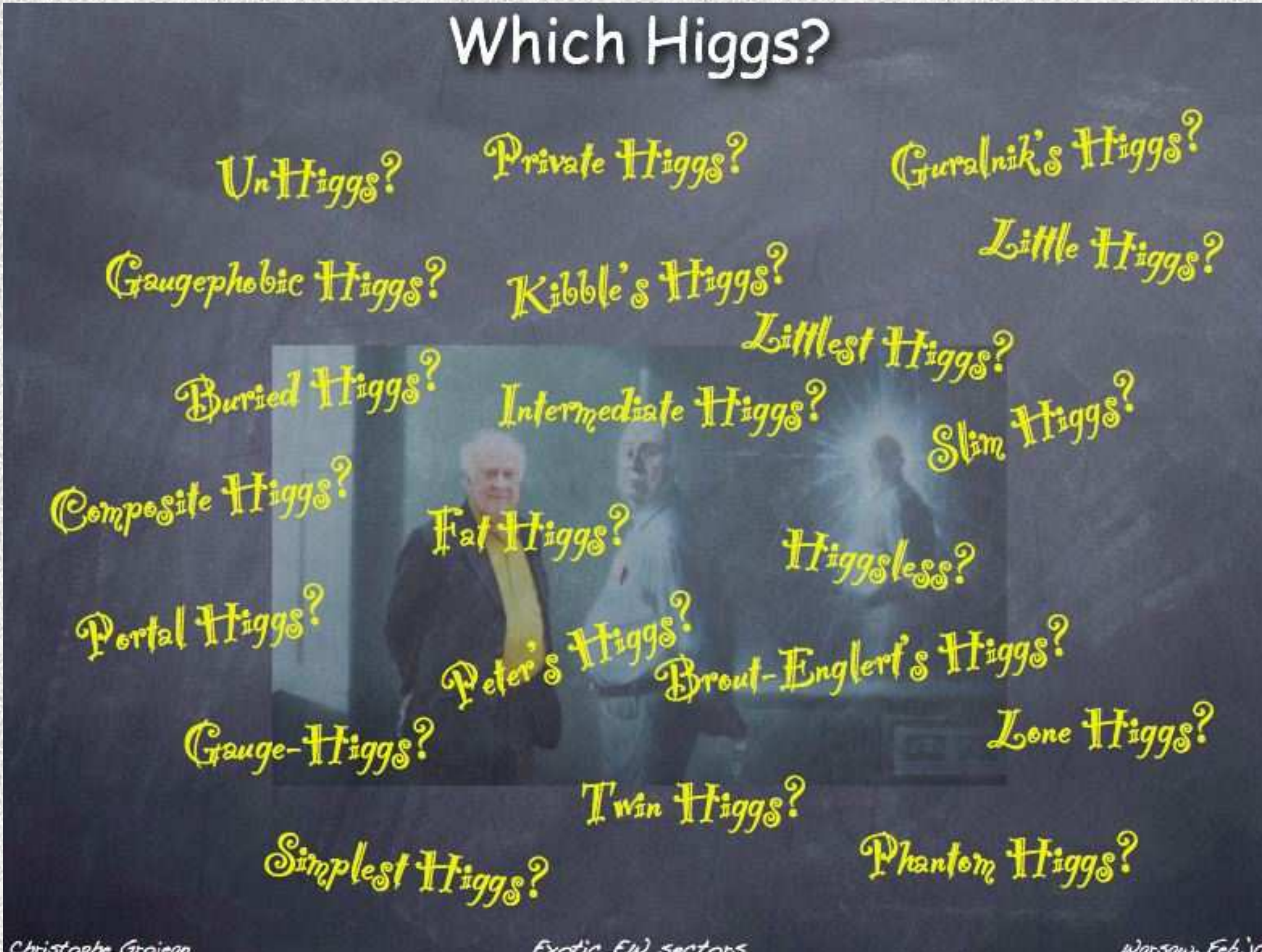


Introduction

Still unclear, the origin of Higgs ??







taken from Grojean's slides

In the gauge-Higgs unification,

1: New structure in the Higgs sector
2: Coupling of new particles to Higgs boson

controlled by higher dimensional gauge invariance

⇓

Deviations from the SM predictions & Collider signatures specific to GHU are expected!!

A Model of GHU

Lagrangian

5D SU(3) x U(1)′ model on S^1/Z_2

$$\mathcal{L} = -\frac{1}{2}\mathrm{Tr}\left(F_{MN}F^{MN}\right) + \bar{\Psi}_{3}^{i=1,2,3}\left(i\Gamma^M D_M - M_d^i \varepsilon(y)\right)\Psi_{3}^{i=1,2,3}$$
$$+ \bar{\Psi}_{\bar{6}}^{i=1,2}\left(i\Gamma^M D_M - M_u^i \varepsilon(y)\right)\Psi_{\bar{6}}^{i=1,2} + \bar{\Psi}_{\overline{15}} i\Gamma^M D_M \Psi_{\overline{15}}$$
$$+ \bar{\Psi}_{10}^{i=1,2,3}\left(i\Gamma^M D_M - M_l^i \varepsilon(y)\right)\Psi_{10}^{i=1,2,3} \qquad \Gamma^M = \left(\gamma^\mu, i\gamma^5\right)$$

Boundary conditions:

S^1: $\Psi(y+2\pi R) = \psi(y)$, Z_2: $\Psi(-y) = \pm\psi(y)$

$$A_\mu = \begin{pmatrix} (+,+) & (+,+) & (-,-) \\ (+,+) & (+,+) & (-,-) \\ (-,-) & (-,-) & (+,+) \end{pmatrix}, A_5 = \begin{pmatrix} (-,-) & (-,-) & (+,+) \\ (-,-) & (-,-) & (+,+) \\ (+,+) & (+,+) & (-,-) \end{pmatrix}$$

Lagrangian

5D SU(3) x U(1)' model on S^1/Z_2

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Boundary conditions:

(+,+) only has massless mode

(+,+): cos(ny/R)
(-,-): sin(ny/R)

$$A_\mu = \begin{pmatrix} (+,+) & (+,+) & (-,-) \\ (+,+) & (+,+) & (-,-) \\ (-,-) & (-,-) & (+,+) \end{pmatrix}, A_5 = \begin{pmatrix} (-,-) & (-,-) & (+,+) \\ (-,-) & (-,-) & (+,+) \\ (+,+) & (+,+) & (-,-) \end{pmatrix}$$

Lagrangian

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$$+\bar{\Psi}_{10}^{i=1,2,3}\left(i\Gamma^{M}D_{M} - M_{l}^{i}\varepsilon(y)\right)\Psi_{10}^{i=1,2,3} \qquad \Gamma^{M} = \left(\gamma^{\mu}, i\gamma^{5}\right)$$

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SU(3) x U(1)′ → SU(2) x U(1)$_Y$ x U(1)$_X$

Lagrangian

5D SU(3) x U(1)′ model on S^1/Z_2

$$\mathcal{L} = -\frac{1}{2}\mathrm{Tr}\left(F_{MN}F^{MN}\right) + \bar{\Psi}_{3}^{i=1,2,3}\left(i\Gamma^{M}D_{M} - M_{d}^{i}\varepsilon(y)\right)\Psi_{3}^{i=1,2,3}$$

$$+ \bar{\Psi}_{\bar{6}}^{i=1,2}\left(i\Gamma^{M}D_{M} - M_{u}^{i}\varepsilon(y)\right)\Psi_{\bar{6}}^{i=1,2} + \bar{\Psi}_{\overline{15}}i\Gamma^{M}D_{M}\Psi_{\overline{15}}$$

$$+ \bar{\Psi}_{10}^{i=1,2,3}\left(i\Gamma^{M}D_{M} - M_{l}^{i}\varepsilon(y)\right)\Psi_{10}^{i=1,2,3} \qquad \Gamma^{M} = \left(\gamma^{\mu}, i\gamma^{5}\right)$$

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0 mode of A_5 = SM Higgs

Fermion matter content

$\mathbf{3} = \mathbf{2}_{L1/6}(Q) + \mathbf{1}_{L-1/3}$
$\quad \mathbf{2}_{R1/6} + \mathbf{1}_{R-1/3}(d_R)$

Down quark sector

$\mathbf{6}^* = \mathbf{3}_{L-1/3} + \mathbf{2}_{L1/6}(Q) + \mathbf{1}_{L2/3}$
$\quad \mathbf{3}_{R-1/3} + \mathbf{2}_{R1/6} + \mathbf{1}_{R2/3}(u_R)$

Up quark sector (except for top)

$\mathbf{10} = \mathbf{4}_{L1/2} + \mathbf{3}_{L0} + \mathbf{2}_{L-1/2}(L) + \mathbf{1}_{L-1}$
$\quad \mathbf{4}_{R1/2} + \mathbf{3}_{R0} + \mathbf{2}_{R-1/2} + \mathbf{1}_{R-1}(e_R)$

Charged lepton sector

$\mathbf{15}^* = \mathbf{5}_{L-4/3} + \mathbf{4}_{L-5/6} + \mathbf{3}_{L-1/3} + \mathbf{2}_{L1/6}(Q) + \mathbf{1}_{L2/3}$
$\quad \mathbf{5}_{R-4/3} + \mathbf{4}_{R-5/6} + \mathbf{3}_{R-1/3} + \mathbf{2}_{R1/6} + \mathbf{1}_{R2/3}(t_R)$

Top quark

Unwanted massless exotics (blue reps) & two extra Qs must be massive by brane localized mass terms

Big Hurdle

In the gauge-Higgs unification,
Yukawa coupling = gauge coupling

How can we get fermion mass hierarchy???

Localizing fermions@different point in 5^{th} direction

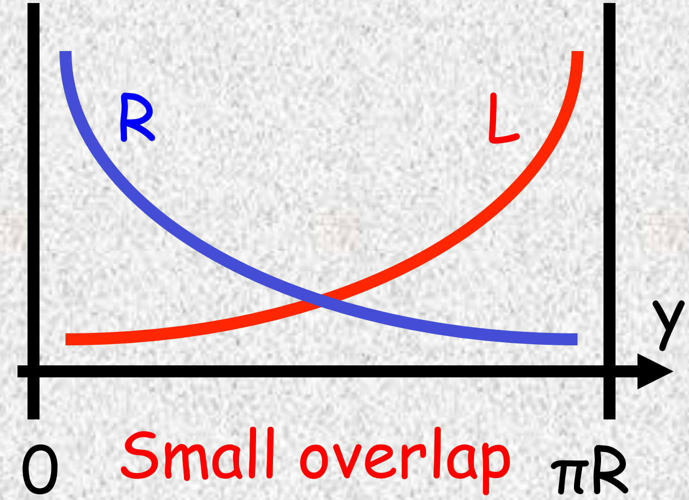
Yukawa ~ exponentially suppressed overlap integral of wave functions

Arkani-Hamed & Schmaltz (1999)

Zero mode wave functions

$$0=\left[\partial_y - M\varepsilon(y)\right]f_L^{(0)}(y)\rightarrow f_L^{(0)}(y)=\sqrt{\frac{M}{e^{2\pi MR}-1}}e^{M|y|}$$

$$0=\left[\partial_y + M\varepsilon(y)\right]f_R^{(0)}(y)\rightarrow f_R^{(0)}(y)=\sqrt{\frac{M}{1-e^{-2\pi MR}}}e^{-M|y|}$$



4D effective Yukawa coupling

$$Y=g_4\int_{-\pi R}^{\pi R} dy f_L^{(0)}(y)\,f_R^{(0)}(y)=g_4\int_{-\pi R}^{\pi R} dy\sqrt{\frac{M^2}{\left(1-e^{-2\pi MR}\right)\left(e^{2\pi MR}-1\right)}}$$

$$\approx 2\pi MRg_4e^{-\pi MR}\le g_4\left(\pi MR\gg 1\right)\Leftrightarrow m_f\le m_W$$

Fermion masses except top is easy to obtain by tuning M

Top in 15* rep ⇒ factor "2" enhancement

Martinelli, Salvatori, Scrucca & Silvestrini (2005)

$\sqrt{N}$ enhancement

Consider a rank N symmetric tensor of SU(3)

$$\begin{array}{|c|c|c|c|c|}\hline & & & \cdots & \\ \hline \end{array}$$ N boxes

Decompose it into SU(2) reps as 3 = 2 + 1
and make a singlet & a doublet

singlet $\begin{array}{|c|c|c|c|c|}\hline 1 & 1 & 1 & \cdots & 1 \\ \hline \end{array}$ unique

doublet $\begin{array}{|c|c|c|c|c|}\hline 1 & 1 & 2 & \cdots & 1 \\ \hline \end{array}$ etc N patterns

Canonical kinetic term ⇒ 1/sqrt[N]

Yukawa = $1_R\ 2_L\ 2_H$ ⇒ N x 1/sqrt[N] = sqrt[N]

Essential Points for calculation (Specific form of KK masses in GHU)

Mass splitting & Coupling to Higgs

KK top

$$m_t^{+(n)} = \frac{n}{R} + m_t \qquad - \frac{m_t}{v} h$$

$$m_t^{-(n)} = \frac{n}{R} - m_t \qquad + \frac{m_t}{v} h$$

KK W

$$m_W^{+(n)} = \frac{n}{R} + m_W \qquad + \frac{m_W}{v} h$$

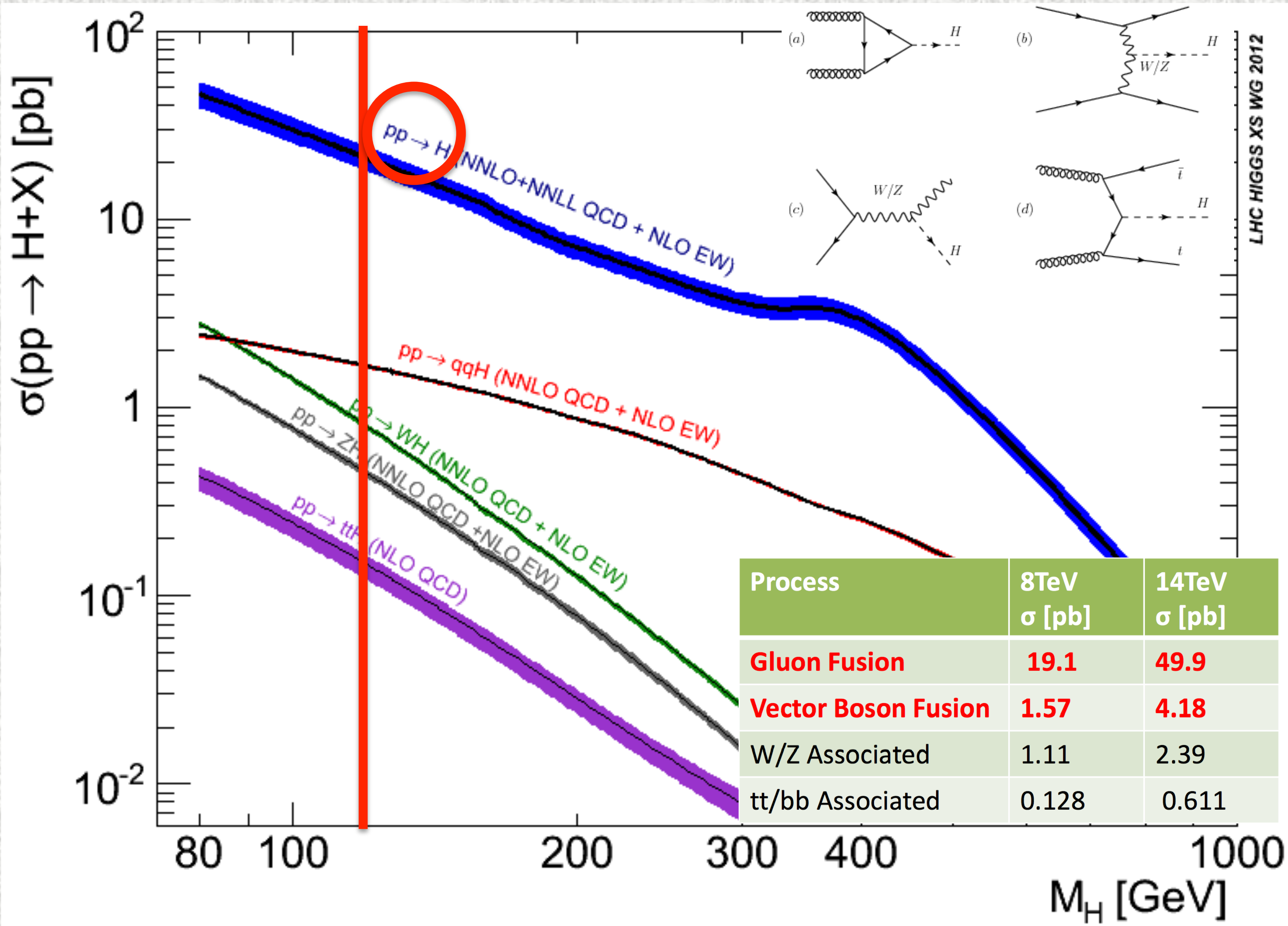
$$m_W^{-(n)} = \frac{n}{R} - m_W \qquad - \frac{m_W}{v} h$$

