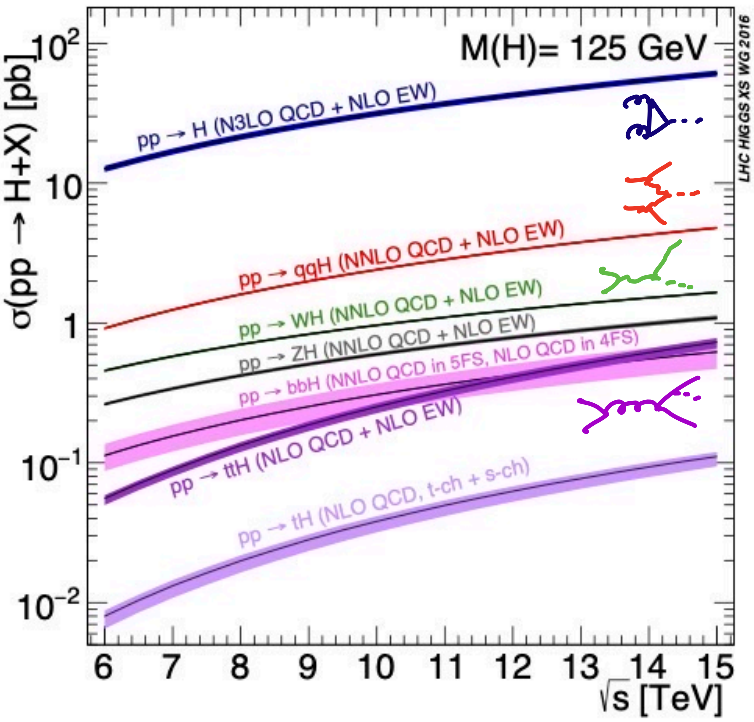
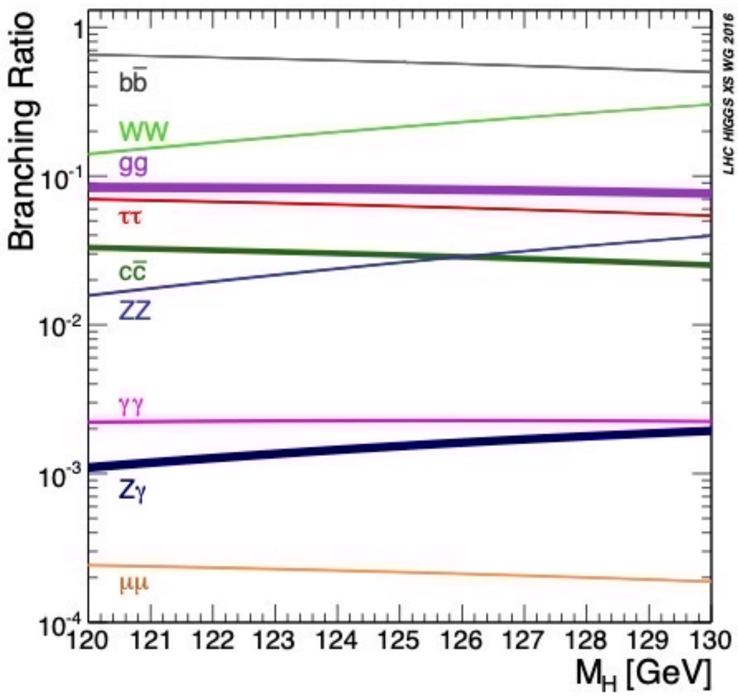
Lecture 19 & 20:

Higgs production cross sections



Higgs decay branching ratios



V.4 Higgs couplings determination

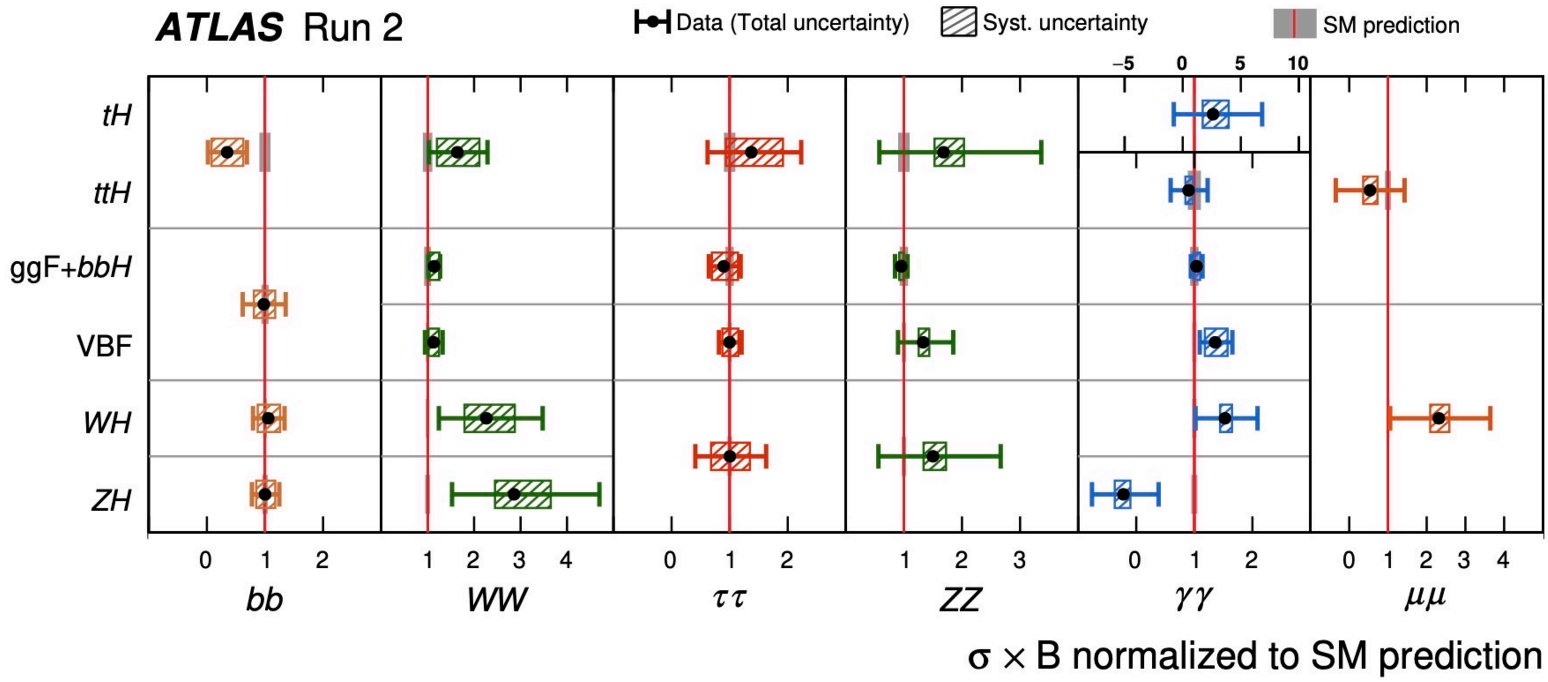
The LHC experiment measure the Higgs production and decay rates, split into the individual channels.

