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Israeli Centers of Research Excellence

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WEIZMANN INSTITUTE OF SCIENCE

What if $\lambda_{hhh} \neq 3m_h^2/v$?

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Work in progress - AE and Yosef Nir

Introduction

- A Higgs boson was found
- It looks like a SM Higgs
- It couples to pairs of heavy gauge bosons – takes part in ElectroWeak symmetry breaking

- Is it the SM Higgs?

Introduction

- Many well-motivated scenarios predict extended Higgs sectors

Different experimental signatures

Not necessarily accompanied by discovery of new particles in the foreseen future

These might be too heavy or too weakly coupled

Introduction

- Precise measurements of Standard Model processes might be the only way to see New Physics imprints

Standard Model

Introduction - Standard Model

- The SM scalar potential is a 2 parameter model

$$V_{SM} = \mu^2|\phi_{SM}|^2 + \lambda|\phi_{SM}|^4$$

with $\lambda = -\mu^2/v^2$

- Both of them are now measured
- A 3rd measurement = a test

$$\lambda_{hhh}^{SM} = \frac{3m_h^2}{v}$$

What if $\lambda_{hhh} \neq 3m_h^2/v$?

- But can we learn something new that cannot be learned otherwise?

YES!

- Gives clean window to the scale of New Physics
- Can distinguish between different New Physics models

What if $\lambda_{hhh} \neq 3m_h^2/v$?

- Define deviations from SM:

$$\delta\lambda_{hhh} = \frac{\lambda_{hhh}}{\lambda_{hhh}^{SM}} - 1 \qquad \delta\lambda_{hVV} = \frac{\lambda_{hVV}}{\lambda_{hVV}^{SM}} - 1$$

- Consider mainly

$$\frac{\delta\lambda_{hhh}}{\delta\lambda_{hVV}}$$

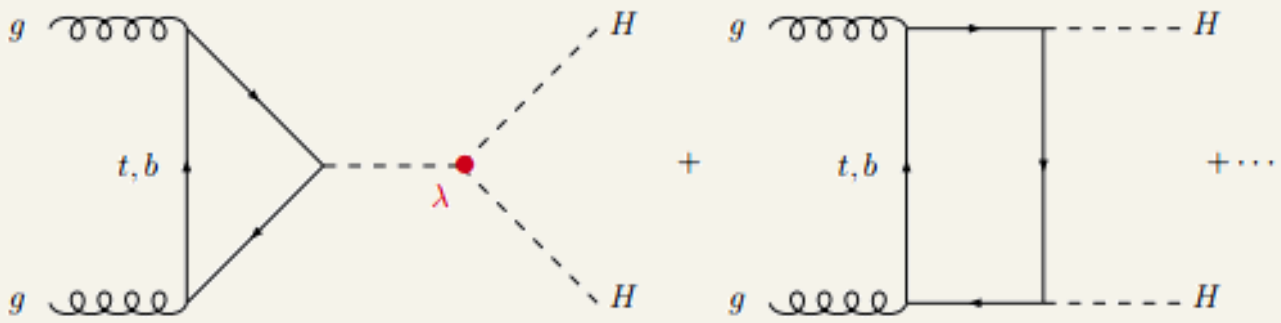
What if $\lambda_{hhh} \neq 3m_h^2/v$?

- Analyze extended Higgs sector models
- In the decoupling limit
  - No direct observation of new particles
  - Small mixing with non Standard Model particles

LHC

λ_{hhh} at the LHC

- Probed by h pair production ~ 30 fb
- Both $gg \to h^* \to hh$ and $gg \to hh$



- Destructive - suppressed for $1 < \frac{\lambda_{hhh}}{\lambda_{hhh}^{SM}} < 3$

λ_{hhh} at the LHC

- $hh \to 4b$ hopeless
- $hh \to bb\gamma\gamma$ the most promising
- $hh \to bb\tau\tau, bbWW, WW\tau\tau$ others

λ_{hhh} at the LHC

- Expected accuracy:

LHC	~30%-50%
ILC	~20%
e^+e^- synchrotron	~30%
photon collider	hopeless

Precise measurement:

not in the near future

λ_{hVV} at the LHC

- Currently: $-15\% \lesssim \delta\lambda_{hVV} \lesssim 5\%$
- Expected:

Experiment	$\sqrt{s}$ in TeV	$\mathcal{L}$ in fb^{-1}	$\delta\lambda_{hVV} \lesssim$
LHC (ATLAS)	14	300	$(2.5-3.3)\,\%$
LHC (CMS)	14	300	$(2.7-5.7)\,\%$
LHC (ATLAS)	14	3000	$(1.6-2.6)\,\%$
LHC (CMS)	14	3000	$(1.0-4.5)\,\%$
ILC	0.25+0.5	250+500	0.39%
ILC	0.25+0.5+1	250+500+1000	0.21%

New Physics

Doublet-Singlet mixing

- The simplest extension:

  additional real singlet scalar

- Spectrum:

  light $h = c_\alpha \phi_{SM} - s_\alpha \phi_S$

  decoupled H

- Decoupling limit:

$$m_H \gg m_h$$
$$s_\alpha \ll 1$$

Doublet-Singlet mixing

$$\delta\lambda_{hVV} \simeq -s_\alpha^2/2$$

$$\delta\lambda_{hhh} \simeq -3s_\alpha^2/2$$

$$\frac{\delta\lambda_{hhh}}{\delta\lambda_{hVV}} \simeq 3$$

A decisive test

$\langle\phi_S\rangle$

Doublet-Doublet mixing

- CP conserving 2HDM

  Motivated by SUSY models
- Spectrum:

  light h

  decoupled $H, A, H^{\pm}$
- Decoupling limit

$$\cos(\beta - \alpha) = \frac{\hat{\lambda} v^2}{m_A^2} \ll 1$$

Doublet-Doublet mixing

$$\delta\lambda_{hVV} \sim -c^2_{\beta-\alpha}$$

$$\delta\lambda_{hhh} \sim -c_{\beta-\alpha}$$

$$\frac{\delta\lambda_{hhh}}{\delta\lambda_{hVV}} \simeq \frac{4m_A^2}{m_h^2} \gg 1$$

Larger signature

m_A

Doublet-Triplet mixing

- Can accommodate neutrino masses
- Additional three triplets χ with $Y = -1,0,1$ preserves custodial symmetry
  $\rho = m_W^2/(m_Z^2 \cos^2\theta_W) = 1$
- Relevant spectrum:

  $h \sim c_\alpha \phi_{SM} - s_\alpha \chi$

  H

  $\tan\theta_H \sim \langle\chi\rangle/\langle\phi_{SM}\rangle$

Doublet-Triplet mixing

- Consider $s_\alpha \ll 1$

$$\frac{\delta\lambda_{hhh}}{\delta\lambda_{hVV}} \simeq -1$$

Decisive test

m_H

(combined with λ_{hff})

Effective interactions

- $V = V_{SM} + \frac{\rho}{\Lambda^2}|\phi_{SM}|^6$

$$\lambda_{hVV} = \lambda_{hVV}^{SM}$$

$$\lambda_{hhh} = \lambda_{hhh}^{SM} + 6\rho\frac{v^3}{\Lambda^2}$$

The only probe for NP

Lessons from $\delta\lambda_{hhh}/\delta\lambda_{hVV}$

Model	$\delta\lambda_{hhh}/\delta\lambda_{hVV}$
1D1S	3
2D	$4m_A^2/m_h^2 \gg 1$
1D3T $(s_\alpha \ll 1)$	-1
Dim 6 EFT	∞

Summary

- A measurement of $\lambda_{hhh} =$ a test for the SM
- It might provide a first hint for New Physics
- The combination of $\delta\lambda_{hhh}$ and $\delta\lambda_{hVV}$ is particularly powerful
- If $\delta\lambda_{hVV} \neq 0$ is observed, an accurate measurement of λ_{hhh} will become highly motivated as a clean window for New Physics

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Thank you!