Collider Signatures of Gauge-Higgs Unification at LHC

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References

- 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)

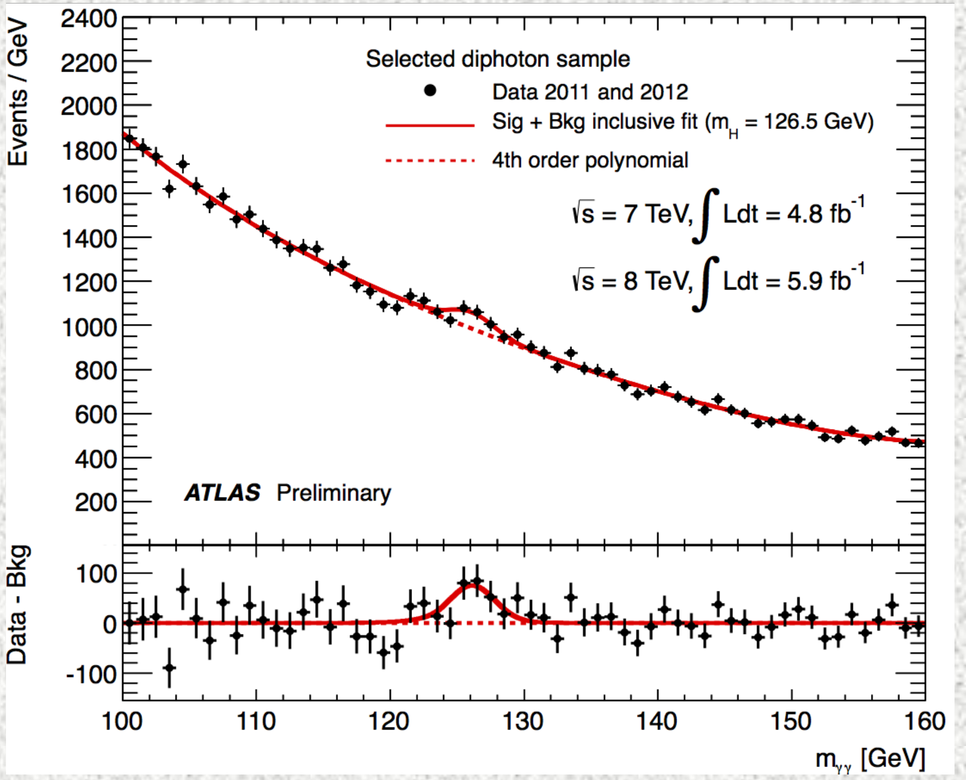
All papers with Nobuchika Okada

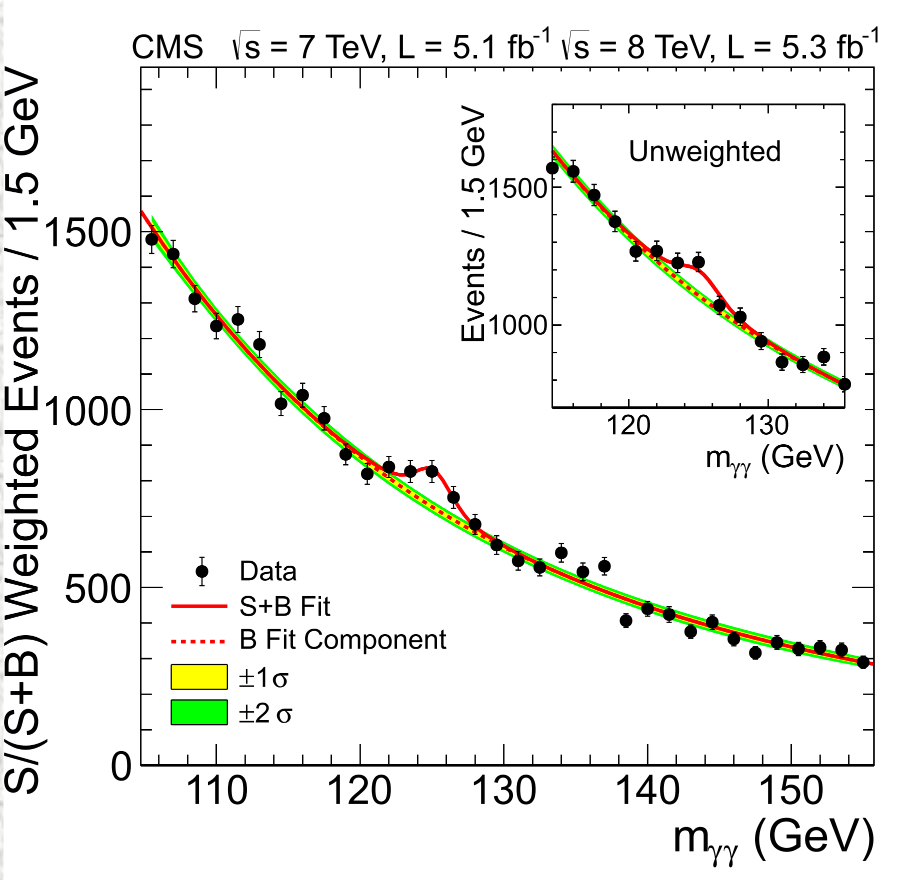
PLAN

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

Introduction

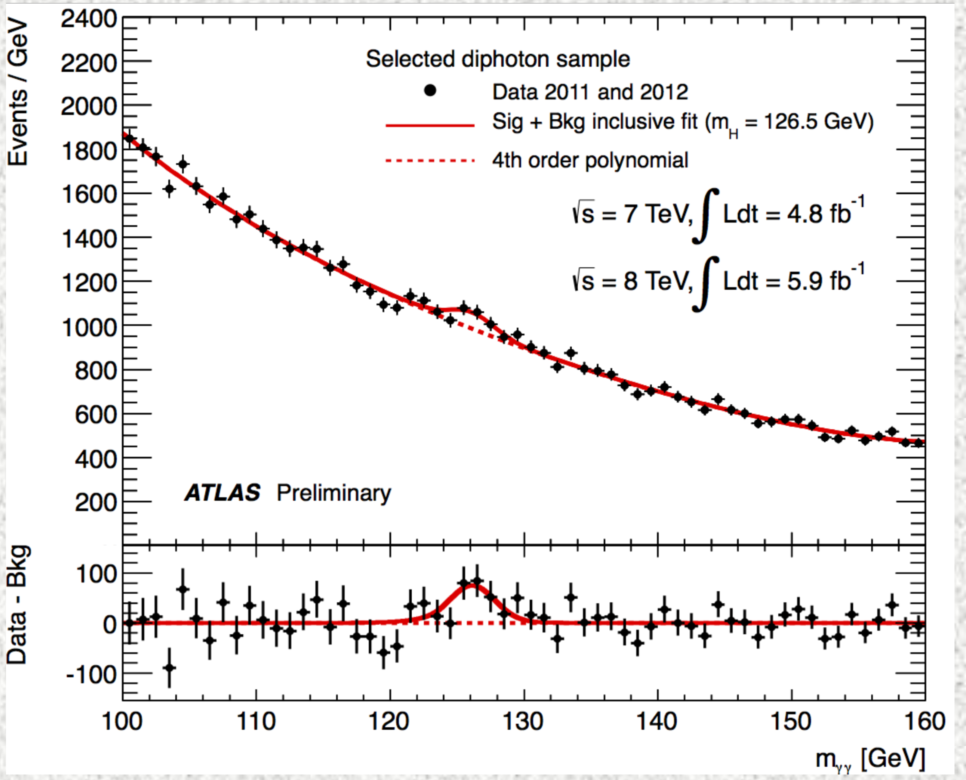
A Higgs was discovored, but…

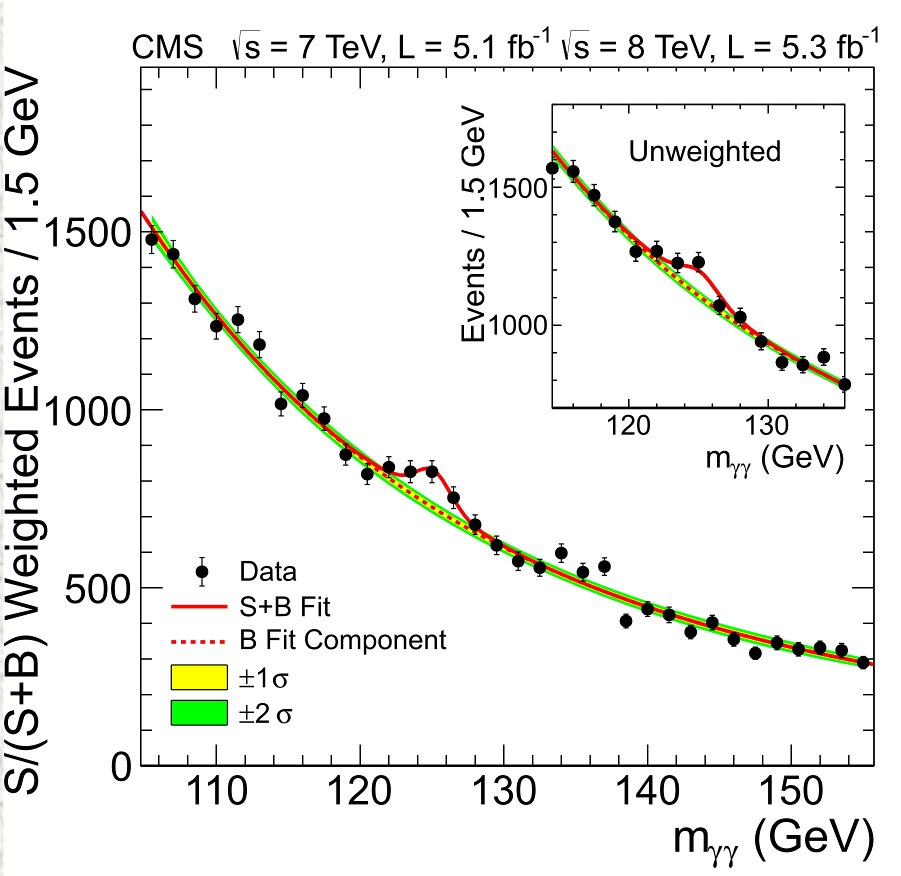




Introduction

Still unclear, the origin of Higgs ??

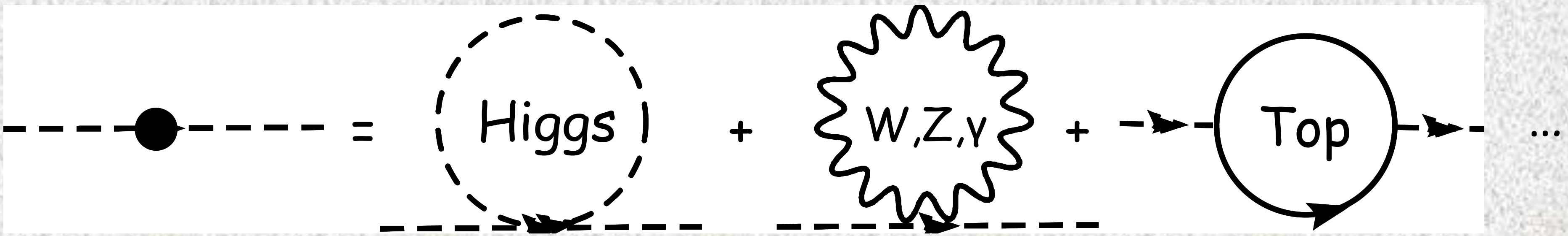




Motivation to consider GHU

One of the problems in the Standard Model:
Hierarchy Problem

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



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

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

In GHU, the SM Higgs is identified with the 5th component of the 5D gauge field

Gauge trf.

$$\because\ A_5 \to A_5 + \partial_5 \varepsilon(x, x_5) + i\left[\varepsilon(x, x_5), A_5\right]$$

forbids a local Higgs mass term $(A_5)^2$

⇒ No quadratic divergence, finite regardless of the nonrenormalizability

$$m_{A_5}^2 \simeq \frac{1}{16\pi^2}\frac{1}{R^2}$$

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

Scrucca, Serone, Silvestrini (2003), Cacciapaglia, Csaki, Park (2006)

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

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

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$$\Gamma^M = \left(\gamma^\mu, i\gamma^5\right)$$

Boundary conditions:

(+,+) only has massless mode

