Phenomenology of Inert Higgs models

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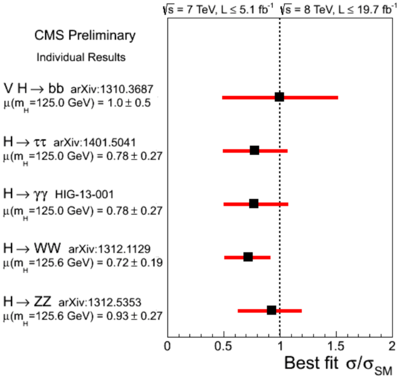
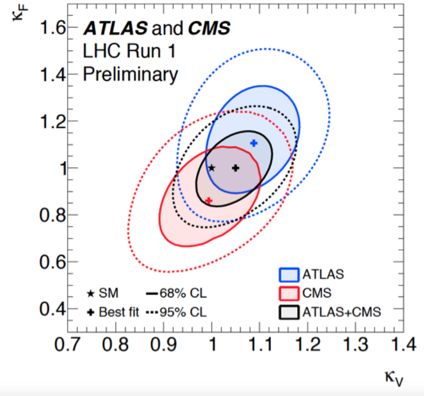
Outlines

- General introduction
- Analysis of Inert Higgs Model
- Invisible decay of the Higgs
- Triple Higgs coupling as a probe of new physics (A.A, A. Jueid JHEP'15)
- Conclusions

CMS and ATLAS results



CMS and ATLAS results: Fit of *hff* and *hVV*



LHC@13 TeV

After the Scalar boson discovery at $7 \oplus 8$ TeV LHC, the mission of the LHC run at 13 TeV is:

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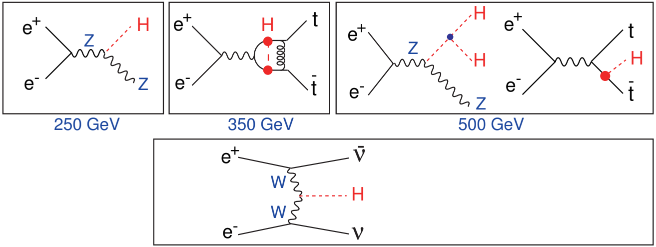
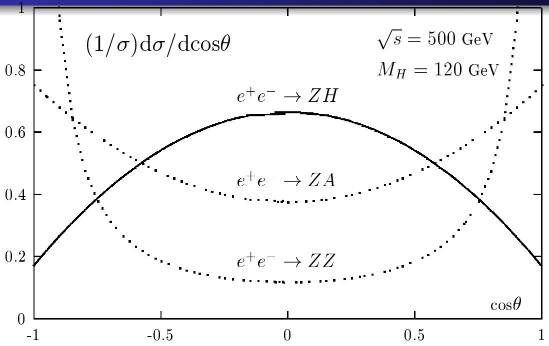
- The improvement of the scalar boson mass and scalar boson coupling measurements.
- Find a clear hint of new physics beyond SM
- Accurate measurements of the scalar boson couplings to SM particles would help to determine if the Higgs-like particle is the SM Higgs or a Higgs that belongs to a higher representations:
  more doublets, doublet & triplets, doublet & singlets

LHC & ILC complementarity



- ILC @ 250 GeV: $e^+e^- \to Z^* \to Zh \to l^+l^-h$:
- Calculate the invariant mass of the system recoiling against l^+,l^- momentum from Z decay independent of how the Higgs boson decays.
- Precise measurement of the Higgs mass, cross section and J^{PC} .

