125 GeV Higgs Boson mass from 5D gauge-Higgs unification

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Ref: Carson & NO, arXiv: 1510.03092
Maru & NO, arXiv: 1303.5810; 1307. 0291; 1310.3348

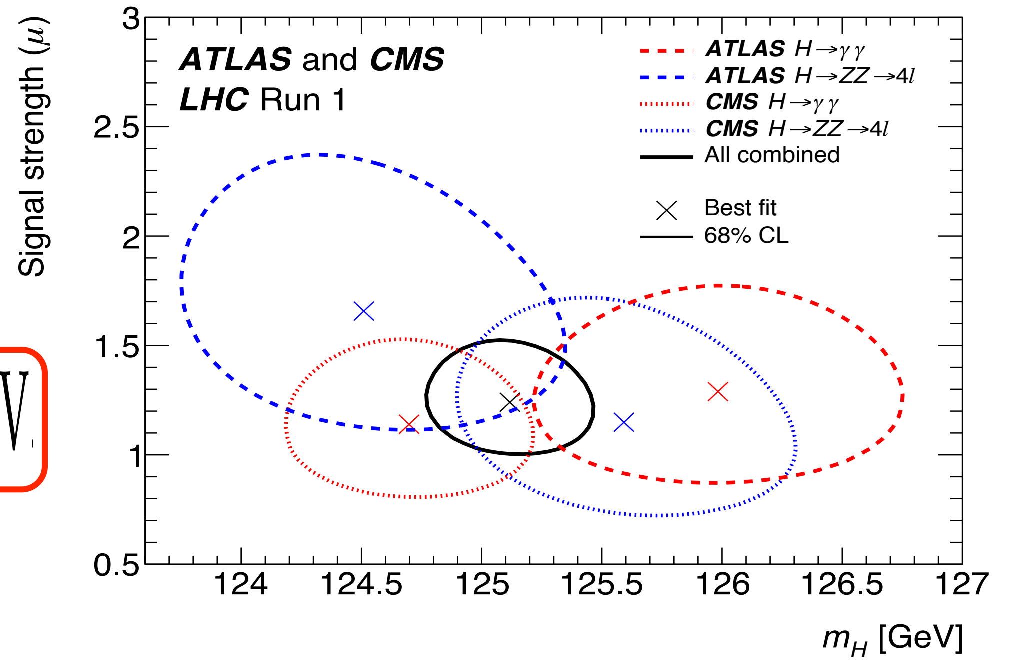
PHENO2016 , University of Pittsburgh, May 10th, 2016

Current status of Higgs Boson

Higgs boson properties
(ATLAS & CMS combined)

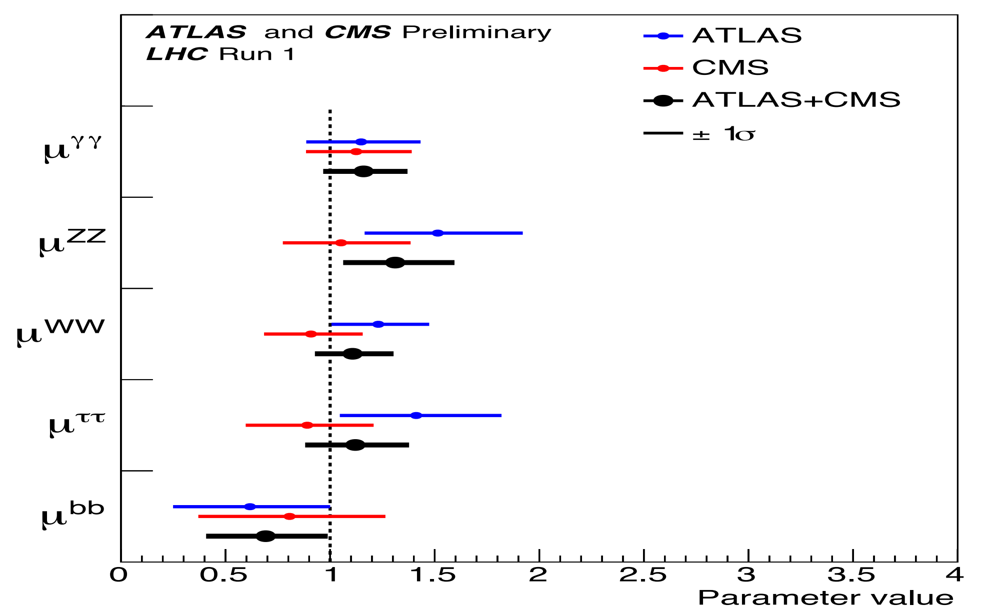
➢ Higgs mass

$$m_H = 125.09 \pm 0.21\,(\text{stat.}) \pm 0.11\,(\text{syst.})\ \text{GeV}$$



➢ Higgs couplings

Consistent with the SM expectations



We still suffering from

The Gauge Hierarchy Problem

Higgs mass corrections are quadratically sensitive to UV physics

- How to protect the corrections?

