Reunión anual de la RED-FAE

Física de Higgs a nivel de un lazo

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5.- *Lepton flavour violating decay.*

6.- *Triple Higgs boson self-coupling.*

7.- *Conclusions.*

INTRODUCTION

Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC ☆

CMS Collaboration *

CERN, ...

Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC ☆

ATLAS Collaboration

This paper is dedic... contributions to th...

$\sqrt{s} = 7$ TeV in 2011 and 5.8 fb^{-1} at $\sqrt{s} = 8$ TeV in 2012.

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ABSTRACT

A search for the Standard Model Higgs boson in proton–proton collisions with the ATLAS detector at the LHC is presented. The datasets used correspond to integrated luminosities of approximately 4.8 fb^{-1} collected at $\sqrt{s} = 7$ TeV in 2011 and 5.8 fb^{-1} at $\sqrt{s} = 8$ TeV in 2012. Individual searches in the channels $H \to ZZ^{(*)} \to 4\ell$, $H \to \gamma\gamma$ and $H \to WW^{(*)} \to e\nu\mu\nu$ in the 8 TeV data are combined with previously published results of searches for $H \to ZZ^{(*)}$, $WW^{(*)}$, $b\bar{b}$ and $\tau^+\tau^-$ in the 7 TeV data and results from improved analyses of the $H \to ZZ^{(*)} \to 4\ell$ and $H \to \gamma\gamma$ channels in the 7 TeV data. Clear evidence for the production of a neutral boson with a measured mass of 126.0±0.4 (stat)±0.4 (sys) GeV is presented. This observation, which has a significance of 5.9 standard deviations, corresponding to a background fluctuation probability of 1.7×10^{-9}, is compatible with the production and decay of the Standard Model Higgs boson.

mass of 126.0±0.4 (stat)±0.4 (sys) GeV

$H \to ZZ^{(*)} \to 4\ell$, $H \to \gamma\gamma$ and $H \to WW^{(*)} \to e\nu\mu\nu$

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HIGGS DECAY MODES AT LHC

Direct measurement

$h^0 \to ZZ^* \to 4\ell$	*ATLAS, Phys.Lett. B 716, 1 (2012)*	$m_h = 126.0 \pm 0.4 \pm 0.4 GeV$
$h^0 \to \gamma\gamma^* \to 4\ell$	*ATLAS, Phys.Rev.D 90, 052004 (2014)*	$m_h = 125.36 \pm 0.41 GeV$
	CMS, Phys.Rev.Lett. 114 191803 (2015)	$m_h = 125.09 \pm 0.21 \pm 0.11 GeV$
$h^0 \to WW^* \to \nu\ell\nu\ell$	*CMS, Phys.Lett.B 716, 30 (2012)*	$m_h = 125.3 \pm 0.4 \pm 0.5 GeV$
$\ell = e, \mu$		
$h^0 \to \tau\tau$, $\tau \to \ell\nu\bar{\nu}$	*CMS, Nature Phys. 10 557 (2014)*	$m_h = 125 GeV$
$\tau \to had. + \bar{\nu}$	*ATLAS, JHEP 1504, 117 (2015)*	$m_h = 125.36 GeV$
$h^0 \to b\bar{b}$	*ATLAS*, JHEP **1501**, 069 (2015)	$m_h = 125.36 GeV$
	CMS, Phys.Rev.D 92 032008 (2015)	$m_h = 125 GeV$

Upper bounds

$h^0 \to \mu\mu$	*ATLAS, Phys.Lett.B 738, 68 (2014)*	$m_h = 125 GeV$
$h^0 \to \mu\mu(ee)$	*CMS, Phys.Rev.D 92 032008 (2015)*	$m_h = 120 - 150 GeV$
$h^0 \to \mu\tau$	*CMS, Phys.Lett. 449, 337 (2015)*	$m_h = 125 GeV$
	ATLAS, JHEP 1511, 211 (2015)	$m_h = 125 GeV$
$h^0 \to Z\gamma \quad Z \to \ell\ell$	*ATLAS, Phys.Lett.B 732, 8 (2014)*	$m_h = 120 - 150 GeV$
	CMS, Phys.Lett.B 753 341 (2016)	$m_h = 125 GeV$

HIGGS DECAY MODES AT LHC

Direct measurement

$h^0 \to ZZ^* \to 4\ell$

$h^0 \to \gamma\gamma^* \to 4\ell$

$h^0 \to WW^* \to \nu\ell\nu\ell$

$\ell = e, \mu$

$h^0 \to \tau\tau, \; \tau \to \ell\nu\bar{\nu}, \; \tau \to had. + \bar{\nu}$

$h^0 \to b\bar{b}$

Upper bounds

$h^0 \to \mu\mu$

$h^0 \to \mu\mu(ee)$

$h^0 \to \mu\tau$

$h^0 \to Z\gamma \quad Z \to \ell\ell$

"The data are found to be compatible with the Standard Model expectations for a Higgs boson at a mass of 125.36 GeV… Together they account for approximately 88 % of all decays of a SM Higgs boson…."

ATLAS, Eur. Phys. J. C (2016) 76:6

ATLAS and CMS, JHEP08 (2016) 045

Exploring electroweak symmetry breaking at the LHC.

$$\mathcal{L}_{ME+h} = \mathcal{L}_{Fermionic} + \mathcal{L}_{Gauge} - V(\Phi)$$

HIGGS PRODUCTION IN THE LHC

Direct measurement

In the SM, Higgs boson production at the LHC mainly occurs through the following processes:

$h^0 \to ZZ^*$

$h^0 \to \gamma\gamma^*$

$h^0 \to WW^*$

$h^0 \to \tau\tau,$

$h^0 \to b\bar{b}$

Upper bounds

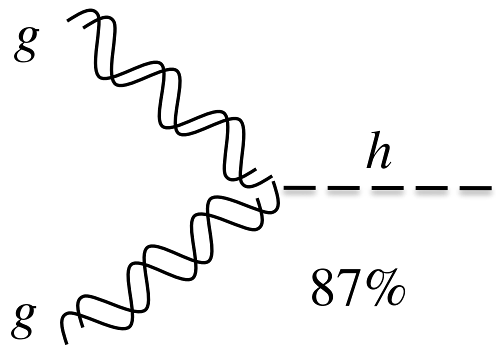
$h^0 \to \mu\mu$

$h^0 \to \mu\mu(ee)$

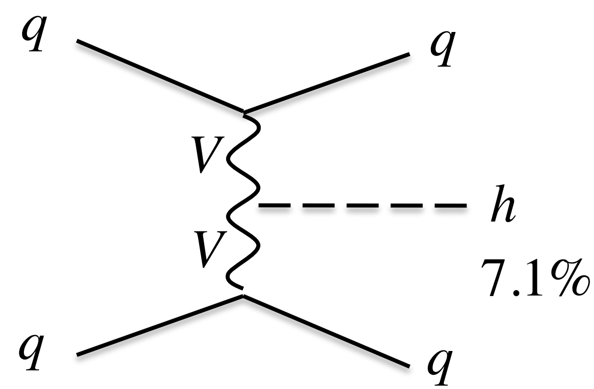
$h^0 \to \mu\tau$

$h^0 \to Z\gamma$

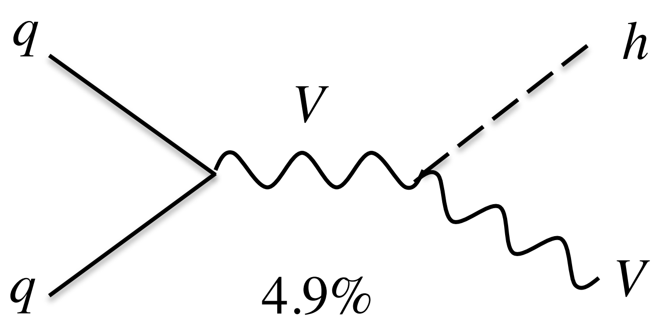
Gluon fusion production



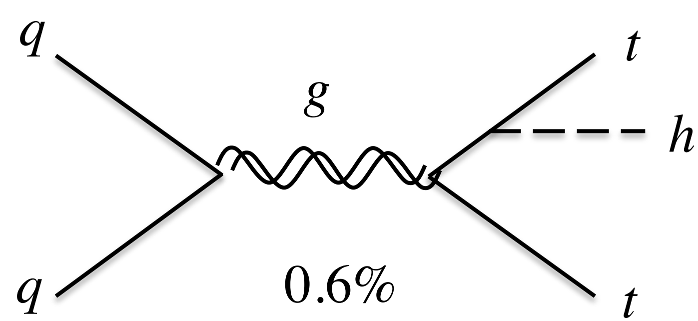
Vector boson fusion production



Associated production with a gauge boson



Associated production with a pair of top quarks



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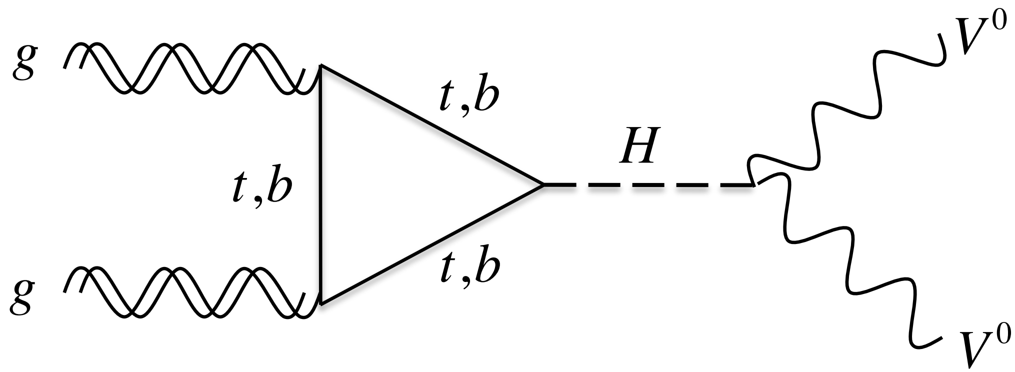
CP VIOLATION IN HIGGS DECAYS

The main mechanism for Higgs boson production at hadron colliders is gluon fusion, in which the gluons couple to Higgs bosons via top and bottom quark loops



The Higgs can be decay into gauge boson, for example:

$$h^0 \to ZZ^* \to 4\ell$$ *ATLAS,PLB716,1(2012)*

$$h^0 \to \gamma\gamma^* \to 4\ell$$ *ATLAS,PRD90,052004(2014)* *CMS, PRL114,191803(2015)*

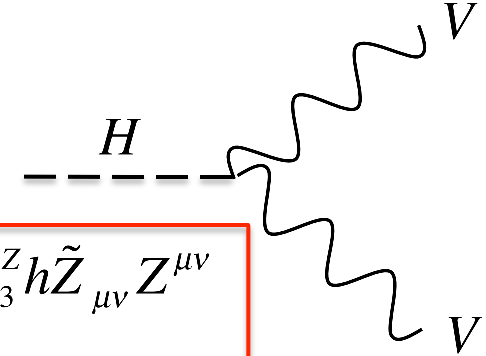
$$h^0 \to WW^* \to \nu\ell\nu\ell$$ *CMS,PLB716,30(2012)*

$$h^0 \to Z\gamma \quad Z \to \ell\ell$$ *ATLAS,PLB732,8(2014)* *CMS,PLB753,341(2016)*

All the results are compatibles with the expectations from a standard model Higgs boson. However, a future deviations from the predictions of the Standard Model can be signal of new physics.

CP VIOLATION IN HIGGS DECAYS

The Higgs boson couplings to gauge bosons is induced at tree level in the SM.
At one loop level we have new interesting contributions:



$$\mathcal{L}_{hZZ} = \frac{g m_Z}{2\cos^2\theta_W} h Z_\mu Z^\mu + a_1^Z Z_{\mu\nu} Z^\nu \partial^\mu h + a_2^Z h Z_{\mu\nu} Z^{\mu\nu} + a_3^Z h \tilde{Z}_{\mu\nu} Z^{\mu\nu}$$

$$\mathcal{L}_{hWW} = g m_W h W_\mu W^\mu + a_1^W W_{\mu\nu} W^\nu \partial^\mu h + a_2^W h W_{\mu\nu} W^{\mu\nu} + a_3^W h \tilde{W}_{\mu\nu} W^{\mu\nu}$$

$$\mathcal{L}_{h\gamma\gamma} = 0 \qquad + a_1^\gamma A_{\mu\nu} A^\nu \partial^\mu h + a_2^\gamma h A_{\mu\nu} A^{\mu\nu} + a_3^\gamma h \tilde{A}_{\mu\nu} A^{\mu\nu}$$

Tree level — CP-even — CP-odd

But in general the vertex function can be written as:

$$\Gamma^{\alpha\beta}(p_1, p_2) = a_1^V g^{\alpha\beta} + a_2^V [(p_1 \cdot p_2) g^{\alpha\beta} - p_1^\alpha p_2^\beta] + a_3^V \varepsilon^{\alpha\beta\mu\nu} p_{1\mu} p_{2\nu}$$

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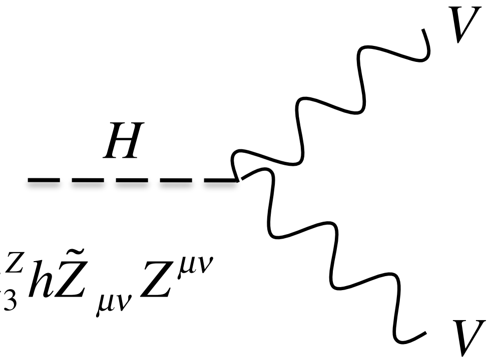