ILC and CP of the Higgs



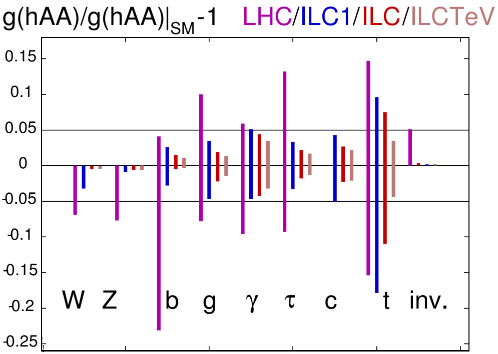
$$\mathcal{M} = \mathcal{M}_{ZH} + i\eta\mathcal{M}_{ZA}$$

$$\frac{d\sigma}{d\cos\theta_Z} \propto \beta_{\Phi Z}\Big(1 + \frac{s\beta_{\Phi Z}^2}{8M_Z^2}\sin^2\theta_Z + \eta\frac{2s\beta_{\Phi Z}}{M_Z^2}\kappa\cos\theta_Z$$

$$+\eta^2\frac{s^2\beta_{\Phi Z}^2}{8M_Z^4}(1+\cos^2\theta_Z)\Big),$$

LHC & ILC complementarity

- M. Peskin, hep-ph/1207.2516



Inert Doublet Model

- The new particle "Higgs like" is consistent with the Higgs boson of the SM but it will take further work to determine whether or not it is the Higgs boson predicted by the SM.
- Non minimal Model: Brout-Englert-Higgs mechanism is the simplest one. Other types of Higgs bosons are predicted by other theories that go beyond SM.

- The new particle "Higgs like" is consistent with the Higgs boson of the SM but it will take further work to determine whether or not it is the Higgs boson predicted by the SM.
- Non minimal Model: Brout-Englert-Higgs mechanism is the simplest one. Other types of Higgs bosons are predicted by other theories that go beyond SM.
- Deshpande-Ma, PRD18 (1978) introduced inert model for EWSB purpose.
- Three decades later, inert model was extended by E. Ma (2006) to include 3 $\mathbb{Z}_2$ odd singlets of ν_R with Majorana masses where ν's mass appear at 1-loop.
- Extensively used also to explain Dark matter of the universe

- The Inert Doublet Model is an extension of SM, the Higgs sector has two $SU(2)$ doublets H_1 and H_2 with $\mathbb{Z}_2$ symmetry. H_1 is the SM-Higgs: responsible for EWSB.
- Under $\mathbb{Z}_2$: all SM particles are even representing the visible sector and only H_2 is odd.
  $\mathbb{Z}_2 \quad \text{symmetry} : H_1 \quad \rightarrow \quad H_1, \quad H_2 \quad \rightarrow \quad -H_2$
  Guarantees the stability of the lightest odd particle LOP.
- Imposing $\mathbb{Z}_2$ imply that $< H_2 >= 0$ and will not have a Yukawa interactions with the SM fermions: no FCNC.
- Due to $\mathbb{Z}_2$ all the inert particles can only appear in pair in their vertices.

The Scalar potential of this model is given by

$$H_1 = \begin{pmatrix} \phi_1^{\pm} \\ v_1/\sqrt{2} + (h + i\chi)/\sqrt{2} \end{pmatrix}, \quad H_2 = \begin{pmatrix} \phi_2^{\pm} \\ (S + iA)/\sqrt{2} \end{pmatrix}$$

$$V = \mu_1^2|H_1|^2 + \lambda_1|H_1|^4 + \mu_2^2|H_2|^2 + \lambda_2|H_2|^4 + \lambda_3|H_1|^2|H_2|^2$$

$$+ \lambda_4|H_1^\dagger H_2|^2 + \frac{\lambda_5}{2}\left\{(H_1^\dagger H_2)^2 + h.c.\right\}$$

- $\lambda_{1,\ldots 4}$ and λ_5 are real.
- Because of $\mathbb{Z}_2$ There is no mixing between the doublets:
- h plays the role of the SM Higgs Boson.
- the free parameters are:

$$m_h, m_S, m_A, m_{H^\pm}, \lambda_2, hDD = \lambda_L = \frac{1}{2}(\lambda_3 + \lambda_4 - \lambda_5)$$