Ex) Supersymmetry: fermions ←→ bosons

$$\Delta m_\psi \sim m_\psi \log \Lambda$$ ←Chiral symmetry

↓ SUSY

$$m_\phi^2 + \Delta m_\phi^2 = (m_\psi + \Delta m_\psi)^2$$

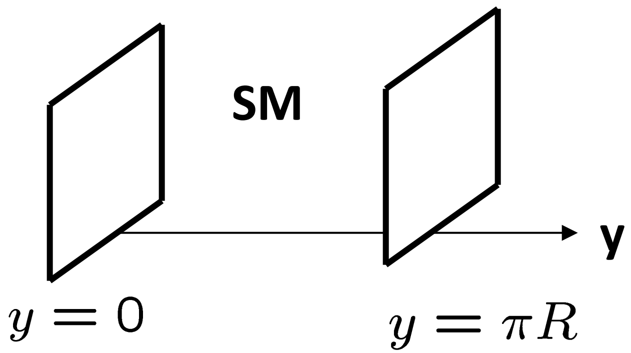
Alternative to SUSY?

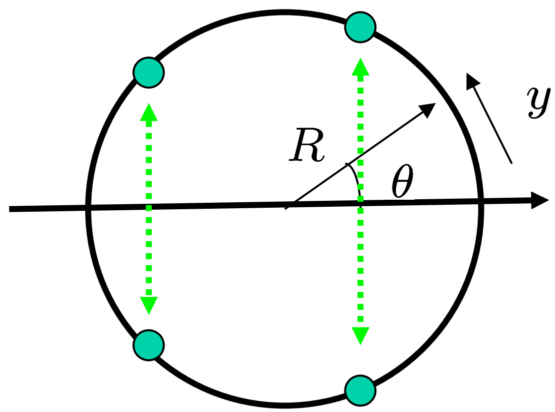
Gauge-Higgs Unification (GHU) Scenario

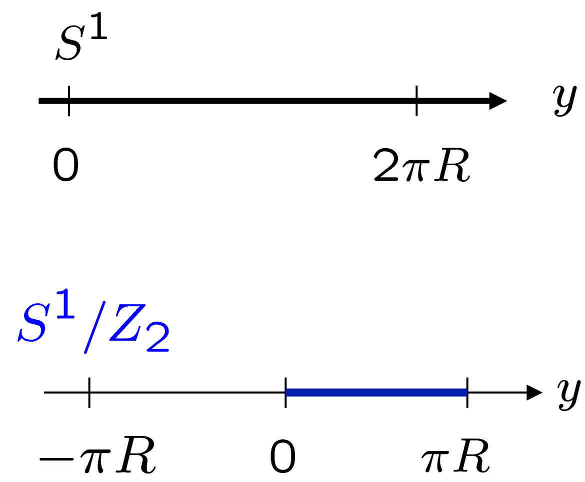
Manton, NPB 158 (1979) 141
Fairlie, PLB 82 (1979) 97
Hosotani, PLB 126 (1983) 309
PLB129 (183) 193

5D Standard Model

5-dim. theory compactified on orbifold S^1/Z_2







All SM fields except Higgs reside in the bulk

Higgs boson is unified into 5th component of gauge fields in higher dimension

Basic structure   5D SU(3) gauge theory (toy model)

$$SU(3) \supset SU(2) \times U(1)$$

SU(3) gauge =

$SU(2)$ **adj**	**doublet**
doublet	**singlet**

Impose non-trivial boundary conditions (parity assignment)

$$A_\mu = \left(\begin{array}{c|c} W_\mu + B_\mu & X_\mu \\ \hline X_\mu^\dagger & B_\mu \end{array}\right) \qquad A_5 = \left(\begin{array}{c|c} W_5 + B_5 & H \\ \hline H^\dagger & B_5 \end{array}\right)$$

◯ **are Z2 even fields, others odd fields**

$$\Phi(x^\mu, y) \to \pm\Phi(x^\mu, -y)$$

Zero modes for odd fields are project out,

So SU(3) is broken to SU(2) times U(1) by this parity assignment

5D SU(3) GHU Lagrangian

5D SU(3) gauge kinetic

$$\mathcal{L}_5^{\text{gauge}} = -\frac{1}{2}\text{tr}\left[\mathcal{F}_{MN}\mathcal{F}^{MN}\right]$$

$$\Rightarrow -\frac{1}{2}\text{tr}\left[W_{\mu\nu}W^{\mu\nu}\right] - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + (D_\mu H)^\dagger D^\mu H$$

SU(2) x U(1)
EW gauge kinetic term

Higgs doublet kinetic term

No Higgs potential @ tree level

Higgs potential is generated at quantum level
with Kaluza-Klein fields

Properties

(1) The SM Higgs doublet is identified as the 5th component of 5D bulk gauge field

(2) Mass term and Higgs self-coupling are protected by the 5D gauge invariance

(3) 5D gauge invariance is broken by the boundary conditions and as a result, Higgs mass and self-coupling are induced through quantum corrections at low energies

(4) However, there is no quadratic divergence in the theory

$$\Delta m_H^2 \sim \frac{g^2}{16\pi^2} M_{\rm KK}^2$$

Actual mass corrections highly depend on bulk fermion contents

(5) Gauge-Higgs condition: $\lambda(\mu = m_{KK}) = 0$

Haba, Matsumoto, NO & Yamashita, JHEP 02 (2006) 073

Effective low energy of 5D flat GHU at E < M_{KK}
= SM (+extra light states) + GH condition for Higgs self-coupling