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$$\mathcal{L}_{hWW} = g m_W h W_\mu W^\mu + a_1^W W_{\mu\nu} W^\nu \partial^\mu h + a_2^W h W_{\mu\nu} W^{\mu\nu} + a_3^W h \tilde{W}_{\mu\nu} W^{\mu\nu}$$

$$\mathcal{L}_{h\gamma\gamma} = 0 \qquad + a_1^\gamma A_{\mu\nu} A^\nu \partial^\mu h + a_2^\gamma h A_{\mu\nu} A^{\mu\nu} + a_3^\gamma h \tilde{A}_{\mu\nu} A^{\mu\nu}$$

CP-even form factors

But in general the vertex function can be written as:

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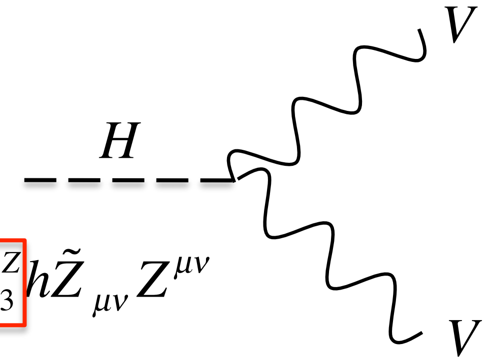

$$\mathcal{L}_{hZZ} = \frac{g m_Z}{2\cos^2\theta_W} h Z_\mu Z^\mu + a_1^Z Z_{\mu\nu} Z^\nu \partial^\mu h + a_2^Z h Z_{\mu\nu} Z^{\mu\nu} + a_3^Z h \tilde{Z}_{\mu\nu} Z^{\mu\nu}$$

$$\mathcal{L}_{hWW} = g m_W h W_\mu W^\mu + a_1^W W_{\mu\nu} W^\nu \partial^\mu h + a_2^W h W_{\mu\nu} W^{\mu\nu} + a_3^W h \tilde{W}_{\mu\nu} W^{\mu\nu}$$

$$\mathcal{L}_{h\gamma\gamma} = 0 \qquad + a_1^\gamma A_{\mu\nu} A^\nu \partial^\mu h + a_2^\gamma h A_{\mu\nu} A^{\mu\nu} + a_3^\gamma h \tilde{A}_{\mu\nu} A^{\mu\nu}$$

CP-odd form factors

But in general the vertex function can be written as:

$$\Gamma^{\alpha\beta}(p_1, p_2) = a_1^V g^{\alpha\beta} + a_2^V [(p_1 \cdot p_2) g^{\alpha\beta} - p_1^\alpha p_2^\beta] + a_3^V \varepsilon^{\alpha\beta\mu\nu} p_{1\mu} p_{2\nu}$$

CP VIOLATION IN HIGGS DECAYS

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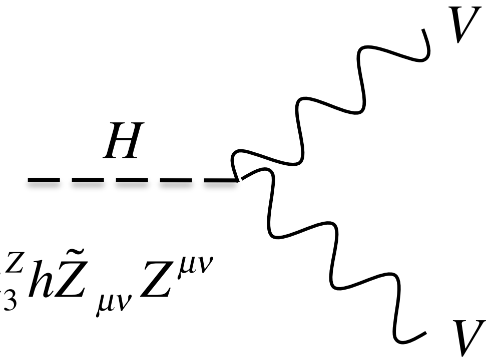

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$$\mathcal{L}_{h\gamma\gamma} = 0 \qquad + \boxed{a_1^\gamma A_{\mu\nu} A^\nu \partial^\mu h + a_2^\gamma h A_{\mu\nu} A^{\mu\nu}} + a_3^\gamma h \tilde{A}_{\mu\nu} A^{\mu\nu}$$

The measurement of Higgs boson production in the diphoton decay channel at 7 and 8 TeV, collected by the ATLAS detector:

$$\mu_{ggh}^{\gamma\gamma} = 1.32 \pm 0.38$$ *ATLAS, PRD90 (2014) 112015*

The Higgs boson mass measured was $m_h = 125.4$ GeV.

"No significant deviations from the predictions of the Standard Model are found"

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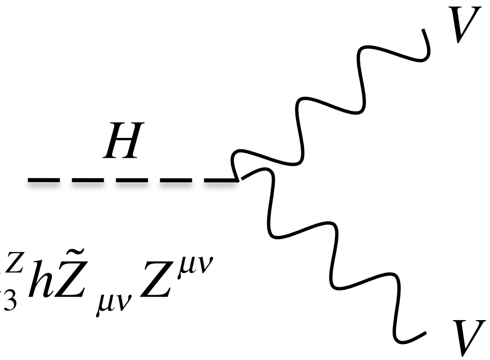

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$$\mathcal{L}_{hWW} = g m_W h W_\mu W^\mu + a_1^W W_{\mu\nu} W^\nu \partial^\mu h + a_2^W h W_{\mu\nu} W^{\mu\nu} + a_3^W h \tilde{W}_{\mu\nu} W^{\mu\nu}$$

$$\mathcal{L}_{h\gamma\gamma} = 0 \qquad + \boxed{a_1^\gamma A_{\mu\nu} A^\nu \partial^\mu h + a_2^\gamma h A_{\mu\nu} A^{\mu\nu}} + a_3^\gamma h \tilde{A}_{\mu\nu} A^{\mu\nu}$$

The measurement of Higgs boson production in the diphoton decay channel at 7 and 8 TeV, collected by the CMS detector:

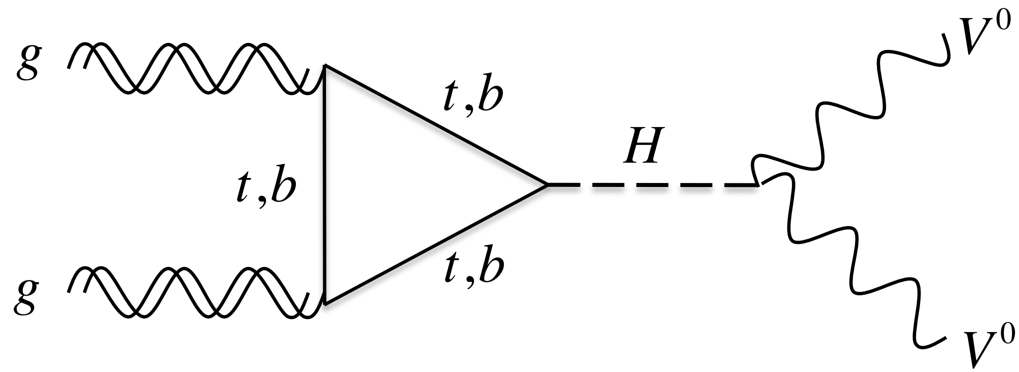
$$\mu_{ggh}^{\gamma\gamma} = 1.13^{+0.37}_{-0.31}$$ *CMS, Eur. Phys. J. C. 74 (2014) 3076*

The Higgs boson mass measured was $m_h = 124.70 \pm 0.34$ GeV.