Often presented as signal strength

$$\mu = \frac{\sigma_{prod} \cdot BR(H \to XX)}{(\sigma_{prod} \cdot BR(H\to XX))_{SM}}$$

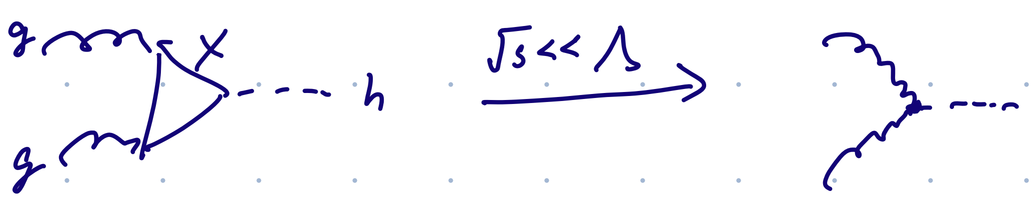
← measurement

← prediction



arXiv: 2207.00092

→ $\mu \neq 1$ would be a sign of physics beyond the SM (BSM). Consider e.g. additional particles X with $m_X \approx \Lambda \gg \sqrt{s}$, coupling to the Higgs and gluons



$$\sim \frac{\tilde{c}_g\, g_s^2}{\Lambda^2}\, \phi^\dagger \phi\, G^a_{\mu\nu} G^{a\mu\nu}$$

Higgs doublet (ϕ)

c.f. heavy top limit, Fermi interaction

⇒ for $\sqrt{s} \ll \Lambda$, the effects of the additional particles can be described by an effective Lagrangian
→ effective field theory (EFT)

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2} \sum_i \alpha_i\, O_i^{(6)} + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

- $\mathcal{O}_i^{(6)}$: dimension 6 operators of SM fields

  e.g. $\Phi^\dagger\Phi\, G^a_{\mu\nu} G^{a\mu\nu}$, $[\Phi]=1$, $[G_{\mu\nu}]=2$, $[\mathcal{L}]=4$

- $\frac{\alpha_i}{\Lambda^2}$ can be calculated for given BSM model

- EFT only valid approximation for $\Lambda \gg \sqrt{s}$

  → need dedicated searches for BSM physics with $\Lambda \lesssim \sqrt{s}$

Table 52: Dimension-6 operators involving Higgs doublet fields or gauge-boson fields. For all $\psi^2\Phi^3$, $\psi^2 X\Phi$ operators and for $\mathcal{O}_{\Phi ud}$ the hermitian conjugates must be included as well.

