$$\phi^\dagger\phi_{min} = v^2/2$$

Nambu-Goldstone boson

change of variables: $\phi = e^{i\theta(x)/v}\left(\frac{v+h(x)}{\sqrt{2}}\right)$

$$|D_\mu\phi|^2 = \frac{1}{2}\left|\partial_\mu h - i\left(gA_\mu - \partial_\mu\frac{\theta}{v}\right)v\right|^2$$

$$= \frac{1}{2}(\partial_\mu h)^2 + \frac{1}{2}g^2v^2\underbrace{\left(A_\mu - \frac{\partial_\mu\theta}{gv}\right)}_{A'_\mu}^2 \qquad \text{note: } F_{\mu\nu} = F'_{\mu\nu}$$

"unitary gauge"

equivalent to choosing $\alpha = -\theta/v$

$$\frac{1}{2}(\partial_\mu h)^2 + \frac{1}{2}g^2v^2A_\mu^2 - \frac{1}{4}F_{\mu\nu}^2 - V\left(\left(\frac{h+v}{\sqrt{2}}\right)^2\right)$$

lesson: can set Goldstone bosons to zero in unitary gauge ☒

Higgs couplings? $\phi = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v+h \end{pmatrix}$

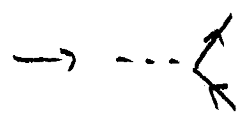
replace $v \to v\left(1+\frac{h}{v}\right)$ in masses

$\Rightarrow$ Higgs couplings follow simply from $v \to v(1+\frac{h}{v})$

and since v enters masses $m_W, m_Z, m_f \propto v$

get $m \to m(1+\frac{h}{v})$

[exception: derivative couplings of h]

fermions: $m_e e_L^+ e_R \quad \to \quad \frac{m_e}{v} h e_L^+ e_R \to$  $-i\frac{m_e}{v}$

Note: $\frac{m_e}{v} = \frac{\lambda_e}{\sqrt{2}} \qquad \lambda_e \sim 3\ 10^{-6}$

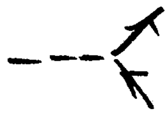
$W^{\pm}$: $m_W^2 W_\mu^+ W^{\mu -} \to m_W^2 (1+\frac{h}{v})^2 g^{\mu\nu} W_\mu^+ W_\nu^-$

 $2i\frac{m_W^2}{v} g^{\mu\nu}$  $i\frac{m_W^2}{v^2} g^{\mu\nu}$

same for Z.

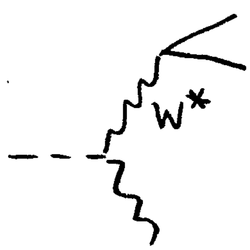
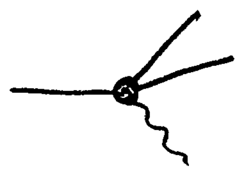
no new parameters $\Rightarrow$ Higgs couplings predicted!

Higgs decays

$h \to b\bar{b}$  $\sim \dfrac{m_b}{v} \sim 10^{-2}$

$$\frac{\Gamma_{b\bar{b}}}{m_h} = \frac{1}{8\pi}\left(\frac{m_b}{v}\right)^2 N_c \left[1-\left(\frac{2m_b}{m_h}\right)^2\right]^{3/2} \approx 10^{-5}$$

actually $\dfrac{\lambda_b(m_h)}{\sqrt{2}}$, extra suppression $\sim 1/2$

$h \to WW^*$  $\overset{\sim}{\Longrightarrow}$  $\sim \dfrac{m_W^2}{v}\dfrac{1}{m_W^2}\, g \sim \dfrac{g}{v}$

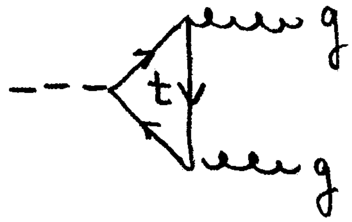
$$\Rightarrow \frac{\Gamma_{WW^*}}{\Gamma_{b\bar{b}}} \sim \frac{g^2/v^2}{m_b^2/v^2}\,\frac{1}{16\pi^2}\, m_h^2 \sim O(1)$$

