Higgs Boson Physics

Ambresh Shivaji

IISER Mohali, Punjab, INDIA

Madgraph School 2019

IMSc Chennai, November 18-22, 2019

The only *fundamental* scalar particle known to us

Neutral under $SU(3)_c$

$$\Uparrow$$

$$Q = 0 \Leftarrow \boxed{\text{Higgs Boson } (H)} \Rightarrow J^{CP} = 0^+$$

$$\Downarrow$$

$$m_H = 125.10 \pm 0.14 \text{ GeV}$$

$$\Gamma_H < 0.013 \text{ GeV (95\% CL)}$$

Its discovery at the LHC (pp collider, $\sqrt{s} = 7 + 8$ TeV) was announced in 2012 by the ATLAS and CMS collaborations.

Standard Model and Electroweak Symmetry Breaking

In the Standard Model (SM), the electroweak (EW) interactions are described by $SU(2)_L \times U(1)_Y$ gauge symmetry group.

Existance of massive gauge bosons of EW interactions $\Longrightarrow$ EW symmetry is broken.

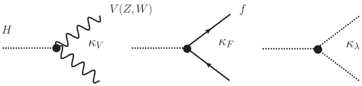
The EWSB is realized with the help of a complex scalar $SU(2)_L$ doublet $\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$.

$$\mathcal{L}_{Higgs} = |D_\mu \Phi|^2 - \sum_f y_f \bar{L}_f \Phi R_f - V(\Phi)$$

$$\begin{aligned}
V(\Phi) &= -\mu^2(\Phi^\dagger\Phi) + \lambda(\Phi^\dagger\Phi)^2 \\
\langle\Phi\rangle &= \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v \end{pmatrix} \Rightarrow m_W, m_Z, m_f \ (v \sim 246 \text{ GeV}) \\
\Phi &= \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v + H \end{pmatrix} \Rightarrow \text{Higgs mass and Higgs couplings}
\end{aligned}$$

Couplings of the Higgs Boson

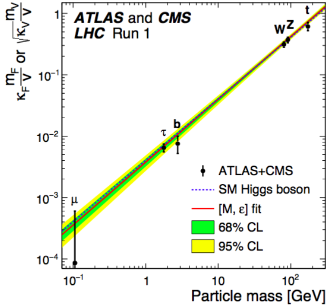
$$\mathcal{L}_{\rm Higgs} = |D_\mu \Phi|^2 - \sum_f y_f \bar{L}_f \Phi R_f - V(\Phi)$$



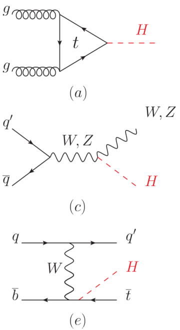
$$g_{Hf\bar{f}} = \frac{m_f}{v},\; g_{HVV} = \frac{2m_V^2}{v},\; g_{HHVV} = \frac{2m_V^2}{v^2},\; g_{HHH} = \frac{3m_H^2}{v},\; g_{HHHH} = \frac{3m_H^2}{v^2}$$

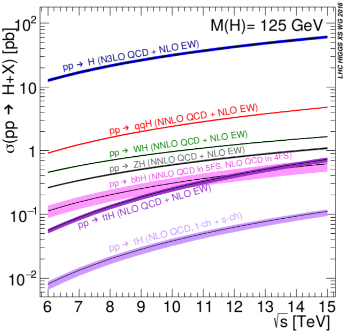
Couplings are proportional to the masses. Notice the mass dependence.

- Higgs couplings with gauge bosons (κ_V) and with heavy fermions (κ_F) are know with an accuracy of 10-20%.
- Higgs-self couplings are practically unconstrained. *More about them later...*



Single Higgs Production



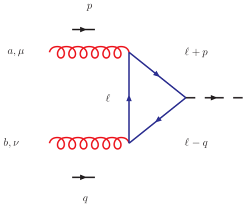


ggF	VBF	VH	$t\bar{t}H$
Fixed order:	Fixed order:	Fixed order:	Fixed order:
NNLO QCD + NLO EW	NNLO QCD	NLO QCD+EW	NLO QCD
(HIGLU, iHixs, FeHiPro, HNNLO)	(VBF@NNLO)	(V2HV and HAWK)	(Powheg)
Resummed:	Fixed order:	Fixed order:	(MG5_aMC@NLO)
NNLO + NNLL QCD	NLO QCD + NLO EW	NNLO QCD	
(HRes)	(HAWK)	(VH@NNLO)	
Higgs p_T:			
NNLO+NNLL			
(HqT, HRes)			
Jet Veto:			
N3LO+NNLL			

State-of-the-art calculations and MC tools

Single Higgs Production: ggF

Dominant production channel, it's a loop-induced process. *Indirectly* sensitive to top-Yukawa coupling.



$$\mathcal{M}^{\mu\nu} = B_{00}\, g^{\mu\nu} + B_{11}\, p^{\nu} q^{\mu} \tag{1}$$

Gauge invariance ($\mathcal{M}^{\mu\nu} p_{\mu} = \mathcal{M}^{\mu\nu} q_{\nu} = 0$) and on-shell conditions $\Rightarrow B_{11} = -B_{00}/p.q$, where $p.q = m_H^2/2$.

$$B_{00} = \mathcal{M}^{\mu\nu} \frac{1}{2}\left(g^{\mu\nu} - \frac{p^{\nu} q^{\mu}}{p.q}\right) \tag{2}$$

At LO, $B_{00} \equiv m_q^2[(16m_q^2 - 8p.q)C_0 + 8]$, where,

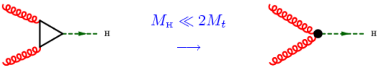
$$C_0 = \int d^4\ell \frac{1}{(\ell^2 - m_q^2)((\ell + p)^2 - m_q^2)((\ell - q)^2 - m_q^2)} \tag{3}$$

Single Higgs Production: ggF

The LO result depends on m_q and m_H.