"All the results are compatibles with the expectations from a standard model Higgs boson"

CP VIOLATION IN HIGGS DECAYS

The CMS collaboration has been exploring the a_3 coupling in different Higgs boson decay to neutral diboson, and from the combined Run 1 and Run 2 analysis.



Where the effective fractional cross sections is defined as follows:

$$f_{a_3} = \frac{|a_3|^2}{\sum_j |a_3^j|^2 \sigma_j} = 0.00^{+0.26}_{-0.09}$$

With 68% C.L. and where σ_j is the cross section for the $h \rightarrow ZZ/Z\gamma^*/\gamma^*\gamma^* \rightarrow 2e\,2\mu$ process.

And the phases $\phi_{a_3} = \arg(a_3/a_1) \rightarrow -0.38 \cos(\phi_{a_3}) < 0.46$ With 95% C.L.

CMS, Arxiv:1707.00541 (2017)

LEPTON FLAVOUR VIOLATING DECAY

Direct measurement

$h^0 \to ZZ^*$

$h^0 \to \gamma\gamma^*$

$h^0 \to WW^*$

$h^0 \to \tau\tau,$

$h^0 \to b\bar{b}$

Upper bounds

$h^0 \to \mu\mu$

$h^0 \to \mu\mu(ee)$

$h^0 \to \mu\tau$

$h^0 \to Z\gamma$

In the SM the lepton flavour violating h→$\mu\tau$ decay is not induced at tree level. The CMS Collaboration has the first direct search for h→$\mu\tau$ decay and reported a slight excess of 2.4 standard deviations. The best fit was:

$$Br(h^0 \to \mu\tau) = 0.84^{+0.39}_{-0.37}\%$$

CMS, Phys.Lett. 749, 337 (2015)

The data sample used in this search was collected in pp collisions at a centre-of mas energy 8TeV, and corresponds to an integrated luminosity of 19.7fb^{-1}.

The ATLAS collaboration find a mild deviation of 1σ significance, and a best fit is of the:

$$Br(h^0 \to \mu\tau) = (0.53 \pm 0.51)\%$$

ATLAS, JHEP11 (2015) 211

At 13 TeV and an with integrated luminosity of 19.7fb^{-1}, CMS reported that “No excess is observed”. The best fit is :

$$Br(h^0 \to \mu\tau) = 0.76^{+0.81}_{-0.84}\%$$

CMS-PAS-HIG-16-005

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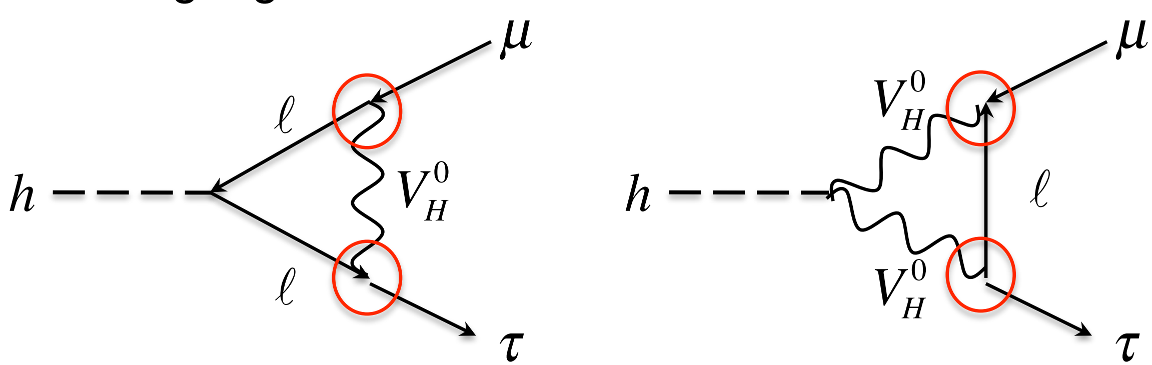
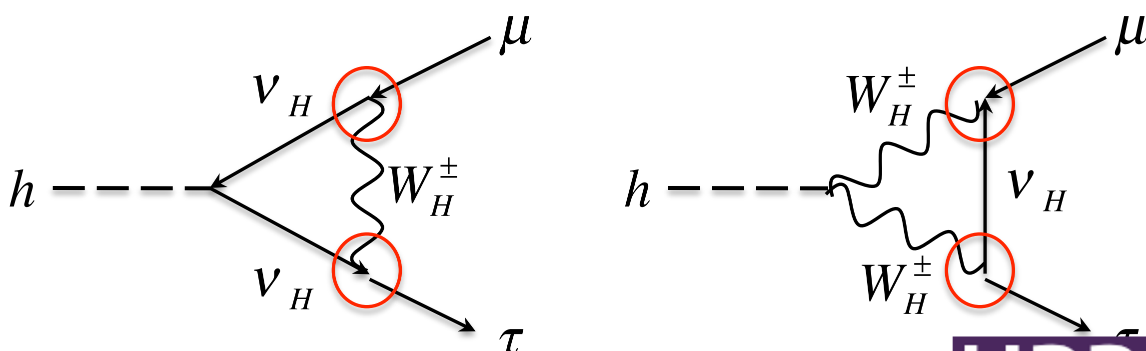
$h^0 \to Z\gamma$

However, in some SM extensions the lepton flavour violation are associated with heavy particles. Thus, the h→$\mu\tau$ decay could be induced to up one loop level.