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

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

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

Lagrangian

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

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$$\mathcal{L} = -\frac{1}{2}\mathrm{Tr}\left(F_{MN}F^{MN}\right) + \bar{\Psi}_{3}^{i=1,2,3}\left(i\Gamma^M D_M - M_d^i \varepsilon(y)\right)\Psi_{3}^{i=1,2,3}$$
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0 mode of A_5 = SM Higgs

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)

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

SU(2) x U(1) gauge fields

Higgs doublet

Fermion matter content

Scrucca, Serone, Silvestrini (2003), Cacciapaglia, Csaki, Park (2006)

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

Down quark sector (d, s, b)

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

Up quark sector (u,c)

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

Charged lepton sector (e, μ, τ)

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

Top quark

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

Fermion matter content

Scrucca, Serone, Silvestrini (2003), Cacciapaglia, Csaki, Park (2006)

$3 = 2_{L1/6}(Q) + 1_{L-1/3}$

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

Down quark sector (d, s, b)

$6^* = 3_{L-1/3} + 2_{L1/6}(Q) + 1_{L2/3}$

$\quad 3_{R-1/3} + 2_{R1/6} + 1_{R2/3}(u_R)$

Up quark sector (u,c)

$10 = 4_{L1/2} + 3_{L0} + 2_{L-1/2}(L) + 1_{L-1}$

$\quad 4_{R1/2} + 3_{R0} + 2_{R-1/2} + 1_{R-1}(e_R)$

Charged lepton sector (e, μ, τ)