Characteristic predictions to "finite" $gg \to H$, $H \to \gamma\gamma$ amplitudes

MN & Okada (2007), NM(2008)

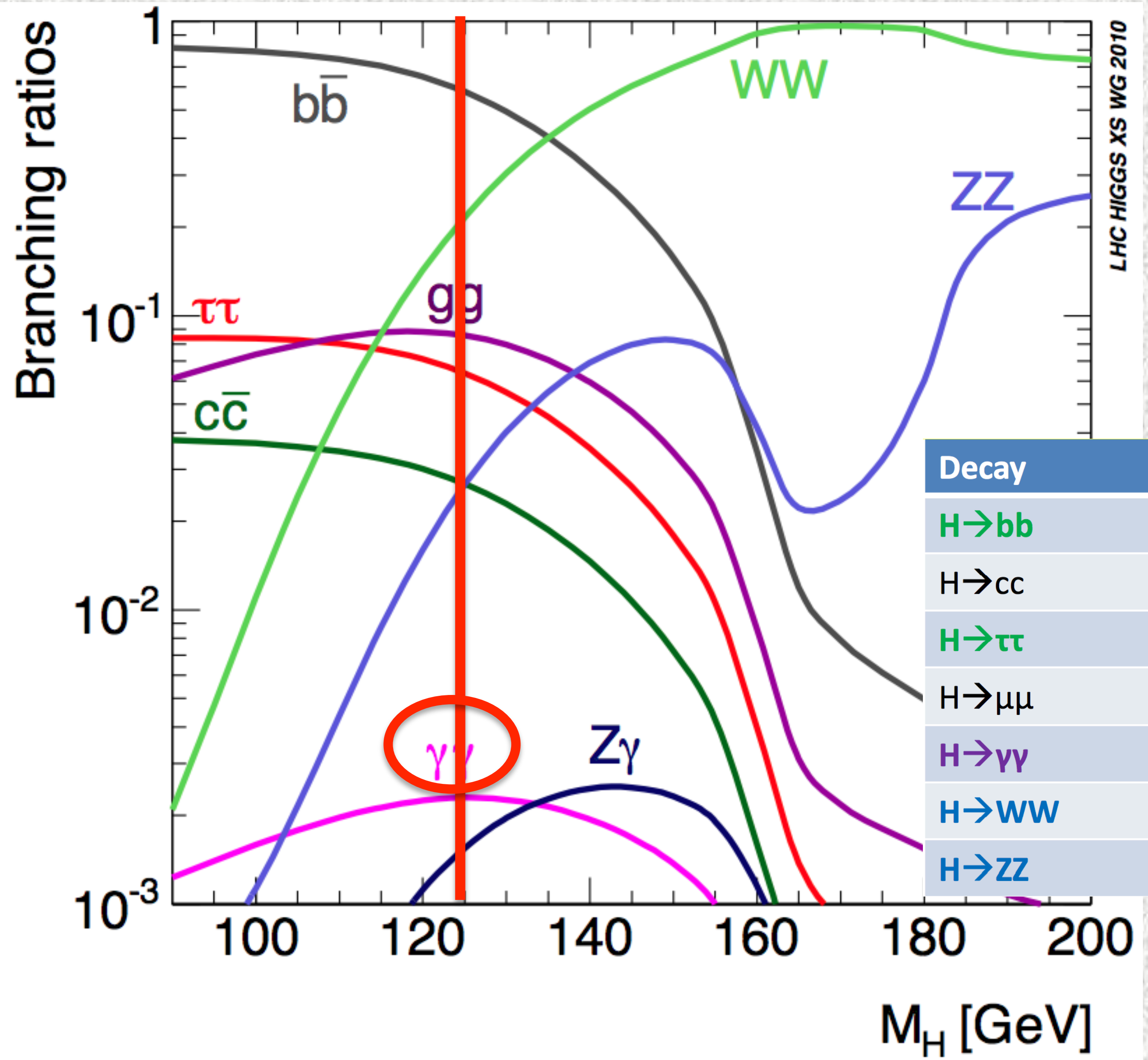
$gg \to H$ & $H \to \gamma\gamma$ in GHU

Higgs production



Process	8TeV σ [pb]	14TeV σ [pb]
Gluon Fusion	19.1	49.9
Vector Boson Fusion	1.57	4.18
W/Z Associated	1.11	2.39
tt/bb Associated	0.128	0.611

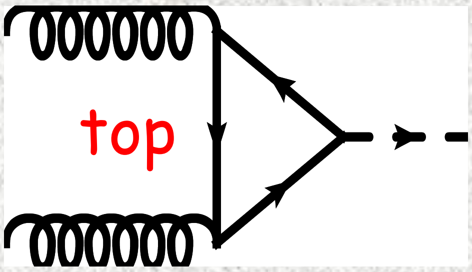
Decay rate of Higgs boson



Decay	Branch in percent
H→bb	57 %
H→cc	2.9%
H→ττ	6.2%
H→μμ	0.02%
H→γγ	0.23%
H→WW	22%
H→ZZ	2.8%

SM contributions

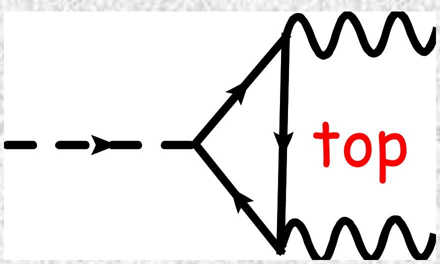
gg -> H

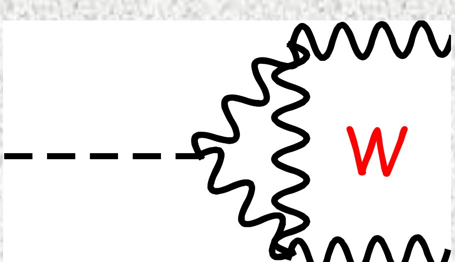


$$\mathcal{L}_{eff} = C_{gg}^{SM} h G^{a\mu\nu} G_{\mu\nu}^{a}$$

$$C_{gg}^{SM} = \frac{\alpha_s}{8\pi v} b_3^t \frac{\partial \ln m_t}{\partial \ln v} = \frac{\alpha_s}{12\pi v}$$

H -> γγ





$$\mathcal{L}_{eff} = C_{\gamma\gamma}^{SM} h F^{\mu\nu} F_{\mu\nu}$$

$$C_{\gamma\gamma}^{SM} = C_{\gamma\gamma}^{top} + C_{\gamma\gamma}^{W} = -\frac{47\alpha_{em}}{72\pi v}$$

$$C_{\gamma\gamma}^{top} = \frac{\alpha_{em}}{6\pi v} \frac{4}{3} \frac{\partial \ln m_t}{\partial \ln v} = \frac{2\alpha_{em}}{9\pi v}$$

$$C_{\gamma\gamma}^{W} = \frac{\alpha_{em}}{8\pi v} (-7) \frac{\partial \ln m_W}{\partial \ln v} = -\frac{7\alpha_{em}}{8\pi v}$$

Higgs Low Energy Theorem

Coefficient of dim 5 operater $hG^a_{\mu\nu}G^{a\mu\nu}$ can be extracted from 1-loop RGE of gauge coupling

Gauge kinetic term

$$\mathcal{L} = -\frac{1}{4g^2(\mu)} G^a_{\mu\nu} G^{a\mu\nu}$$

β-function coefficient below and above M(v)

1-loop RGE

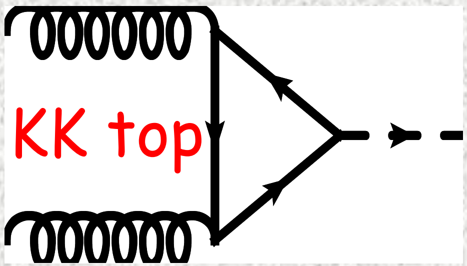
$$\frac{1}{g^2(\mu)} = \frac{1}{g^2(\Lambda)} + \frac{b_3}{8\pi^2} \ln\frac{\Lambda}{\mu} + \frac{\Delta b_3}{8\pi^2} \ln\frac{\Lambda}{M(v)}$$

Higgs VEV dependent threshold

Under $v \to v + h$, and extracting $O(h)$ term, we find

$$\mathcal{L}_{eff} = \frac{\Delta b_3}{32\pi^2} \left(\frac{\partial}{\partial v} \ln M(v) \right) h G^a_{\mu\nu} G^{a\mu\nu}$$

KK mode contributions: gg → H



$$\mathcal{L}_{eff} = C_{gg}^{KK} h G^{a\mu\nu} G^{a}_{\mu\nu}$$

$$C_{gg}^{KKtop} = \frac{\alpha_S}{8\pi v}\frac{2}{3}\sum_{n=1}^{\infty}\frac{\partial}{\partial \ln v}\left[\ln\left(m_n + m_t\right) + \ln\left(m_n - m_t\right)\right]$$

$m_n = n/R$

$$= \frac{\alpha_S}{12\pi v}\sum_{n=1}^{\infty}\left[\frac{m_t}{m_n + m_t} - \frac{m_t}{m_n + m_t}\right]$$

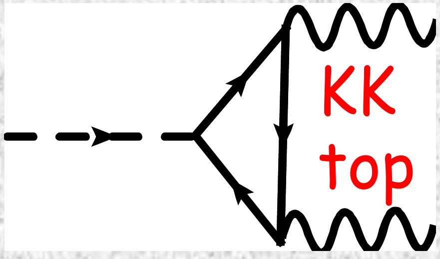
log∞ - log∞ = finite

$$\cong -\frac{\alpha_S}{12\pi v} 2\sum_{n=1}^{\infty}\frac{m_t^2}{m_n^2}\left(m_t^2 \ll m_n^2\right) = -\frac{\alpha_S}{12\pi v}\frac{1}{3}\left(\pi m_t R\right)^2$$

Opposite sign to SM ⇒ destructive

KK mode contributions: H → γγ

$$\mathcal{L}_{eff} = C_{\gamma\gamma}^{KK} h F^{\mu\nu} F_{\mu\nu}$$



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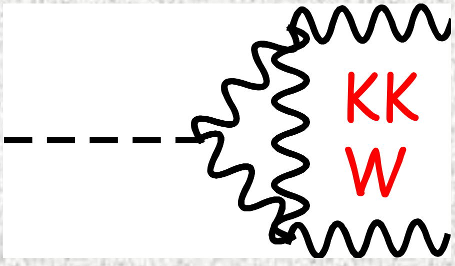


$$C_{\gamma\gamma}^{KKtop} = \frac{\alpha_{em}}{6\pi v}\frac{4}{3}\sum_{n=1}^{\infty}\frac{\partial}{\partial \ln v}\left[\ln\left(m_n + m_t\right) + \ln\left(m_n - m_t\right)\right]$$

$$\cong -\frac{2\alpha_{em}}{9\pi v}\frac{1}{3}\left(\pi m_t R\right)^2$$

Opposite sign to SM

$$C_{\gamma\gamma}^{KKW} = \frac{\alpha_{em}}{8\pi v}(-7)\sum_{n=1}^{\infty}\frac{\partial}{\partial \ln v}\left[\ln\left(m_n + m_W\right) + \ln\left(m_n - m_W\right)\right]$$

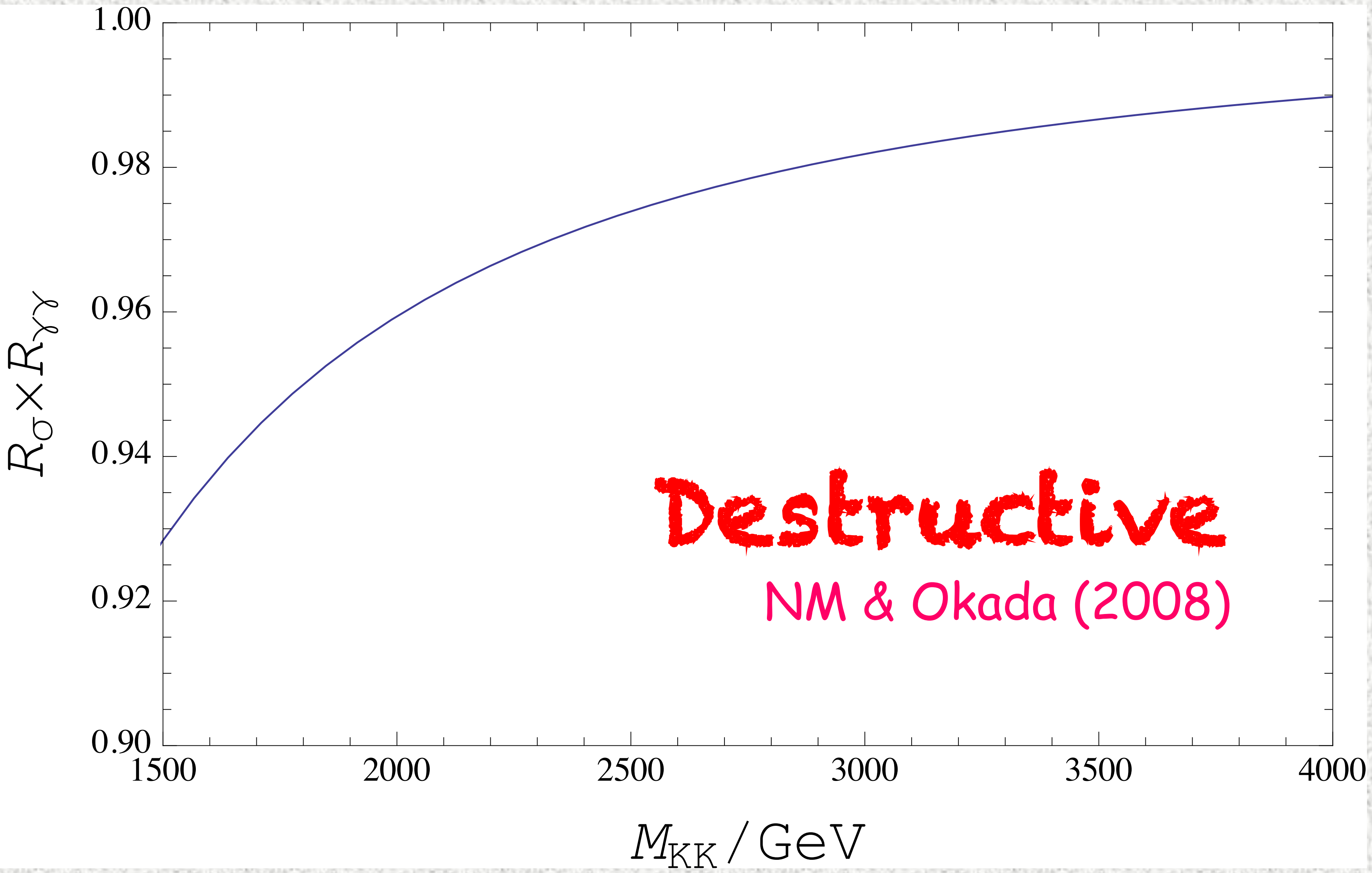
$$\cong +\frac{7\alpha_{em}}{8\pi v}\frac{1}{3}\left(\pi m_W R\right)^2$$

Opposite sign to SM

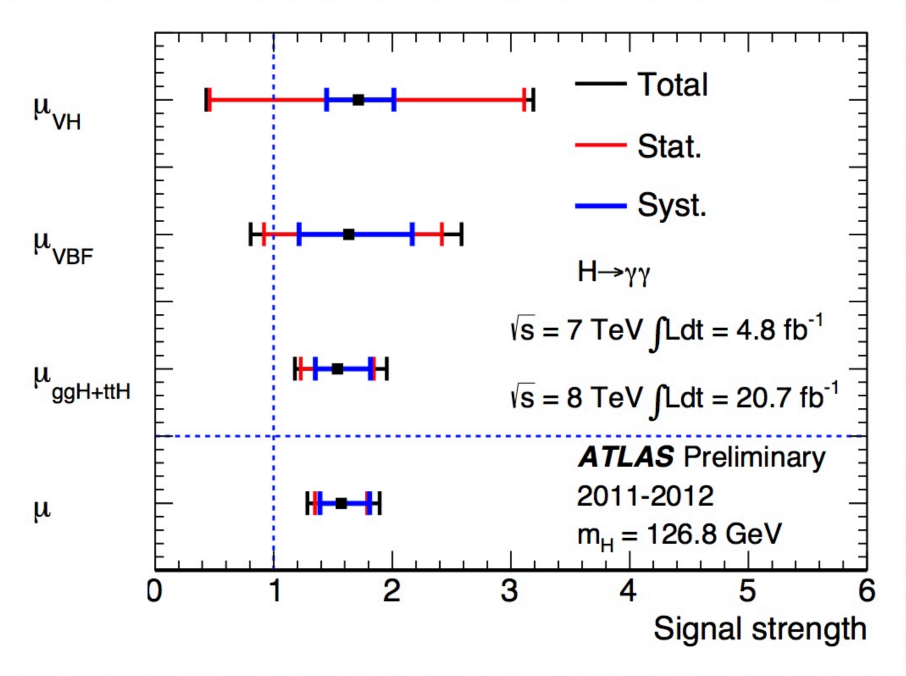
	$gg \to H$	$H \to \gamma\gamma$
Top	$\dfrac{\alpha_S}{12\pi v}$	$\dfrac{2\alpha_{em}}{9\pi v}$
W		$-\dfrac{7\alpha_{em}}{8\pi v}$
KK Top	$-\dfrac{\alpha_S}{12\pi v}\dfrac{1}{3}(\pi m_t R)^2$	$-\dfrac{2\alpha_{em}}{9\pi v}\dfrac{1}{3}(\pi m_t R)^2$
KK W		$\dfrac{7\alpha_{em}}{8\pi v}\dfrac{1}{3}(\pi m_W R)^2$
GHU/SM	$1-\dfrac{1}{3}(\pi m_t R)^2$	$1+\dfrac{1}{141}(\pi m_W R)^2$

KK mode contributions: opposite sign!!