Heavy neutral gauge boson contributions



Heavy charged gauge boson contributions



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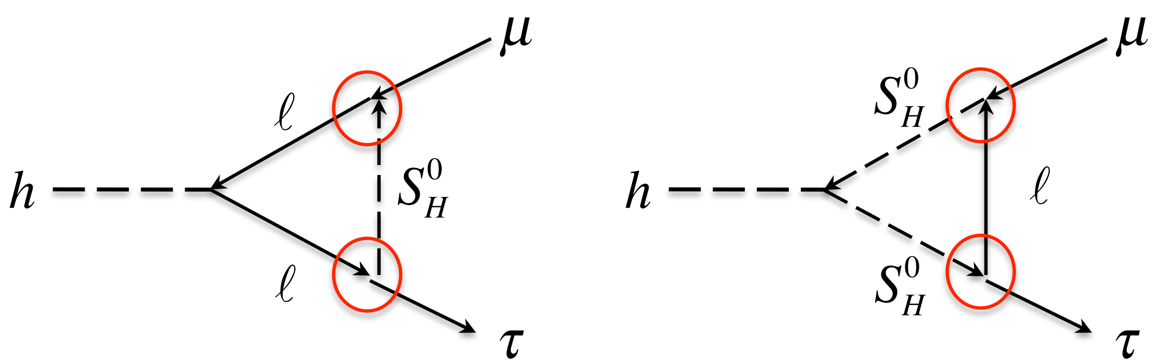

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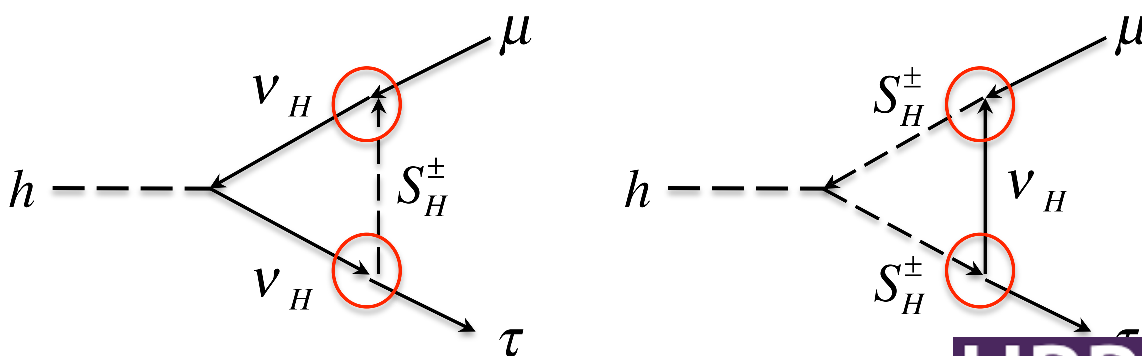

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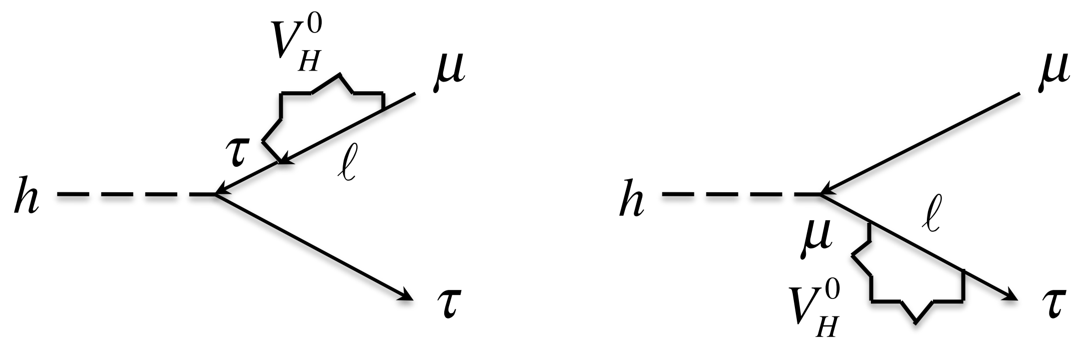
Additional diagrams are needed to cancel UV divergences

Heavy neutral gauge boson contributions



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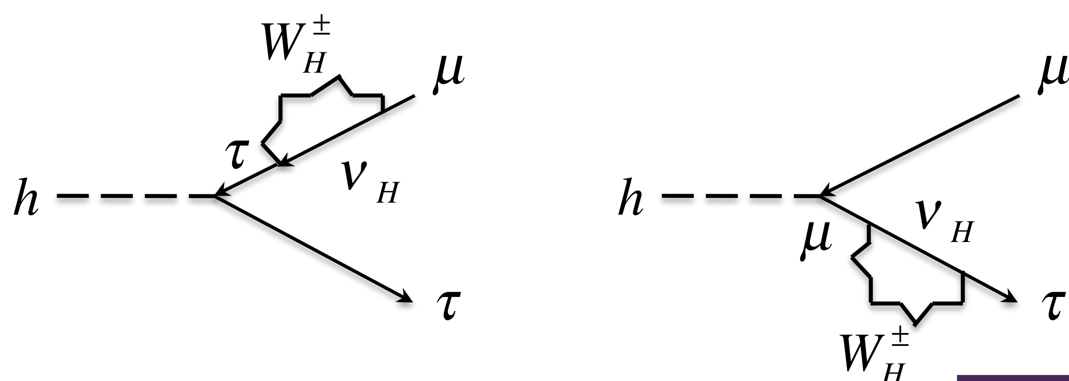

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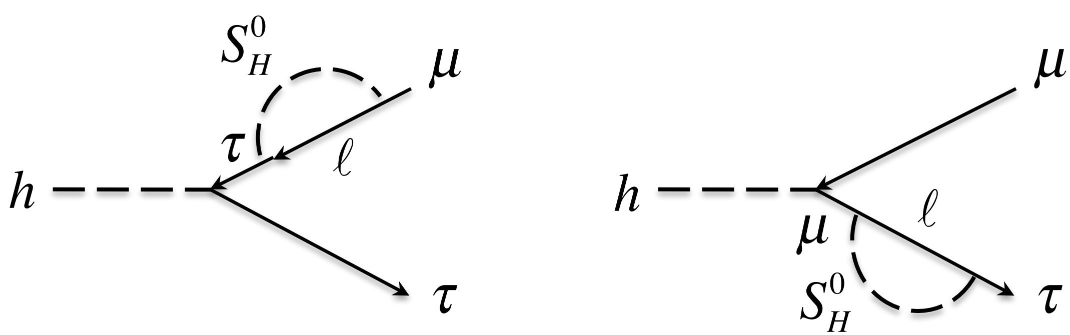

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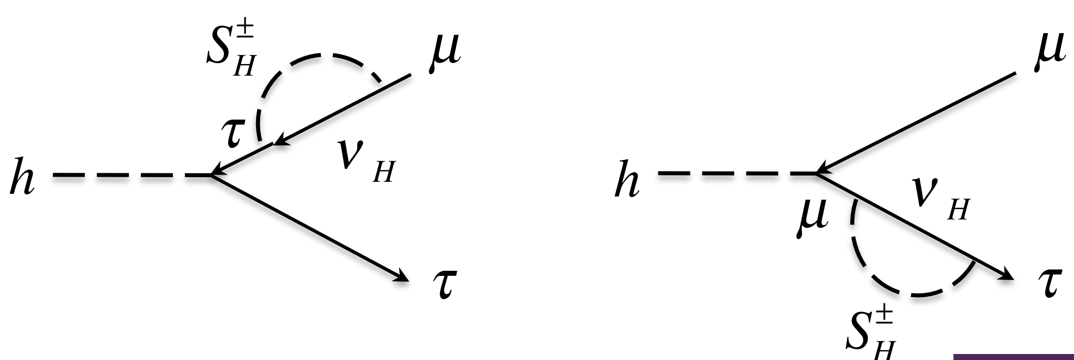

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$h^0 \to \mu\tau$

$h^0 \to Z\gamma$

The matrix element for this coupling can be written as follows:

$$\mathcal{M} = \bar{u}(m_\tau)(A + iB\gamma^5)u(m_\mu)$$

Where A and B are one-loop form factors.