<u>We calculated effective quartic coupling in 2 ways</u>

(1) 1-loop effective potential in 5D GHU

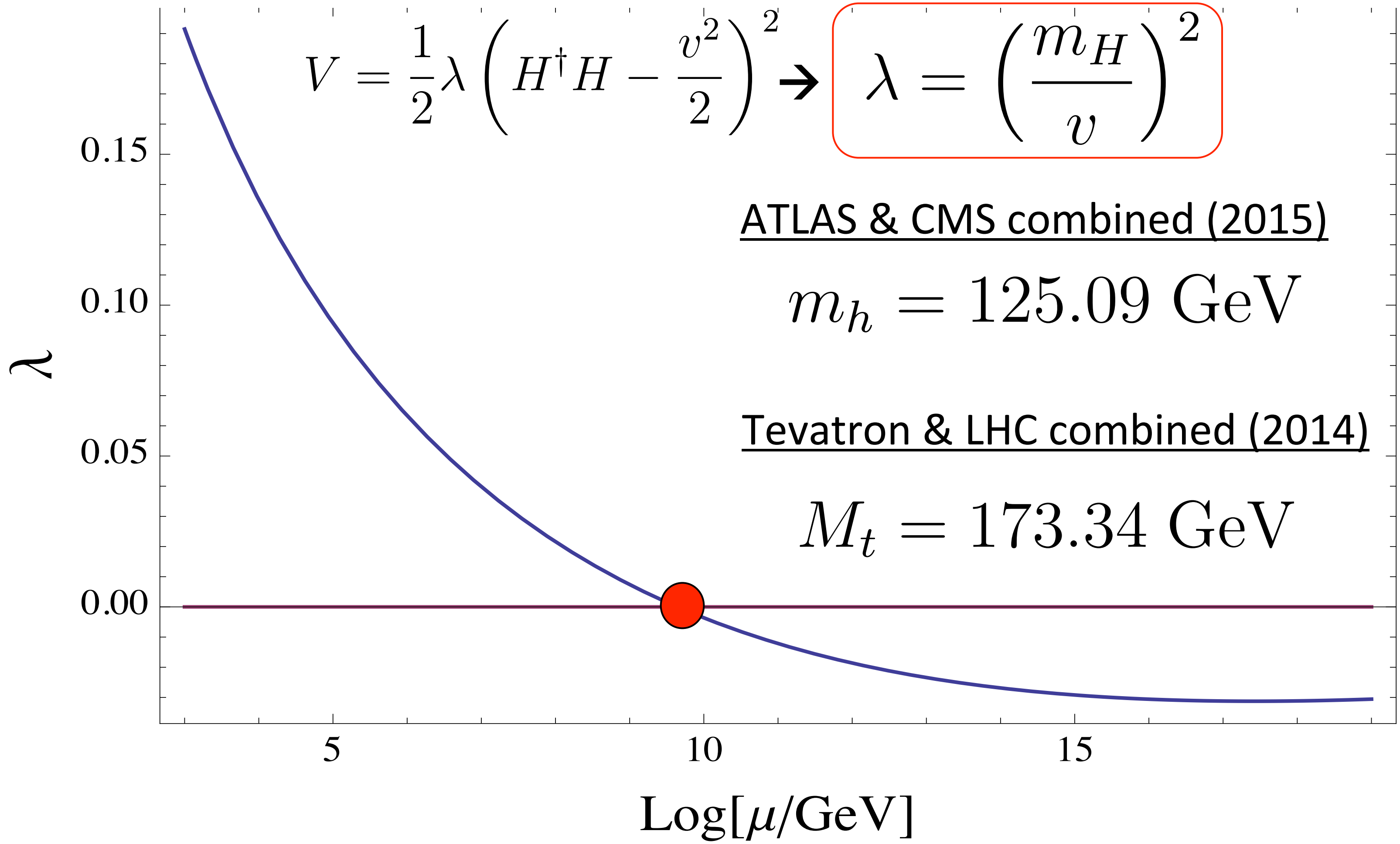
$$\lambda_{eff} = \frac{\beta_\lambda}{2}\left[2\ln\left(\frac{\phi}{m_{KK}}\right) - \frac{25}{6}\right]$$

(2) 1-loop effective potential in SM with a cutoff

$$\lambda_{eff} = \lambda(\Lambda) + \frac{\beta_\lambda}{2}\left[2\ln\left(\frac{\phi}{\Lambda}\right) - \frac{25}{6}\right]$$

Leading log RGE solution with B.C. $\lambda(\Lambda \to m_{KK}) = 0$

UV completion of the SM in the GHU → SM with $\lambda(M_{\rm KK}) = 0$



``Instability Problem'' in SM ←→ In 5D GHU, $M_{\rm KK} \simeq 10^{10}$ GeV

Can we lower the KK mass scale to O(1 TeV), while reproducing m_h=125 GeV?

→ Introduce extra bulk fermions

Maru & NO,
arXiv: 1303.5810;
arXiv: 1307.0291;
arXiv: 1210.3348

Realistic SU(3) x U(1)' GHU with bulk fermions

with bulk mass
Color singlet/triplet
Periodic/Antiperiodic boundary condition

Examples:

$$\mathbf{6} = \mathbf{1}_{-2/3} \oplus \mathbf{2}_{-1/6} \oplus \mathbf{3}_{1/3},$$

$$\mathbf{10} = \mathbf{1}_{-1} \oplus \mathbf{2}_{-1/2} \oplus \mathbf{3}_{0} \oplus \mathbf{4}_{1/2}$$

$$\mathbf{15} = \mathbf{1}_{-4/3} \oplus \mathbf{2}_{-5/6} \oplus \mathbf{3}_{-1/3} \oplus \mathbf{4}_{1/6} \oplus \mathbf{5}_{2/3}$$

$\mathbf{R}_Q$ ← SU(2) representation (R); ← U(1) charge in SU(3) (Q)

$$Q_{\mathrm{EM}} = Q + Q'$$

125 GeV Higgs boson mass from GH condition

Carson & NO, arXiv: 1510.03092

Example 1: $\mathbf{6} = \mathbf{1}_{-2/3} \oplus \mathbf{2}_{-1/6} \oplus \mathbf{3}_{1/3}$;

$$\mathcal{L} \supset -Y_S \overline{D} H S - Y_D \overline{D} T H^\dagger$$

with $Y_S = Y_D = -i g_2$ @ E = M*kk*

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

$$m_n = n M_{\mathrm{KK}}$$

PB fermion: n=0, 1, 2, 3, ….