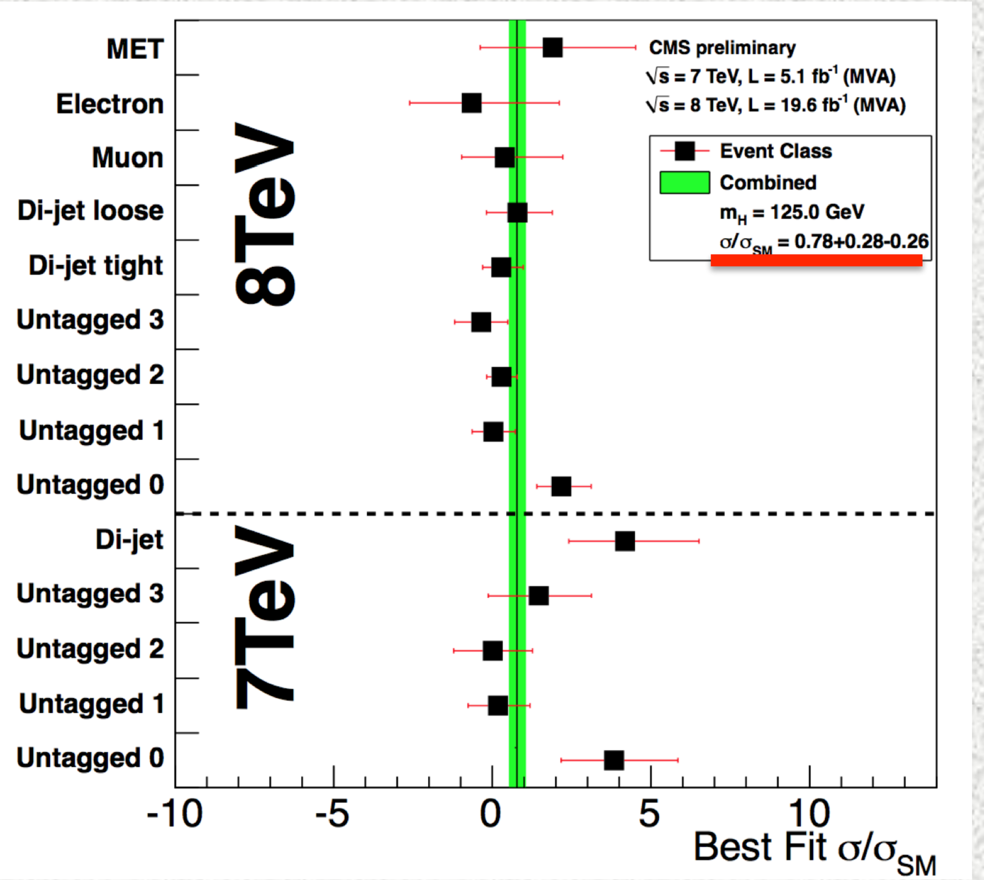
$(gg \to H \to \gamma\gamma)_{GHU} / (gg \to H \to \gamma\gamma)_{SM}$



Diphoton decay data



$$\sigma/\sigma_{SM} = 1.57 \pm 0.22(\mathrm{stat}) \\ + 0.24 - 0.18(\mathrm{syst})$$



Extension is required

Two extensions

1:Color Singlet Fermions

&

2:Colored Fermions

Why fermions??

∵ KK fermion contributions to

$(H\to\gamma\gamma)_{\text{KK fermions}}/(H\to\gamma\gamma)_{SM} > 0$

	$gg \to H$	$H \to \gamma\gamma$
Top	$\frac{\alpha_S}{12\pi v}$	$\frac{2\alpha_{em}}{9\pi v}$
W		$-\frac{7\alpha_{em}}{8\pi v}$
KK Top	$-\frac{\alpha_S}{12\pi v}\frac{1}{3}(\pi m_t R)^2$	$-\frac{2\alpha_{em}}{9\pi v}\frac{1}{3}(\pi m_t R)^2$
KK W		$\frac{7\alpha_{em}}{8\pi v}\frac{1}{3}(\pi m_W R)^2$
GHU/SM	$1-\frac{1}{3}(\pi m_t R)^2$	$1+\frac{1}{141}(\pi m_W R)^2$

Negative

KK mode contributions: opposite sign!!

Color Singlet Fermions

"Diphoton Decay Excess and 125 GeV Higgs Boson in Gauge-Higgs Unification"
NM and Nobuchika Okada
PRD87 095019 (2013)

Simplest extension:

"Extra Leptons"

(colored particles greatly affect gg->H, but discuss later)

Two examples:

10, 15 reps. of SU(3) with bulk mass

& half-periodic BC $\psi(y+2\pi R) = -\psi(y)$

No unwanted massless fermions

1st KK mass = 1/(2R)

⇒ Higgs mass enhancement

Helpful to adjust 125 GeV Higgs

Diphoton decay from 10 & 15

$$C_{\gamma\gamma}^{KKlepton10} = (Q-1)^2 F(3m_W) + (Q-1)^2 F(m_W) + Q^2 F(2m_W) + (Q+1)^2 F(m_W)$$

$$C_{\gamma\gamma}^{KKlepton15} = (Q-4/3)^2 F(4m_W) + (Q-4/3)^2 F(2m_W) + (Q-1/3)^2 F(3m_W)$$
$$+ (Q-1/3)^2 F(m_W) + (Q+2/3)^2 F(2m_W) + (Q+5/3)^2 F(m_W)$$

Q: U(1)' charge

$$F(m_W) = \frac{\alpha_{em}}{6\pi v} N_f m_W \sum_{n=0}^{\infty} \left[\frac{\frac{n+1/2}{R} + m_W}{M^2 + \left(\frac{n+1/2}{R} + m_W\right)^2} - \frac{\frac{n+1/2}{R} - m_W}{M^2 + \left(\frac{n+1/2}{R} - m_W\right)^2} \right]$$

$$\cong -\frac{\alpha_{em}}{3\pi v} N_f m_W^2 \sum_{n=0}^{\infty} \frac{\left(\frac{n+1/2}{R}\right)^2 - M^2}{\left[\left(\frac{n+1/2}{R}\right)^2 + M^2\right]^2} \left(m_W^2 \ll m_n^2\right) = -\frac{\alpha_{em}}{6\pi v} N_f \frac{(\pi m_W R)^2}{\cosh(\pi M R)}$$

Negative

Mass eigenvalues & charges of 10 & 15

$$10 = 1_{-1} + 2_{-1/2} + 3_0 + 4_{1/2}$$

U(1) charge of SU(2)xU(1)

"elemag charge" of SU(2)xU(1)

$$\left(m_{n,-1}^{(\pm)}\right)^2 = \left(m_{n+1/2}^{(\pm)} \pm 3m_W\right)^2 + M^2, \left(m_{n+1/2}^{(\pm)} \pm m_W\right)^2 + M^2$$

$$\left(m_{n,0}^{(\pm)}\right)^2 = \left(m_{n+1/2}^{(\pm)} \pm 2m_W\right)^2 + M^2, m_{n+1/2}^2 + M^2$$

$$\left(m_{n,+1}^{(\pm)}\right)^2 = \left(m_{n+1/2}^{(\pm)} \pm m_W\right)^2 + M^2, \left(m_{n,+2}^{(\pm)}\right)^2 = m_{n+1/2}^2 + M^2$$

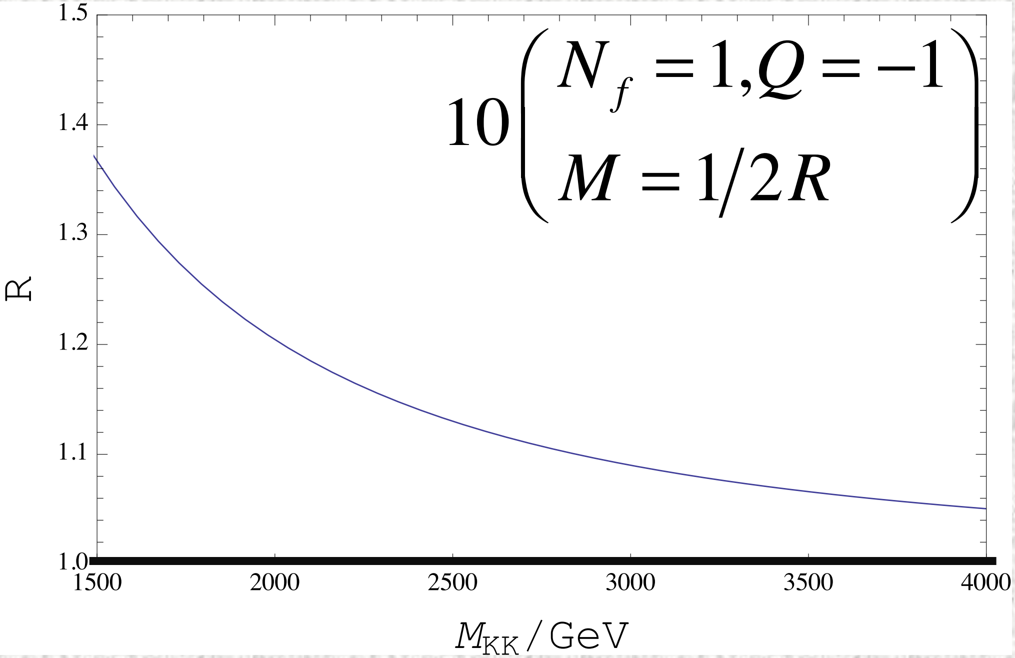
$$15 = 1_{-4/3} + 2_{-5/6} + 3_{-1/3} + 4_{1/6} + 5_{2/3}$$

$$\left(m_{n,-4/3}^{(\pm)}\right)^2 = \left(m_{n+1/2}^{(\pm)} \pm 4m_W\right)^2 + M^2, \left(m_{n+1/2}^{(\pm)} \pm 2m_W\right)^2 + M^2, m_{n+1/2}^2 + M^2$$

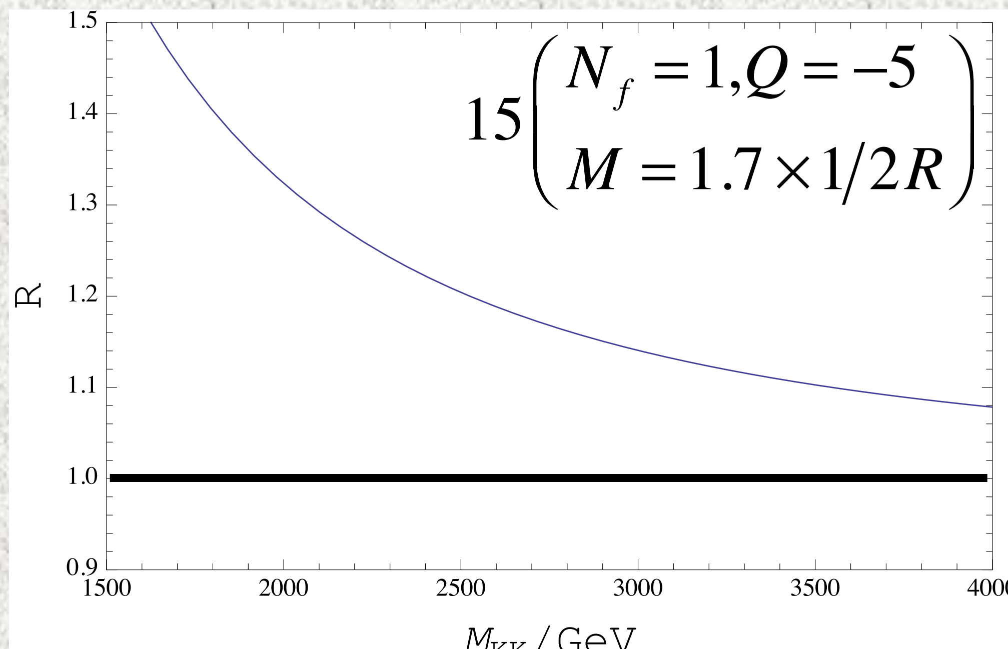
$$\left(m_{n,-1/3}^{(\pm)}\right)^2 = \left(m_{n+1/2}^{(\pm)} \pm 3m_W\right)^2 + M^2, \left(m_{n+1/2}^{(\pm)} \pm m_W\right)^2 + M^2$$

$$\left(m_{n,2/3}^{(\pm)}\right)^2 = \left(m_{n+1/2}^{(\pm)} \pm 2m_W\right)^2 + M^2, m_{n+1/2}^2 + M^2$$

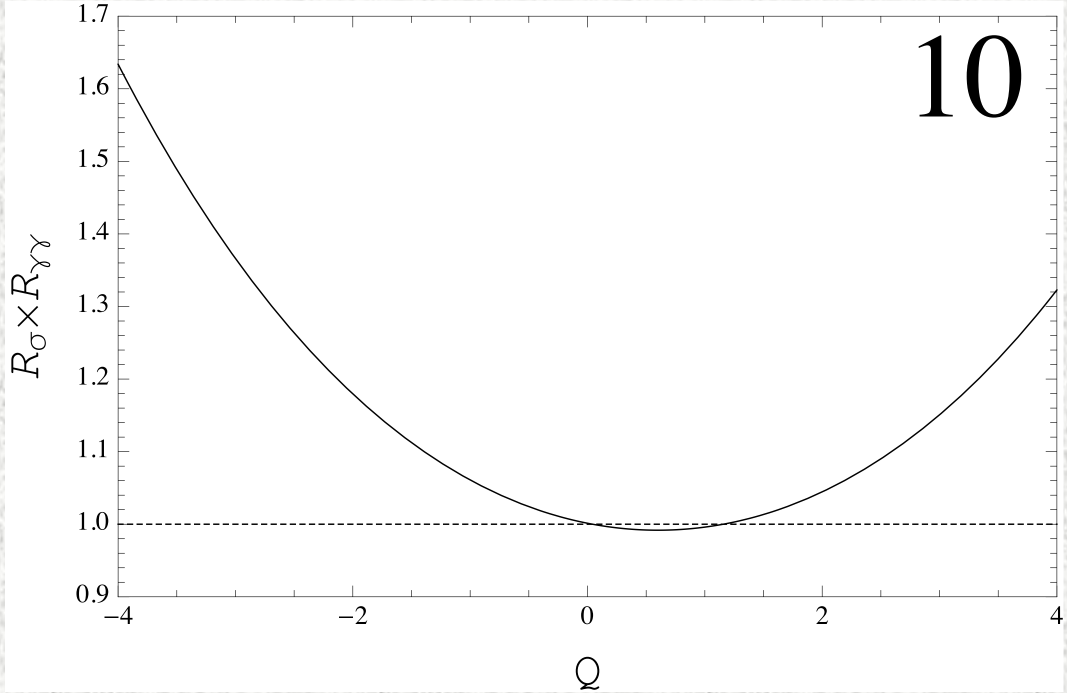
$$\left(m_{n,5/3}^{(\pm)}\right)^2 = \left(m_{n+1/2}^{(\pm)} \pm m_W\right)^2 + M^2, \left(m_{n,8/3}^{(\pm)}\right)^2 = m_{n+1/2}^2 + M^2$$



$$R = \frac{\sigma(gg \to H)_{GHU+10} \times BR(H \to \gamma\gamma)_{GHU+10}}{\sigma(gg \to H)_{SM} \times BR(H \to \gamma\gamma)_{SM}}$$