In $m_q \to \infty$ limit, the amplitude becomes independent of the quark mass in the loop.
Note that the amplitude does not vanish $\Rightarrow$ violation of Decoupling theorem.

$$\mathcal{M}^{\mu\nu} \to \frac{\alpha_s}{3\pi v}(p.q\ g^{\mu\nu} - p^{\nu} q^{\mu}) \tag{4}$$



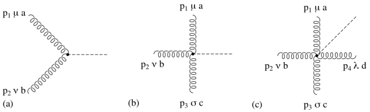
We get and effective ggH vertex.

This feature can be utilized to probe the existence of heavy up or down type quarks beyond SM.

Single Higgs Production: ggF

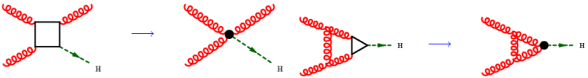
The effective ggH vertex can be obtained from an effective Lagrangian (HEFT),

$$\mathcal{L}_{\text{eff}} = -\frac{1}{4}\left(1 - \frac{\alpha_s}{3\pi}\frac{H}{v}\right)G^{\mu\nu}G_{\mu\nu} \tag{5}$$



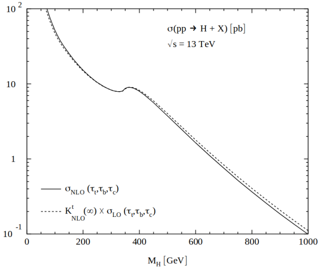
Exercise: Derive the Feynman Rules.

The effective Lagrangian is useful in calculating higher order corrections to $gg \to H$. For example, at NLO

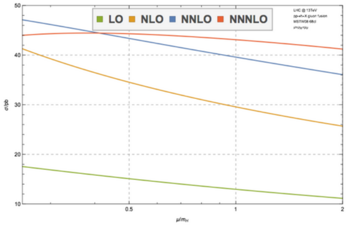


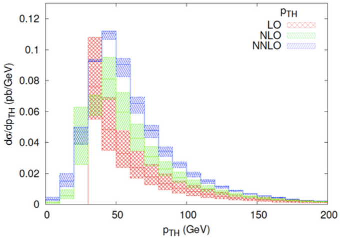
Single Higgs Production: ggF

Exact vs HEFT



Scale dependence and $p_T(H)$ distribution





More on NLO in Huasheng Shao's Talk...

Single Higgs Production: ggF

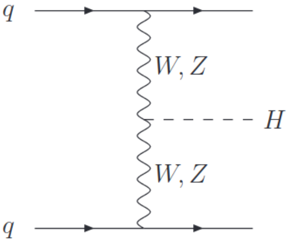
The most updated result for 13 TeV LHC, $m_H = 125$ GeV and $\mu_F = \mu_R = m_H/2$:

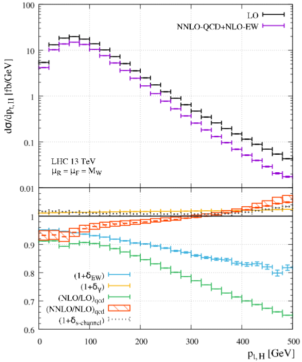
$$\sigma_{\rm ggH} = 48.58\ \text{pb}^{+4.56\%}_{-6.72\%}\,(\text{Theory})$$

$$\begin{aligned}
48.58\,\text{pb} = \quad & 16.00\,\text{pb} && (+32.9\%) && (\text{LO, rEFT}) \\
& +20.84\,\text{pb} && (+42.9\%) && (\text{NLO, rEFT}) \\
& -\ \ 2.05\,\text{pb} && (-4.2\%) && ((t,b,c),\ \text{exact NLO}) \\
& +\ \ 9.56\,\text{pb} && (+19.7\%) && (\text{NNLO, rEFT}) \\
& +\ \ 0.34\,\text{pb} && (+0.7\%) && (\text{NNLO},\ 1/m_t) \\
& +\ \ 2.40\,\text{pb} && (+4.9\%) && (\text{EW, QCD-EW}) \\
& +\ \ 1.49\,\text{pb} && (+3.1\%) && (\text{N}^3\text{LO, rEFT})
\end{aligned}$$

Single Higgs Production: VBF

Characteristic features:
two hard jets in the forward and backward regions of the detector.
no gluon radiation from central-rapidity region



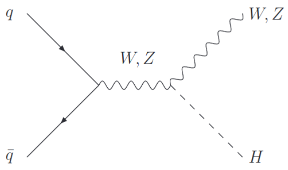


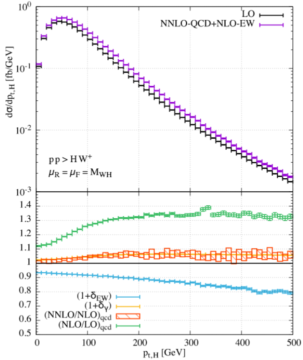
These features allow to distinguish them
from $gg \to H + 2j$ and
$qq' \to VH \to H + 2j$

Sensitive to VVH couplings. Results known at NNLO (QCD) and NLO(EW).

Single Higgs Production: VH

Drell-Yan like production, sensitive to VVH couplings.