HP fermion: n → n+1/2

M: bulk mass

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

$$\mathcal{L} \supset -Y_S \overline{D} H S - Y_D \overline{D} T H^\dagger - Y_T \overline{F} T H$$

with
$$Y_S = Y_T = -i\sqrt{3/2}\, g_2$$
$$Y_D = -i\sqrt{2}\, g_2$$
@ E = M*kk*

$$\left(m^{(\pm)}_{n,-1}\right)^2 = (m_n \pm 3m_W)^2 + M^2, \quad (m_n \pm m_W)^2 + M^2,$$
$$\left(m^{(\pm)}_{n,0}\right)^2 = (m_n \pm 2m_W)^2 + M^2, \quad m_n^2 + M^2,$$
$$\left(m^{(\pm)}_{n,+1}\right)^2 = (m_n \pm m_W)^2 + M^2,$$
$$\left(m^{(\pm)}_{n,+2}\right)^2 = m_n^2 + M^2.$$

$$m_n = n M_{\mathrm{KK}}$$

PB fermion: n=0, 1, 2, 3, ...
HP fermion: n → n+1/2

M: bulk mass

RG Analysis

- Gauge Higgs Condition: $\lambda(M_{\mathrm{KK}}) = 0$
- Relation between Yukawa & gauge couplings @ E = M*kk*

6-plet case: $Y_S = Y_D = -ig_2$

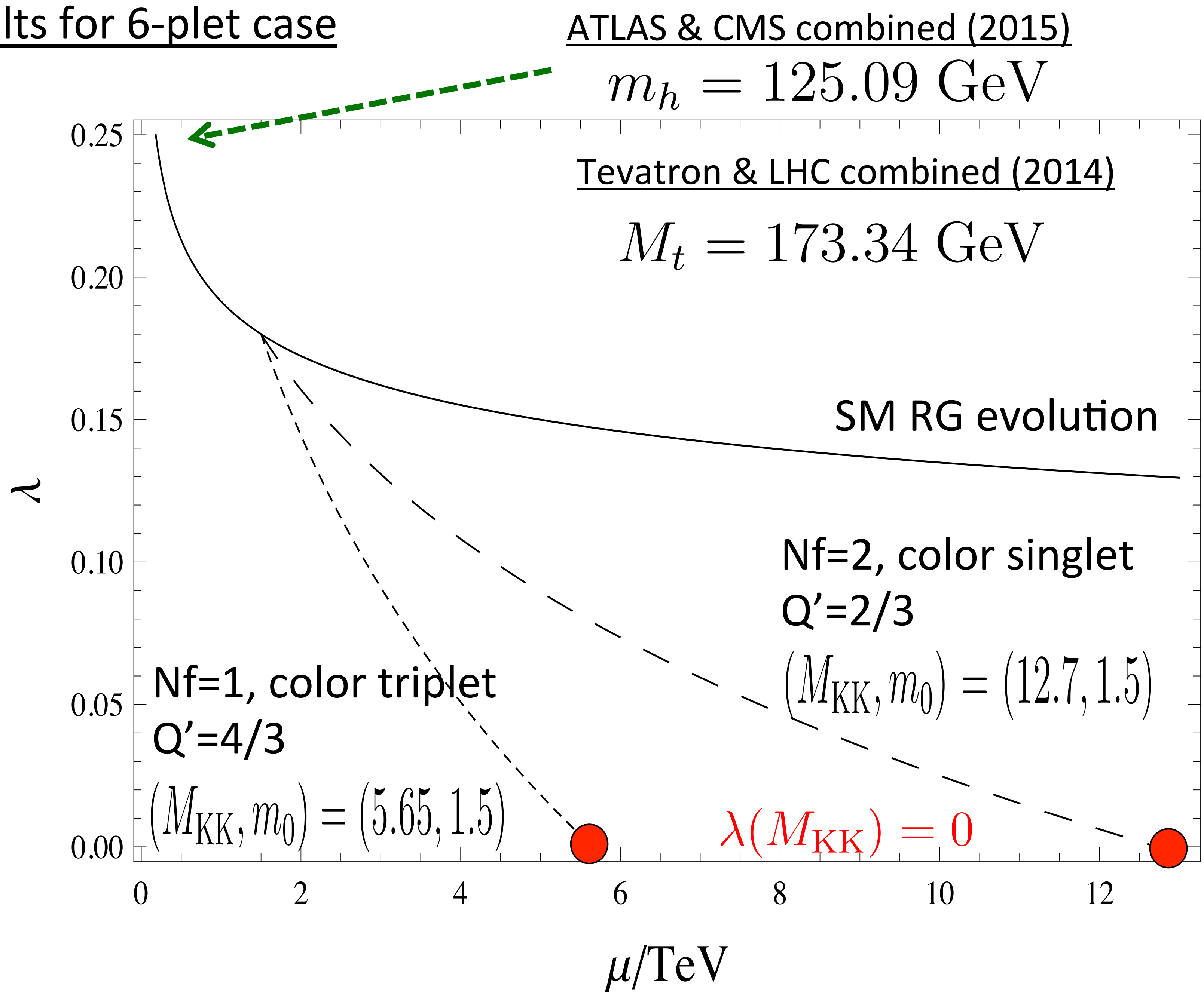
10-plet case:
$$Y_S = Y_T = -i\sqrt{3/2}\ g_2$$
$$Y_D = -i\sqrt{2}\ g_2$$