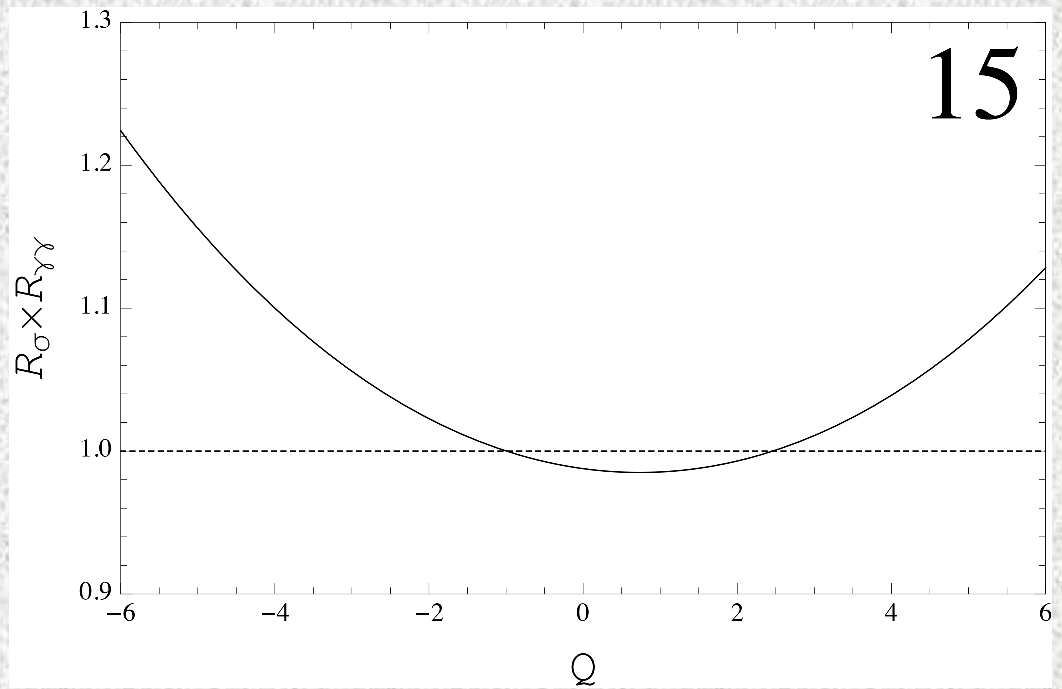


$$R = \frac{\sigma(gg \to H)_{GHU+15} \times BR(H \to \gamma\gamma)_{GHU+15}}{\sigma(gg \to H)_{SM} \times BR(H \to \gamma\gamma)_{SM}}$$



$$R = \frac{\sigma(gg \to H)_{GHU} \times BR(H \to \gamma\gamma)_{GHU}}{\sigma(gg \to H)_{SM} \times BR(H \to \gamma\gamma)_{SM}}$$

1/R = 3TeV fixed



Higgs mass analysis

Higgs mass analysis by 4D EFT approach

In GHU, m_H likely to be small ∵ loop generated

Instead of 5D Higgs potential minimization,
solve 1-loop RGE for Higgs quartic coupling λ
by imposing BC λ =0@1/R "gauge-Higgs condition"

Haba, Matsumoto, Okada & Yamashita (2006, 2008)

Natural realization of GHU in 4D viewpoint:
V_H = 0 above 1/R by 5D gauge invariance

Furthermore, NO vacuum instability

This approach greatly simplifies Higgs mass study

1-loop RGE for λ

$$\frac{d\lambda}{d\ln\mu}=\frac{1}{16\pi^2}\left[12\lambda^2-\left(\frac{9}{5}g_1^2+9g_2^2\right)\lambda+\frac{9}{4}\left(\frac{3}{25}g_1^4+\frac{2}{5}g_1^2g_2^2+g_2^4\right)\right.$$
$$\left.+4\left(3y_t^2+N_fC_q(R)\left(\sqrt{2}g_2\right)^2\right)\lambda-4\left(3y_t^4+N_fC_f(R)\left(\sqrt{2}g_2\right)^4\right)\right](\mu\geq M)$$

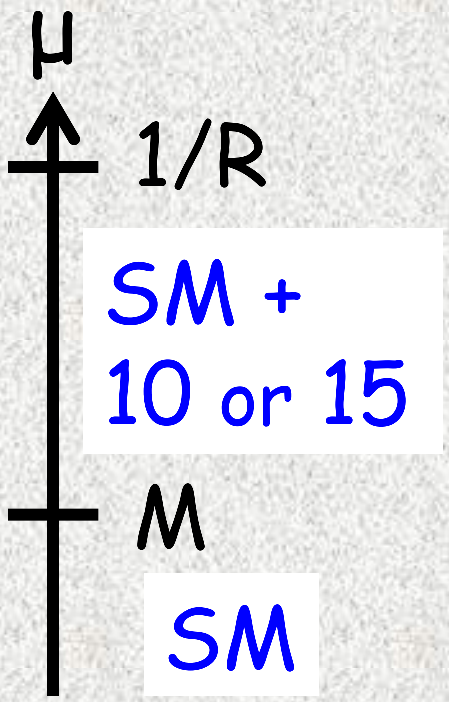
$$\frac{d\lambda}{d\ln\mu}=\frac{1}{16\pi^2}\left[12\lambda^2-\left(\frac{9}{5}g_1^2+9g_2^2\right)\lambda+\frac{9}{4}\left(\frac{3}{25}g_1^4+\frac{2}{5}g_1^2g_2^2+g_2^4\right)+12y_t^2\lambda-12y_t^4\right](\mu<M)$$

$$C_f(10)=2\left[(3/2)^4+(1/2)^4+1^4+(1/2)^4\right]$$

$$C_q(10)=2\left[(3/2)^2+(1/2)^2+1^2+(1/2)^2\right]$$

$$C_f(15)=2\left[2^4+1^4+(3/2)^4+(1/2)^4+1^4+(1/2)^4\right]$$

$$C_q(15)=2\left[2^2+1^2+(3/2)^2+(1/2)^2+1^2+(1/2)^2\right]$$



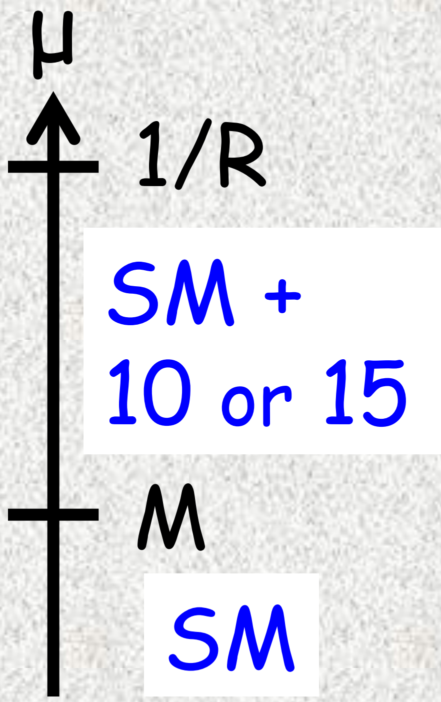
1-loop RGE for λ

$$\frac{d\lambda}{d\ln\mu} = \frac{1}{16\pi^2}\Bigg[12\lambda^2 - \left(\frac{9}{5}g_1^2 + 9g_2^2\right)\lambda + \frac{9}{4}\left(\frac{3}{25}g_1^4 + \frac{2}{5}g_1^2 g_2^2 + g_2^4\right)$$

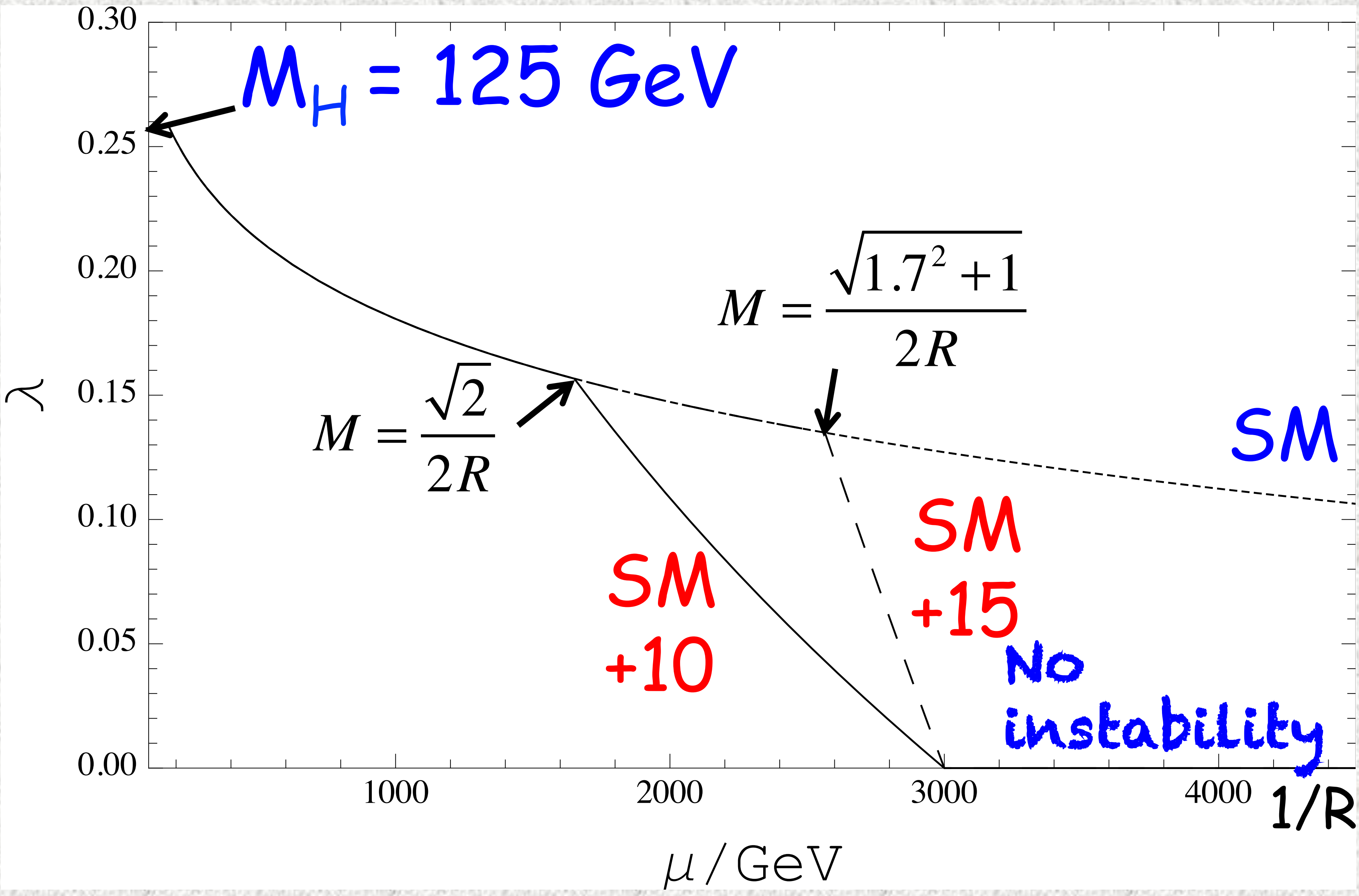
$$+4\left(3y_t^2 + N_f C_q(R)\left(\sqrt{2}g_2\right)^2\right)\lambda - 4\left(3y_t^4 + N_f C_f(R)\left(\sqrt{2}g_2\right)^4\right)\Bigg](\mu \geq M)$$

$$\frac{d\lambda}{d\ln\mu} = \frac{1}{16\pi^2}\left[12\lambda^2 - \left(\frac{9}{5}g_1^2 + 9g_2^2\right)\lambda + \frac{9}{4}\left(\frac{3}{25}g_1^4 + \frac{2}{5}g_1^2 g_2^2 + g_2^4\right) + 12y_t^2\lambda - 12y_t^4\right](\mu < M)$$

- Contributions from 1st KK mode with mass 1/(2R) in 10 or 15 rep.
- 2nd term $\propto (\sqrt{2}g_2)^4$ dominated
- Negative sign



Numerical results for 1-loop RGE of λ



TeV Scale Colored Fermions

"125 GeV Higgs Boson & TeV Scale Colored Fermion in Gauge-Higgs Unification"

NM and Nobuchika Okada

arXiv: 1310.3348

Another possibility to realize 125 GeV Higgs mass by introducing extra colored fermions

Colored fermions contribute to $gg \to H$ destructively

$\Rightarrow$ LHC Data put a lower bound for KK masses

$\Rightarrow$ It would be interesting
if the lower bound is within a detectable range
w/o contradicting 125 GeV Higgs mass

Result:

M_{KK}=2-3TeV for $\sigma(gg \to H)/\sigma_{SM} \sim 0.9$-$0.95$

Extra colored fermions have half-periodic BC

⇒ the lightest KK particle (LKP) is stable,
but stable colored particle is cosmologically disfavor

⇒ introduce the mixing btw the LKP & SM quarks on the brane for decay to SM quarks

⇒ U(1)′ charge fixed to be -1/3 (2/3) for down(up)-type quarks

⇒ Q=2/3, 5/3 for **10**-plet, Q=1, 2 for **15**-plet
(Q-1=-1/3, 2/3 for 10, Q-4/3=-1/3 or 2/3)

Mass eigenvalues & charges of 10 & 15

$10 = 1_{-1} + 2_{-1/2} + 3_0 + 4_{1/2}$

U(1) charge of SU(2)xU(1)

"elemag charge" of SU(2)xU(1)

$$\left(m_{n,-1}^{(\pm)}\right)^2 = \left(m_{n+1/2}^{(\pm)} \pm 3m_W\right)^2 + M^2, \left(m_{n+1/2}^{(\pm)} \pm m_W\right)^2 + M^2$$

$$\left(m_{n,0}^{(\pm)}\right)^2 = \left(m_{n+1/2}^{(\pm)} \pm 2m_W\right)^2 + M^2, m_{n+1/2}^2 + M^2$$

$$\left(m_{n,+1}^{(\pm)}\right)^2 = \left(m_{n+1/2}^{(\pm)} \pm m_W\right)^2 + M^2, \left(m_{n,+2}^{(\pm)}\right)^2 = m_{n+1/2}^2 + M^2$$

$15 = 1_{-4/3} + 2_{-5/6} + 3_{-1/3} + 4_{1/6} + 5_{2/3}$

$$\left(m_{n,-4/3}^{(\pm)}\right)^2 = \left(m_{n+1/2}^{(\pm)} \pm 4m_W\right)^2 + M^2, \left(m_{n+1/2}^{(\pm)} \pm 2m_W\right)^2 + M^2, m_{n+1/2}^2 + M^2$$

$$\left(m_{n,-1/3}^{(\pm)}\right)^2 = \left(m_{n+1/2}^{(\pm)} \pm 3m_W\right)^2 + M^2, \left(m_{n+1/2}^{(\pm)} \pm m_W\right)^2 + M^2$$

$$\left(m_{n,2/3}^{(\pm)}\right)^2 = \left(m_{n+1/2}^{(\pm)} \pm 2m_W\right)^2 + M^2, m_{n+1/2}^2 + M^2$$

$$\left(m_{n,5/3}^{(\pm)}\right)^2 = \left(m_{n+1/2}^{(\pm)} \pm m_W\right)^2 + M^2, \left(m_{n,8/3}^{(\pm)}\right)^2 = m_{n+1/2}^2 + M^2$$

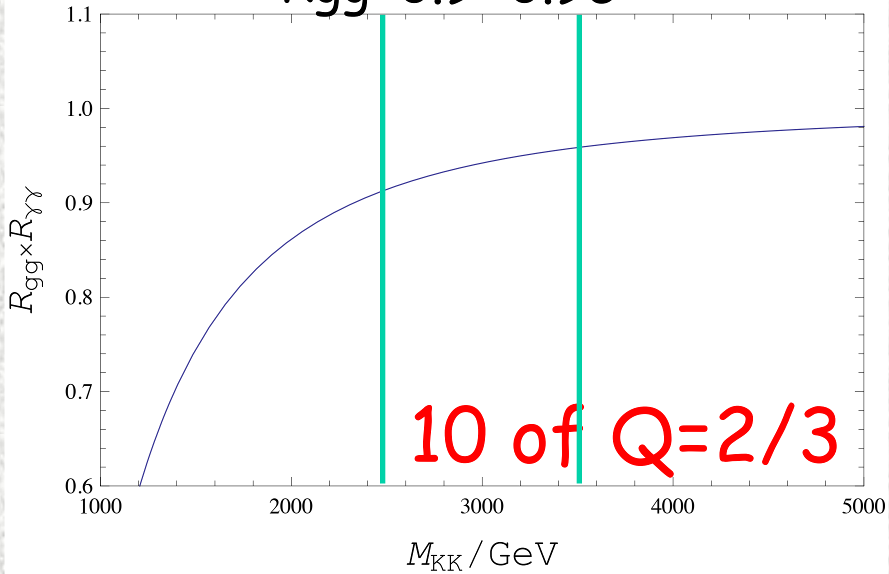
Lower bound on KK scale etc from gluon fusion

