Lecture 2 : Higgs and di-Higgs at LHC

Last lecture: discussed Higgs potential in detail,
introduced κ_λ coupling modifier

Today: • more on precision measurements in Higgs sector (VEV, mass, couplings)
• overview of di-Higgs analyses in ATLAS

---

1. VEV measurement → in muon decays

We know that:

$$v = \frac{1}{\sqrt{\sqrt{2}\, G_F}} \qquad G_F \text{ - Fermi constant}$$

→ we need a precise measurement of G_F

→ this can be obtained by measuring muon lifetime in a muon on target experiment (**MuLan** collaboration, PSI)

$$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$$

and then:

$$\frac{1}{\tau_\mu} = \frac{G_F^2 m_\mu^5}{192\pi^3}(1 + \underbrace{\Delta q}_{\text{QED \& hadronic corrections}})$$

giving $v = 246$ GeV

2. Higgs sector at the LHC → precision measurements from ATLAS & CMS

- mass → current most precise value: 125.09 GeV
  → Run 1 combination of data from ATLAS & CMS from two channels with best mass resolution:

$$H \to \gamma\gamma$$
$$H \to ZZ^* \to 4l$$

$H \to \gamma\gamma$: narrow resonant signal peak above a large continuum background ~ several hundred signal events

$H \to ZZ \to 4l$: very little background ~ several tens signal events

---

⇒ how is m_H measured?
↳ quick recap of the maximum profile - likelihood ratios method

$$\Lambda(\alpha) = \frac{L(\alpha, \hat{\hat{\theta}}(\alpha))}{L(\hat{\alpha}, \hat{\theta})}$$

$\hat{\hat{}}$ → max. likelihood estimate for given α

$\hat{}$ → unconditional max. likelihood

L - likelihood function
α - parameters of interest (here m_H)
θ - nuisance parameters

→ L is constructed using signal (from MC) and background (MC or data-driven) pdf's & depends on the discriminating variable e.g. for $H \to \gamma\gamma$: diphoton mass
$H \to 4l$: four-lepton mass

• measurements of Higgs boson production cross sections and branching fractions
→ measured global Higgs signal yield (normalised to the SM prediction):
ATLAS: 1.06 ± 0.06 (means: agreement with the SM)
→ possible interpretation of the results in terms of Kappa (κ) framework (modifiers of SM couplings - Higgs to other particles)
and/or SMEFT → set limits on parameters
2HDM

▶▶ general conclusion: no significant deviation from the SM observed (see Fig. 1)
↳ all cross-sections give a total compatibility with the SM prediction corresponding to the p-value of $p_{SM} = 79\%$

• κ - framework: study modifications to Higgs couplings related to BSM physics
→ take leading order contributions of each production and decay process:

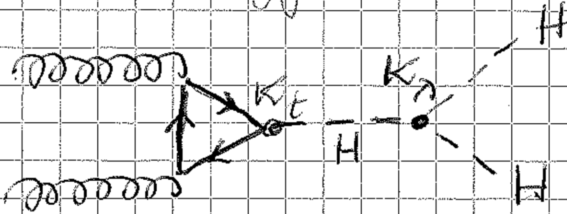
$$\kappa_j^2 = \frac{\sigma_j}{\sigma_j^{SM}}$$

Following kappas are measured in single Higgs production:
κ_Z, κ_W, κ_b, κ_t, κ_τ, κ_μ,
κ_g, κ_γ, $\kappa_{Z\gamma}$ (although $H \to Z\gamma$ not yet observed)

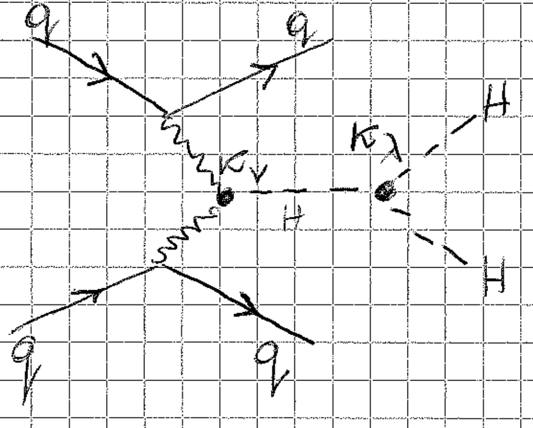
To measure κ_λ and κ_{2V} → we use di-Higgs