For $m_\mu = m_\tau \approx 0$, the decay widths has the following form:

$$\Gamma(h \to \mu\tau) \approx \frac{m_h}{8\pi}(|A|^2 + |B|^2)$$

LEPTON FLAVOUR VIOLATING DECAY

Phenomelogical results

Direct measurement

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$h^0 \to Z\gamma$

Heavy rigth-handed neutrino $\sim 10^{-5}$	*Phys. Lett. B 285 (1992) 68-74*
The minimal SUSY SM $\sim 10^{-2}$	*Phys. Rev. D62 (2000) 116005*
Type-I see-saw $\sim 10^{-5}$	*Phys. Rev. D71 (2005) 035011*
The minimal SUSY neutrino See-Saw $\sim 10^{-8}$	*Phys. Lett. B679 (2009) 376381*
SUSY economical 331 $\sim 10^{-8}$	*Nucl. Phys. B864 (2012) 85112*
SUSY without R-parity $\sim 10^{-5}$	*Europhys. Lett. 101 (2013) 31003*
Vector-like leptons motivated by Composite Higgs models $\sim 10^{-5}$	*JHEP 05 (2014) 092*
Inverse see-saw $\sim 10^{-9}$-10^{-10}	*Phys. Rev. D91 (2015) 015001*
Simplest Little Higgs Model $\sim 10^{-12}$	*Phys. Rev. D94 (2016) 056001*
Little Higgs Model with T-parity $\sim 10^{-4}$-10^{-5}	*J.P.C.S.761 (2016) 1, 012051*
THDM with 4F $\sim 10^{-5}$-10^{-6}	*ArXiv:170.00100*

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TRIPLE HIGGS BOSON SELF-COUPLING

Direct measurement

$h^0 \to ZZ^* \to 4\ell$

$h^0 \to \gamma\gamma^* \to 4\ell$

$h^0 \to WW^* \to \nu\ell\nu\ell$

$\ell = e, \mu$

$h^0 \to \tau\tau$, $\tau \to \ell\nu\bar{\nu}$, $\tau \to had. + \bar{\nu}$

$h^0 \to b\bar{b}$

Upper bounds

$h^0 \to \mu\mu$

$h^0 \to \mu\mu(ee)$

$h^0 \to \mu\tau$

$h^0 \to Z\gamma$, $Z \to \ell\ell$

"The data are found to be compatible with the Standard Model expectations for a Higgs boson at a mass of 125.36 GeV… Together they account for approximately 88 % of all decays of a SM Higgs boson…."

ATLAS, Eur. Phys. J. C (2016) 76:6

ATLAS and CMS, JHEP08 (2016) 045

Exploring electroweak symmetry breaking at the LHC.

$$\mathcal{L}_{ME+h} = \mathcal{L}_{Fermionic} + \mathcal{L}_{Gauge} - V(\Phi)$$

Higgs self-couplings

$$V(\Phi) = -\lambda v^2 \Phi^\dagger \Phi + \lambda(\Phi^\dagger\Phi)^2$$
$$= \lambda v^2 h^2 + \lambda v h^3 + \tfrac{1}{4}\lambda h^4$$

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Exploring electroweak symmetry breaking at the LHC.

"Searches for both resonant and nonresonant Higgs boson pair production… No evidence of their production is observed…."

ATLAS, Phys. Rev. D 92, 092004 (2015)

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$h^{0*} \to h^0 h^0$
- $\to \gamma\gamma b\bar{b}$ — *ATLAS*, PRL.114, 081802 (2015). *CMS*, PRD.94, 052012 (2016).
- $\to b\bar{b}b\bar{b}$ — *ATLAS*, EPJC75, 412 (2015). *CMS PAS HIG-16-026*.

$h^{0*} \to h^0 h^0$
- $\to \tau\tau b\bar{b}$
- $\to \gamma\gamma WW$

ATLAS, PRD92, 092004 (2015)

$h^{0*} \to h^0 h^0 \to b\bar{b}VV \to b\bar{b}\ell\ell\nu\nu$ — *CMS PAS HIG-17-006*.

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$h^0 \to Z\gamma \quad Z \to \ell\ell$

"The cross sections for three Higgs boson production processes are reduced by three orders of magnitude compared to those for the double Higgs boson production ...."

Eur. Phys. J. C 10, 45 (1999)

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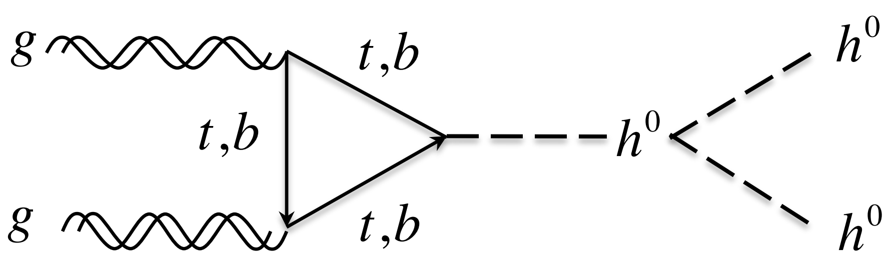
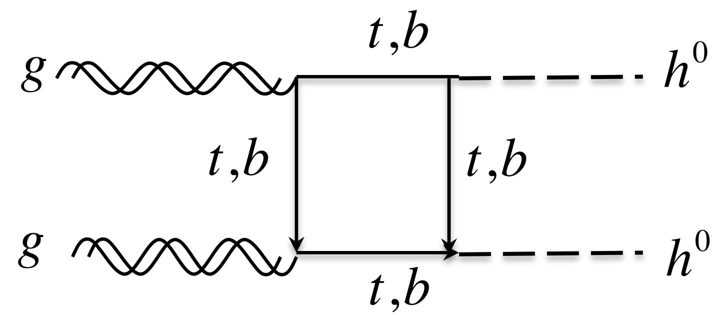
TRIPLE HIGGS BOSON SELF-COUPLING

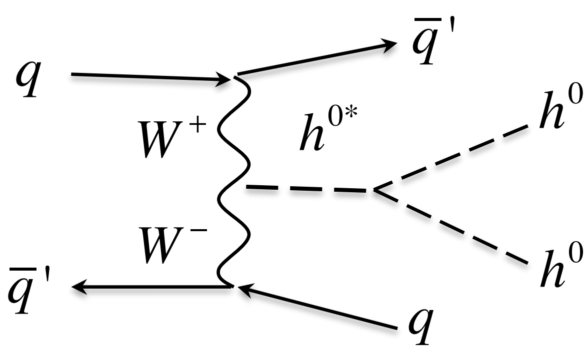
Two Higgs production in hadron collider

Self-coupling hhh



Background



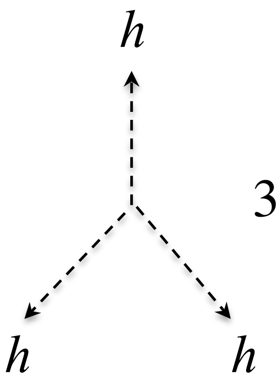


"The phenomenology calculations show that it is difficult to measure the trilinear Higgs self-coupling at the large Hadron collider (LHC) due to the large QCD background….."