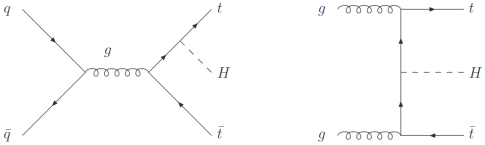


Channel through which $H \to b\bar{b}$ is detected in the boosted regime.

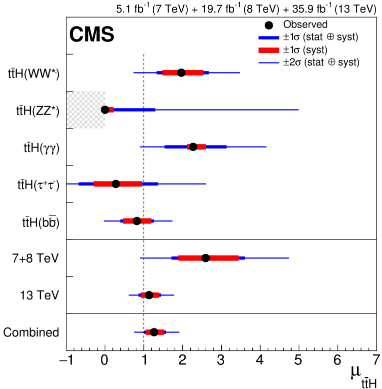
Results known at NNLO (QCD) (including NLO correction to loop-induced $gg \to ZH$) and NLO(EW).

Single Higgs Production: ttH

Directly sensitive to the top-Yukawa coupling. Has been observed recently.



NLO QCD corrections increase the cross section by 20%. NLO EW are also known.

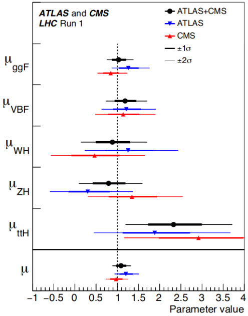


Single Higgs Production

PDG2017

$\sqrt{s}$ (TeV)	Production cross section (in pb) for $m_H = 125\,\text{GeV}$					
	ggF	VBF	WH	ZH	$t\bar{t}H$	total
1.96	$0.95^{+17\%}_{-17\%}$	$0.065^{+8\%}_{-7\%}$	$0.13^{+8\%}_{-8\%}$	$0.079^{+8\%}_{-8\%}$	$0.004^{+10\%}_{-10\%}$	1.23
7	$16.9^{+5\%}_{-5\%}$	$1.24^{+2\%}_{-2\%}$	$0.58^{+3\%}_{-3\%}$	$0.34^{+4\%}_{-4\%}$	$0.09^{+8\%}_{-14\%}$	19.1
8	$21.4^{+5\%}_{-5\%}$	$1.60^{+2\%}_{-2\%}$	$0.70^{+3\%}_{-3\%}$	$0.42^{+5\%}_{-5\%}$	$0.13^{+8\%}_{-13\%}$	24.2
13	$48.6^{+5\%}_{-5\%}$	$3.78^{+2\%}_{-2\%}$	$1.37^{+2\%}_{-2\%}$	$0.88^{+5\%}_{-5\%}$	$0.50^{+9\%}_{-13\%}$	55.1
14	$54.7^{+5\%}_{-5\%}$	$4.28^{+2\%}_{-2\%}$	$1.51^{+2\%}_{-2\%}$	$0.99^{+5\%}_{-5\%}$	$0.60^{+9\%}_{-13\%}$	62.1

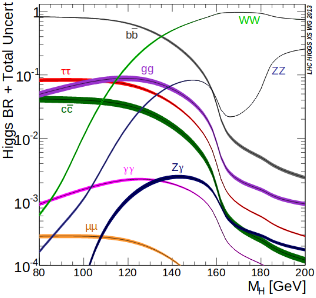
Signal strength for production, $\boxed{\mu_i = \frac{\sigma^{\text{Exp.}}(i \to H)}{\sigma^{\text{SM}}(i \to H)}}$. Assuming SM Higgs BRs,



Higgs Boson Decay

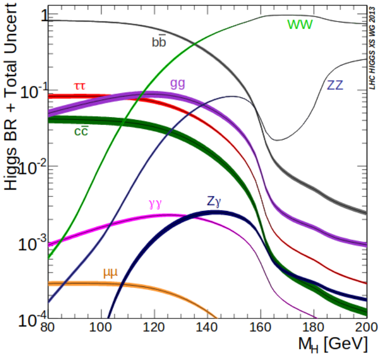
Computation of decay width is required to interpret the experimental data.

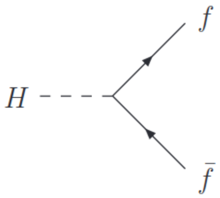
$m_H = 125$ GeV



Decay channel	Branching ratio	Rel. uncertainty
$H \to \gamma\gamma$	2.27×10^{-3}	$^{+5.0\%}_{-4.9\%}$
$H \to ZZ$	2.62×10^{-2}	$^{+4.3\%}_{-4.1\%}$
$H \to W^+W^-$	2.14×10^{-1}	$^{+4.3\%}_{-4.2\%}$
$H \to \tau^+\tau^-$	6.27×10^{-2}	$^{+5.7\%}_{-5.7\%}$
$H \to b\bar{b}$	5.84×10^{-1}	$^{+3.2\%}_{-3.3\%}$
$H \to Z\gamma$	1.53×10^{-3}	$^{+9.0\%}_{-8.9\%}$
$H \to \mu^+\mu^-$	2.18×10^{-4}	$^{+6.0\%}_{-5.9\%}$

Higgs Boson Decay to Fermions



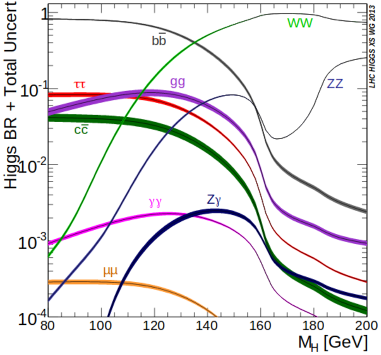


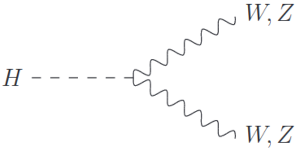
$$\Gamma[H \to f\bar{f}] = \frac{N_c G_F M_H}{4\sqrt{2}\pi}\, m_f^2$$

$H \longrightarrow b\bar{b}$ is the dominant decay mode among all, followed by $H \longrightarrow \tau^+\tau^-$ and $H \longrightarrow c\bar{c}$.