Φ^6 and $\Phi^4 D^2$	$\psi^2\Phi^3$	X^3
$\mathcal{O}_\Phi = (\Phi^\dagger\Phi)^3$	$\mathcal{O}_{e\Phi} = (\Phi^\dagger\Phi)(\bar{l}\,\Gamma_e e\Phi)$	$\mathcal{O}_G = f^{ABC} G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$
$\mathcal{O}_{\Phi\Box} = (\Phi^\dagger\Phi)\Box(\Phi^\dagger\Phi)$	$\mathcal{O}_{u\Phi} = (\Phi^\dagger\Phi)(\bar{q}\,\Gamma_u u\widetilde{\Phi})$	$\mathcal{O}_{\widetilde{G}} = f^{ABC} \widetilde{G}^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$
$\mathcal{O}_{\Phi D} = (\Phi^\dagger D^\mu\Phi)^*(\Phi^\dagger D_\mu\Phi)$	$\mathcal{O}_{d\Phi} = (\Phi^\dagger\Phi)(\bar{q}\,\Gamma_d d\Phi)$	$\mathcal{O}_W = \varepsilon^{IJK} W^{I\nu}_\mu W^{J\rho}_\nu W^{K\mu}_\rho$
		$\mathcal{O}_{\widetilde{W}} = \varepsilon^{IJK} \widetilde{W}^{I\nu}_\mu W^{J\rho}_\nu W^{K\mu}_\rho$
$X^2\Phi^2$	**$\psi^2 X\Phi$**	**$\psi^2\Phi^2 D$**
$\mathcal{O}_{\Phi G} = (\Phi^\dagger\Phi) G^A_{\mu\nu} G^{A\mu\nu}$	$\mathcal{O}_{uG} = (\bar{q}\sigma^{\mu\nu}\frac{\lambda^A}{2}\Gamma_u u\widetilde{\Phi}) G^A_{\mu\nu}$	$\mathcal{O}^{(1)}_{\Phi l} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{l}\gamma^\mu l)$
$\mathcal{O}_{\Phi\widetilde{G}} = (\Phi^\dagger\Phi) \widetilde{G}^A_{\mu\nu} G^{A\mu\nu}$	$\mathcal{O}_{dG} = (\bar{q}\sigma^{\mu\nu}\frac{\lambda^A}{2}\Gamma_d d\Phi) G^A_{\mu\nu}$	$\mathcal{O}^{(3)}_{\Phi l} = (\Phi^\dagger i\overleftrightarrow{D}^I_\mu\Phi)(\bar{l}\gamma^\mu\tau^I l)$
$\mathcal{O}_{\Phi W} = (\Phi^\dagger\Phi) W^I_{\mu\nu} W^{I\mu\nu}$	$\mathcal{O}_{eW} = (\bar{l}\sigma^{\mu\nu}\Gamma_e e\tau^I\Phi) W^I_{\mu\nu}$	$\mathcal{O}_{\Phi e} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{e}\gamma^\mu e)$
$\mathcal{O}_{\Phi\widetilde{W}} = (\Phi^\dagger\Phi) \widetilde{W}^I_{\mu\nu} W^{I\mu\nu}$	$\mathcal{O}_{uW} = (\bar{q}\sigma^{\mu\nu}\Gamma_u u\tau^I\widetilde{\Phi}) W^I_{\mu\nu}$	$\mathcal{O}^{(1)}_{\Phi q} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{q}\gamma^\mu q)$
$\mathcal{O}_{\Phi B} = (\Phi^\dagger\Phi) B_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{dW} = (\bar{q}\sigma^{\mu\nu}\Gamma_d d\tau^I\Phi) W^I_{\mu\nu}$	$\mathcal{O}^{(3)}_{\Phi q} = (\Phi^\dagger i\overleftrightarrow{D}^I_\mu\Phi)(\bar{q}\gamma^\mu\tau^I q)$
$\mathcal{O}_{\Phi\widetilde{B}} = (\Phi^\dagger\Phi) \widetilde{B}_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{eB} = (\bar{l}\sigma^{\mu\nu}\Gamma_e e\Phi) B_{\mu\nu}$	$\mathcal{O}_{\Phi u} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{u}\gamma^\mu u)$
$\mathcal{O}_{\Phi WB} = (\Phi^\dagger\tau^I\Phi) W^I_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{uB} = (\bar{q}\sigma^{\mu\nu}\Gamma_u u\widetilde{\Phi}) B_{\mu\nu}$	$\mathcal{O}_{\Phi d} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{d}\gamma^\mu d)$
$\mathcal{O}_{\Phi\widetilde{W}B} = (\Phi^\dagger\tau^I\Phi) \widetilde{W}^I_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{dB} = (\bar{q}\sigma^{\mu\nu}\Gamma_d d\Phi) B_{\mu\nu}$	$\mathcal{O}_{\Phi ud} = i(\widetilde{\Phi}^\dagger D_\mu\Phi)(\bar{u}\gamma^\mu\Gamma_{ud} d)$

arXiv: 1307.1347

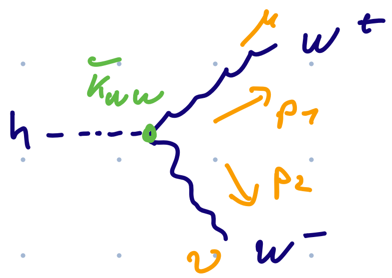
In unitary gauge, with $\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v+h \end{pmatrix}$, the effective Lagrangian can be written as

$$\mathcal{L}_{EFT} = \frac{1}{2}(\partial_\mu h)^2 - \frac{1}{2} m^2 h^2 - \kappa_3 \left(\frac{m_h^2}{2v}\right) h^3 - \sum_\psi m_\psi \bar{\psi}\psi \left(1 + \kappa_\psi \frac{h}{v} + \ldots\right)$$
$$+ m_W^2 W_\mu^+ W^{-\mu} \left(1 + \kappa_W \, 2\frac{h}{v} + \ldots\right) + \ldots Z$$
$$+ \frac{h}{v} \cdot \left(\bar{\kappa}_{WW} \frac{\alpha}{\pi} W_{\mu\nu}^+ W^{-\mu\nu} + \ldots ZZ, Z\gamma, \gamma\gamma + \bar{\kappa}_g \frac{\alpha_s}{12\pi} G_{\mu\nu}^a G^{a\mu\nu} \right)$$
$$+ \ldots$$