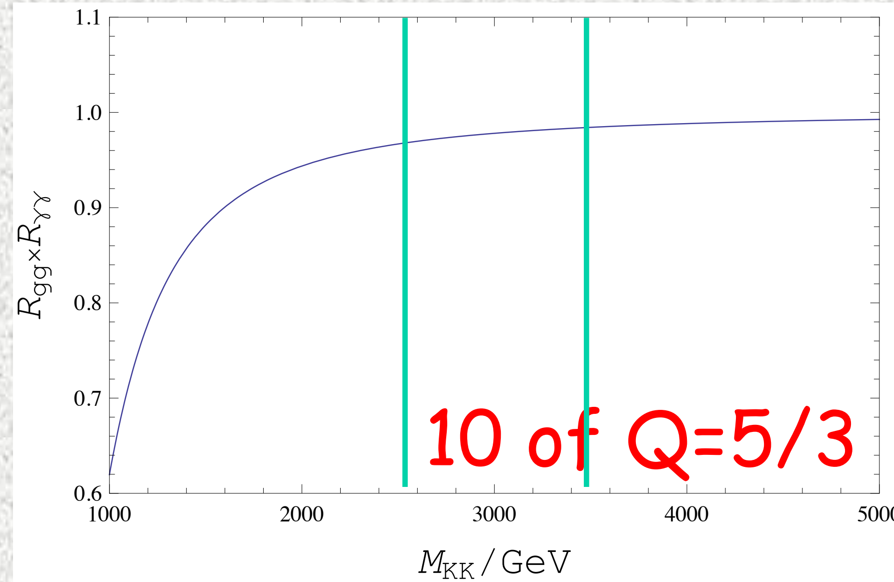
10-plet	$R_{gg} = 0.9$	$R_{gg} = 0.95$
$M_{\rm KK}$ (TeV)	2.54	3.45
$m_0^{(\pm)}$ (TeV)	2.05	2.91
$m_{\rm lightest}$ (TeV)	1.91	2.77

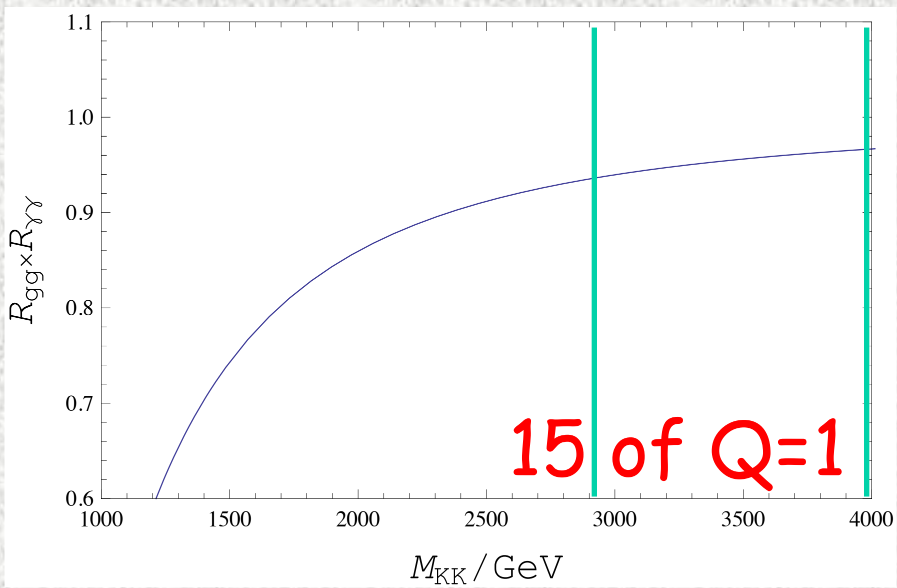
15-plet	$R_{gg} = 0.9$	$R_{gg} = 0.95$
$M_{\rm KK}$ (TeV)	2.88	4.05
$m_0^{(\pm)}$ (TeV)	2.73	3.87
$m_{\rm lightest}$ (TeV)	2.57	3.71

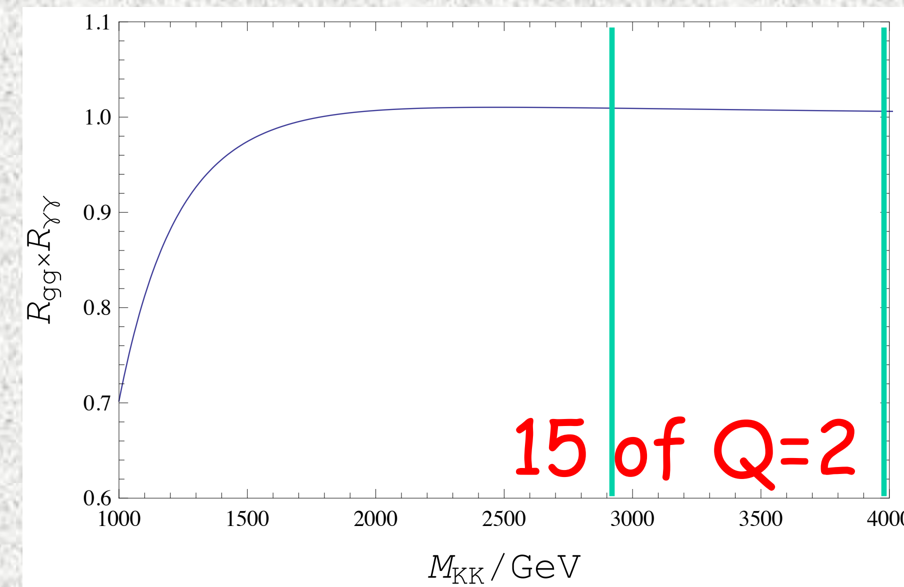
Diphoton Decay Signal Strength

Rgg=0.9 0.95

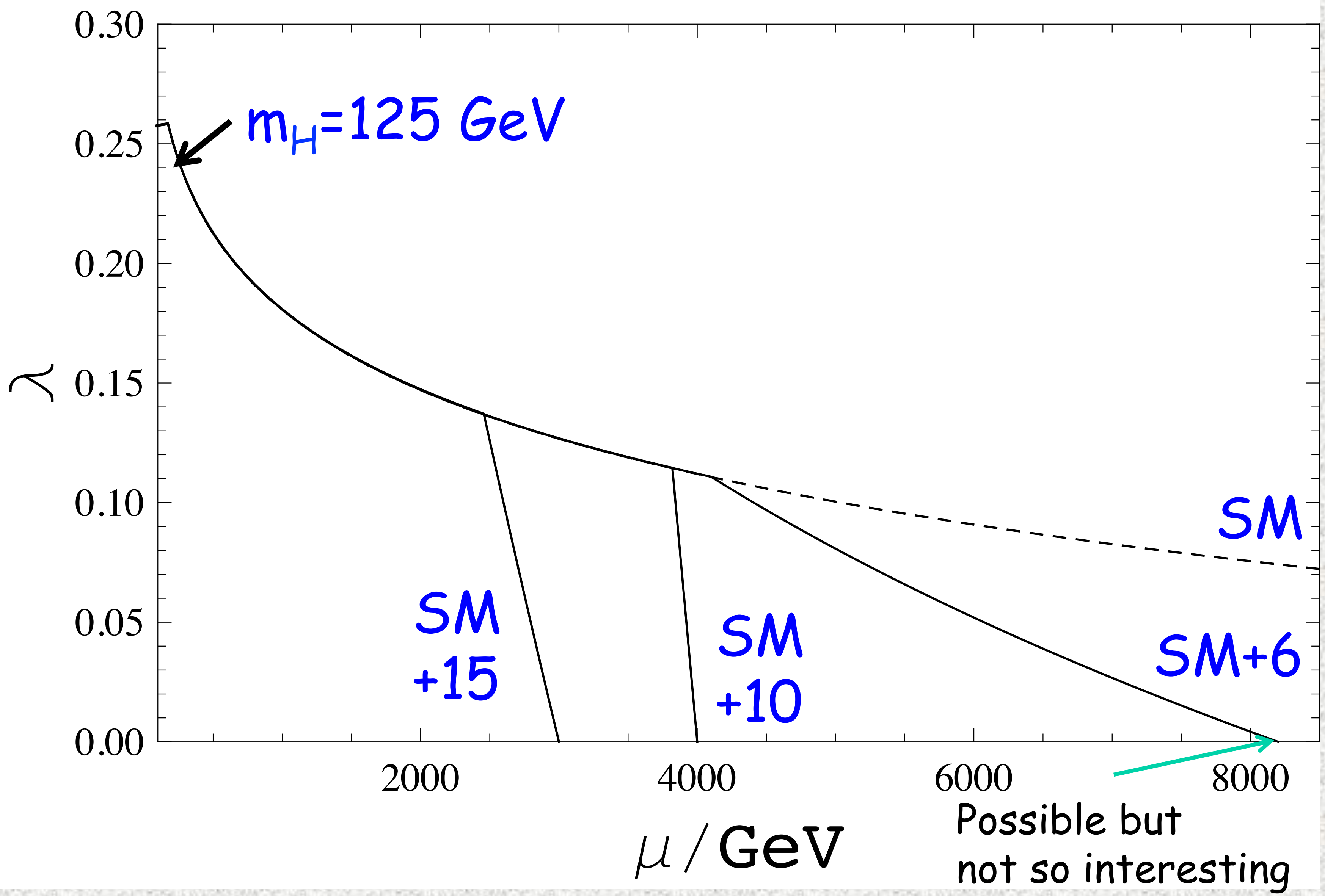








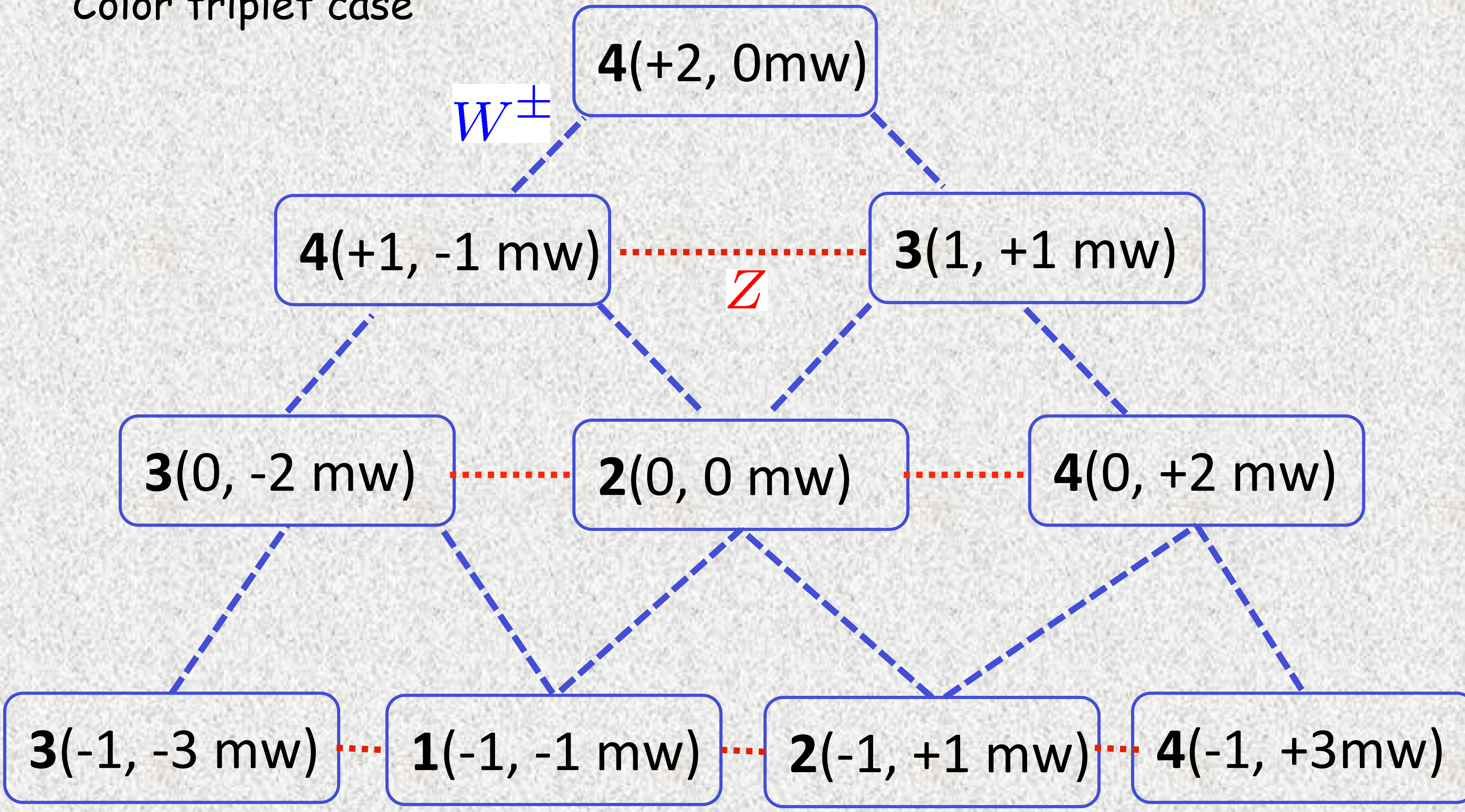
1-loop RGE for Higgs quartic coupling



Interactions between KK modes & W, Z

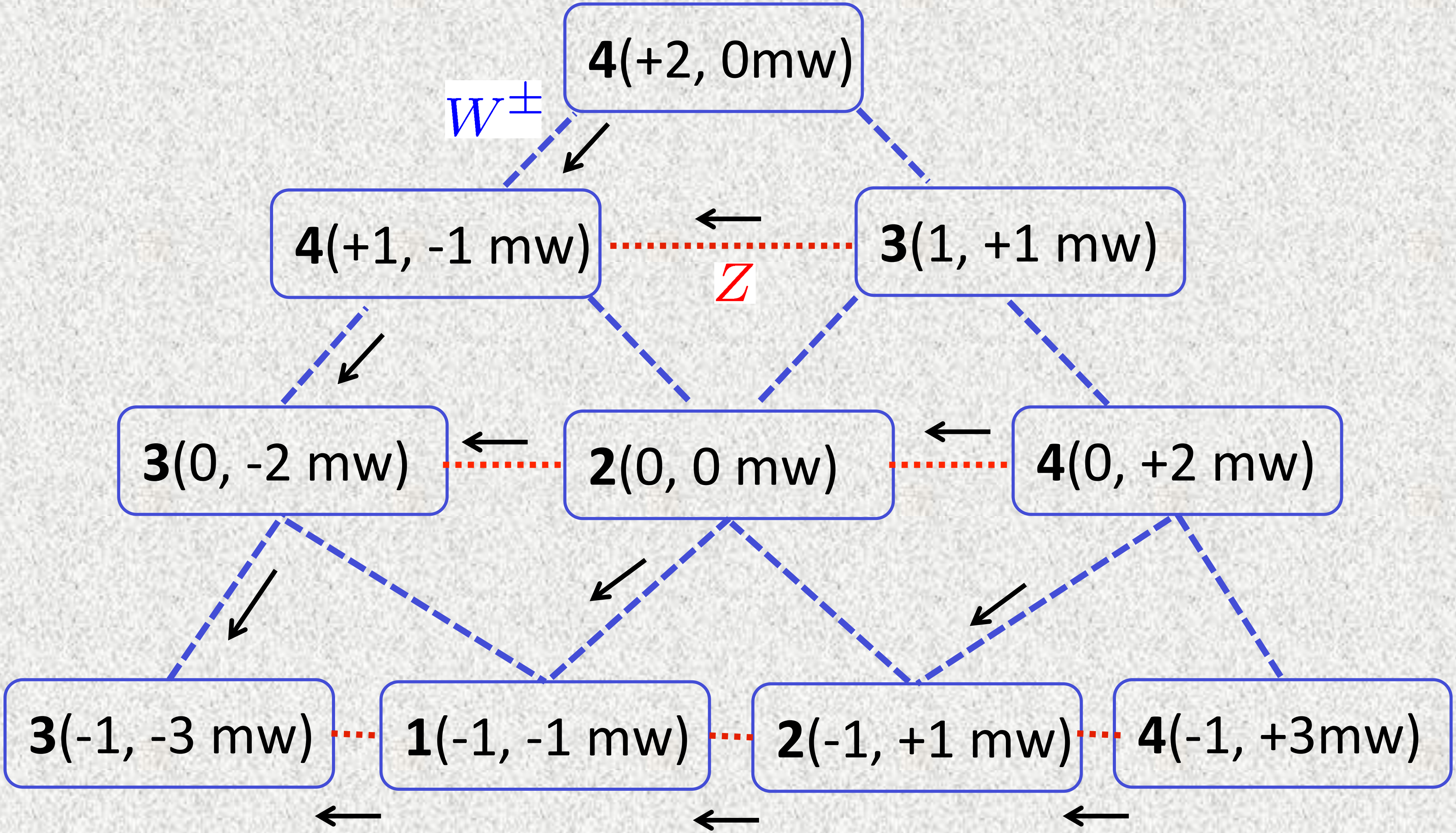
Ex: 10-plet: $10 = 1_{-1} \oplus 2_{-1/2} \oplus 3_0 \oplus 4_{1/2}$