Known up to N4LO (QCD) and NLO (EW).

Higgs Boson Decay to Gauge Bosons





$$\Gamma(h \to WW^*) = \frac{3g^4 m_h}{512\pi^3} F\left(\frac{M_W}{m_h}\right)$$

$$\Gamma(h \to ZZ^*) = \frac{g^4 m_h}{2048 \cos_W^4 \pi^3}\left(7 - \frac{40}{3}s_W^2 + \frac{160}{9}s_W^4\right) F\left(\frac{M_Z}{m_h}\right),$$

$$F(x) = -\,|\,1 - x^2\,|\left(\frac{47}{2}x^2 - \frac{13}{2} + \frac{1}{x^2}\right) + 3(1 - 6x^2 + 4x^4)\,|\ln x\,| + \frac{3(1 - 8x^2 + 20x^4)}{\sqrt{4x^2 - 1}}\cos^{-1}\left(\frac{3x^2 - 1}{2x^3}\right)$$

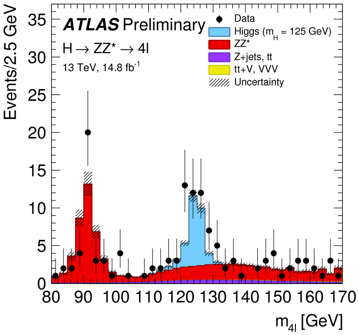
For $m_H = 125$ GeV, one of the two vector bosons is always off-shell.

Invisible decay mode: $H \to ZZ^* \to 4\nu$.

WW^* and ZZ^* interfere in $2\ell 2\nu$ final state.

Higgs Boson Decay to Gauge Bosons

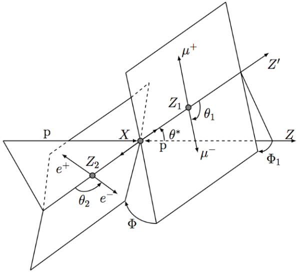
$H \to 4\ell$ $(2e2\mu)$ $(4e)$ (4μ) is very clean, allows reconstruction of the Higgs mass.

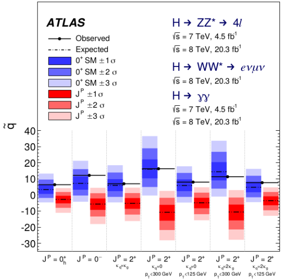


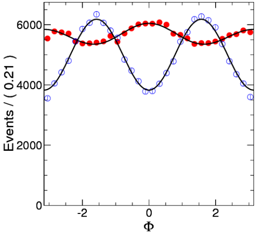
Has been the discovery mode.

Higgs Boson Decay to Gauge Bosons

$H \to ZZ^* \to 4\ell$ decay mode can be utilized to fix the spin and CP-properties of the Higgs boson.



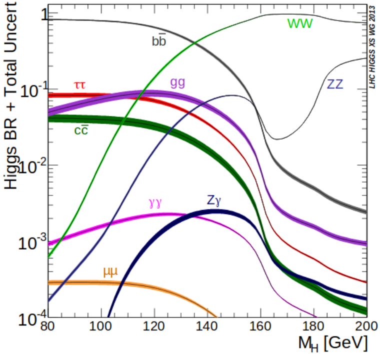


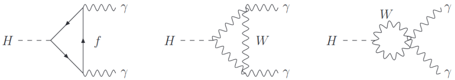


CP-even (red) vs CP-odd (blue)

Higgs Boson Decay to Gauge Bosons

Loop-induced decay to di-photon.





$$\Gamma\left[H \to \gamma\gamma\right] = \frac{G_F\,\alpha^2\,M_H^3}{128\,\sqrt{2}\,\pi^3}\left|\sum_f N_{cf} e_f^2 A_f^H(\tau_f) + A_W^H(\tau_W)\right|^2$$

$$\begin{aligned} A_f^H(\tau) &= 2\tau\left[1 + (1-\tau) f(\tau)\right] \\ A_W^H(\tau) &= -\left[2 + 3\tau + 3\tau(2-\tau) f(\tau)\right] \\ f(\tau) &= \begin{cases} \arcsin^2 \dfrac{1}{\sqrt{\tau}} & \tau \geq 1 \\ -\dfrac{1}{4}\left[\log \dfrac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}} - i\pi\right]^2 & \tau < 1 \end{cases} \end{aligned}$$

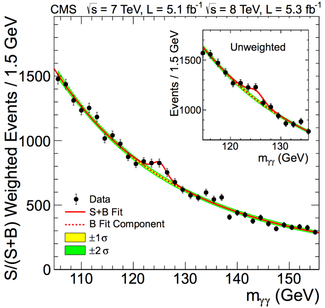
Dominated by W-loop contribution.

Destructive intereference between t-loop and W-loop contributions.

No decoupling for large loop masses.

Higgs Boson Decay to Gauge Bosons

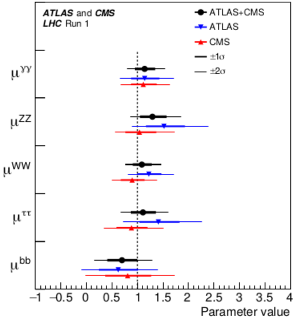
Another Higgs discovery mode.