Theoretical constraints

- Electroweak Precision Tests

– Global electroweak fit trough the oblique S, T and U parameters

$$
\begin{aligned}
S &= \frac{1}{2\pi}\left[\frac{1}{6}\log(\frac{m_S^2}{m_{H^\pm}^2}) - \frac{5}{36} + \frac{m_S^2 m_A^2}{3(m_A^2 - m_S^2)^2}\right. \\
&\left. + \frac{m_A^4(m_A^2 - 3m_S^2)}{6(m_A^2 - m_S^2)^3}\log(\frac{m_A^2}{m_S^2})\right] \qquad (1) \\
T &= \frac{1}{32\pi^2\alpha v^2}\left[F(m_{H^\pm}^2, m_A^2) + F(m_{H^\pm}^2, m_S^2) - F(m_A^2, m_S^2)\right] \qquad (2)
\end{aligned}
$$

where the function F is defined by
where

$$
F(x,y) = \frac{x+y}{2} - \frac{xy}{x-y}\log(\frac{x}{y})
$$

- Pertubativity and unitarity:
  – All quartic couplings obey: $|\lambda_i| \leq 8\pi$
- Tree-level unitarity is preserved in variety of scattering processes. The eigenvalues are:
  $e_{1,2} = \lambda_3 \pm \lambda_4, \quad e_{3,4} = \lambda_3 \pm \lambda_5, \quad e_{5,6} = \lambda_3 + 2\lambda_4 \pm 3\lambda_5$
  $e_{7,8} = -\lambda_1 - \lambda_2 \pm \sqrt{(\lambda_1 - \lambda_2)^2 + \lambda_4^2},$
  $e_{9,10} = -3\lambda_1 - 3\lambda_2 \pm \sqrt{9(\lambda_1 - \lambda_2)^2 + (2\lambda_3 + \lambda_4)^2}$
  Akeroyd, Arhrib, Naimi PLB'2000

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- Vacuum Stability
  – The potential V must be bounded from below:
  $\lambda_{1,2} > 0,$
  $\lambda_3 + \lambda_4 - |\lambda_5| + 2\sqrt{\lambda_1\lambda_2} > 0, \qquad \lambda_3 + 2\sqrt{\lambda_1\lambda_2} > 0$

Experimental constraints

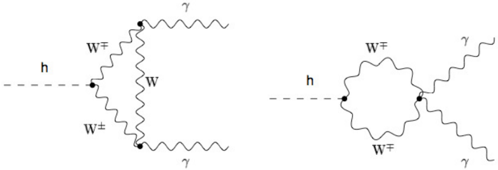
- in order not to allow for: $W^\pm \to AH^\pm, SH^\pm$ and $Z \to AS, H^\mp H^\pm$, we impose

$$m_{S,A} + m_{H^\pm} \quad > \quad m_W \quad , \quad m_A + m_S > m_Z \ , \ 2m_{H^\pm} > m_Z$$

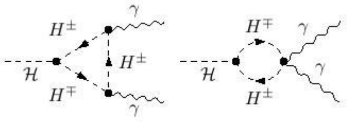
- S: is the LOP $A \to ZS$, $H^\pm \to W^\pm A$ or $H^\pm \to W^\pm S$
- $e^- e^+ / pp \to H^\pm H^\mp, H^\pm A, H^\pm S, SA$
  similar to $e^- e^+ / pp \to \chi_i^\mp \chi_j^\pm, \chi_i^0 \chi_j^0$ (in MSSM) :
  Dileptons $+ \not{E}$ or Trilepton $+ \not{E}$
- $m_{H^\pm} >$ 80-90 GeV, $\max(m_S, m_A) >$ 100 GeV

Higgs decays

- $h \to \gamma\gamma$ is loop-induced process: new physics can easily affect it.
- In the SM, $h \to \gamma\gamma$ is dominated by W loops



- $H^{\pm}$ loops can interfere constructively or destructively with W loops



$h \to \gamma\gamma$ and $h \to Z\gamma$

$$\Gamma\,(h \to \gamma\gamma) \;=\; \frac{\alpha^2 G_F m_h^2}{128\sqrt{2}\pi^3}\left| top + W + \frac{(m_{H^\pm}^2 - \mu_2^2)}{2 s_W m_W}\,\frac{m_W^2}{m_{H^\pm}^2} F_0(\tau_{H^\pm}) \right|^2,$$