→ anomalous couplings:

- modified coupling strength κ_i — SM: $\kappa_i = 1$
- new couplings $\bar{\kappa}_i$ — SM: $\bar{\kappa}_i = 0$

→ new tensor structures, e.g.



$$\sim g^{\mu\nu} + \frac{p_2^\mu p_1^\nu - p_1 p_2 \, g^{\mu\nu}}{2 m_W^2}$$

κ - framework   details 1307.1347

simplified approach for studying anomalous couplings;

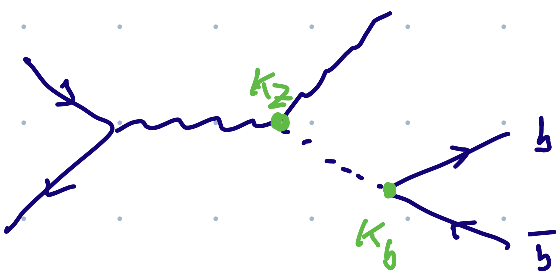
assumptions:

- only modifications of coupling strengths κ_i, no new coupling structures
- Higgs width $\Gamma_{H,tot}$ negligible
  → can factorize cross section for process

$$\sigma(ii \to H \to ff) = \sigma(ii \to H) \cdot \frac{\Gamma(H \to ff)}{\Gamma_{H,tot}}$$

E.g. for ZH production with $H \to b\bar{b}$ decay

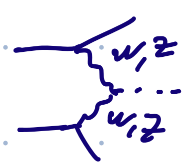
$$\sigma(q\bar{q} \to ZH \to Z, b\bar{b}) = \sigma(q\bar{q} \to ZH)_{SM} \cdot \frac{\Gamma(H \to b\bar{b})_{SM}}{\Gamma_{H,tot,SM}} \cdot \frac{\kappa_Z^2 \cdot \kappa_b^2}{\kappa_H^2}$$



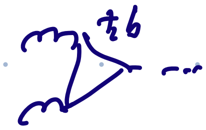
for loop-induced processes and VBF production:
define scaling factors

$$\kappa_{VBF}^2(\kappa_W, \kappa_Z) = \frac{\kappa_W^2 \sigma_{WW} + \kappa_{ZZ} \sigma_{ZZ}}{\sigma_{WW} + \sigma_{ZZ}}$$

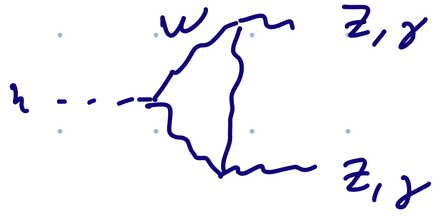
$\sigma = \sigma^{SM}$



$$\kappa_g^2(\kappa_t, \kappa_b) = \frac{\kappa_t^2\, \sigma_{tt} + \kappa_b^2\, \sigma_{bb} + \kappa_t \kappa_b\, \sigma_{tb}}{\sigma_{tt} + \sigma_{bb} + \sigma_{tb}}$$



$\kappa_{\gamma\gamma}^2$, $\kappa_{Z,\gamma}^2$



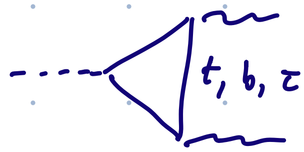


Table 36: LO coupling scale factor relations for Higgs boson cross sections and partial decay widths relative to the SM. For a given m_{H} hypothesis, the smallest set of degrees of freedom in this framework comprises κ_{W}, κ_{Z}, κ_{b}, κ_{t}, and κ_τ. For partial widths that are not detectable at the LHC, scaling is performed via proxies chosen among the detectable ones. Additionally, the loop-induced vertices can be treated as a function of other κ_i or effectively, through the κ_{g} and κ_γ degrees of freedom which allow probing for BSM contributions in the loops. Finally, to explore invisible or undetectable decays, the scaling of the total width can also be taken as a separate degree of freedom, κ_{H}, instead of being rescaled as a function, $\kappa_{\mathrm{H}}^2(\kappa_i, m_{\mathrm{H}})$, of the other scale factors.

Production modes

$$\frac{\sigma_{\mathrm{ggH}}}{\sigma_{\mathrm{ggH}}^{\mathrm{SM}}} = \begin{cases} \kappa_{\mathrm{g}}^2(\kappa_{\mathrm{b}}, \kappa_{\mathrm{t}}, m_{\mathrm{H}}) \\ \kappa_{\mathrm{g}}^2 \end{cases} \tag{94}$$

$$\frac{\sigma_{\mathrm{VBF}}}{\sigma_{\mathrm{VBF}}^{\mathrm{SM}}} = \kappa_{\mathrm{VBF}}^2(\kappa_{\mathrm{W}}, \kappa_{\mathrm{Z}}, m_{\mathrm{H}}) \tag{95}$$

$$\frac{\sigma_{\mathrm{WH}}}{\sigma_{\mathrm{WH}}^{\mathrm{SM}}} = \kappa_{\mathrm{W}}^2 \tag{96}$$

$$\frac{\sigma_{\mathrm{ZH}}}{\sigma_{\mathrm{ZH}}^{\mathrm{SM}}} = \kappa_{\mathrm{Z}}^2 \tag{97}$$

$$\frac{\sigma_{\mathrm{t\bar{t}H}}}{\sigma_{\mathrm{t\bar{t}H}}^{\mathrm{SM}}} = \kappa_{\mathrm{t}}^2 \tag{98}$$