$15^* = 5_{L-4/3} + 4_{L-5/6} + 3_{L-1/3} + 2_{L1/6}(Q) + 1_{L2/3}$

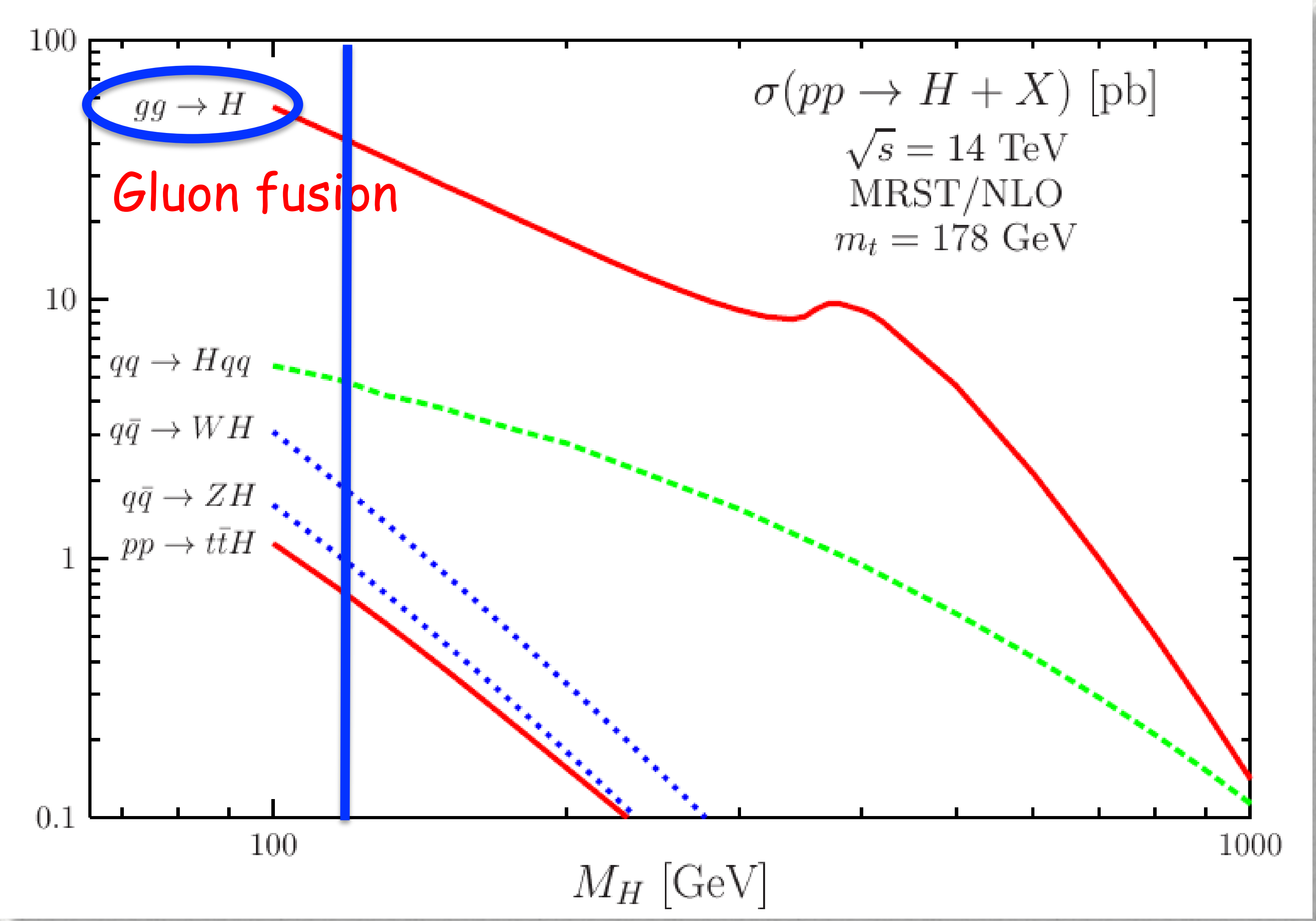
$\quad 5_{R-4/3} + 4_{R-5/6} + 3_{R-1/3} + 2_{R1/6} + 1_{R2/3}(t_R)$

Top quark

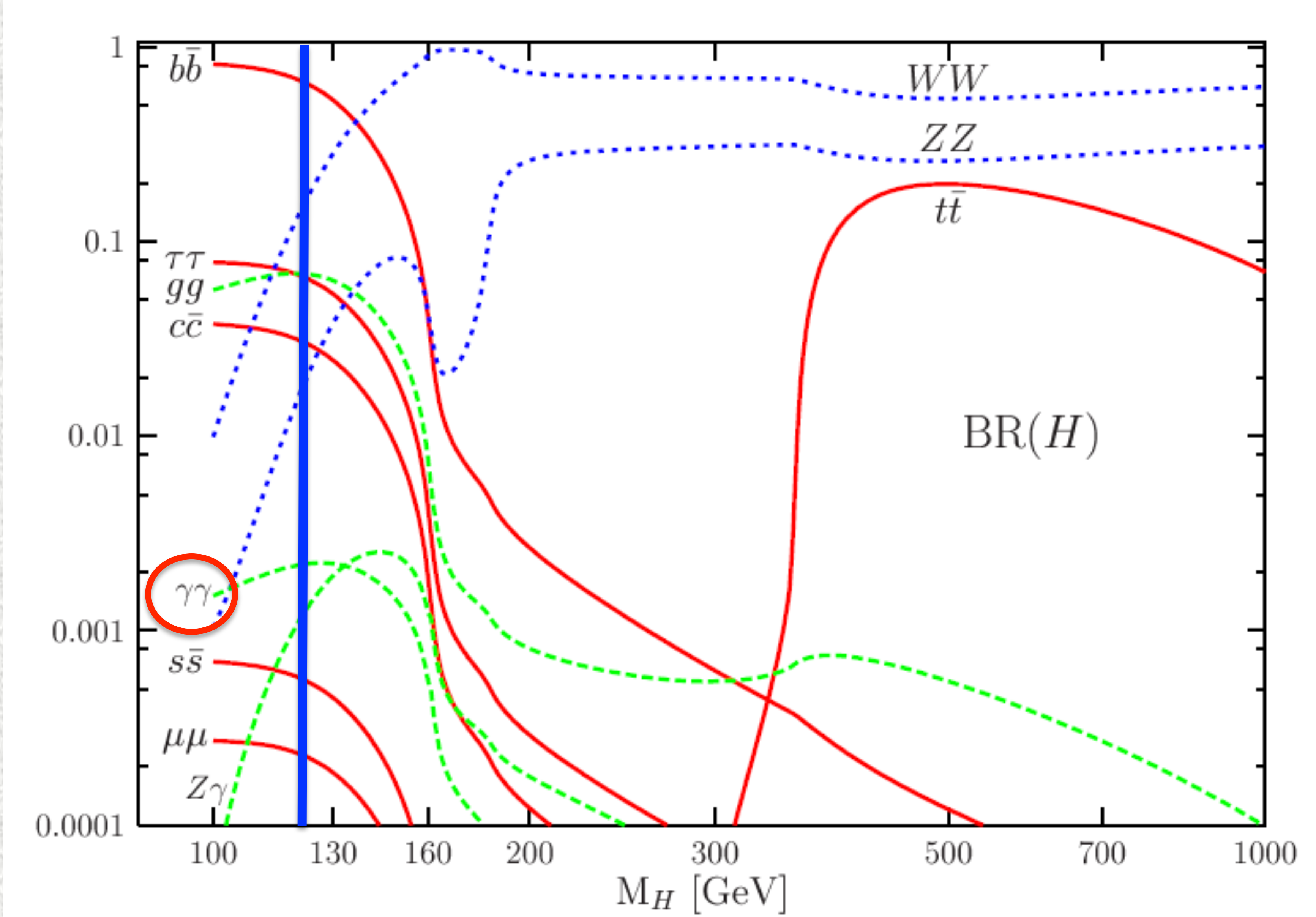
Unwanted massless exotics (blue reps) & a half of extra Qs must be massive by brane localized mass terms