$H \to Z\gamma$ is also loop-induced decay but it's very rare.

Higgs Boson Decay

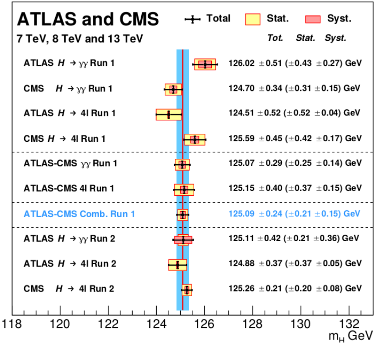
Signal strength for decay, $\boxed{\mu_f = \frac{BR^{\text{Exp.}}_{H\to f}}{BR^{\text{SM}}_{H\to f}}}$. Assuming SM production rates,



Decay channel	Branching ratio	Rel. uncertainty
$H \to \gamma\gamma$	2.27×10^{-3}	$^{+5.0\%}_{-4.9\%}$
$H \to ZZ$	2.62×10^{-2}	$^{+4.3\%}_{-4.1\%}$
$H \to W^+W^-$	2.14×10^{-1}	$^{+4.3\%}_{-4.2\%}$
$H \to \tau^+\tau^-$	6.27×10^{-2}	$^{+5.7\%}_{-5.7\%}$
$H \to b\bar{b}$	5.84×10^{-1}	$^{+3.2\%}_{-3.3\%}$
$H \to Z\gamma$	1.53×10^{-3}	$^{+9.0\%}_{-8.9\%}$
$H \to \mu^+\mu^-$	2.18×10^{-4}	$^{+6.0\%}_{-5.9\%}$

Higgs Boson Mass

ATLAS and CMS collaborations rely on the two high mass resolution and sensitive channels, $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^{*} \rightarrow 4\ell$.



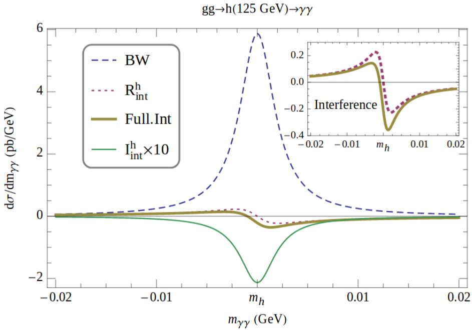
Higgs Boson Width

$$\Gamma_H^{\mathrm{SM}} = 4.07\ \mathrm{MeV}^{+4.0\%}_{-3.9\%} \text{ for } m_H = 125\ \mathrm{GeV}$$

Sensitivity to Higgs decay width via intereference effect. For example, the interference effect between the signal: $gg \to h \to \gamma\gamma$ and background: $gg \to \gamma\gamma$

$$A_h \equiv A_{gg\to h\to\gamma\gamma} \propto \frac{\hat{s}}{\hat{s} - m_h^2 + i\Gamma_h m_h} F_{gg} F_{\gamma\gamma}$$

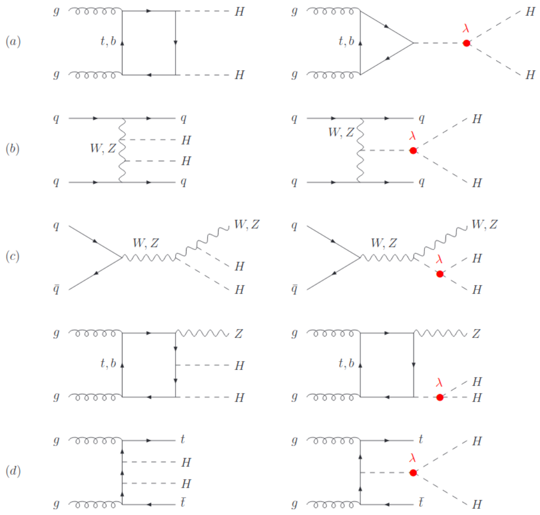
$$\sigma = \sigma_{\mathrm{BW}}^{\mathrm{SM}} \left(1 + \frac{\sigma_{\mathrm{int}}^{\mathrm{SM}}}{\sigma_{\mathrm{BW}}^{\mathrm{SM}}} \sqrt{\frac{\Gamma_h}{\Gamma_h^{\mathrm{SM}}}} \right) \simeq \sigma_{\mathrm{BW}}^{\mathrm{SM}} \left(1 - 2\% \sqrt{\frac{\Gamma_h}{\Gamma_h^{\mathrm{SM}}}} \right)$$



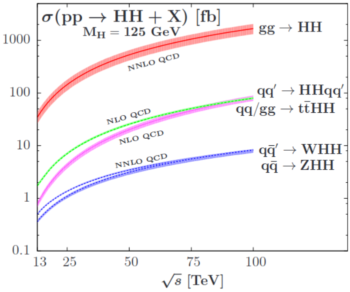
1704.08259

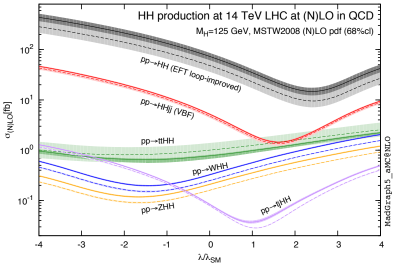
Double Higgs Production

Can provide information on Higgs-self coupling parameter (λ).