- Solving RGEs with the above boundary conditions

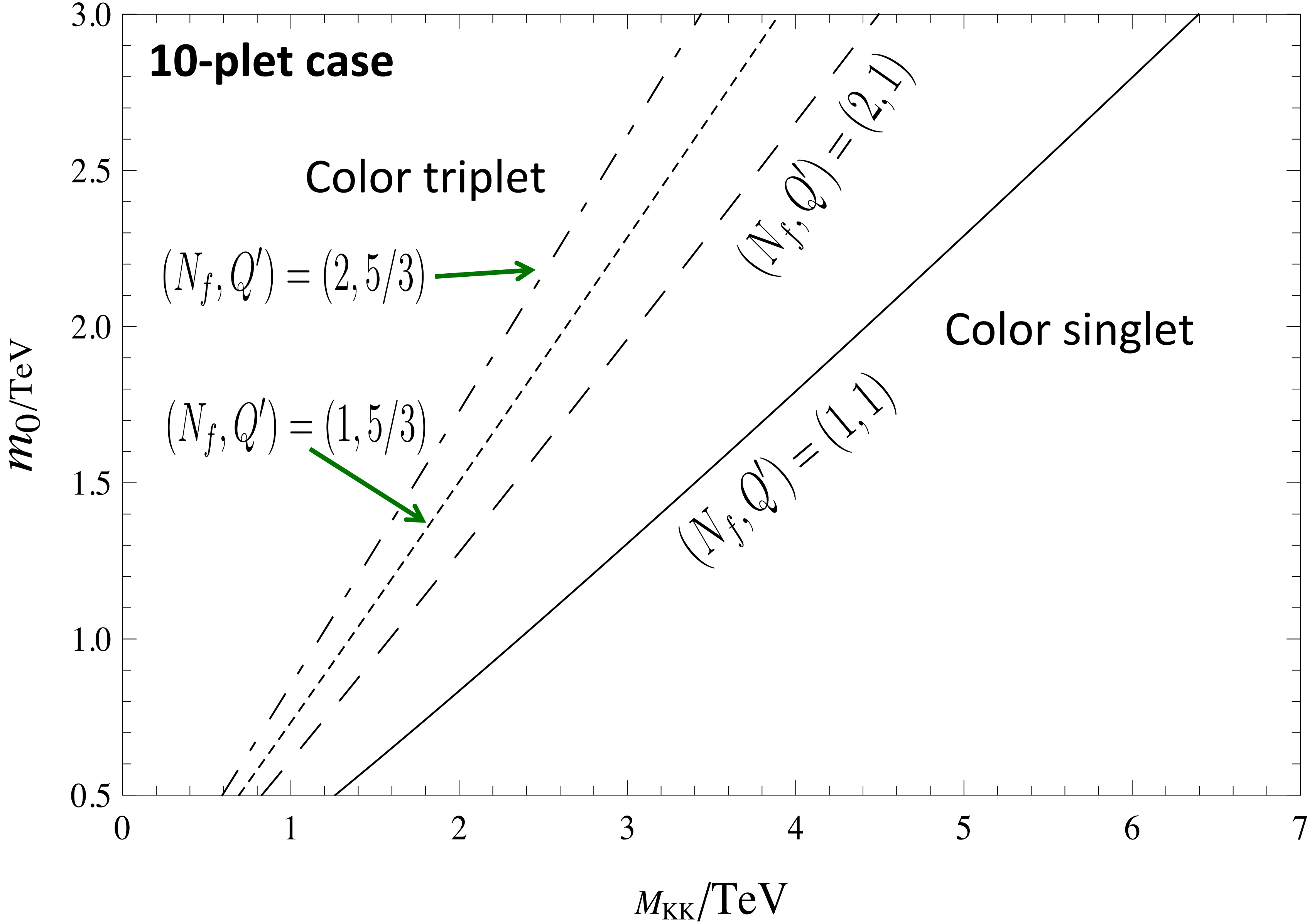
Free parameters:
$$m_0 = M \ \text{ or } \ \sqrt{M^2 + \frac{1}{2} M_{\mathrm{KK}}}$$
$$M_{\mathrm{KK}}$$