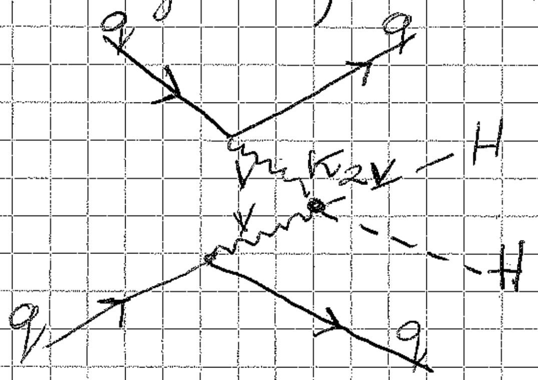
κ_λ in ggF

(κ_λ could also be constrained by single Higgs)

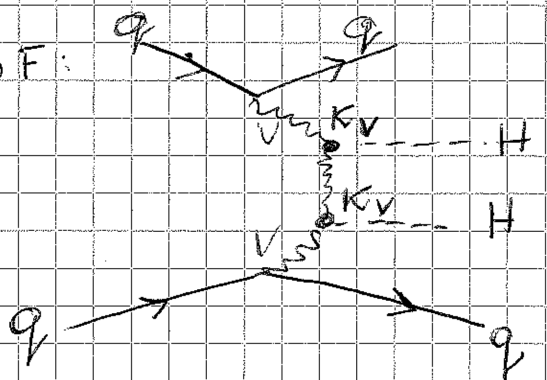


but κ_λ also in VBF production (vector boson fusion) as well as: κ_{2V}





also possible for VBF:



How do we explore κ_λ / κ_{2V} experimentally?

→ ideal: measure cross section for various diHiggs production modes and decay channels & interpret the results in κ-framework

↳ but we don't have enough events

(ggF: $\sigma_{SM} \approx 30\,fb$, VBF $\sigma_{SM} \approx 1.7\,fb$)

↳ instead we set upper limits on the cross section for different values of κ_λ (κ_{2V}) and we constrain their possible values.

• Limits are set using the frequentist CL_s method. μ is the signal strength.
At 95% CL:

$$CL_s = \frac{CL_{s+b}}{CL_b} = \frac{p(q_\mu \geq q_{\mu,obs} | s+b)}{p(q_\mu \geq q_{\mu,obs} | b)}$$

$CL_s \leq 0.05$ means μ is excluded.
q - a test statistic related to the one-sided profile likelihood ratio. it measures level of compatibility of data with signal and backgr. model

$$\tilde{q}_\mu = \begin{cases} -2\ln\left(\frac{L(\mu, \hat{\hat{\theta}}(\mu))}{L(0, \hat{\hat{\theta}}(0))}\right), & \hat{\mu} < 0 \\ -2\ln\left(\frac{L(\mu, \hat{\theta}(\mu))}{L(\hat{\mu}, \hat{\theta})}\right), & 0 \leq \hat{\mu} \leq \mu \\ 0, & \hat{\mu} > \mu \end{cases}$$

• production modes considered: ggF & VBF
decay channels mainly contributing to current best results: bbbb, $bb\tau\tau$, $bb\gamma\gamma$
(also studied in ATLAS: bbVV, bbll, multilepton)
→ Why those 3?
↳ balance between high branching fraction and purity of the channel (little background)

channel	branching fraction	
bbbb	34%	→ highest BF but challenging QCD background

$bb\tau\tau$	BF 7.3%	→ moderate BF, but taus are effective at rejecting multi-jet background
$bb\gamma\gamma$	0.26%	→ low BF, but great di-photon mass resolution

↳ current best non-resonant result: combination of $bb\tau\tau$ and $bb\gamma\gamma$ channels