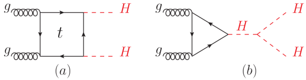


Double Higgs Production





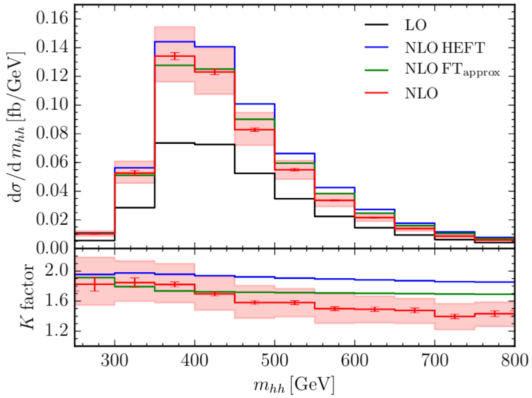
Dominant production mode is via gluon fusion.



The two diagrams interefere destructively.

Double Higgs Production

$\sqrt{s}$	LO	B-i. NLO HEFT	NLO FT_{approx}	NLO
14 TeV	$19.85^{+27.6\%}_{-20.5\%}$	$38.32^{+18.1\%}_{-14.9\%}$	$34.26^{+14.7\%}_{-13.2\%}$	$32.91^{+13.6\%}_{-12.6\%}$
100 TeV	$731.3^{+20.9\%}_{-15.9\%}$	$1511^{+16.0\%}_{-13.0\%}$	$1220^{+11.9\%}_{-10.7\%}$	$1149^{+10.8\%}_{-10.0\%}$



[1608.04798]

Summary

Being the only fundamental scalar, Higgs has every special place in the particle spectrum of the SM.

We now know its mass ($\sim$ 125 GeV) and its couplings with heavy fermions and gauge bosons are determined with an accuracy of 10-20%.

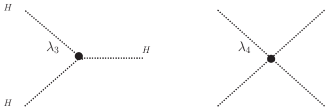
It has a very narrow width ($\sim$ 4 MeV).

The information on Higgs self-couplings is not available.

Higgs self-couplings

$$V^{SM}(\Phi) = -\mu^2(\Phi^\dagger\Phi) + \lambda(\Phi^\dagger\Phi)^2$$

$$\text{EWSB} \Rightarrow V(H) = \frac{1}{2}m_H^2 H^2 + \lambda_3 v H^3 + \frac{1}{4}\lambda_4 H^4.$$



The mass and the self-couplings of the Higgs boson depend only on λ and $v = (\sqrt{2}G_\mu)^{-1/2}$,

$$m_H^2 = 2\lambda v^2;\ \lambda_3^{SM} = \lambda_4^{SM} = \lambda.$$

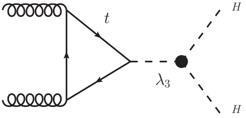
$$m_H = 125\text{ GeV and } v \sim 246\text{ GeV}, \Rightarrow \boxed{\lambda \simeq 0.13}.$$

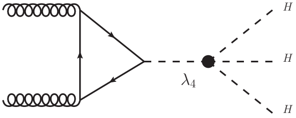
Presence of new physics at higher energy scales can contribute to the Higgs potential and modify the Higgs self-couplings.

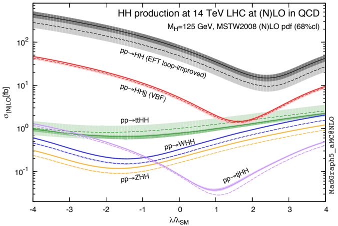
Independent measurements of λ_3 and λ_4 are crucial.

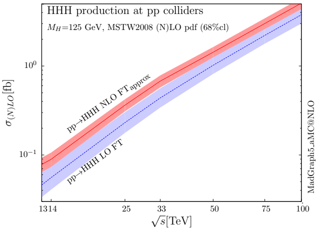
Direct determination of Higgs self-couplings

Information on λ_3 and λ_4 can be extracted by studying multi-Higgs production processes.







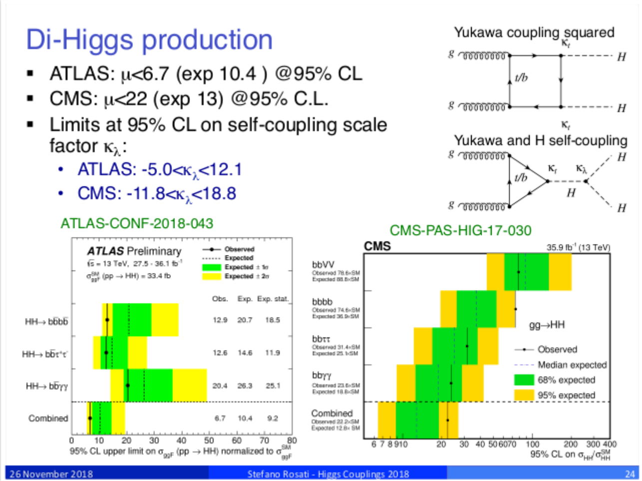


[Frederix et al. '14, 1408.6542]

Very challenging due to small cross sections: ~33 fb (HH), ~ 0.1 fb (HHH)

Compare it with the single Higgs production ($gg \to H$) *cross section:* ~ 50 pb

Current and future experimental sensitivity ($\kappa_\lambda = \lambda_3/\lambda_3^{\mathrm{SM}}$)

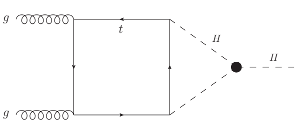


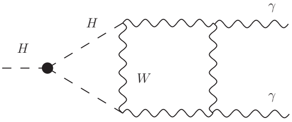
ATLAS (HL-LHC, $2b2\gamma$): [ATL-PHYS-PUB-2017-001],

$$\kappa_\lambda < -0.8 \text{ and } \kappa_\lambda >\sim 7.7$$

Bounds are sensitive to κ_t value.