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

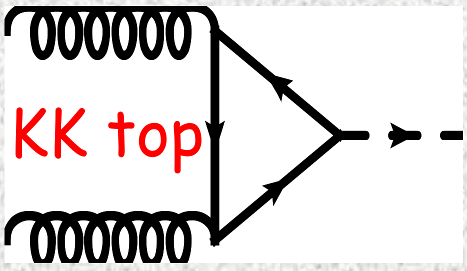
Higgs production



Decay rate of Higgs boson



KK mode contributions: gg → H



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

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

m_n=n/R

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

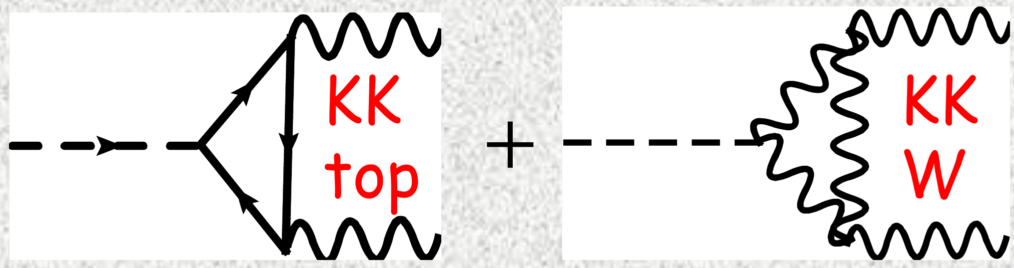
log∞ - log∞ = finite

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

Opposite sign to SM ⇒ destructive

KK mode contributions: H → γγ

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



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

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

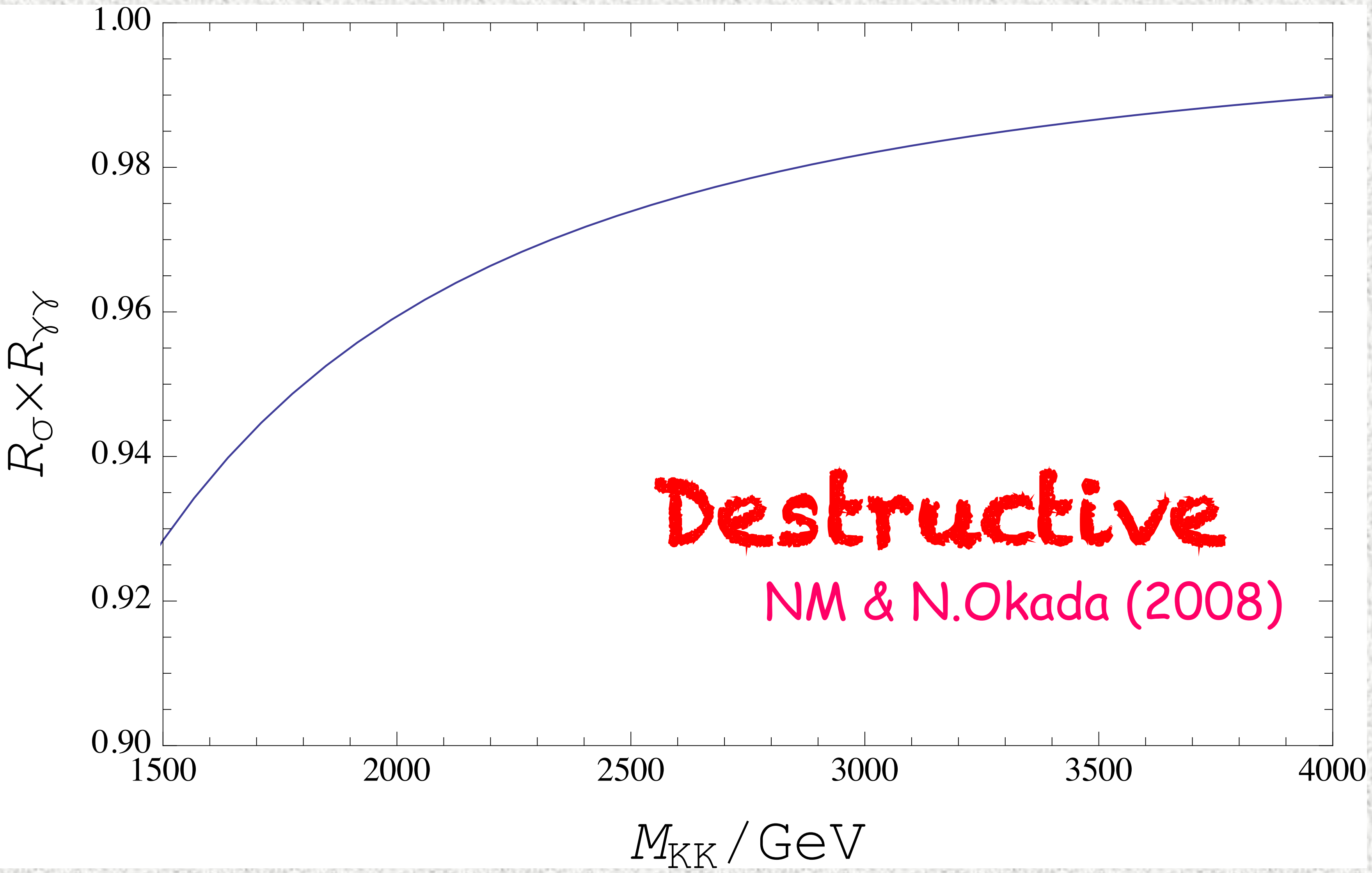
Opposite sign to SM

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

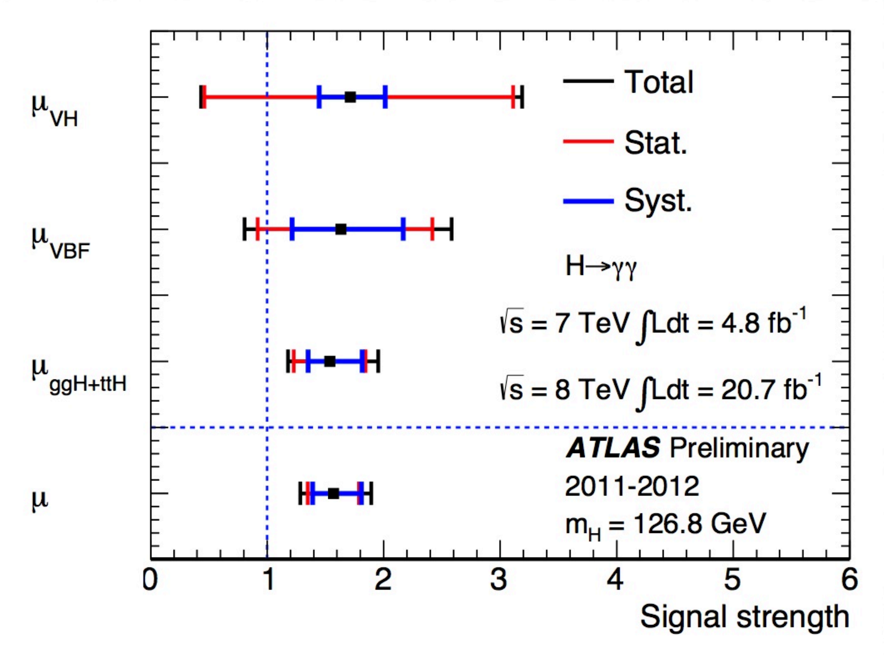
$$\cong +\frac{7\alpha_{em}}{8\pi v}\frac{1}{3}\left(\pi m_W R\right)^2$$