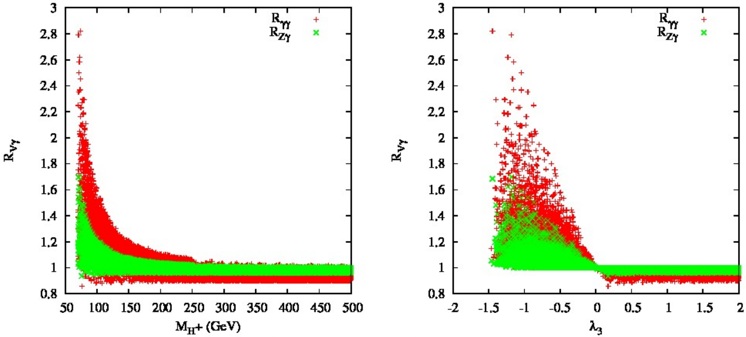
$$\Gamma\,(h \to Z\gamma) \;=\; \frac{G_F^2 m_W^2\, s_W^2\, \alpha\, m_h^3}{64\,\pi^4}\left(1 - \frac{m_Z^2}{m_h^2}\right)^3 \left| top + W + \right.$$
$$\left. + \frac{1 - 2 s_W^2}{s_W c_W}\,\frac{m_{H^\pm}^2 - \mu_2^2}{m_{H^\pm}^2} I_1(\tau_H, \lambda_H) \right|^2 \qquad (3)$$

where $\tau_i = 4m_i^2/m_h^2$ and $\lambda_i = 4m_i^2/m_Z^2$, $(i = t, W, H^\pm)$.
$h \to \gamma\gamma, Z\gamma$ are controlled by:

$$g_{hH^\pm H^\mp} = 2\,\frac{m_W s_W}{e}\lambda_3 = \frac{e}{2 s_W m_W}(m_{H^\pm}^2 - \mu_2^2)$$

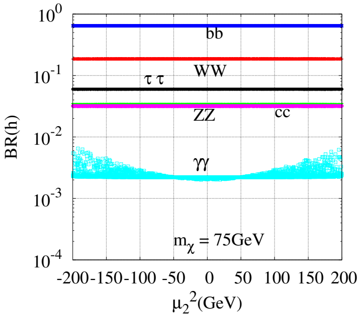
A. Arhrib, R. Benbrik, N. Gaur PLB-2012

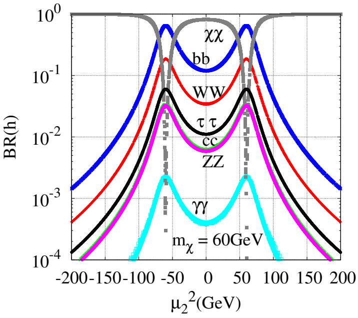
$$R_{V\gamma} \;=\; \frac{\sigma(gg \to h) \times Br(h \to V\gamma)}{\sigma(gg \to h)^{SM} \times Br(h \to V\gamma)^{SM}} = \frac{Br(h \to V\gamma)}{Br(h \to V\gamma)^{SM}}$$



A. Arhrib, R. Benbrik, T.C. Yuan EPJC-2014

Higgs Branching ratios





$$h\chi\chi = \propto (m_\chi^2 - \mu_2^2)/v$$

Status of Higgs invisible decay

- At LHC with vector boson fusion at 7, 8 and 13 TeV, $Br(H \to inv) < 24$ %, JHEP'17, 1610.09218
- At LHC with vector boson fusion at 8 TeV $Br(H \to inv) < 28$ %, ATLAS; 1508.07869

Invisible decay: global fits

G. Bellanger et al : 1306.2941; K. Cheung et al 1302.3794 J. Espinosa et al 1205.6790

- c_V, c_U, c_D are the gauge bosons and fermions coupling normalized to SM. In SM $c_{V,U,D} = 1$
- $c_\gamma = \bar{c}_\gamma^{SM} + \Delta c_\gamma$ and $c_g = \bar{c}_g^{SM} + \Delta c_g$
- At 95% C.L, the branching ratio of the invisible decays:
  1. $c_{V,U,D} = 1$, $\Delta c_{\gamma,g} = 0$: SM-like but allowing invisible decays: $Br(h \to inv) < 19\%$
  2. $c_{V,U,D} = 1$, but $\Delta c_{\gamma,g}$ free : $Br(h \to inv) < 29\%$
  3. $c_{V,U,D}$ free and $\Delta c_{\gamma,g} = 0$: $Br(h \to inv) < 36\%$
  4. $c_{V,U,D}$ free and $\Delta c_{\gamma,g}$ free: $Br(h \to inv) < 38\%$