Indirect determination of λ_3 in single Higgs





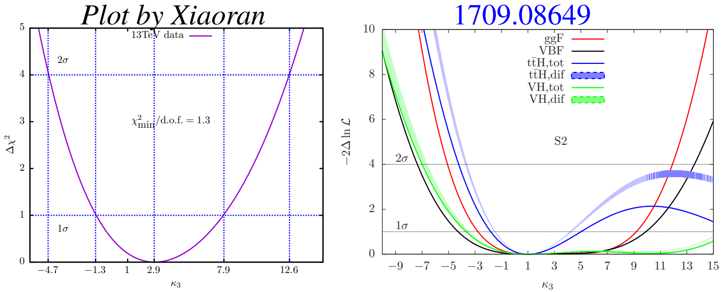
Gorbahn, Haisch: 1607.03773; Degrassi, Giardino, Maltoni, Pagani: 1607.04251; Bizon, Gorbahn, Haisch, Zanderighi: 1610.05771; Di Vita, Grojean, Panico, Riembau, Vantalon: 1704.01953; Maltoni, Pagani, AS, Zhao: 1709.08649

Master formula: *Anomalous trilinear coupling* ($\kappa_3 = \lambda_3/\lambda_3^{\rm SM}$)

$$\Sigma_{\rm NLO}^{\rm BSM} = Z_H^{\rm BSM}[\Sigma_{\rm LO}(1 + \kappa_3 C_1 + \delta Z_H) + \Delta_{\rm NLO}^{\rm SM}]$$

$$Z_H^{\rm BSM} = \frac{1}{1-(\kappa_3^2-1)\delta Z_H}, \quad \delta Z_H = -1.536 \times 10^{-3}$$

Current and future reach at the LHC



13 TeV:

$$-4.7 < \kappa_3 < 12.6$$

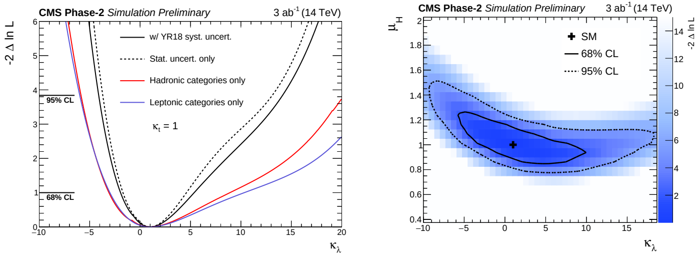
HL-LHC:

$$-2 \lesssim \kappa_3 \lesssim 8$$

CMS Projections: HL-LHC

tH + ttH: using the calculation of Maltoni, Pagani, AS, Zhao: 1709.08649

[CMS-PAS-FTR-18-020]



$$-3 \lesssim \kappa_\lambda \lesssim 13$$

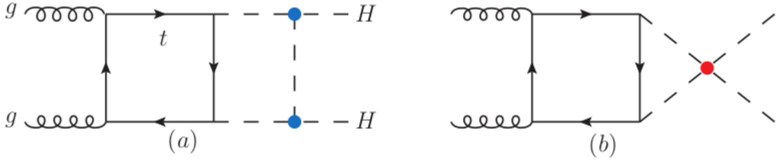
Question: *Can we extend this strategy to double Higgs production ?*

Maltoni, Pagani, Zhao: 1802.07616; Bizon, Haisch, Rottoli: 1810.04665; Borowka, Duhr, Maltoni, Pagani, AS, Zhao: 1811.12366

Indirect determination of λ_4 in double Higgs

At LO, the $gg \to HH$ amplitude is sensitive to only λ_3.

λ_4 affects $gg \to HH$ amplitude at two-loop level via NLO EW corrections.



EFT framework is necessary in order to vary cubic and quartic couplings independently in a consistent way.

$$V^{\mathrm{NP}}(\Phi) \equiv \sum_{n=3}^{\infty} \frac{c_{2n}}{\Lambda^{2n-4}} \left(\Phi^\dagger \Phi - \frac{1}{2} v^2\right)^n .$$

This also ensures gauge invariance and UV finiteness in our calculation.

NP Paramterization

$$V(H) = \frac{1}{2}m_H^2 H^2 + \lambda_3 v H^3 + \frac{1}{4}\lambda_4 H^4 + \lambda_5 \frac{H^5}{v} + O(H^6),$$

$$\kappa_3 \equiv \frac{\lambda_3}{\lambda_3^{\rm SM}} = 1 + \frac{c_6 v^2}{\lambda\Lambda^2} \quad \equiv \quad 1 + \bar{c}_6,$$

$$\kappa_4 \equiv \frac{\lambda_4}{\lambda_4^{\rm SM}} = 1 + \frac{6 c_6 v^2}{\lambda\Lambda^2} + \frac{4 c_8 v^4}{\lambda\Lambda^4} \quad \equiv \quad 1 + 6\bar{c}_6 + \bar{c}_8 \,.$$

We can trade κ_3 and κ_4 with parameters $\bar{c}_6$ and $\bar{c}_8$.

$$\bar{c}_6 \quad \equiv \quad \frac{c_6 v^2}{\lambda\Lambda^2} = \kappa_3 - 1\,,$$

$$\bar{c}_8 \quad \equiv \quad \frac{4 c_8 v^4}{\lambda\Lambda^4} = \kappa_4 - 1 - 6(\kappa_3 - 1)\,.$$