Color triplet case



Heavy fermion cascades

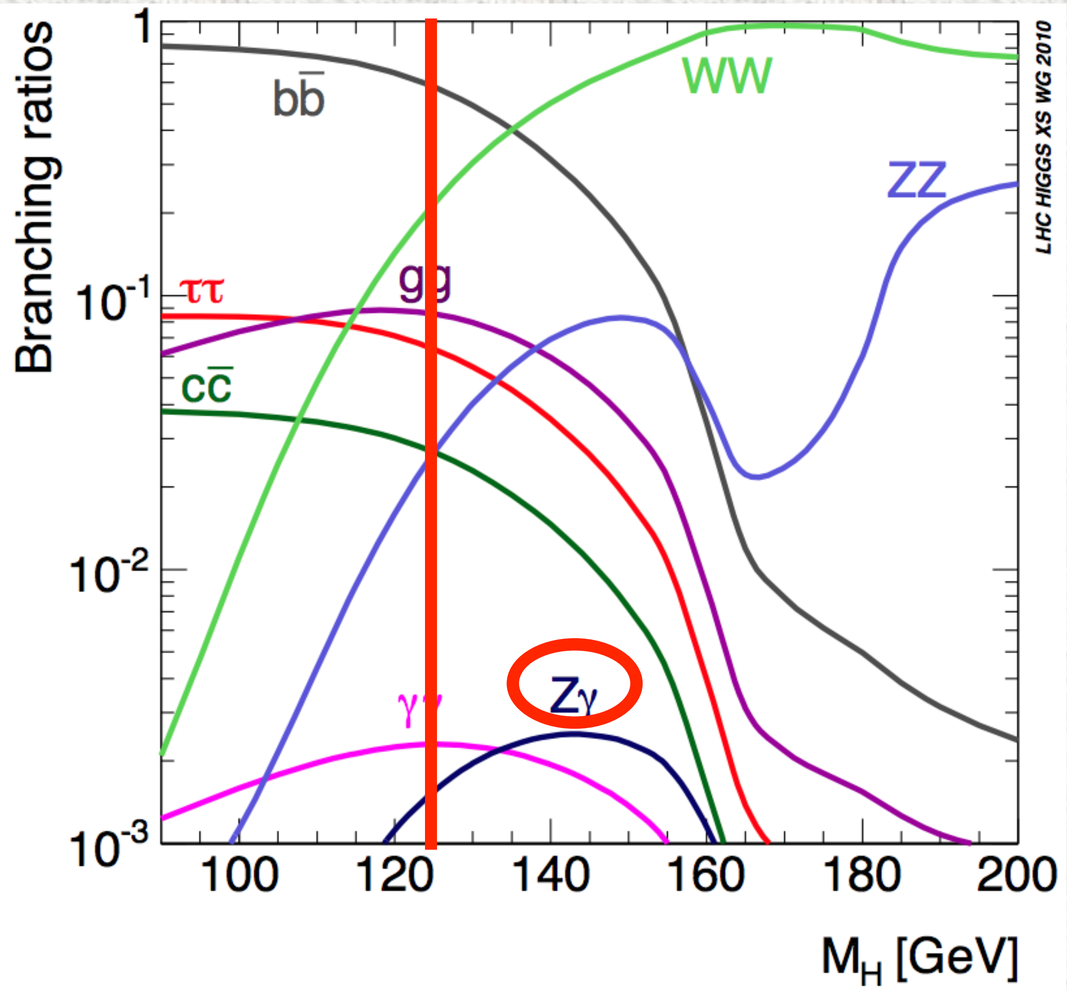
Ex: 10-plet: $10 = 1_{-1} \oplus 2_{-1/2} \oplus 3_0 \oplus 4_{1/2}$



$H \to Z \gamma$

"H to Z Gamma in Gauge-Higgs Unification"
NM & Nobuchika Okada,
PRD88 (2013) 037701

A Comment on $H \to Z\gamma$



KK modes have EW charges

↓

Naturally, a deviation of $Z\gamma$ decay from the SM prediction expected

Model dep.
Correlation btw $\gamma\gamma$ & $Z\gamma$ is interesting

No KK mode contributions to $Z\gamma$ decay@1-loop

Simple reason: in the mass eigenstates, H and γ couples to KK modes with same mass eigenstates, but Z does not

Fermion coupling

$$\left(\bar{\psi}_0^{(n)},\bar{\psi}_+^{(n)},\bar{\psi}_-^{(n)}\right)\begin{pmatrix} 2\gamma_\mu/\sqrt{3} & W_\mu^+ & W_\mu^+ \\ W_\mu^- & -\gamma_\mu/\sqrt{3} & -Z_\mu \\ W_\mu^- & -Z_\mu & -\gamma_\mu/\sqrt{3} \end{pmatrix}\gamma^\mu\begin{pmatrix}\psi_0^{(n)}\\ \psi_+^{(n)}\\ \psi_-^{(n)}\end{pmatrix},\psi_{0,\pm}^{(n)}:\frac{n}{R},\frac{n}{R}\pm m_f$$

ZW^nW^n coupling

$$Z_\mu\left(W_{\mu\nu+}^{\mp(n)},W_{\mu\nu-}^{\mp(n)}\right)\begin{pmatrix}0 & \mp i\\ \pm i & 0\end{pmatrix}\left(W_{\nu+}^{\pm(n)},W_{\nu-}^{\pm(n)}\right)$$

$$W_{\mu\pm}^{(n)}:n/R\pm m_W,W_{\mu\nu}\equiv\partial_\mu W_\nu-\partial_\nu W_\mu$$

$Z\gamma W^nW^n$ coupling

$$Z^\mu\gamma_\nu\left(W_{\mu+}^{\mp(n)},W_{\mu-}^{\mp(n)}\right)\begin{pmatrix}0 & -i\\ i & 0\end{pmatrix}\begin{pmatrix}W_+^{\pm\nu(n)}\\ W_-^{\pm\nu(n)}\end{pmatrix}+2Z_\mu\gamma^\mu\left(W_{\nu+}^{\mp(n)},W_{\nu-}^{\mp(n)}\right)\begin{pmatrix}0 & i\\ -i & 0\end{pmatrix}\begin{pmatrix}W_+^{\pm\nu(n)}\\ W_-^{\pm\nu(n)}\end{pmatrix}$$

In SU(3) GHU, No H-Z-γ coupling@1-loop found

Correct even in SU(3)xU(1)' GHU??

- In Hasegawa & Lim (2016), it was shown that d=6 operator describing $H\to Z\gamma$ is (not) forbidden in SU(3)(xU(1)) GHU
- Hosotani et al. (2015) has obtained nonzero but tiny value of $H\to Z\gamma$ in warped SO(5)xU(1) GHU

We investigated $H\to Z\gamma$@1-loop in SU(3)xU(1) GHU and verified a nonzero result

NM & Onogi (in progress)

Summary

- We have calculated KK mode contributions to
  $gg \to H$ & $H \to \gamma\gamma$ @LHC in 5D SU(3)xU(1)' GHU
- Simplest model cannot explain the data
- Extra fermions can enhance $H \to \gamma\gamma$ as we like
  by adjusting U(1)' charges

  ex. Color singlet & Colored fermions
  in 10 & 15 reps. of SU(3) w/ bulk mass
  & half-periodic BC
- These fermions also help to enhance Higgs mass

Summary

- 1-loop RGE analysis of Higgs quartic coupling with GH condition $\lambda=0@M_{KK}$
  ⇒ No instability
- Extra fermions are (some kind of) Z_2 odd & stable due to the half-periodic BC

(i) Color singlet case ⇒ LKP can be DM candidate in case of vanishing electric charge (10: 2TeV, 15: 3TeV)

(ii) Colored case ⇒ TeV scale LKP decay to the SM quark by the mixing

Backup Slides

Lagrangian

5D SU(3) x U(1)′ model on S^1/Z_2

$$\mathcal{L} = -\frac{1}{2}\mathrm{Tr}\left(F_{MN}F^{MN}\right) + \bar{\Psi}_3^{i=1,2,3}\left(i\Gamma^M D_M - M_d^i \varepsilon(y)\right)\Psi_3^{i=1,2,3}$$
$$+\bar{\Psi}_{\bar{6}}^{i=1,2}\left(i\Gamma^M D_M - M_u^i \varepsilon(y)\right)\Psi_{\bar{6}}^{i=1,2} + \bar{\Psi}_{\overline{15}} i\Gamma^M D_M \Psi_{\overline{15}}$$
$$+\bar{\Psi}_{10}^{i=1,2,3}\left(i\Gamma^M D_M - M_l^i \varepsilon(y)\right)\Psi_{10}^{i=1,2,3} \qquad \Gamma^M = \left(\gamma^\mu, i\gamma^5\right)$$

Boundary conditions:

(+,+) only has massless mode

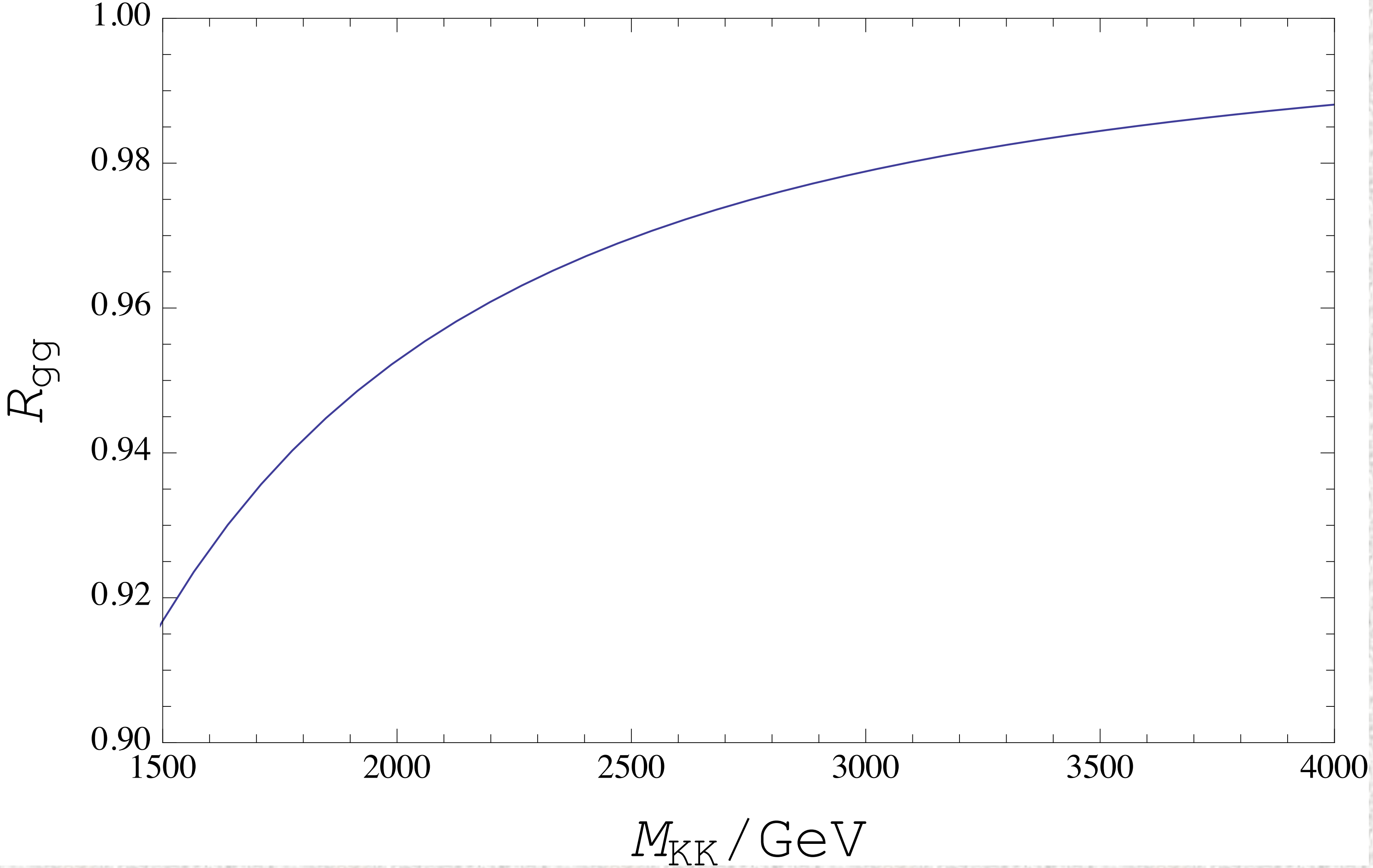
(+,+): cos(ny/R)

(-,-): sin(ny/R)

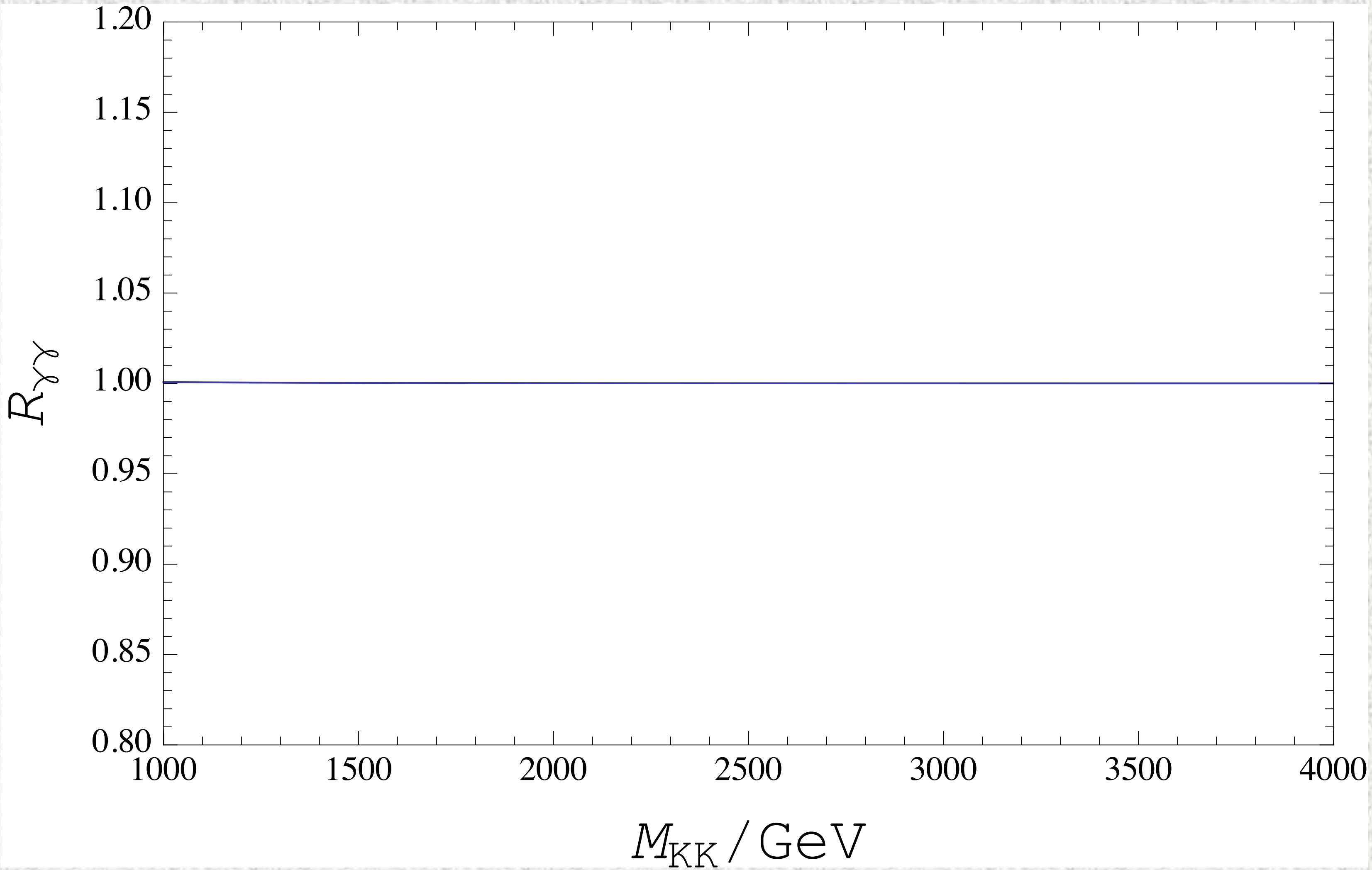
$$A_\mu^{(0)} = \frac{1}{2}\begin{pmatrix} W_\mu^3 + B_\mu^3/\sqrt{3} & \sqrt{2}W_\mu^+ & 0 \\ \sqrt{2}W_\mu^- & -W_\mu^3 & 0 \\ 0 & 0 & -2B_\mu/\sqrt{3} \end{pmatrix}, A_5^{(0)} = \frac{1}{2}\begin{pmatrix} 0 & 0 & H^+ \\ 0 & 0 & H^0 \\ H^- & H^{0*} & 0 \end{pmatrix}$$