Detectable decay modes

$$\frac{\Gamma_{\mathrm{WW}^{(*)}}}{\Gamma_{\mathrm{WW}^{(*)}}^{\mathrm{SM}}} = \kappa_{\mathrm{W}}^2 \tag{99}$$

$$\frac{\Gamma_{\mathrm{ZZ}^{(*)}}}{\Gamma_{\mathrm{ZZ}^{(*)}}^{\mathrm{SM}}} = \kappa_{\mathrm{Z}}^2 \tag{100}$$

$$\frac{\Gamma_{\mathrm{b\bar{b}}}}{\Gamma_{\mathrm{b\bar{b}}}^{\mathrm{SM}}} = \kappa_{\mathrm{b}}^2 \tag{101}$$

$$\frac{\Gamma_{\tau^-\tau^+}}{\Gamma_{\tau^-\tau^+}^{\mathrm{SM}}} = \kappa_\tau^2 \tag{102}$$

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{\mathrm{SM}}} = \begin{cases} \kappa_\gamma^2(\kappa_{\mathrm{b}}, \kappa_{\mathrm{t}}, \kappa_\tau, \kappa_{\mathrm{W}}, m_{\mathrm{H}}) \\ \kappa_\gamma^2 \end{cases} \tag{103}$$

Currently undetectable decay modes

$$\frac{\Gamma_{\mathrm{t\bar{t}}}}{\Gamma_{\mathrm{t\bar{t}}}^{\mathrm{SM}}} = \kappa_{\mathrm{t}}^2 \tag{104}$$

$$\frac{\Gamma_{\mathrm{gg}}}{\Gamma_{\mathrm{gg}}^{\mathrm{SM}}} : \text{see Section 10.2.2}$$

$$\frac{\Gamma_{\mathrm{c\bar{c}}}}{\Gamma_{\mathrm{c\bar{c}}}^{\mathrm{SM}}} = \kappa_{\mathrm{t}}^2 \tag{105}$$

$$\frac{\Gamma_{\mathrm{s\bar{s}}}}{\Gamma_{\mathrm{s\bar{s}}}^{\mathrm{SM}}} = \kappa_{\mathrm{b}}^2 \tag{106}$$

$$\frac{\Gamma_{\mu^-\mu^+}}{\Gamma_{\mu^-\mu^+}^{\mathrm{SM}}} = \kappa_\tau^2 \tag{107}$$

$$\frac{\Gamma_{\mathrm{Z}\gamma}}{\Gamma_{\mathrm{Z}\gamma}^{\mathrm{SM}}} = \begin{cases} \kappa_{(\mathrm{Z}\gamma)}^2(\kappa_{\mathrm{b}}, \kappa_{\mathrm{t}}, \kappa_\tau, \kappa_{\mathrm{W}}, m_{\mathrm{H}}) \\ \kappa_{(\mathrm{Z}\gamma)}^2 \end{cases} \tag{108}$$