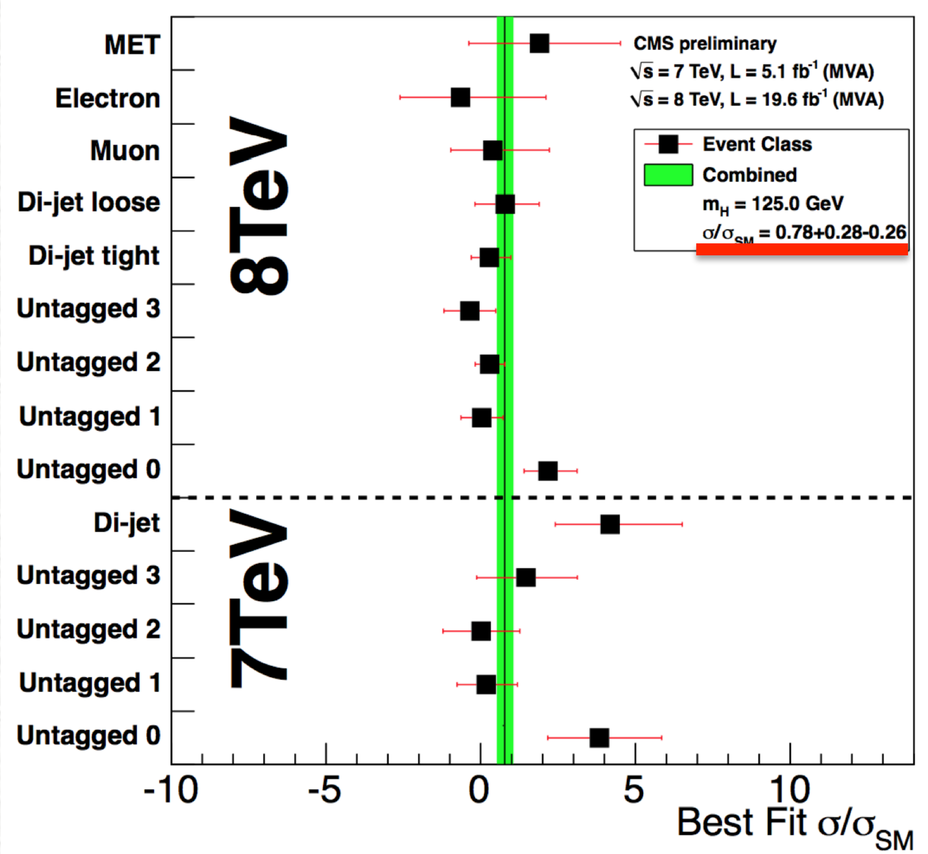
Opposite sign to SM

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



Diphoton decay excess





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

Extension is required

One of the simplest extensions:

"extra leptons"

(colored particles greatly affect the gluon fusion)

NM & N.Okada, PRD87 (2013) 095019

Contributions of KK fermions to $H \to \gamma\gamma$ constructive

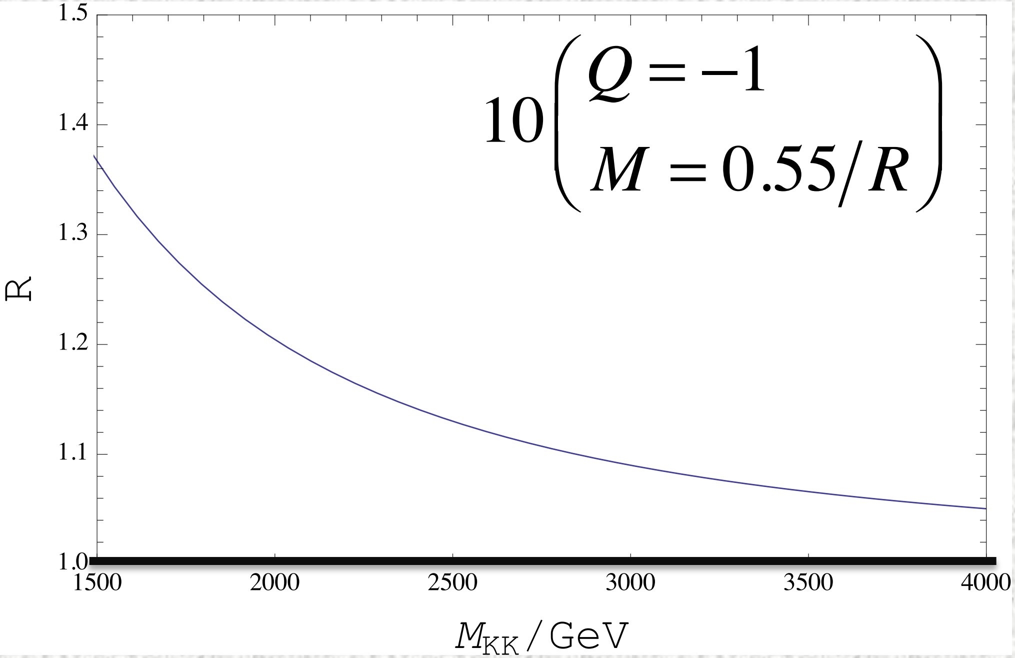
$\because\ C_{\gamma\gamma}^{SM} < 0$ & $C_{\gamma\gamma}^{KK\ fermions} < 0 \Rightarrow C_{\gamma\gamma}^{KK\ fermions}/C_{\gamma\gamma}^{SM} > 0$

Two examples: **10, 15** plets of SU(3) with bulk mass & half-periodic BC $\psi(y+2\pi R) = -\psi(y)$