3 body final state

dim'l analysis

$h \to gg$ no coupling because $m_g = 0$

BUT

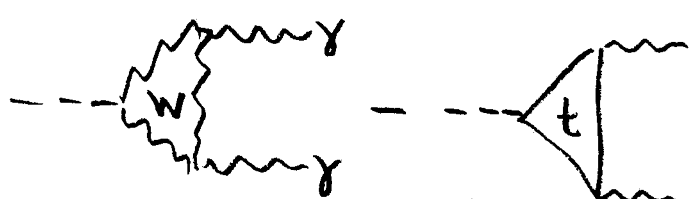


$$\sim \underbrace{\frac{1}{16\pi^2}}_{\uparrow \text{ loop}} \underbrace{g_s^2 \lambda_t}_{\text{couplings}} \underbrace{\frac{1}{m_t}}_{\text{dimensional analysis}} \underbrace{\left(p_1^\mu p_2^\nu - p_1 \cdot p_2 \, g^{\mu\nu}\right)}_{\text{gauge invariance}}$$

$$\sim \frac{\alpha_s}{4\pi} \frac{1}{v} \left(\;''\; \right)$$

$$\Rightarrow \frac{\Gamma_{gg}}{m_h} \sim \left(\frac{\alpha_s}{4\pi}\right)^2 \frac{1}{8\pi} \lesssim 10^{-5}$$

$h \to \gamma\gamma$



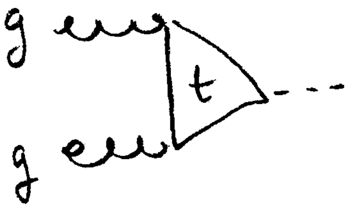
$$\sim \frac{\alpha}{4\pi} \frac{1}{v} \left(\;''\; \right)$$

partially cancel

m=125.11 GeV, Γ=4.1MeV

final	$b\bar{b}$	WW^*	gg	$\tau\bar{\tau}$	$c\bar{c}$	ZZ^*	$\gamma\gamma$	γZ	$\mu^+\mu^-$
Br [%]	58	22	8.2	6.3	2.9	2.6	0.23	0.15	0.022
ATLAS or CMS	>5σ	>10σ	-	>5σ	2σ	>10σ	>10σ	3σ	3σ

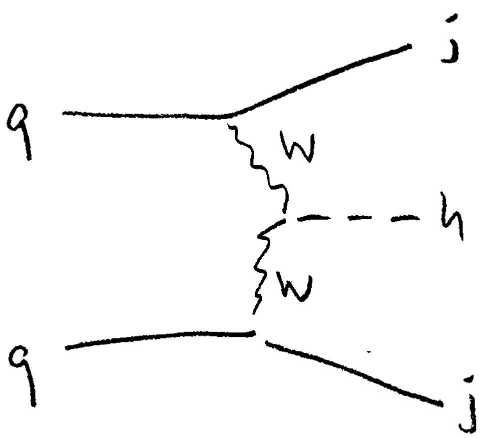
h production (125.11 GeV 13.6 TeV HXSWG)



$\sigma = 52\ \text{pb} \pm 5\%$

↖ pdfs, scale

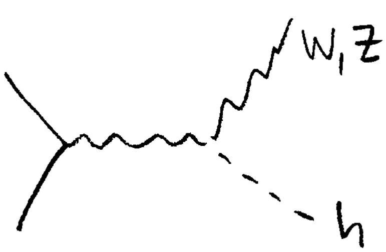
"Vector boson fusion"



$\sigma = 4.1 \pm 2\%$

forward jet tags, "seen" in $\gamma\gamma$

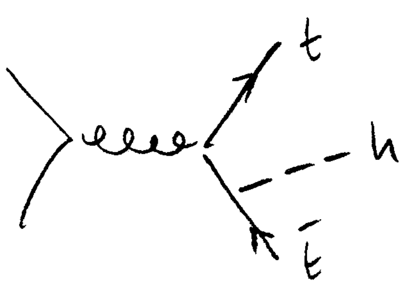
"Associated"



$\overset{W}{1.5} + \overset{Z}{0.9}\ \text{pb}$

(important @ LEP, LC)

$t\bar{t}h$



0.57 pb

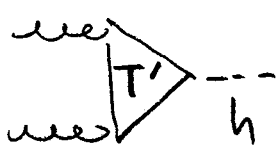
Invisible h decays? ($h \to$ dark matter, ν's, ...)

none in SM

$$\text{Events}_i = \sigma \cdot \frac{\Gamma_i}{\Gamma_{tot}} \leftarrow \Gamma_{SM} + \Gamma_{non\text{-}SM}$$

$\Rightarrow$ uniform decrease of signal in all channels

- today $\sim 20\%$ $Br_{inv.}$ allowed
- flat direction: $\sigma \uparrow$, $\Gamma_{non\text{-}SM} \uparrow$

$\delta\sigma$:  (does not enhance VBF!)