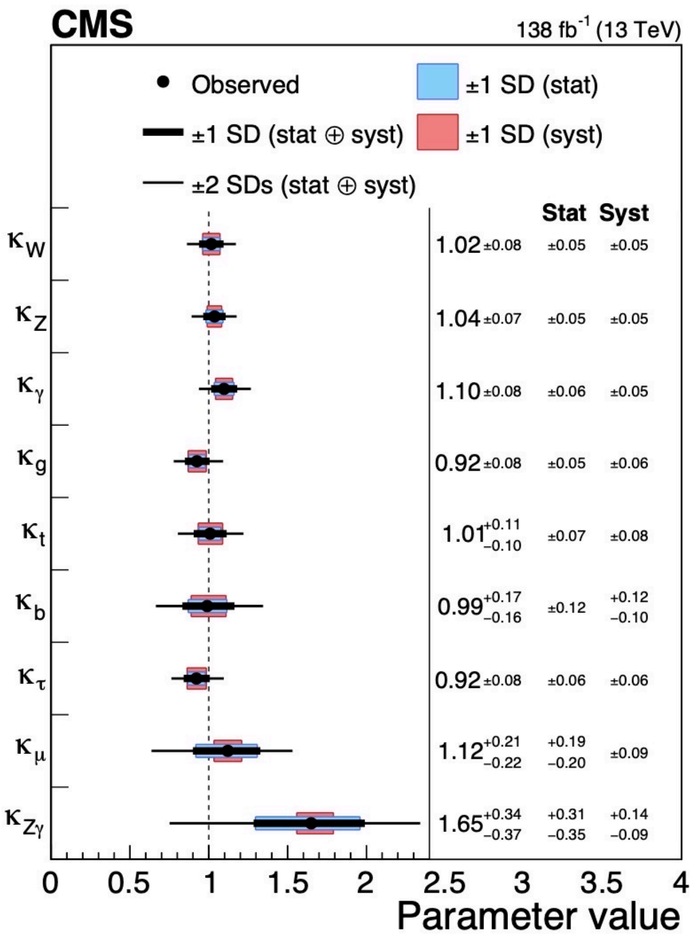
Total width

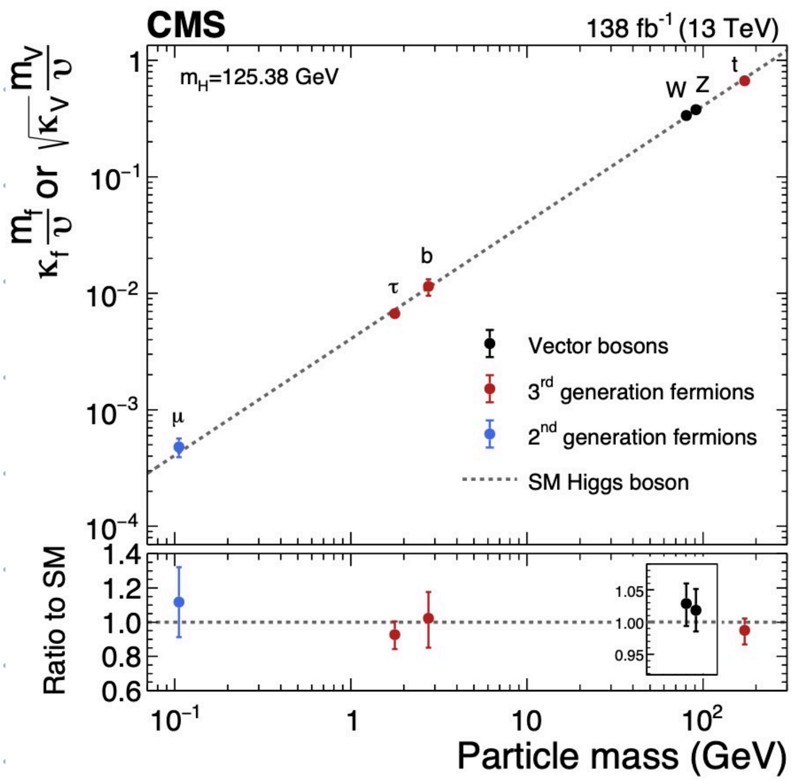
$$\frac{\Gamma_{\mathrm{H}}}{\Gamma_{\mathrm{H}}^{\mathrm{SM}}} = \begin{cases} \kappa_{\mathrm{H}}^2(\kappa_i, m_{\mathrm{H}}) \\ \kappa_{\mathrm{H}}^2 \end{cases} \tag{109}$$

arXiv: 1307.1347

=> combined fit of coupling modifiers using all production and decay channels

arXiv: 2207.00043





-> Higgs coupling ~ m

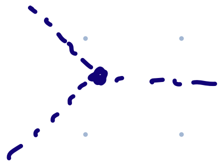
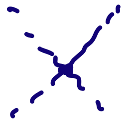
-> most couplings known with ~10% accuracy, in agreement with SM predictions

Higgs self-coupling measurement

$$V(\phi) = -\mu^2 |\phi|^2 + \frac{\lambda}{4} |\phi|^4$$

$$\sim -\frac{1}{2} m_h h^2 + \frac{\lambda_{H^3}}{3!} h^3 + \frac{\lambda_{H^4}}{4!} h^4$$

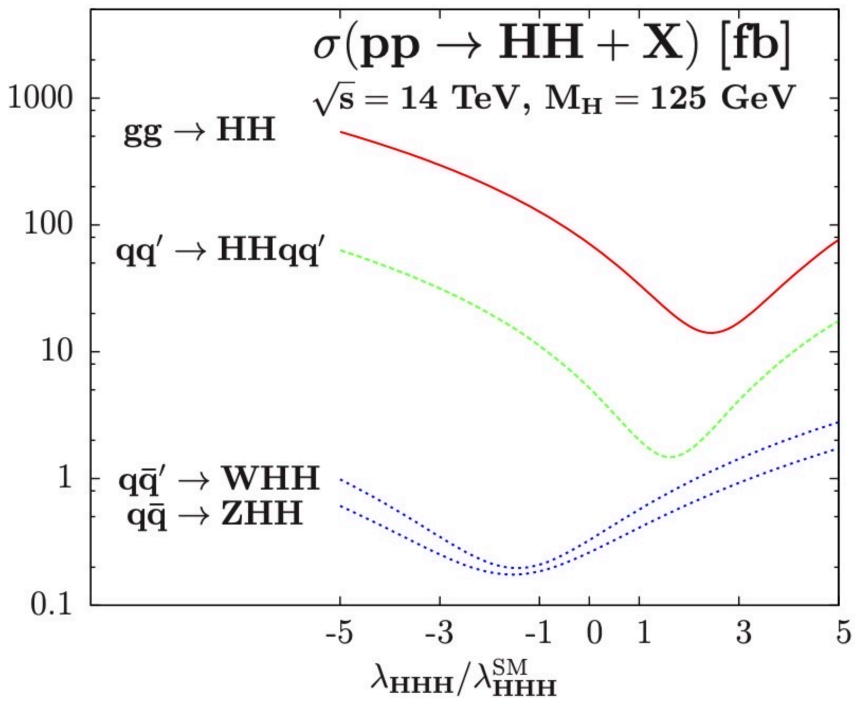
=> measurements of the self couplings is direct probe of the Higgs potential.