N_f : # of bulk fermions

Results for 6-plet case

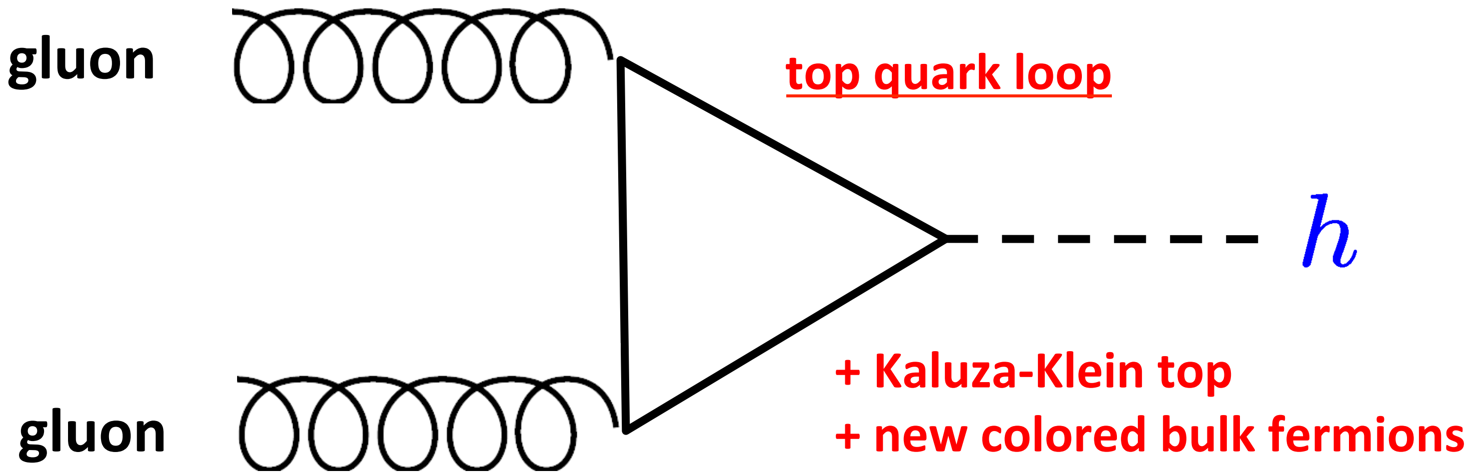


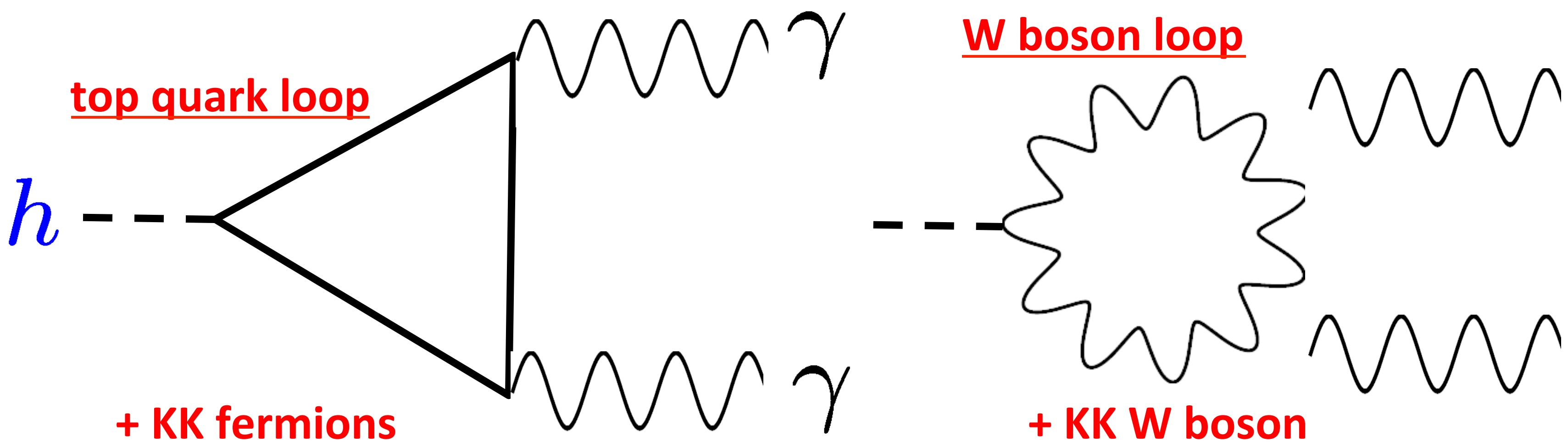
M_{KK} V.S m_0 in order to reproduce m_h=125.09 GeV



Contributions to effective Higgs boson couplings

Kaluza-Klein modes of the SM particle and new bulk fermions contribute Higgs-to-digluon, diphoton couplings