$\delta\Gamma$: $\Gamma_{SM} \sim \Gamma_{b\bar{b}} \propto \left(\frac{m_b}{v}\right)^2 \sim 10^{-4}$ v. small

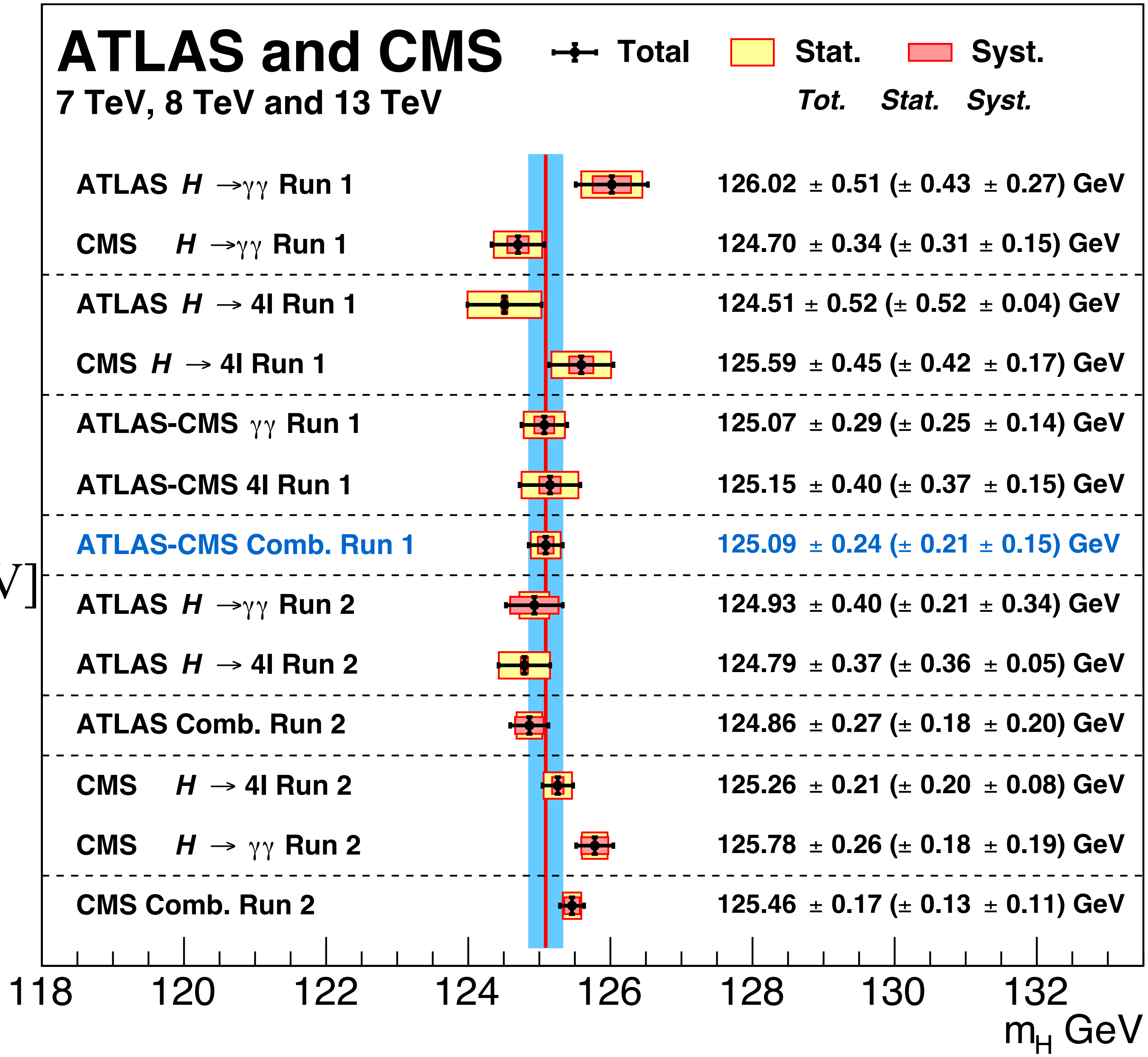
easy to compete with

e.g. $h \to \chi\chi$ (Dark Matter)