No unwanted massless fermions

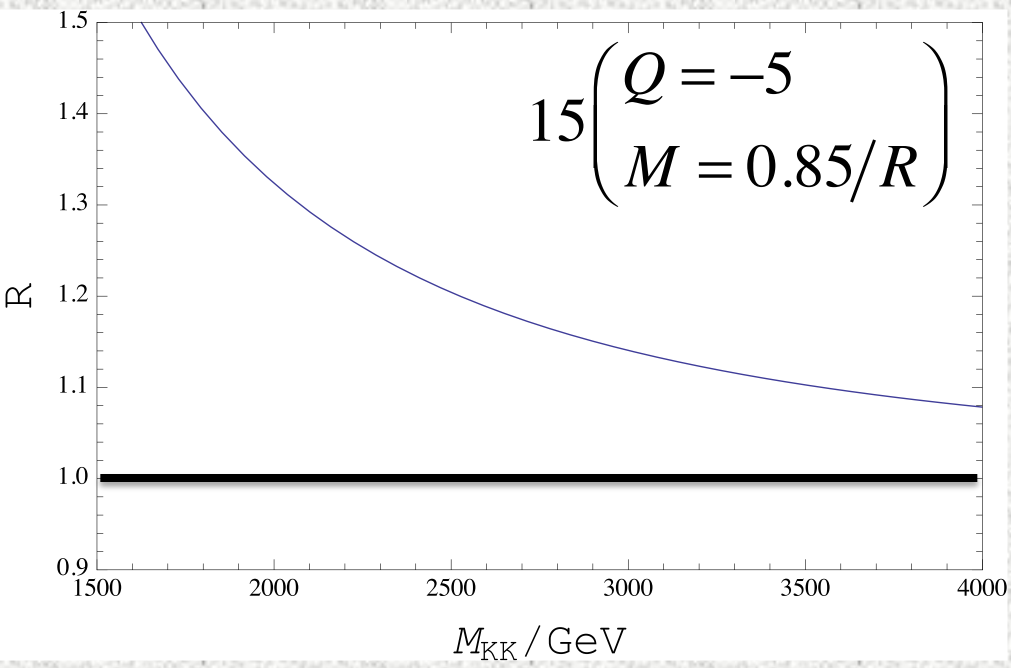
1st KK mass = 1/(2R) ⇒ Higgs mass

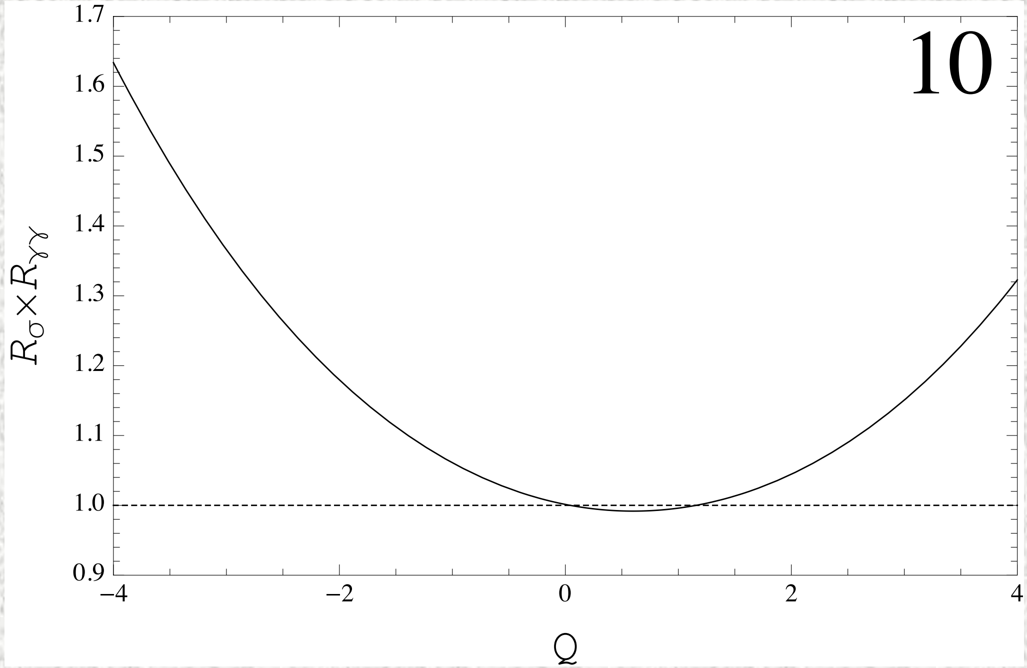
Helpful to adjust 126 GeV Higgs



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

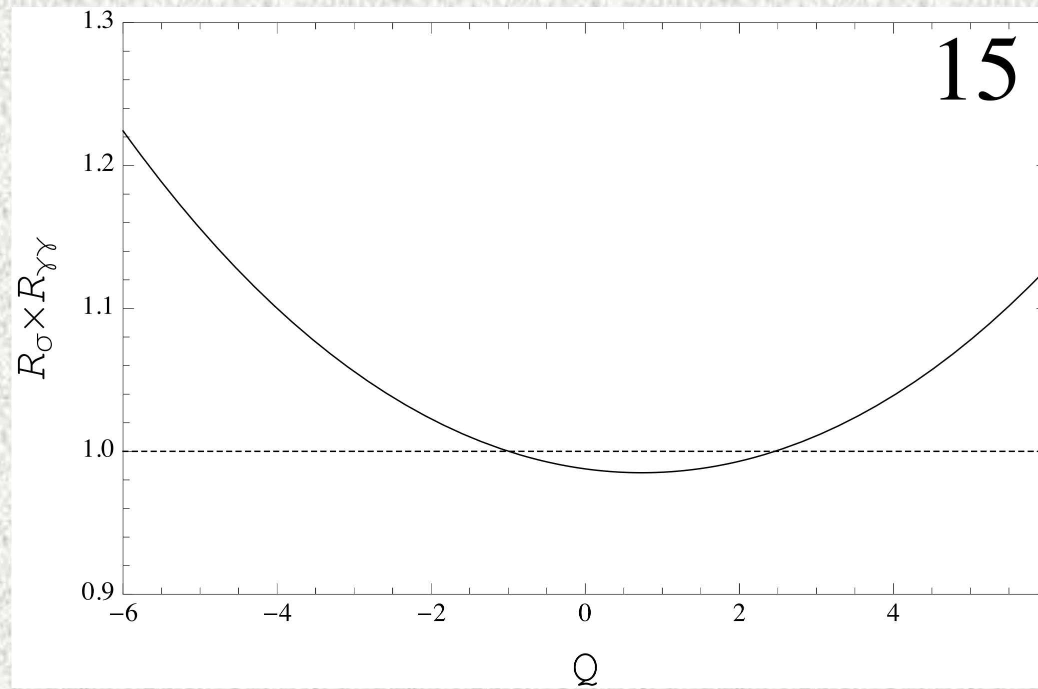
$$R = \frac{\sigma(gg \to H)_{GHU+15} \times BR(H \to \gamma\gamma)_{GHU+15}}{\sigma(gg \to H)_{SM} \times BR(H \to \gamma\gamma)_{SM}}$$