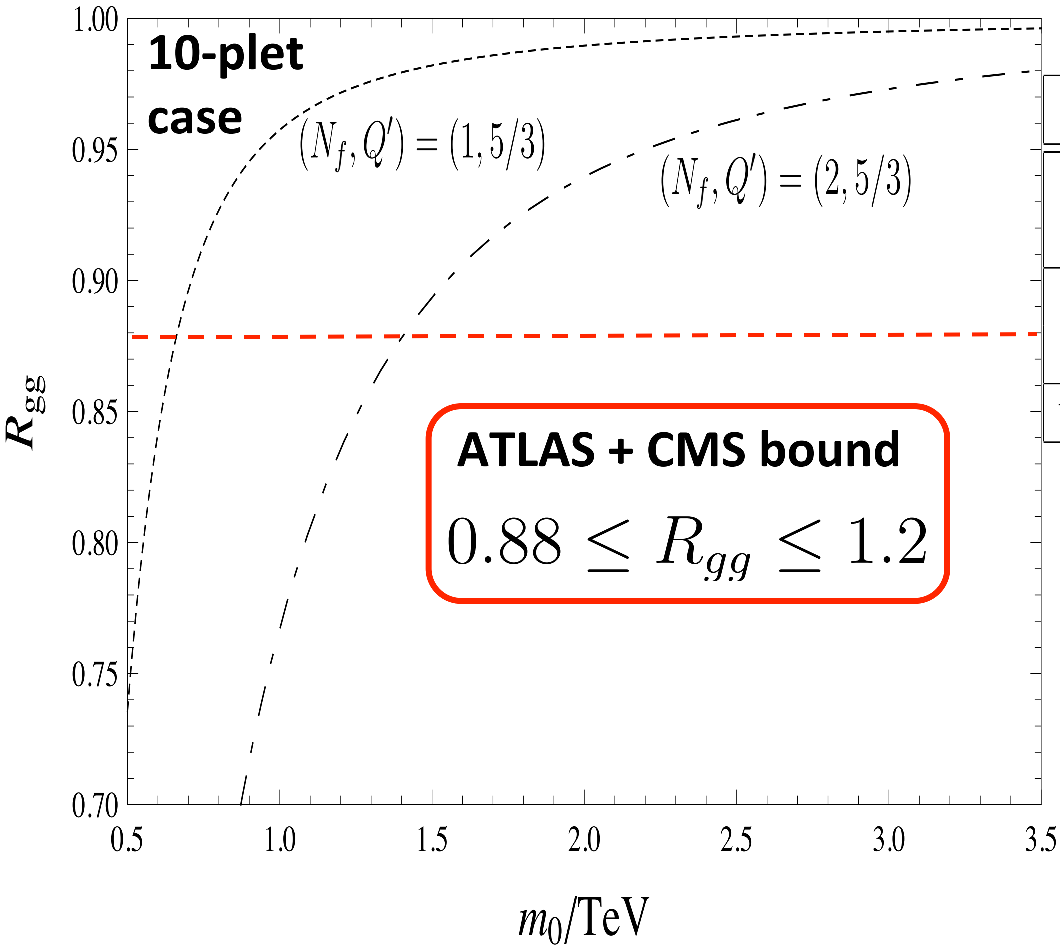


SU(3) x U(1)' GHU model

Carson & NO., arXiv: 1510.03092

with 10-plet bulk color triplet-fermion realizing mh=125.09 GeV

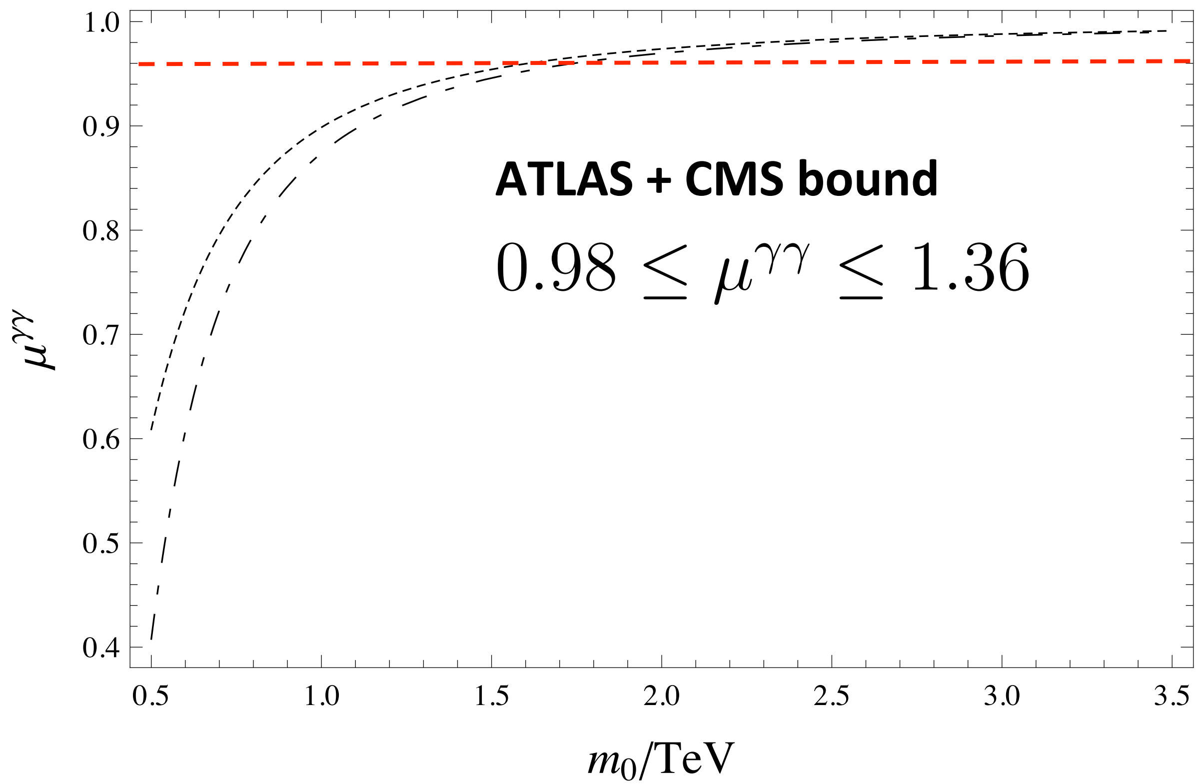
The KK mode contribution to Higgs-digluon coupling alters the Higgs boson production cross section at LHC