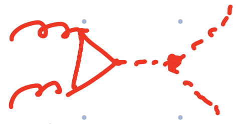
 $\sim \lambda_{H^3} = \lambda = \dfrac{3 m_h^2}{v}$  $\sim \lambda_{H^4} = \dfrac{3 m_h^2}{v^2}$

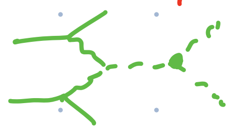
→ requires Higgs pair production → HHH production

double / triple Higgs production cross sections:

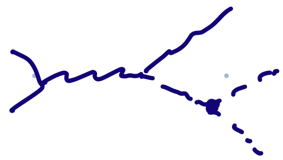
arXiv: 1212.5581



gluon fusion 

VBF 

Higgsstrahlung



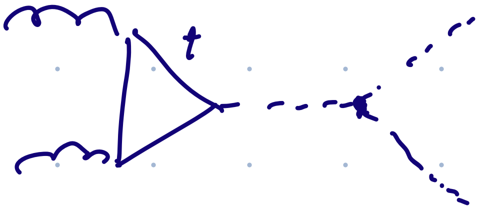
→ same production mechanisms as single H, but (much) smaller cross sections:

$\sigma(gg \to H) \approx 50\,pb = 50\,000\,fb$

$\sigma(gg \to HH) \approx 35\,fb$

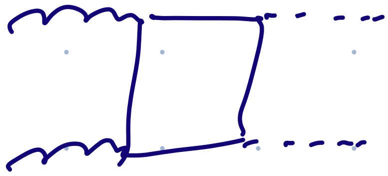
$\sigma(gg \to HHH) \approx 0{,}1\,fb$ → too small for measurement at LHC

Only some of the diagrams contain self coupling, e.g. for $gg \to HH$,



$\mathcal{M}_\Delta$

$+$



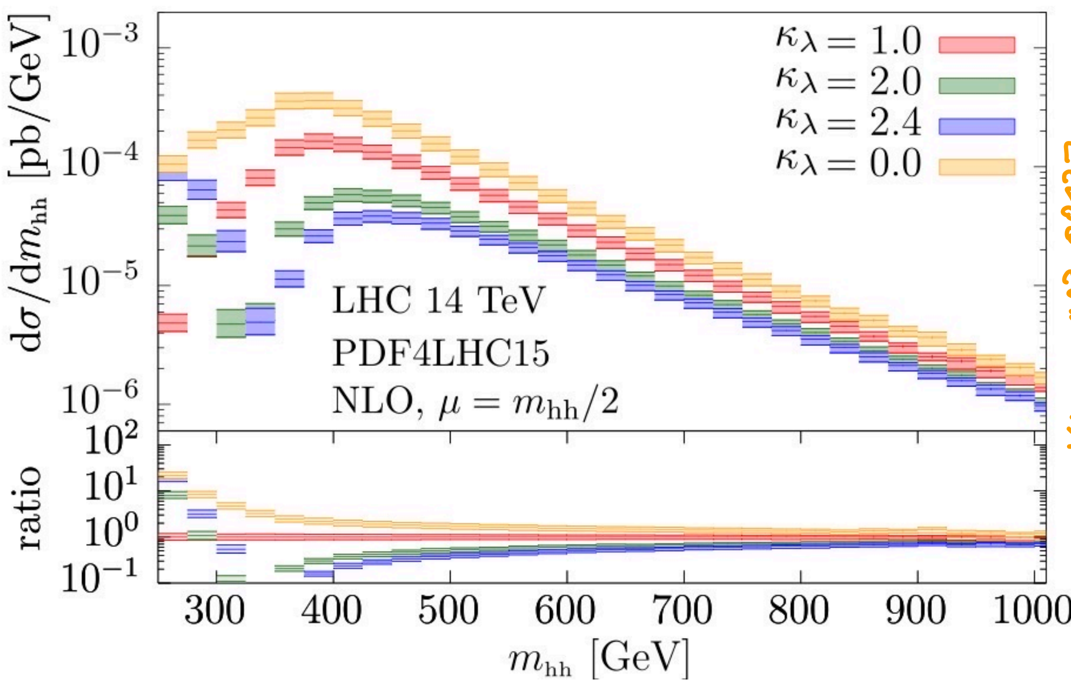
$\mathcal{M}_\square$

$\rightarrow \quad \sigma \sim \left| \lambda \cdot \mathcal{M}_\Delta + \mathcal{M}_\square \right|^2$