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

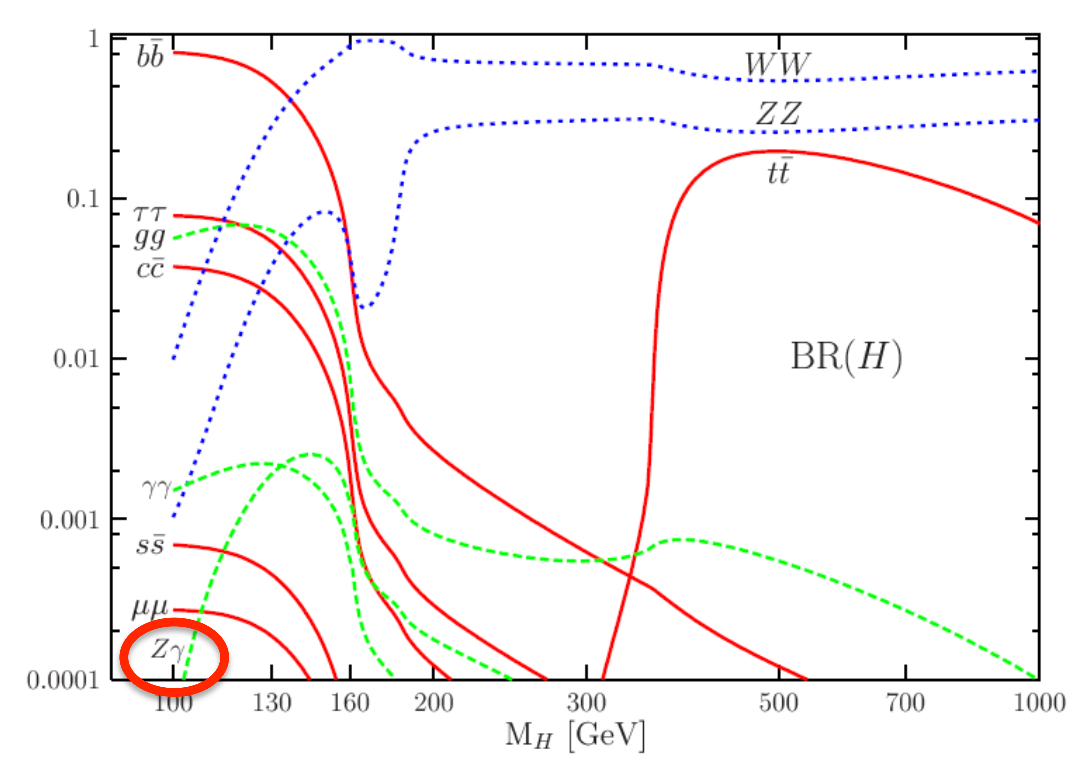
1/R = 3TeV fixed



$H \to Z\gamma$ in GHU

H→Zγ in GHU

NM & N.Okada, PRD88 (2013) 037701



KK modes have electroweak charges

↓

Naturally expect deviation of Zγ decay from the SM prediction

Model dep. Correlation btw γγ & Zγ is interesting

Our result is very striking!!

No KK mode contributions to Zγ decay@1-loop

Simple reason: Higgs & photon couples to KK modes with same mass eigenstates,

Z does NOT

Fermion coupling

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

ZWⁿWⁿ coupling

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

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

ZγWⁿWⁿ coupling

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

No H-Z-γ coupling@1-loop found

Summary

- We calculated KK mode contributions to
  $gg \to H$ & $H \to \gamma\gamma$ @LHC in 5D SU(3)xU(1)' GHU
- Minimal model cannot explain the data (NM & Okada)
- Extra leptons can enhance $H \to \gamma\gamma$ as we like
  by adjusting U(1)' charges
  ex. 10 & 15 plets of SU(3)
  w/ bulk mass & half-periodic BC
- Lightest KK lepton with a mass 1-3TeV
  ⇒ DM candidate in case of zero U(1)em charge
- No KK mode contributions to $H \to Z\gamma$@1-loop

Thank you very much for your attention

Backup Slides

Summary

- 1-loop RGE analysis of Higgs quartic coupling with GH condition $\lambda=0@M_{KK}$

  ⇒ 10 with M=0.55/R, 15 with M=0.85/R
  ⇒ 125 GeV Higgs
  ⇒ No instability

- Extra leptons are (some kind of) Z_2 odd & stable due to the half-periodic BC

  ⇒ lightest KK leptons of 1∼3 TeV mass can be DM candidate in case of vanishing electric charge

- No KK mode contribution to $H\to Z\gamma$@1-loop

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 $\lambda = 0@1/R$ "gauge-Higgs condition"

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

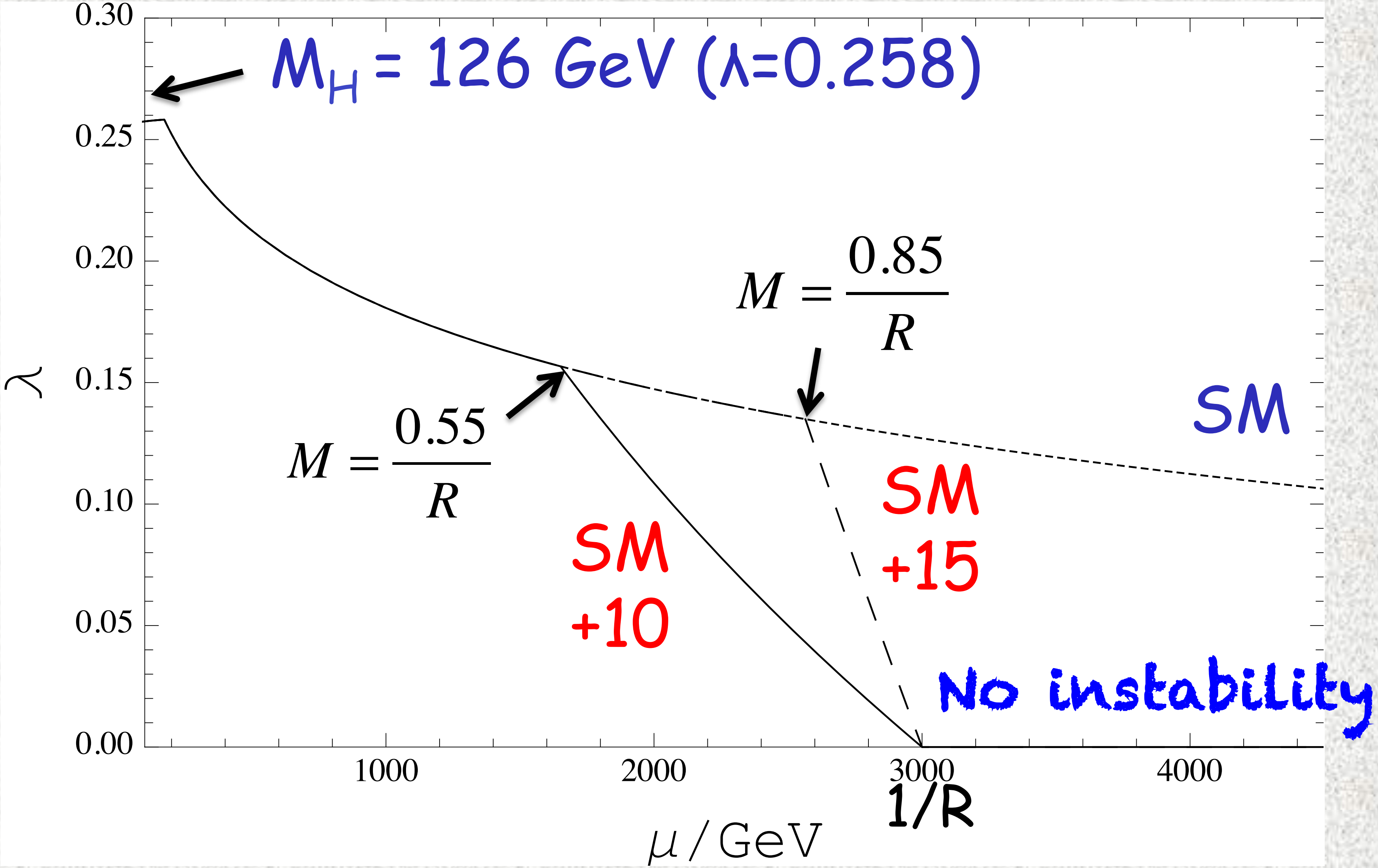
Natural realization of GHU in 4D viewpoint:

$V_H = 0$ above 1/R by 5D gauge invariance

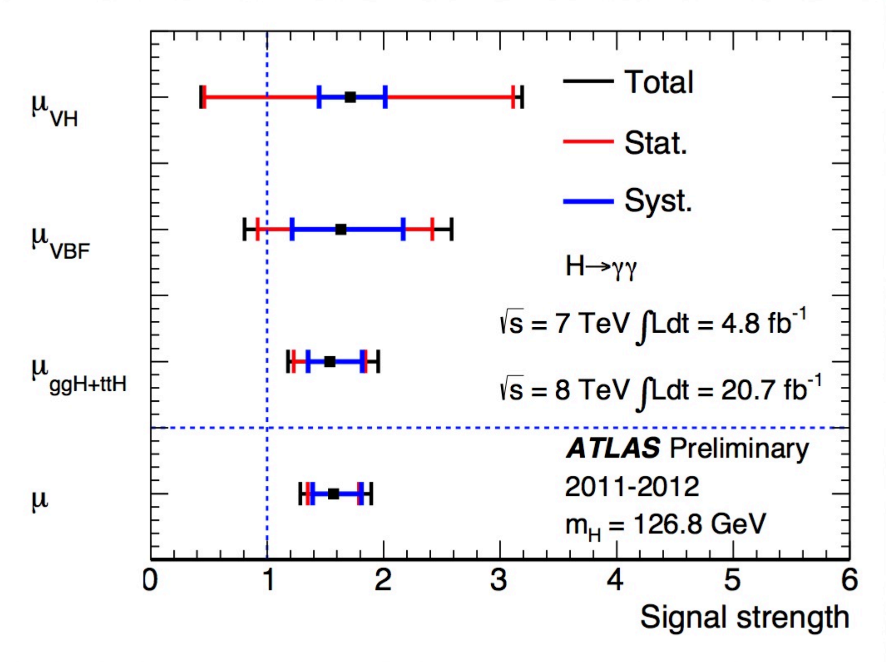
Furthermore, NO vacuum instability

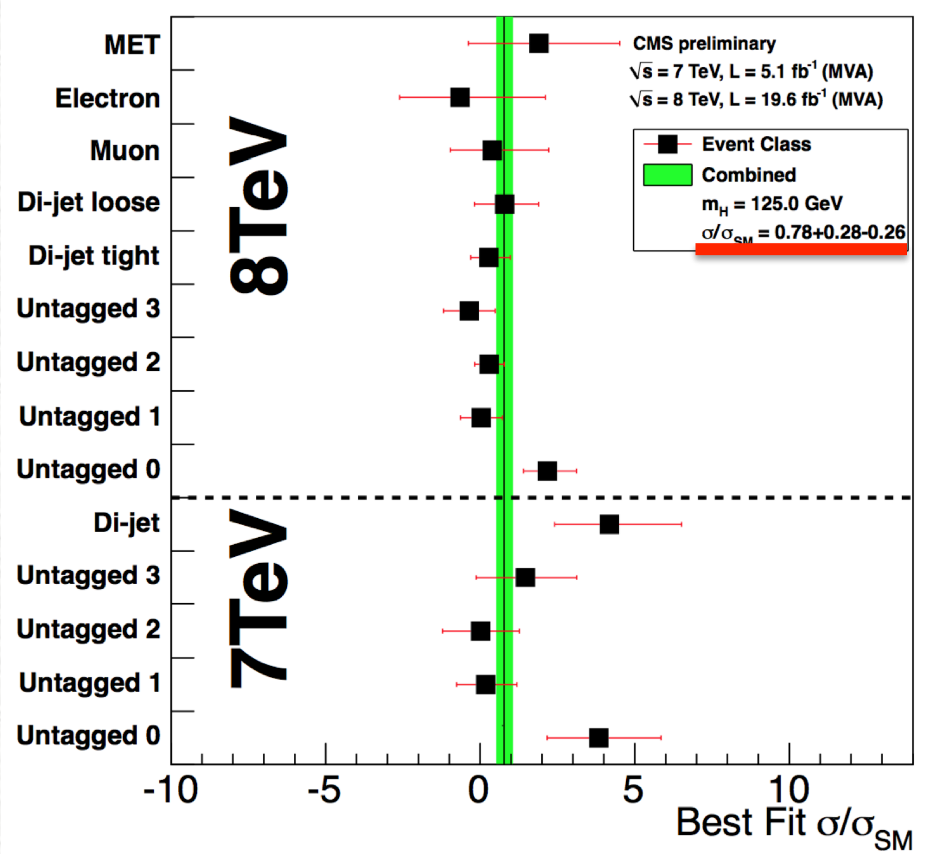
This approach greatly simplifies Higgs mass study

Numerical results for 1-loop RGE of λ



Diphoton decay excess





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

Hint for New Physics??

	$gg \to H$	$H \to \gamma\gamma$
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!!

KK mass mixing after EW symmetry breaking

$$A_\mu^{(0)} = \frac{1}{2}\begin{pmatrix} \frac{2}{\sqrt{3}}\gamma_\mu & \sqrt{2}W_\mu^+ & 0 \\ \sqrt{2}W_\mu^- & -Z_\mu - \frac{\gamma_\mu}{\sqrt{3}} & 0 \\ 0 & 0 & Z_\mu - \frac{\gamma_\mu}{\sqrt{3}} \end{pmatrix}, A_\mu^{(n)} = \frac{1}{2}\begin{pmatrix} \frac{2}{\sqrt{3}}\gamma_\mu^{(n)} & \sqrt{2}W_\mu^{+(n)} & \sqrt{2}A_\mu^{+(n)} \\ \sqrt{2}W_\mu^{-(n)} & -Z_\mu^{(n)} - \frac{\gamma_\mu^{(n)}}{\sqrt{3}} & A_\mu^{6(n)} - iA_\mu^{7(n)} \\ \sqrt{2}A_\mu^{-(n)} & A_\mu^{6(n)} + iA_\mu^{7(n)} & Z_\mu^{(n)} - \frac{\gamma_\mu^{(n)}}{\sqrt{3}} \end{pmatrix}$$

No mixing

$W^{\pm(n)} \Leftrightarrow A^{\pm(n)}$

$Z^{(n)} \Leftrightarrow A^{7(n)}$

$$\left(\bar{\psi}_{1L}^{(0)}, \bar{\psi}_{2L}^{(0)}, \bar{\psi}_{3R}^{(0)}\right)\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -m \\ 0 & -m & 0 \end{pmatrix}\begin{pmatrix} \psi_{1L}^{(0)} \\ \psi_{2L}^{(0)} \\ \psi_{3R}^{(0)} \end{pmatrix} + \left(\bar{\psi}_1^{(n)}, \bar{\psi}_2^{(n)}, \bar{\psi}_3^{(n)}\right)\begin{pmatrix} m_n & 0 & 0 \\ 0 & m_n & -m \\ 0 & -m & m_n \end{pmatrix}\begin{pmatrix} \psi_1^{(n)} \\ \psi_2^{(n)} \\ \psi_3^{(n)} \end{pmatrix},$$

chiral $\Rightarrow$ no mass splitting

Vector-like $\Rightarrow$ mass splitting