$$\mathcal{L} \sim \frac{H^\dagger H}{M} \chi\chi \to \frac{v}{M} h\chi\chi \quad \Rightarrow M \sim 10\,\text{TeV}$$

for $\Gamma_{\chi\chi} \approx \Gamma_{b\bar{b}}$

PDG
compilation
2018



PDG 2024 [GeV]
125.20+-0.11

Figure 11.4: Summary of the CMS and ATLAS mass measurements in the $\gamma\gamma$ and ZZ channels in Run 1 and Run 2.

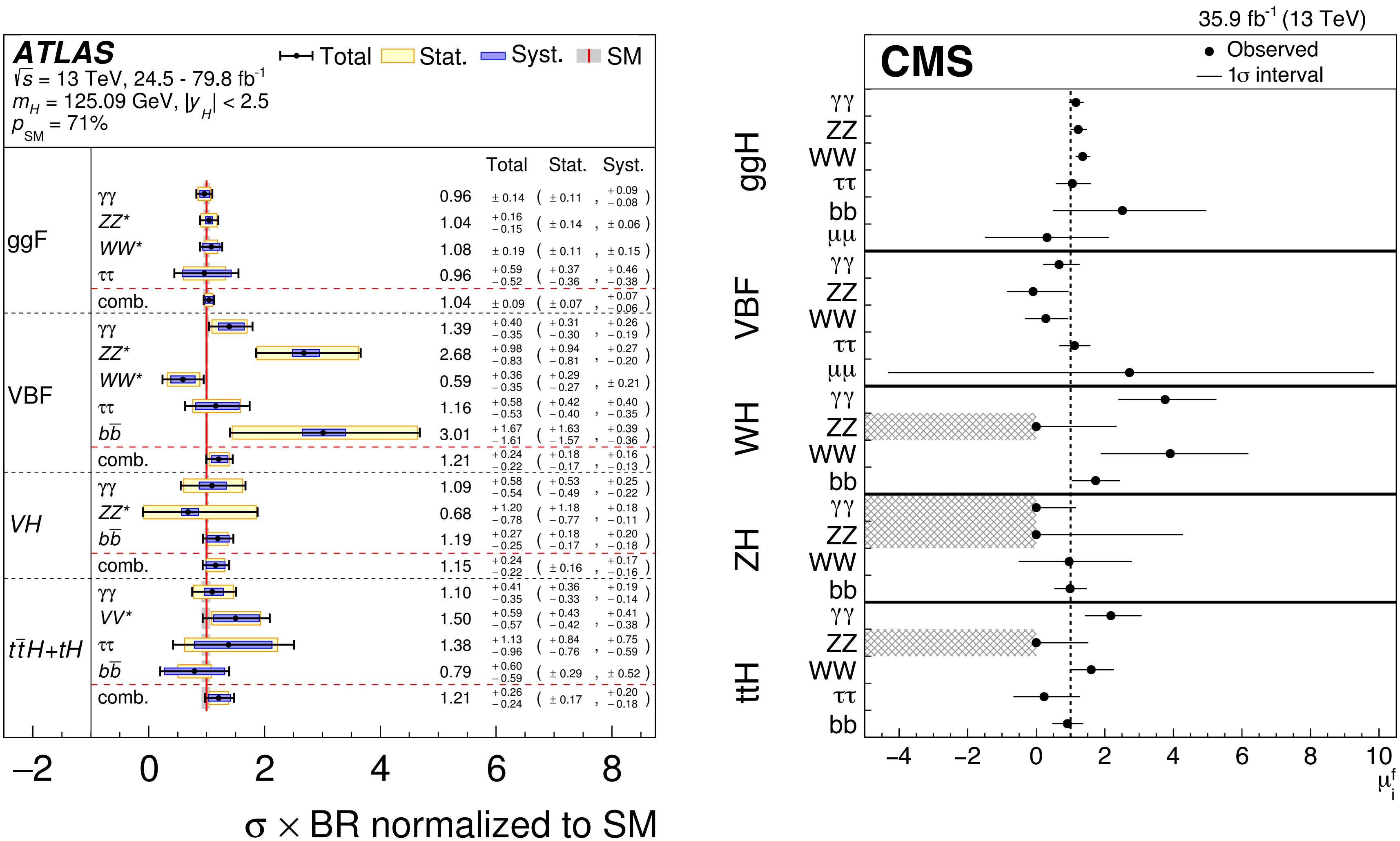


Figure 11.8: Combined measurements of the products $\sigma \cdot \mathrm{BR}$, normalised to the SM predictions, for the five main production and five main decay modes. The hatched combinations require more data for a meaningful confidence interval to be provided.