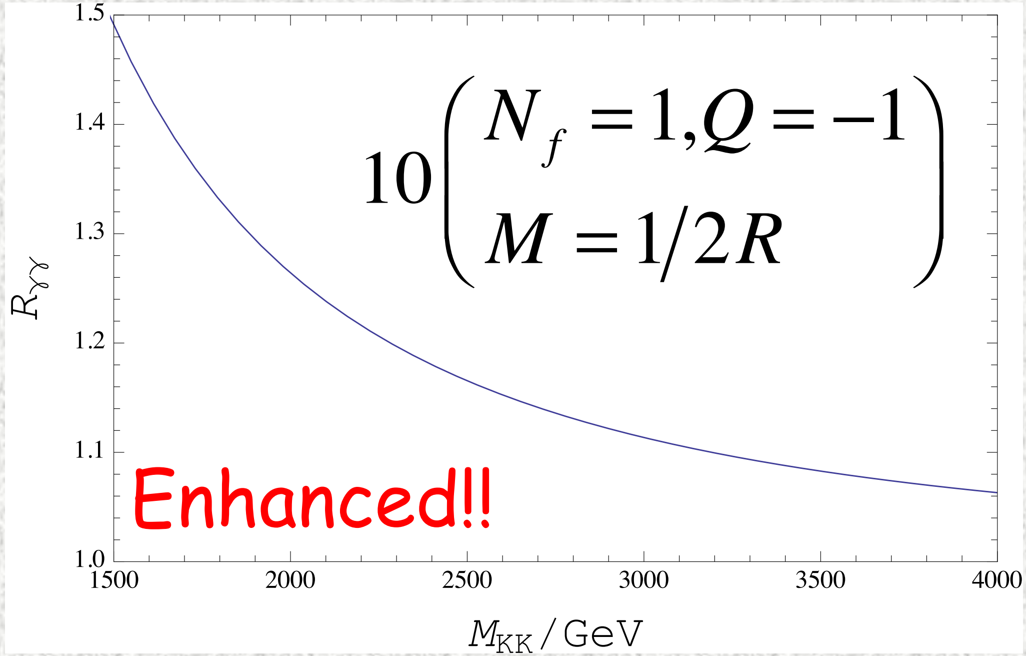
$$M_{W_n} = \frac{n+\alpha}{R}, M_{Z_n} = \frac{n+2\alpha}{R}, M_{\gamma_n} = \frac{n}{R}, \left\langle A_5^{(0)} \right\rangle = \frac{\alpha}{g_5 R}$$

$\sigma(gg \to H)_{GHU} / \sigma(gg \to H)_{SM}$



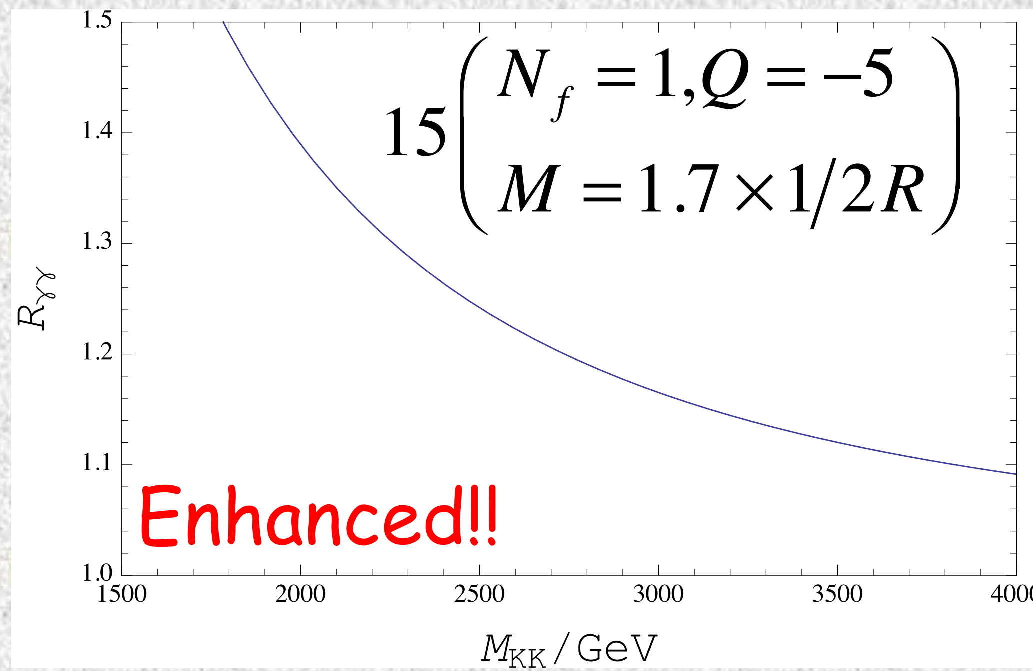
$\Gamma(H\to\gamma\gamma)_{GHU}/\Gamma(H\to\gamma\gamma)_{SM}$



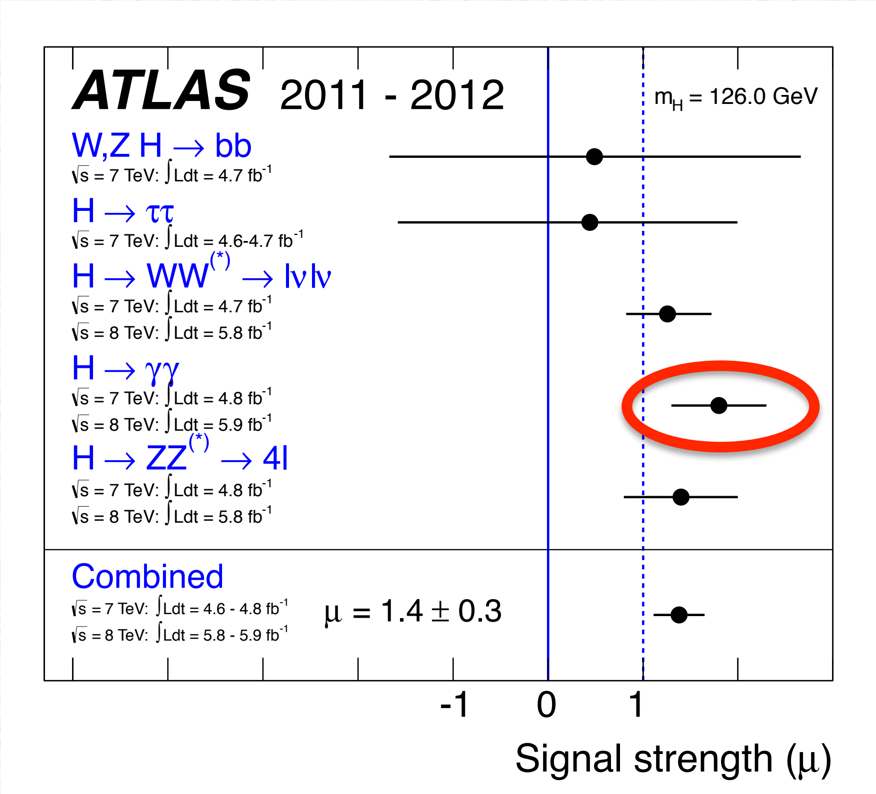


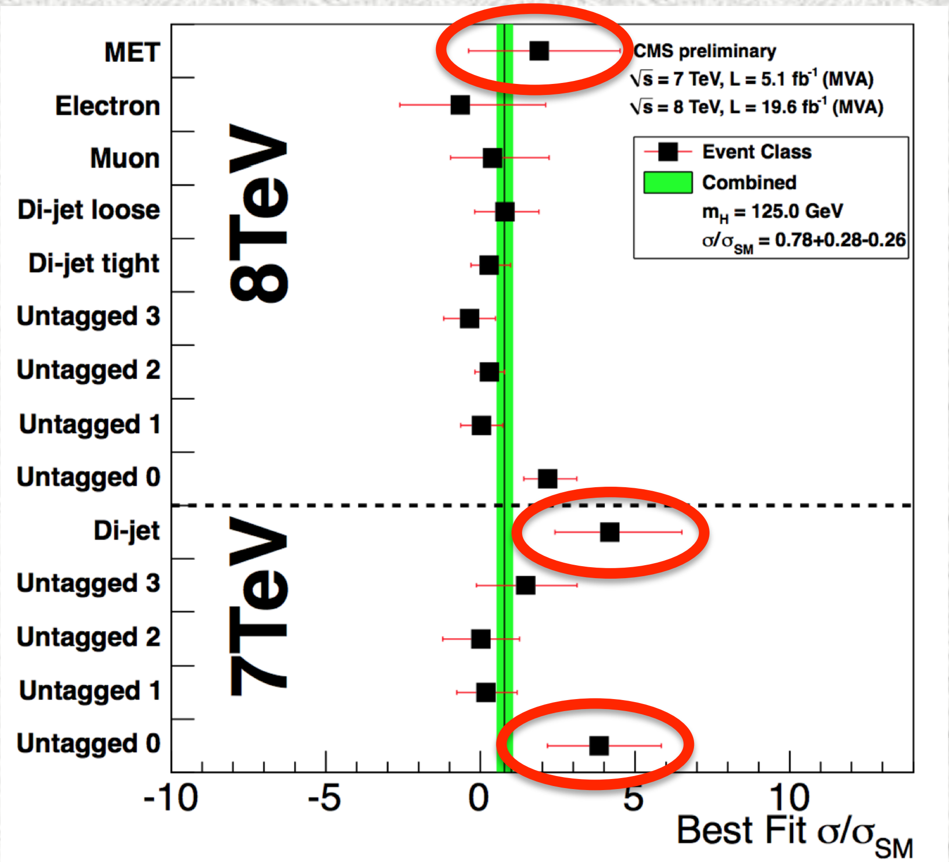
$$R_{\gamma\gamma} = \frac{BR(H \to \gamma\gamma)_{GHU+10}}{BR(H \to \gamma\gamma)_{SM}}$$

$$R_{\gamma\gamma} = \frac{BR(H \to \gamma\gamma)_{GHU+15}}{BR(H \to \gamma\gamma)_{SM}}$$



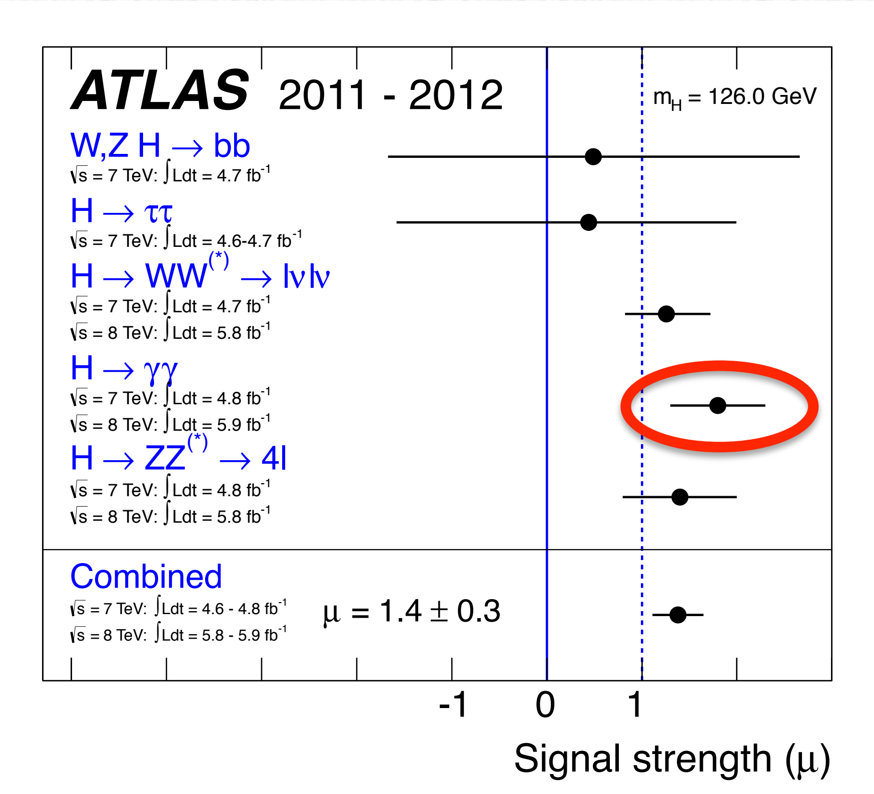
Diphoton decay excess

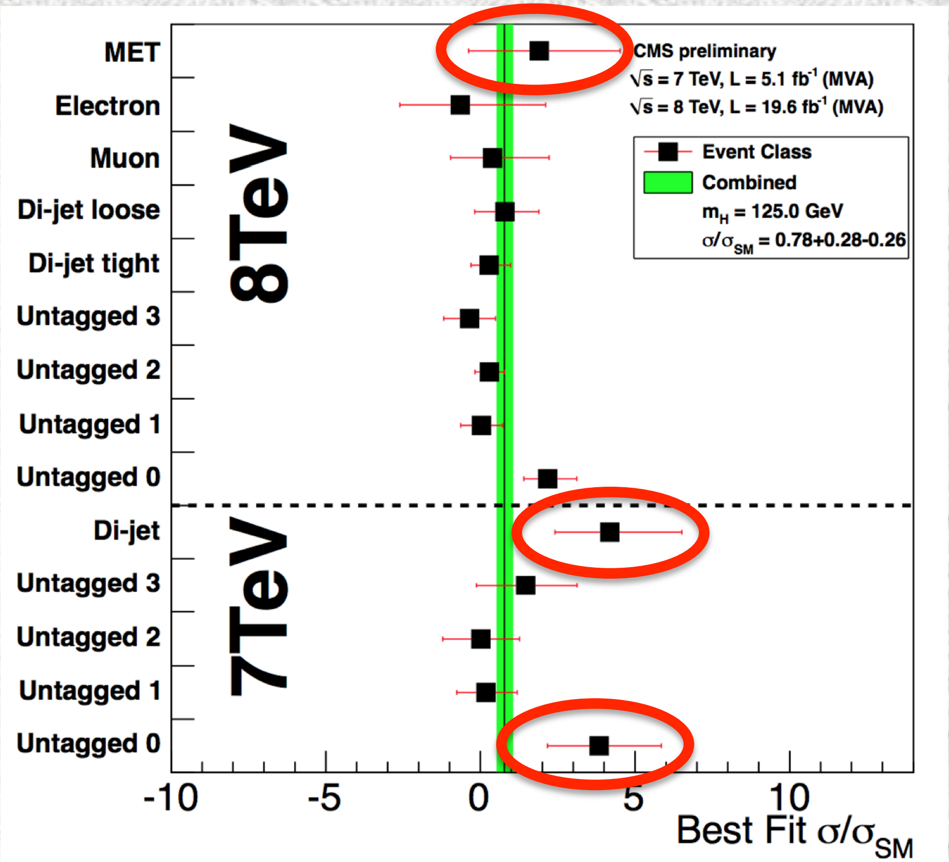




Hint for New Physics??

Diphoton decay excess





In this talk, we show that the diphoton decay excess can be explained in gauge-Higgs unification

Weinberg angle in GHU

If SU(3)→SU(2)$_L$xU(1)$_Y$: U(1) normalization fixed

Check the hypercharge of Higgs doublet

$$\delta_{U(1)} A_5^{(0)} = g\left[T^8, A_5^{(0)}\right] = \frac{g}{2\sqrt{3}}\left[\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -2 \end{pmatrix}, \begin{pmatrix} 0 & 0 & H^+ \\ 0 & 0 & H^0 \\ H^- & H^{0*} & 0 \end{pmatrix}\right]$$

$$= \frac{g}{2\sqrt{3}}\begin{pmatrix} 0 & 0 & H^+ \\ 0 & 0 & H^0 \\ -2H^- & -2H^{0*} & 0 \end{pmatrix} - \frac{g}{2\sqrt{3}}\begin{pmatrix} 0 & 0 & -2H^+ \\ 0 & 0 & -2H^0 \\ H^- & H^{0*} & 0 \end{pmatrix} = \frac{g\sqrt{3}}{2}\begin{pmatrix} 0 & 0 & H^+ \\ 0 & 0 & H^0 \\ -H^- & -H^{0*} & 0 \end{pmatrix}$$

$$\sin^2\theta_W = \frac{g_Y^2}{g^2+g_Y^2} = \frac{\left(\sqrt{3}g\right)^2}{g^2+\left(\sqrt{3}g\right)^2} = \frac{3}{4} \gg 0.23(\text{Exp})$$

Too Big!!