	BC	$N_f^{(HP)}$	Q	m_0 (TeV)	M_{KK} (TeV)
6-plet	P	1	4/3	0.685	2.83
6-plet	P	2	4/3	0.710	1.64
10-plet	P	1	5/3	0.663	0.908
10-plet	HP	1	5/3	1.41	1.64
top quark KK mode					1.26

Lightest KK colored fermion Mass > 700 GeV – 1.4 TeV

The KK mode contribution to Higgs-digphoton coupling alters the signal strength of Higgs-to-diphoton channel



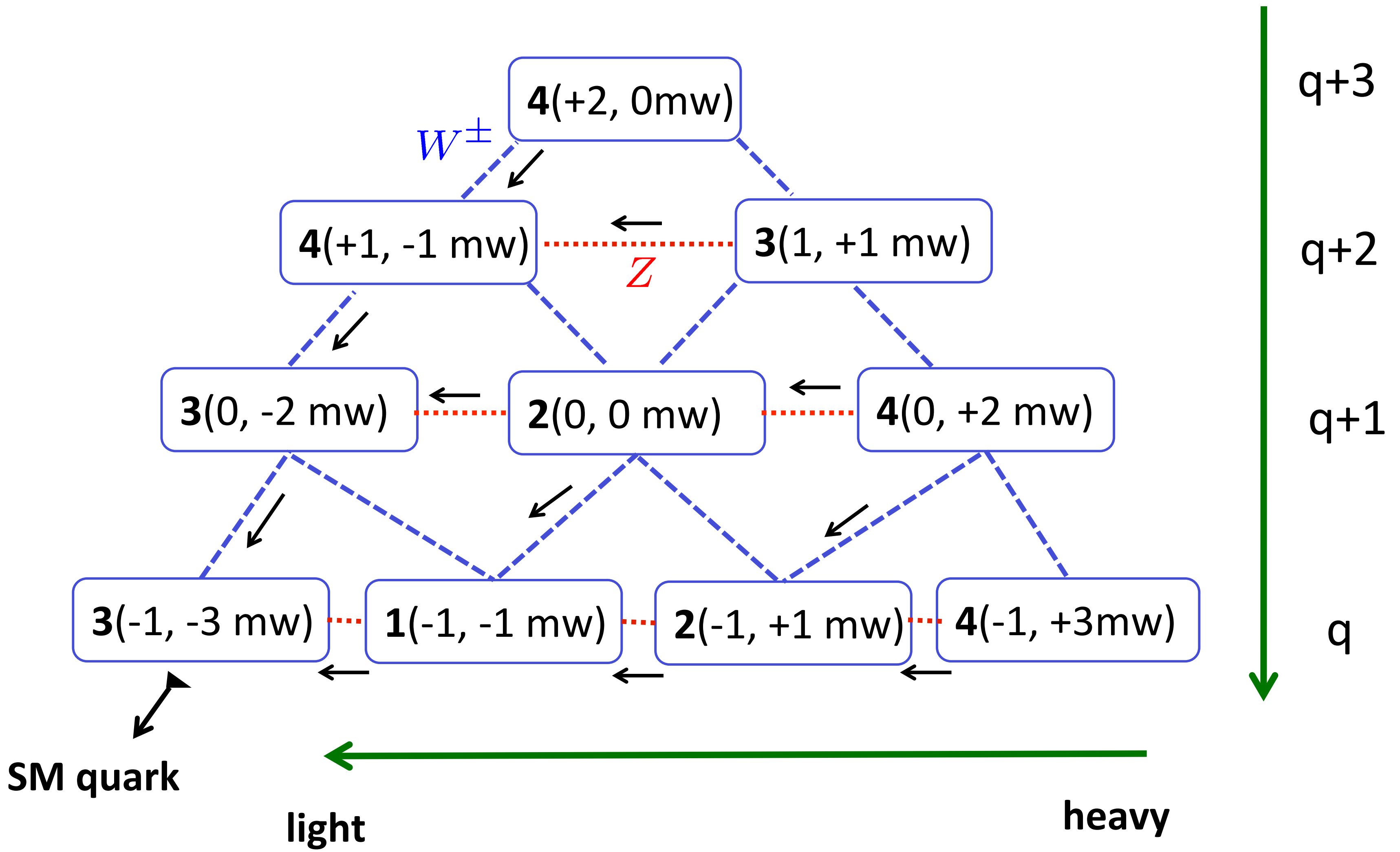
	BC	$N_f^{(HP)}$	Q	m_0 (TeV)	M_{KK} (TeV)
10-plet	P	1	5/3	2.30	3.01
10-plet	HP	1	5/3	2.46	2.83

Bulk Fermion Hunting at LHC Run-2

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

Maru & N.O.,
arXiv: 1310.3348

Exotic quark production → cascade decays



Conclusions

The Higgs boson is finally discovered!

Higgs physics, one of the most important research area in particle physics, has just begun.

There are many things to do to test the SM Higgs sector.

Observed Higgs boson properties have lots of implications to new physics beyond the SM.

Gauge-Higgs unification as UV completion of the Standard Model

Quadratic divergence free → KK mode mass as an effective cutoff

Gauge-Higgs condition → new interpretation of a vanishing
Higgs quartic coupling

Reproducing Higgs mass 125 GeV
with (half)periodic fermions
GH condition at TeV

New contributions to Higgs-diguon/diphoton coupling

Measured Higgs properties constrain KK mass ~> 1 TeV.

Hunting KKs @ LHC Run 2