The Phenomenological quantity of interest

Inclusive/differential cross section

$$\sigma_{\rm NLO}^{\rm pheno} = \sigma_{\rm LO} + \Delta\sigma_{\bar{c}_6} + \Delta\sigma_{\bar{c}_8} \,,$$

EFT insertion at one-loop :

$$\sigma_{\rm LO} = \sigma_0 + \sigma_1 \bar{c}_6 + \sigma_2 \bar{c}_6^2 \,,$$

EFT insertions at two-loop :

$$\Delta\sigma_{\bar{c}_6} = \bar{c}_6^2 \left[\sigma_{30}\bar{c}_6 + \sigma_{40}\bar{c}_6^2\right] + \tilde{\sigma}_{20}\bar{c}_6^2 \,,$$

$$\Delta\sigma_{\bar{c}_8} = \bar{c}_8 \left[\sigma_{01} + \sigma_{11}\bar{c}_6 + \sigma_{21}\bar{c}_6^2\right],$$

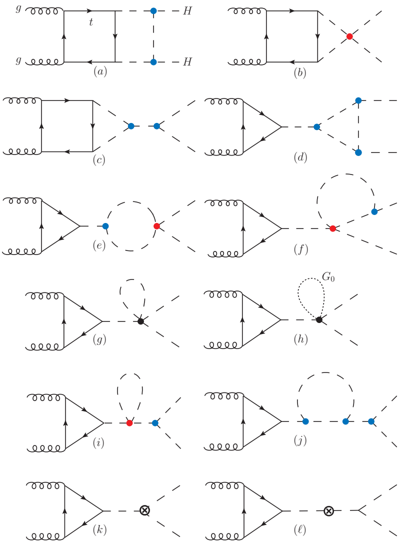
Taking an agnostic view on possible values of κ_3 and κ_4, we have ignored the SM EW corrections, and have kept highest powers of $\bar{c}_6$ in $\Delta\sigma_{\bar{c}_6}$.

The quantity $\Delta\sigma_{\bar{c}_8}$ is the most relevant part of our computation and it solely induces the sensitivity on $\bar{c}_8$.

We assume that higher order QCD corrections factorize from two-loop EW effects.

Relevant two-loop topologies

Non-factorizable, factorizable and counterterms:



Effect on inclusive cross section

For α_s, $\mu_R = \mu_F = \frac{1}{2}m(HH)$ while $\mu_{\mathrm{EFT}} = 2m_H$.

One-loop:

$\sqrt{s}$ [TeV]	σ_0 [fb]	σ_1 [fb]	σ_2 [fb]
14	19.49 -	-15.59 (-80.0%)	5.414 (27.8%)
100	790.8 -	-556.8 (-70.5%)	170.8 (21.6%)

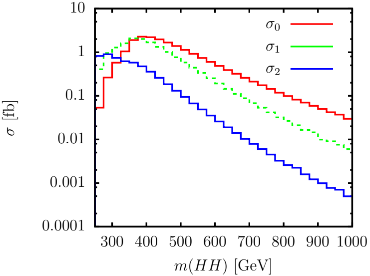
Two-loop:

$\sqrt{s}$ [TeV]	$\tilde{\sigma}_{20}$ [fb]	σ_{30} [fb]	σ_{40} [fb]	σ_{01} [fb]	σ_{11} [fb]	σ_{21} [fb]
14	0.7112 (3.6%)	-0.5427 (-2.8%)	0.0620 (0.3%)	0.3514 (1.8%)	-0.0464 (-0.2%)	-0.1433 (-0.7%)
100	24.55 (3.1%)	-16.53 (-2.1%)	1.663 (0.2%)	12.932 (1.6%)	-0.88 (-0.1%)	-4.411 (-0.6%)

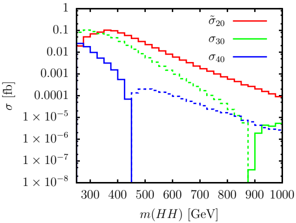
Cross sections grow considerably with energy. The contributions (numbers in brackets) from $\bar{c}_6$ and $\bar{c}_8$ slowly decrease wrt the SM LO prediction.

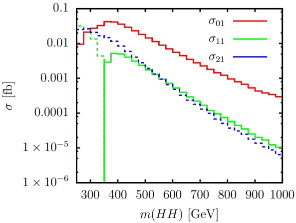
Effect on differential cross section

One-loop



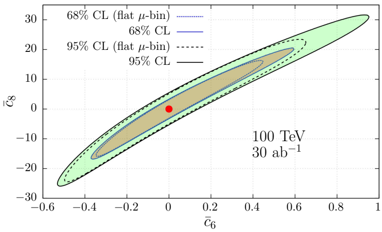
Two-loop

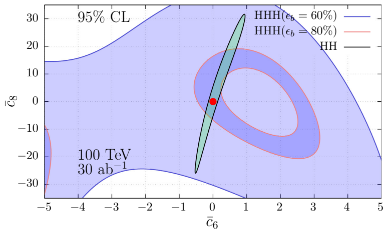




The dashed lines show absolute values of -ve contributions.

Projections for 100 TeV *pp* collider





For $\kappa_3 = 1$, at 95% CL

$-6 \lesssim \kappa_4 \lesssim 18$ [Direct from $HHH(4b2\gamma)$]

$-4.2 \lesssim \kappa_4 \lesssim 6.7$ [Indirect from $HH(2b2\gamma)$]

At 100 TeV *pp* collider, the *HH* channel would be more sensitive to independent variation in self-couplings than *HHH* channel.