Table 11.6: Summary of the results of searches for a Higgs boson in association with a top quark pair by ATLAS and CMS. The results are given in terms of a measured signal strength. When available, the statistical and systematic contributions to the total uncertainty are reported separately and in this order. The ATLAS [161] and CMS [162] diphoton results indicated by (∗) are not included in the overall combinations which include versions of the diphoton analyses with smaller Run 2 datasets. The combination includes the $t\bar{t}(H \to b\bar{b})$ channels reported in Table 11.5.

$t\bar{t}H$	ATLAS Run 1	CMS Run 1	ATLAS Run 2	CMS Run 2
$H \to \gamma\gamma$	$1.3\ {}^{+2.6}_{-1.7}\ {}^{+2.5}_{-1.7}$	$1.2\ {}^{+2.5}_{-1.7}\ {}^{+2.6}_{-1.8}$	$1.38\ {}^{+0.33}_{-0.31}\ {}^{+0.26}_{-0.18}$ (∗)	$2.27^{+0.86}_{-0.74}$ (∗)
$H \to 4\ell$	—	—	$1.2\ {}^{+1.4}_{-0.8}$ (∗)	0.0 ± 1.2 (∗)
$WW/\tau\tau/ZZ$	$1.4\ \pm 0.6\ \pm 1.0$	3.3 ± 1.4	$1.56\ {}^{+0.30}_{-0.29}\ {}^{+0.30}_{-0.27}$	$0.96\ {}^{+0.34}_{-0.31}$
Comb.	$1.7\ \pm 0.5\ \pm 0.8$	$2.6\ {}^{+1.0}_{-0.9}$	$1.32\ \pm 0.18\ {}^{+0.21}_{-0.19}$	$1.49\ \pm 0.16\ {}^{+0.27}_{-0.21}$