Way out to get a correct Weinberg angle

Additional U(1)

$SU(3) \times U(1)' \rightarrow SU(2)_L \times U(1)_Y \times U(1)_X$

Scrucca, Serone & Silvestrini (2003)

$$A_Y = \frac{g' A_8 + \sqrt{3} g A'}{\sqrt{3g^2 + g'^2}}, A_X = \frac{\sqrt{3} g A_8 - g' A'}{\sqrt{3g^2 + g'^2}}$$

$$\Rightarrow \delta_{U(1)} A_5^{(0)} = \frac{g'}{\sqrt{3g^2 + g'^2}} g \left[T^8, A_5^{(0)} \right] \Rightarrow g_Y = \frac{\sqrt{3} g g'}{\sqrt{3g^2 + g'^2}}$$

$$\sin^2 \theta_W = \frac{g_Y^2}{g^2 + g_Y^2} = \frac{3}{4 + 3 g^2 / g'^2}$$

Adjustable by g'

Electroweak symmetry breaking

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

is radiatively triggered by nonzero $\langle A_5 \rangle$

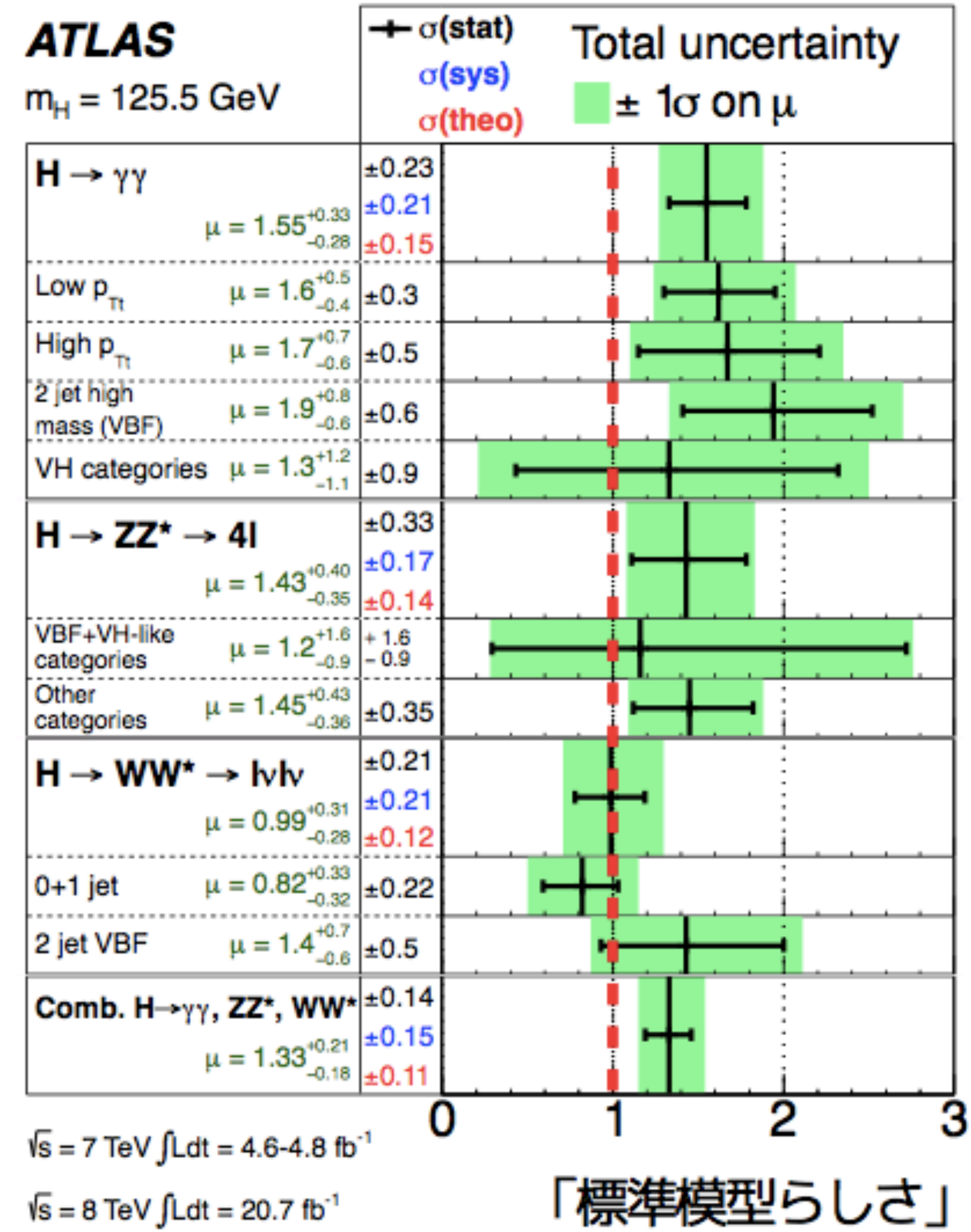
(Hosotani mechanism)

Ratio of GHU to SM

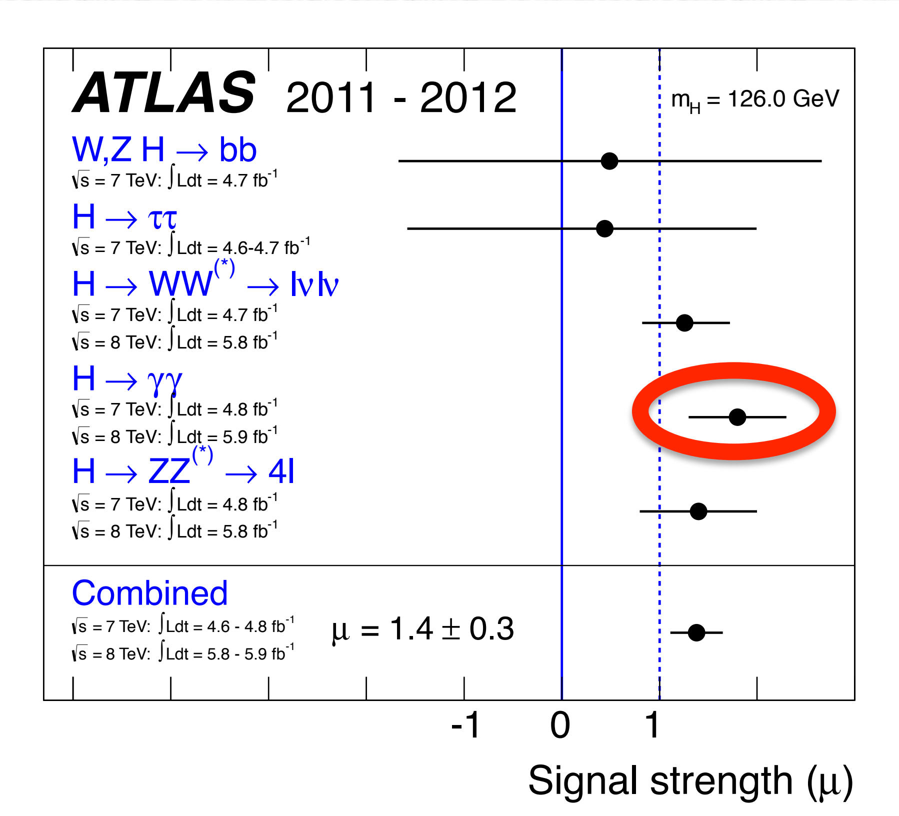
$$R_\sigma \equiv \left(1+\frac{C_{gg}^{KKtop}}{C_{gg}^{top}}\right)^2 \cong \left(1-\frac{1}{3}(\pi m_t R)^2\right)^2 \cong \left(1-\frac{4}{3}(\pi m_W R)^2\right)^2$$

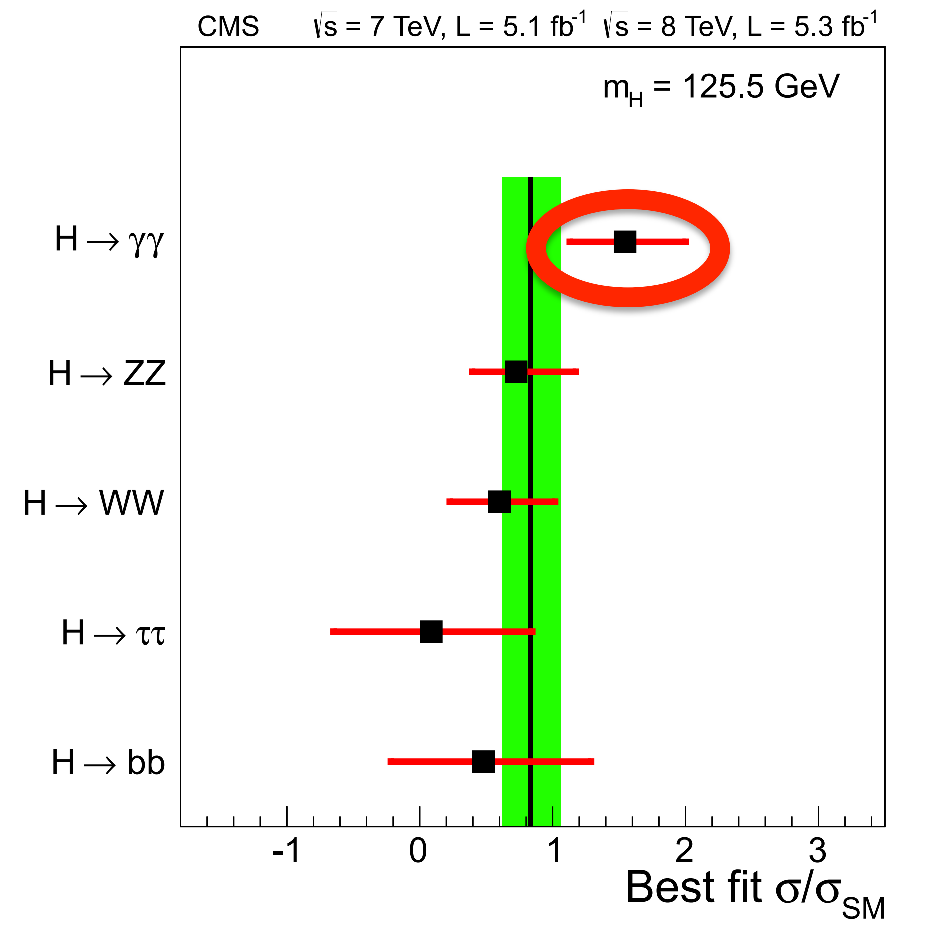
$$R_{\gamma\gamma} \equiv \left(1+\frac{C_{\gamma\gamma}^{KKtop}+C_{\gamma\gamma}^{KKW}}{C_{\gamma\gamma}^{top}+C_{\gamma\gamma}^{W}}\right)^2 \cong \left(1+\frac{1}{141}(\pi m_W R)^2\right)^2$$

$$R \equiv R_\sigma \times R_{\gamma\gamma} \cong \left(1-\frac{187}{141}(\pi m_W R)^2\right)^2$$


ATLAS
m_H = 125.5 GeV
σ(stat)
σ(sys)
σ(theo)
Total uncertainty
± 1σ on μ
H → γγ
μ = 1.55 +0.33 −0.28
±0.23
±0.21
±0.15
Low p_Tt μ = 1.6 +0.5 −0.4 ±0.3
High p_Tt μ = 1.7 +0.7 −0.6 ±0.5
2 jet high mass (VBF) μ = 1.9 +0.8 −0.6 ±0.6
VH categories μ = 1.3 +1.2 −1.1 ±0.9
H → ZZ* → 4l
μ = 1.43 +0.40 −0.35
±0.33
±0.17
±0.14
VBF+VH-like categories μ = 1.2 +1.6 −0.9 + 1.6 − 0.9
Other categories μ = 1.45 +0.43 −0.36 ±0.35
H → WW* → lνlν
μ = 0.99 +0.31 −0.28
±0.21
±0.21
±0.12
0+1 jet μ = 0.82 +0.33 −0.32 ±0.22
2 jet VBF μ = 1.4 +0.7 −0.6 ±0.5
Comb. H→γγ, ZZ*, WW*
μ = 1.33 +0.21 −0.18
±0.14
±0.15
±0.11
0
1
2
3
√s = 7 TeV ∫Ldt = 4.6-4.8 fb⁻¹
√s = 8 TeV ∫Ldt = 20.7 fb⁻¹
「標準模型らしさ」

LHC data: $R = R_\sigma \times R_{\gamma\gamma} = 1.5\text{-}2.0$





Extension is required

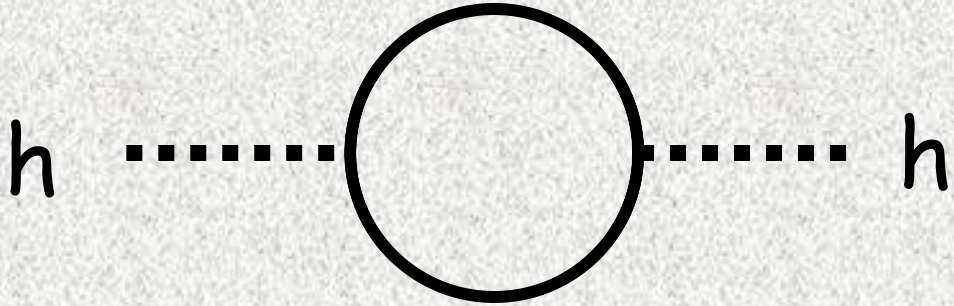
Similar type of deviations from the SM are also seen in

SUSY, Little Higgs

Common feature among GH, SUSY & LH:

Quadratic divergence in m_h^2 canceled by top partner effects

This can be seen diagrammatically as follows

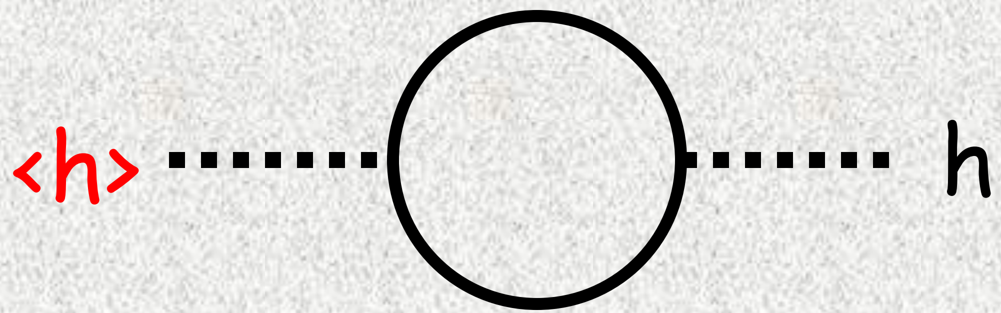


Start with Higgs self-energy diagram

Similar type of deviations from the SM are also seen in
SUSY, Little Higgs

Common feature among GH, SUSY & LH:
Quadratic divergence in m_h^2 canceled
by top partner effects

This can be seen diagrammatically as follows

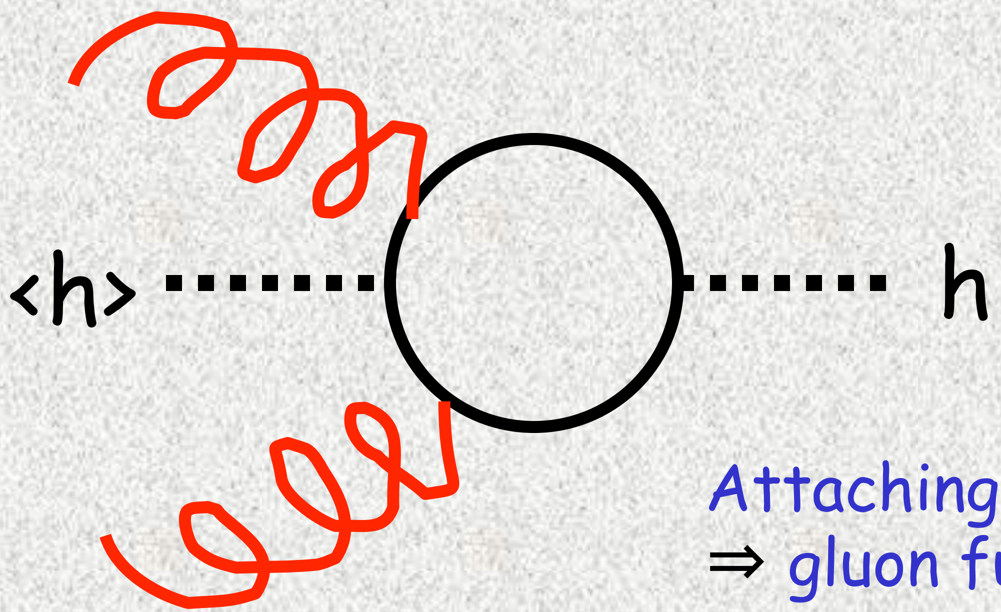


Replace one of the Higgs with VEV!

Similar type of deviations from the SM are also seen in
SUSY, Little Higgs

Common feature among GH, SUSY & LH:
Quadratic divergence in m_h^2 canceled
by top partner effects

This can be seen diagrammatically as follows



Attaching 2 gluon lines
⇒ gluon fusion diagram!!