Phys. Rev. Lett. 89, 151801 (2002)

TRIPLE HIGGS BOSON SELF-COUPLING

Self-coupling *hhh* at tree and one loop level in SM

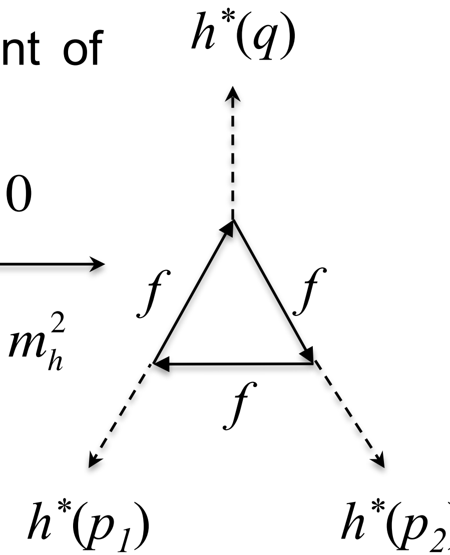


At tree level the self-coupling hhh is independent of the higgs bosons 4-momentum.

$$3\frac{m_h^2}{v} \approx 190.549 GeV$$

$$q + p_1 + p_2 = 0$$

$$q^2 \neq p_1^2 \neq p_2^2 \neq m_h^2$$



At one loop level and with off-shell Higgs, we need more driagrams to satisfy Bose symmetry.

$$+\begin{pmatrix} q \\ p_1 \rightleftarrows p_2 \end{pmatrix} + \begin{pmatrix} q \rightleftarrows p_1 \\ p_2 \end{pmatrix} + \begin{pmatrix} q \rightleftarrows p_2 \\ p_1 \end{pmatrix} + \begin{pmatrix} p_1 \rightleftarrows p_2 \\ q \rightleftarrows p_1 \end{pmatrix} + \begin{pmatrix} p_1 \rightleftarrows p_2 \\ q \rightleftarrows p_2 \end{pmatrix}$$

$$= \Gamma_{h^* h^* h^*}(q^2, p_1^2, p_2^2) = \frac{3m_h^2}{v}\lambda_{hhh}$$

Here λ_{hhh} is the correction to self-coupling hhh.

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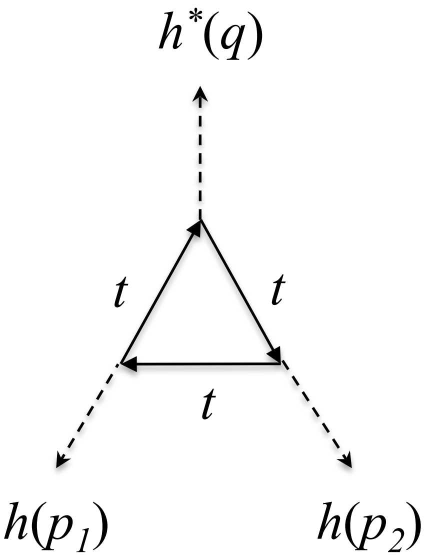
TRIPLE HIGGS BOSON SELF-COUPLING

Self-coupling *hhh* at one-loop level in SM



$$\lambda_f^{ME}(q^2) = \frac{g m_f^2 s_f^2 N_c}{3!16\pi^2 m_W^2}\left[18 - \int_{x=0}^{1}\int_{y=0}^{1-x} \Xi_f^{ME}(x,y,s_f,s_q)dxdy\right]$$

where $s_k=m_k/m_h$ and $s_q=q/m_h$, further the dimensionlees function given by:

$$\Xi_f^{ME} = \frac{4s_f^2 - 2y + s_q^2(2y-1)}{s_f^2 + y(y-1) + s_q^2 x(x+y-1)} + \frac{4s_f^2 - 2x + s_q^2(2x-1)}{s_f^2 + x^2 + s_q^2(y-1) + x(s_q^2 y - 1)} + \frac{4s_f^2 + s_q^2(1-2x-2y) + 2(x+y-1)}{s_f^2 + x^2 + y(y-1) + x[1+(s_q^2-2)y]}$$

The correction to self-coupling λ_{hhh} is:

$$\lambda^{ME}(m_h^2) \approx 9.1404\%$$ *arXiv:1610.06299*

Top quark

previous results*:

$$\lambda_{top}^{ME}(m_h^2) \approx 9.14693\%$$

Phys. Lett. B558, 157 (2003)

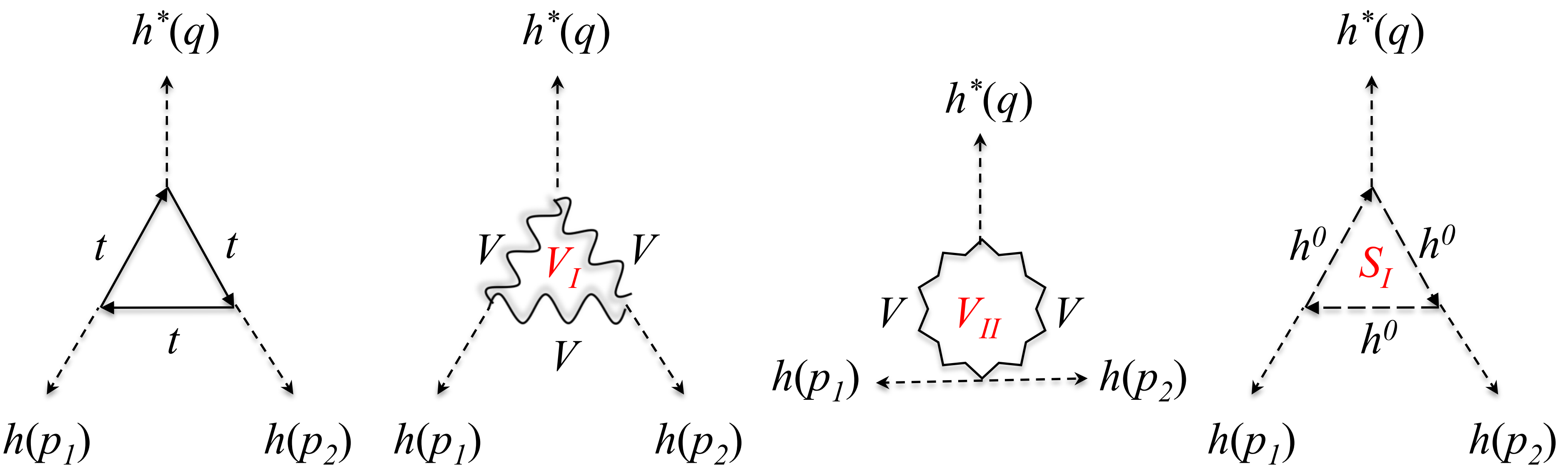
$$\lambda_{top}^{ME}(m_h^2) \approx 9.8221\%$$