Invisible decay in the Inert

The invisible Higgs boson decay branching ratio

$$BR(h \to \text{invisible}) = \frac{\Gamma(h \to \chi\chi)}{\Gamma_{tot}(h)} = \frac{\Gamma(h \to \chi\chi)}{\Gamma_{SM}(h) + \Gamma(h \to \chi\chi)} ,$$

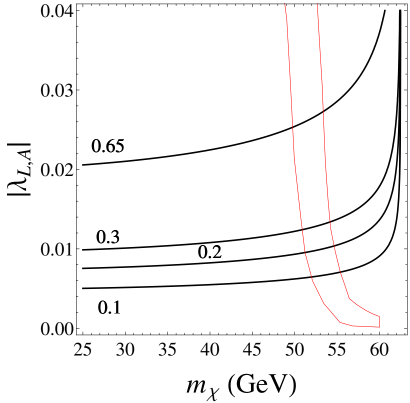
with $\Gamma_{SM}(h) = 4.02$ MeV

$$\Gamma(h \to \chi\chi) = \frac{g_{h\chi\chi}^2}{32\pi m_h} \sqrt{1 - \frac{4m_\chi^2}{m_h^2}} ,$$

with

$$g_{h\chi\chi} = -2v\lambda_{\chi\chi} \;\text{ with }\; \lambda_{\chi\chi} = \begin{cases} \lambda_L & \text{if} \quad \chi = \mathrm{S} , \\ \lambda_A & \text{if} \quad \chi = \mathrm{A} . \end{cases}$$

Invisible decay in the Inert



red band: $\Omega_{\rm CDM} h^2 = 0.1199 \pm 0.0027$ at 3σ

Arhrib, Y.L. Tsai and Q. Yuan and T.C. Yuan, JCAP'14

likelihood analysis

Measurement	Mean	Error: exp., th.	Distribution
m_h (by CMS)	$125.8\mathrm{GeV}$	$0.6\mathrm{GeV}$, $0.0\mathrm{GeV}$	Gaussian
Ωh^2	0.1199	0.0027, 10%	Gaussian
S	0.05	0.09, 0.0	Gaussian
T	0.08	0.07, 0.0	Gaussian
$BR(h \to \mathrm{inv})$	0.65	5%, 10%	Error fn.
$R_{\gamma\gamma}$ (CMS)	0.78	0.28, 20%	Gaussian

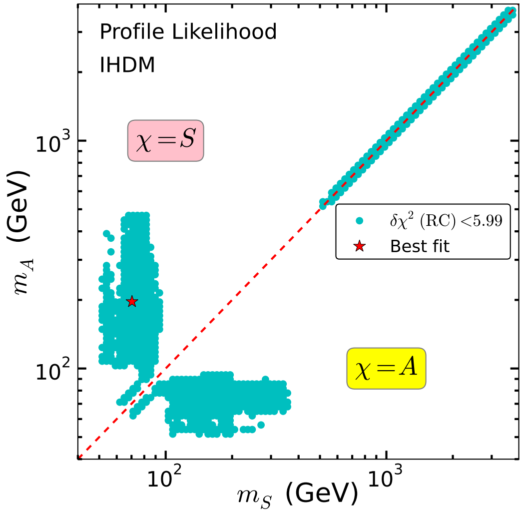
The Gaussian likelihood distribution is

$$\mathcal{L}_{\mathrm{Gaussian}} = e^{-\frac{\chi^2}{2}} ,$$

$$\chi^2 = \frac{(\mathrm{prediction} - \mathrm{experimental\,central\,value})^2}{\sigma^2 + \tau^2},$$

σ and (τ) are experimental error (resp theoretical)