$\rightarrow$ σ is quadratic function in λ,

minimum not at $\lambda = 0$, but at $\lambda \approx 2.4\, \lambda_{SM}$

additional sensitivity to λ due to affect on differential distributions



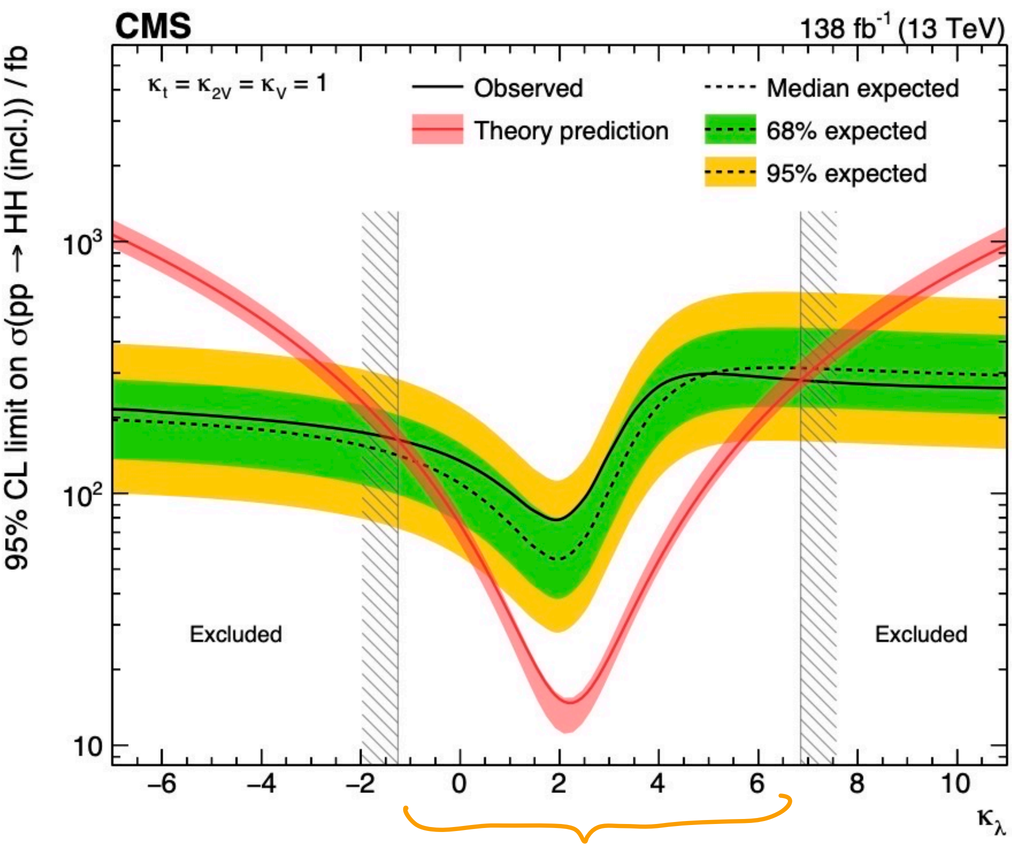
arXiv : 1903.08137

So far HH production has not been observed, but upper bounds on the production cross section have been set, restricting the values of κ_λ to $[-0.5, 6.3]$

ATLAS arXiv 2211.01216

At the High-Luminosity LHC ($\int L \approx 3000\ fb^{-1}$) it is expected that κ_λ can be constrained to $[0, 2.5]$

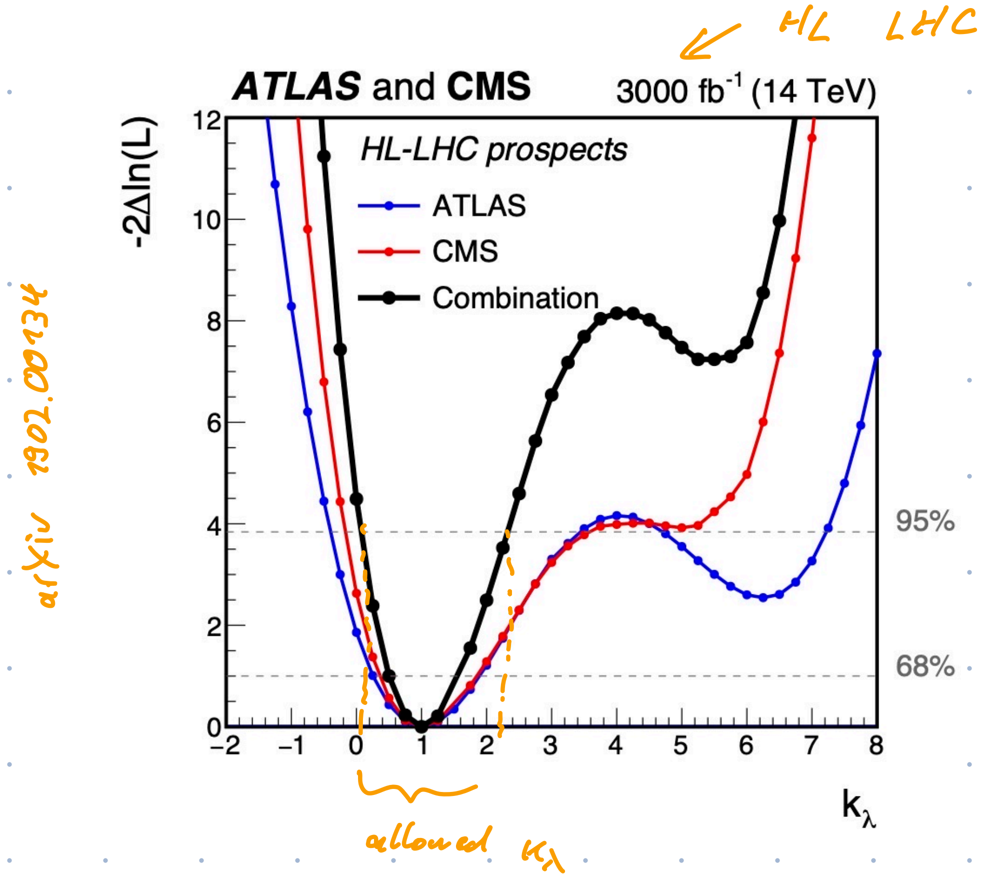
arXiv 2207.00043



← theory predictions of $\sigma(\kappa_\lambda)$

← upper limit on σ

allowed κ_λ



ATLAS and CMS
3000 fb^{-1} (14 TeV)
HL-LHC prospects
ATLAS
CMS
Combination
-2Δln(L)
95%
68%
k_λ
HL LHC
arXiv 1902.00134
allowed κ_λ