Eur. Phys. J. C23, 163 (2002)

*With some approximations for the 4-momentum magnitude of the off-shell scalar boson:

TRIPLE HIGGS BOSON SELF-COUPLING

Self-coupling *hhh* at one-loop level in SM



The correction to self-coupling λ_{hhh} is:

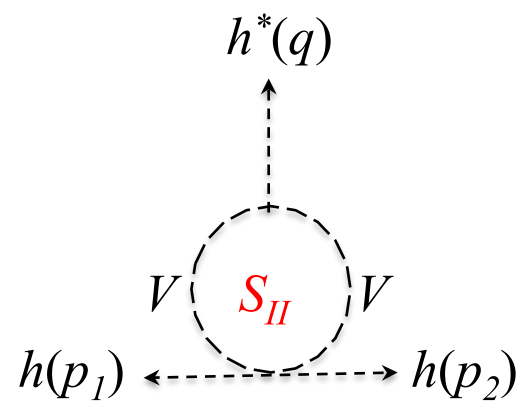
$$\lambda^{ME}(m_h^2) \approx 9.1404\% + 0.0726\% + 1.8397\% \approx 11.0528\%$$

Top quark

Gauge bosons

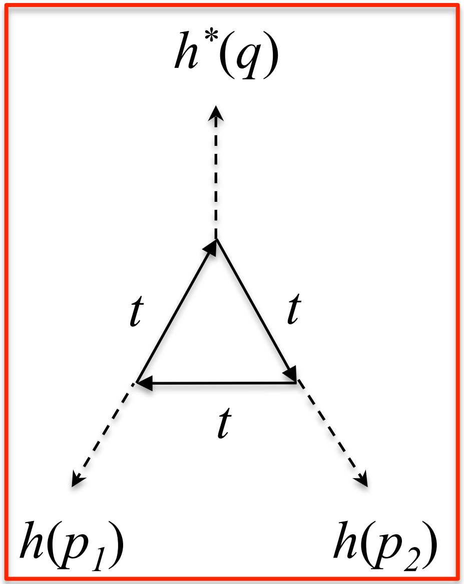
Self-coupling

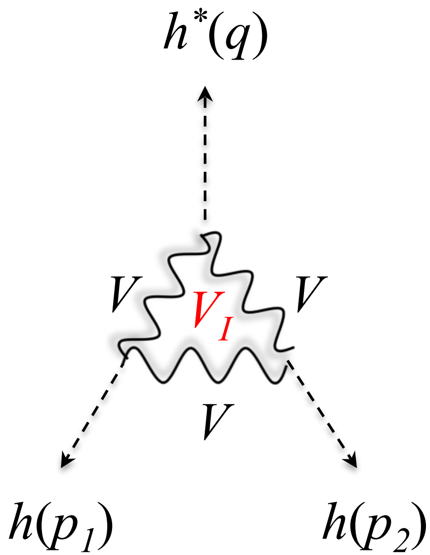
Total

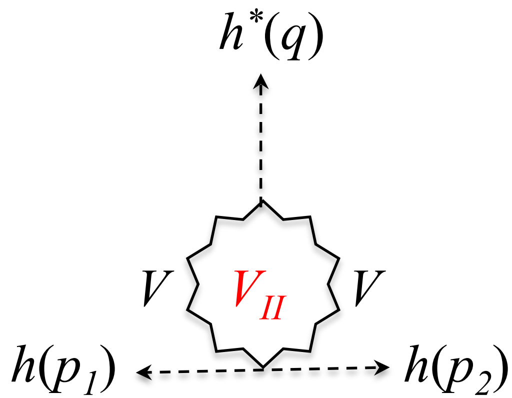


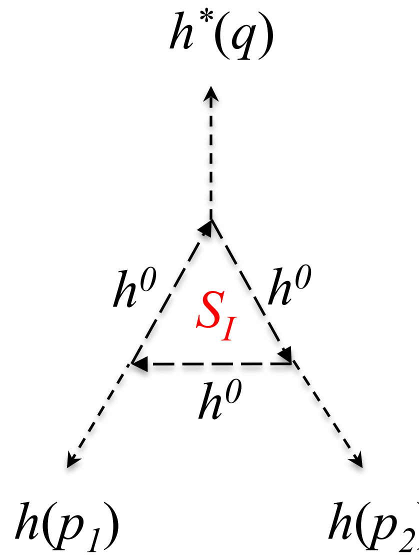
TRIPLE HIGGS BOSON SELF-COUPLING

Self-coupling *hhh* at one-loop level in SM





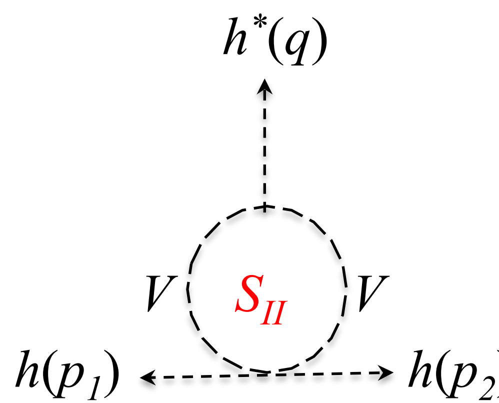




The correction to self-coupling λ_{hhh} is:

$$\lambda^{ME}(m_h^2) \approx 9.1404\% + 0.0726\% + 1.8397\% \approx 11.0528\%$$

Thus, the main contribution comes from the top quark. Therefore, the largest correction to the λ_{hhh} parameter comes from the heavy fermions of any SM extensions.



CONCLUSIONS

The radiative corrections are crucial to understand the production and decay of Higgs boson at LHC. They also, open a theoretical window for physics beyond SM.