Profile likelihood



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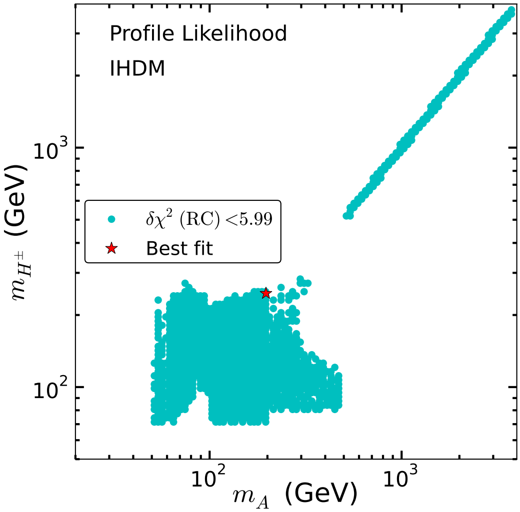

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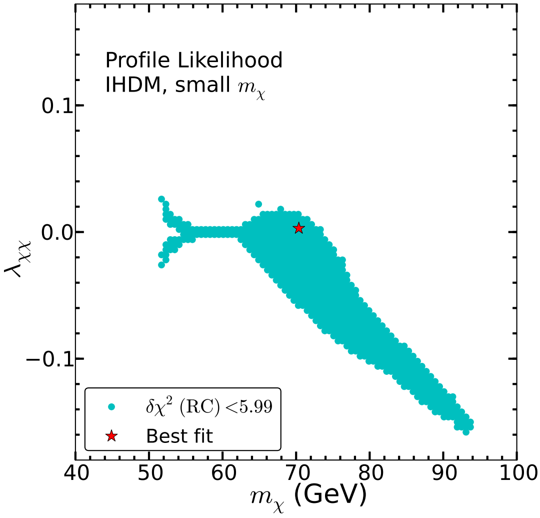

Triple Higgs coupling

- In order to establish the Higgs mechanism for EWSB we need also to measure the **self-couplings hhh and hhhh**
- The measurement of the triple couplings, if precise enough, can help distinguishing between various extensions of the SM.
- $\lambda_{hhh} > 1.2\lambda_{hhh}^{SM}$ well motivated by electroweak baryogenesis.

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- $\sigma_{hh}^{NLO}[\mathrm{fb}] = 9.66\lambda^2 y_t^2 - 49.9\lambda y_t^3 + 70.1 y_t^4 + \mathcal{O}(y_b y_t^2)$
  $\lambda = \lambda_{hhh}/\lambda_{hhh}^{SM} = 1 + \delta$ and $y_f = 1$

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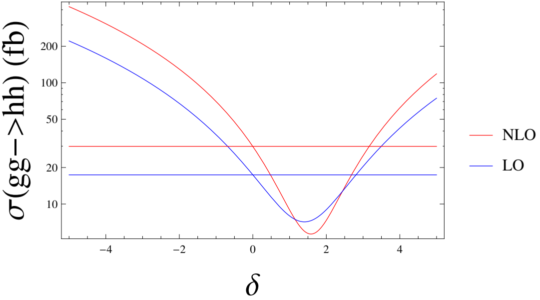

ATLAS analysis

- at 14 TeV with 3000 fb^{-1}, $gg \to h^* \to hh \to b\bar{b}\gamma\gamma$ leads to 8 event in the SM corresponding to a signal significance of 1.3 σ.
  The analysis also foresee an exclusion of BSM with $\lambda_{hhh}/\lambda_{SM} \leq -1.3$ and $\lambda_{hhh}/\lambda_{SM} \geq 8.7$
  ATLAS note: ATL-PHYS-PUB-2014-019
- At 14 TeV with 3000 fb^{-1}, $gg \to h^* \to hh \to b\bar{b}\tau^+\tau^-$, ATLAS can set an upper limit on the di-Higgs production of $4.3\times\sigma(hh \to b\bar{b}\tau^+\tau^-)$ which can be translated to an exclusion on $\lambda_{hhh}/\lambda_{SM} \leq -4$ and $\lambda_{hhh}/\lambda_{SM} \geq 12$.
  ATLAS note: ATL-PHYS-PUB-2015-046