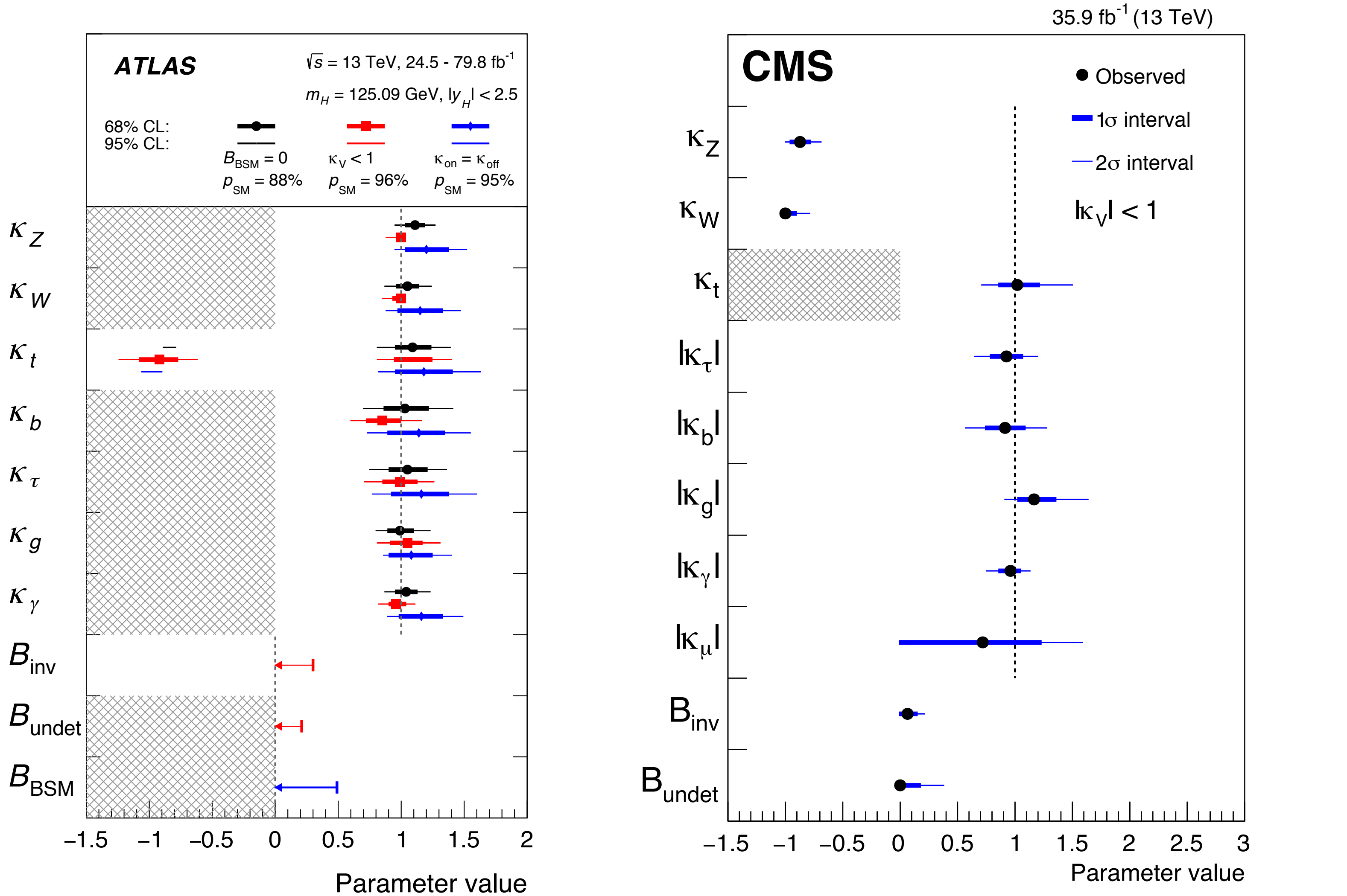
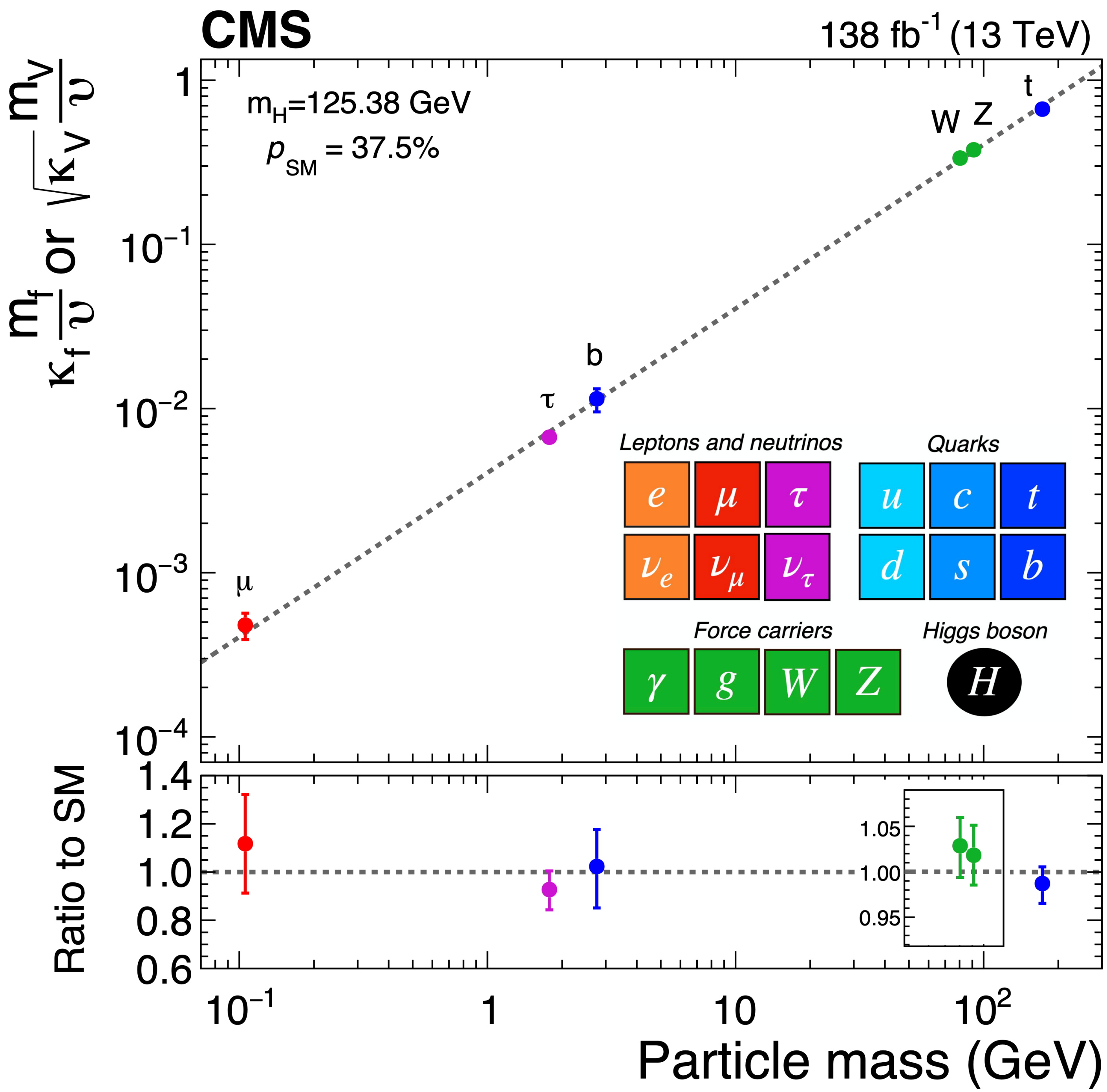