LHC 14 TeV

$$\sigma_{hh}^{NLO}[\text{fb}] = 9.66\lambda^2 y_t^2 - 49.9\lambda y_t^3 + 70.1 y_t^4 + \mathcal{O}(y_b y_t^2)$$
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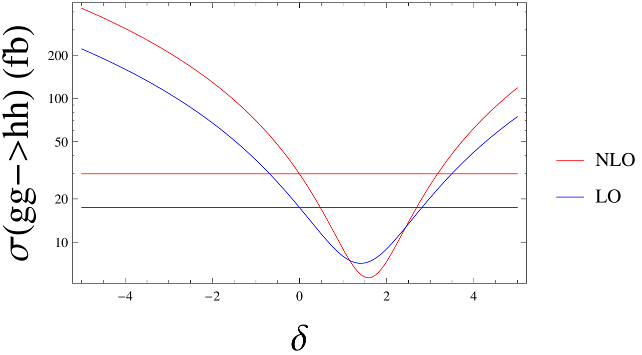
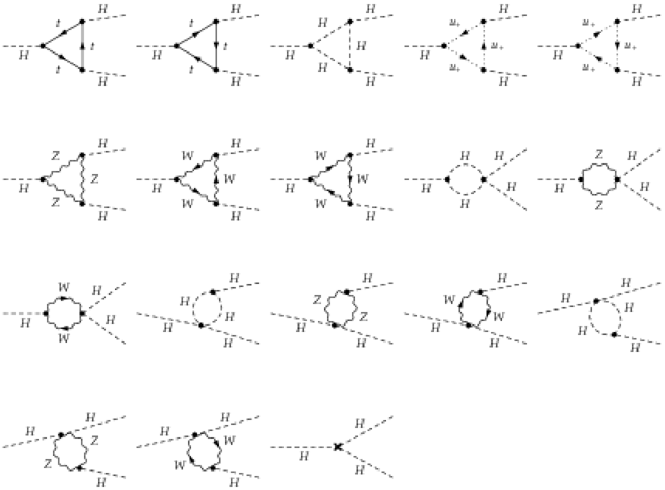


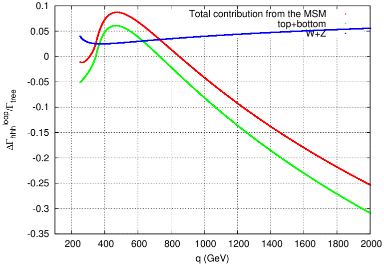
$H^* \rightarrow HH:SM$



1-loop triple hhh in SM

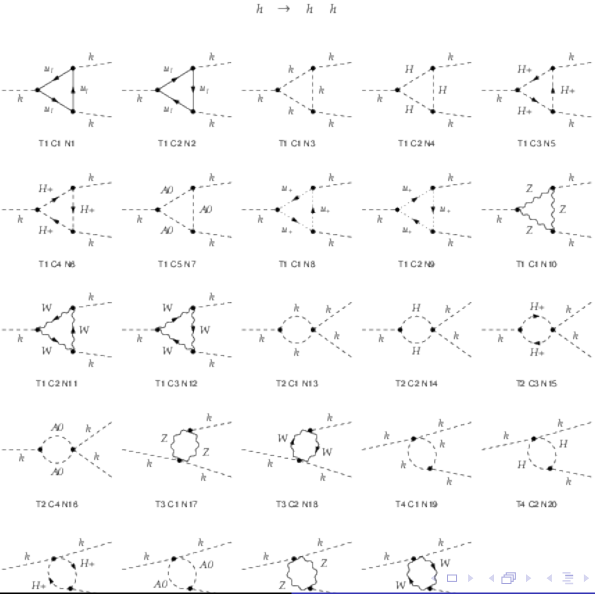
on-shell renormalization

- $hhh = 3\ e\ m_h^2/(2m_W s_w)$
- on-shell renormalization for: Higgs field, m_h, m_W, m_Z
- on-shell definition for $s_W^2 = 1 - m_W^2/m_Z^2$
- renormalization of the electric charge: e

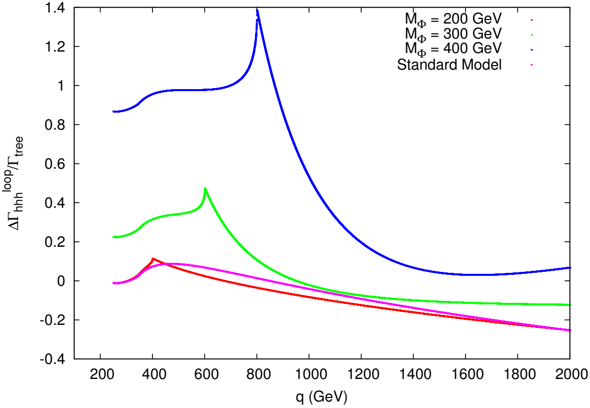


1-loop radiative corrections to hhh in SM

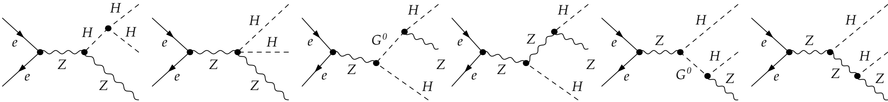
IHDM


h → h h
T1 C1 N1
T1 C2 N2
T1 C1 N3
T1 C2 N4
T1 C3 N5
T1 C4 N6
T1 C5 N7
T1 C1 N8
T1 C2 N9
T1 C1 N10
T1 C2 N11
T1 C3 N12
T2 C1 N13
T2 C2 N14
T2 C3 N15
T2 C4 N16
T3 C1 N17
T3 C2 N18
T4 C1 N19
T4 C2 N20

IHDM, $M_\Phi = m_A = m_S = m_{H^\pm}$



triple Higgs coupling at ILC



- At ILC with $\sqrt{s} = 500$ GeV, $\sigma(e^+e^- \to Zhh) = 0.14$fb
- At ILC $e^+e^- \to Zhh \to l^+l^- b\bar{b}b\bar{b}$: to extract the coupling hhh one needs 1 ab^{-1} luminosity at $\sqrt{s} = 500$ GeV
- $hhh = hhh_{SM}(1+\delta)$

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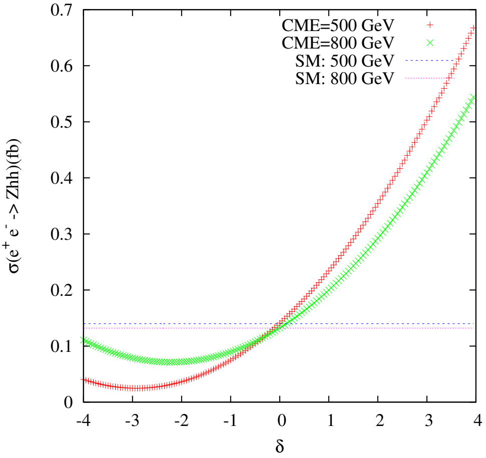
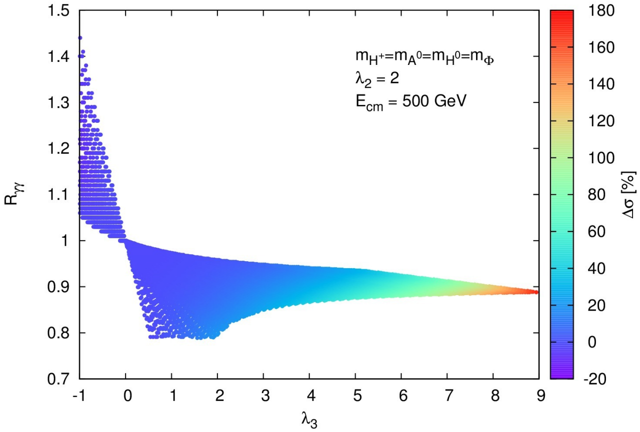


$R_{\gamma\gamma}$ vs $\Delta\sigma(e^+e^- \to Zhh)$



Conclusions

- SM is a viable theory for strong and electroweak interactions
- At the moment, no sign of new physics at LHC.
- Scale of new physics is may be higher than we expect
- LHC-data can already put some constraints on physics beyond SM
- triple Higgs coupling could be a good probe of physics beyond SM