Figure 11.14: ATLAS [213] (left) and CMS [214] (right) combined measurements of coupling modifiers in the $\kappa_V < 1$ scenario, and in the case of the ATLAS measurements with the assumption $\text{BR}_{\text{BSM}} = 0$ and using the off-shell Higgs measurements.


CMS
138 fb^-1 (13 TeV)
m_H=125.38 GeV
p_SM = 37.5%
μ
τ
b
W
Z
t
Leptons and neutrinos
Quarks
e μ τ
ν_e ν_μ ν_τ
u c t
d s b
Force carriers
Higgs boson
γ g W Z
H
κ_f m_f/υ or √κ_V m_V/υ
Ratio to SM
Particle mass (GeV)
1
10^−1
10^−2
10^−3
10^−4
1.4
1.2
1.0
0.8
0.6
1.05
1.00
0.95
10^−1
1
10
10^2

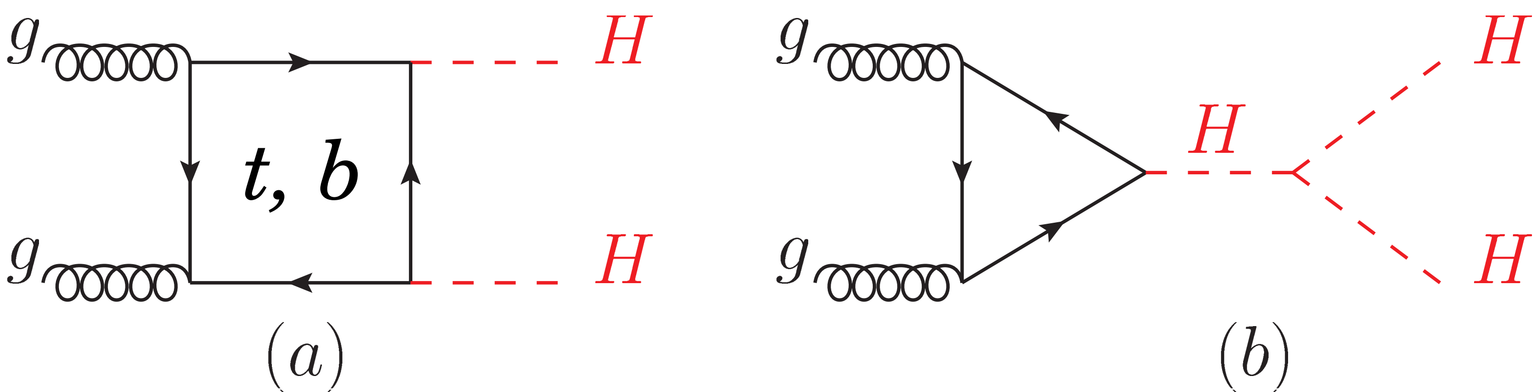


Figure 11.5: Feynman diagrams contributing at leading order to Higgs boson pair production through (a) a top- and bottom-quark loop and (b) through the self coupling of the Higgs boson.