↳ see fig. 2

↳ κ_λ constrained to an interval $[-1, 6.6]$

SM cross section limit: 3.1 × SM

→ combination of all channels is ongoing

↳ better / more constrained limits on κ_λ & κ_{2V}

→ much better limits (potentially a measurement) expected at HL-LHC or FCC

↳ projection studies ongoing

↳ more statistics, however also a lot of pile-up

Next lecture: HH → 4b analysis

↳ how can it contribute to this great result

↳ how challenging QCD background is dealt with

Figure 1

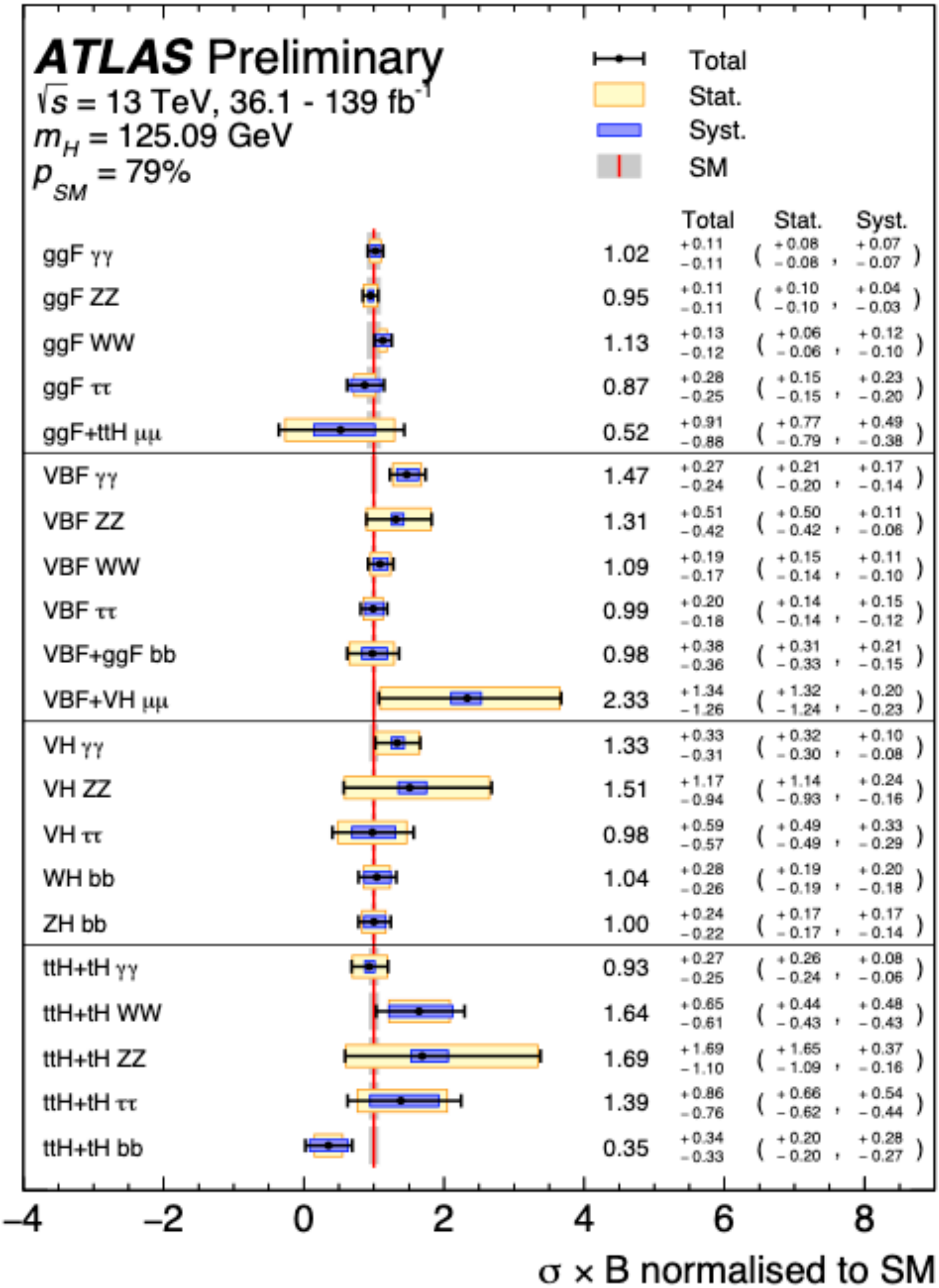
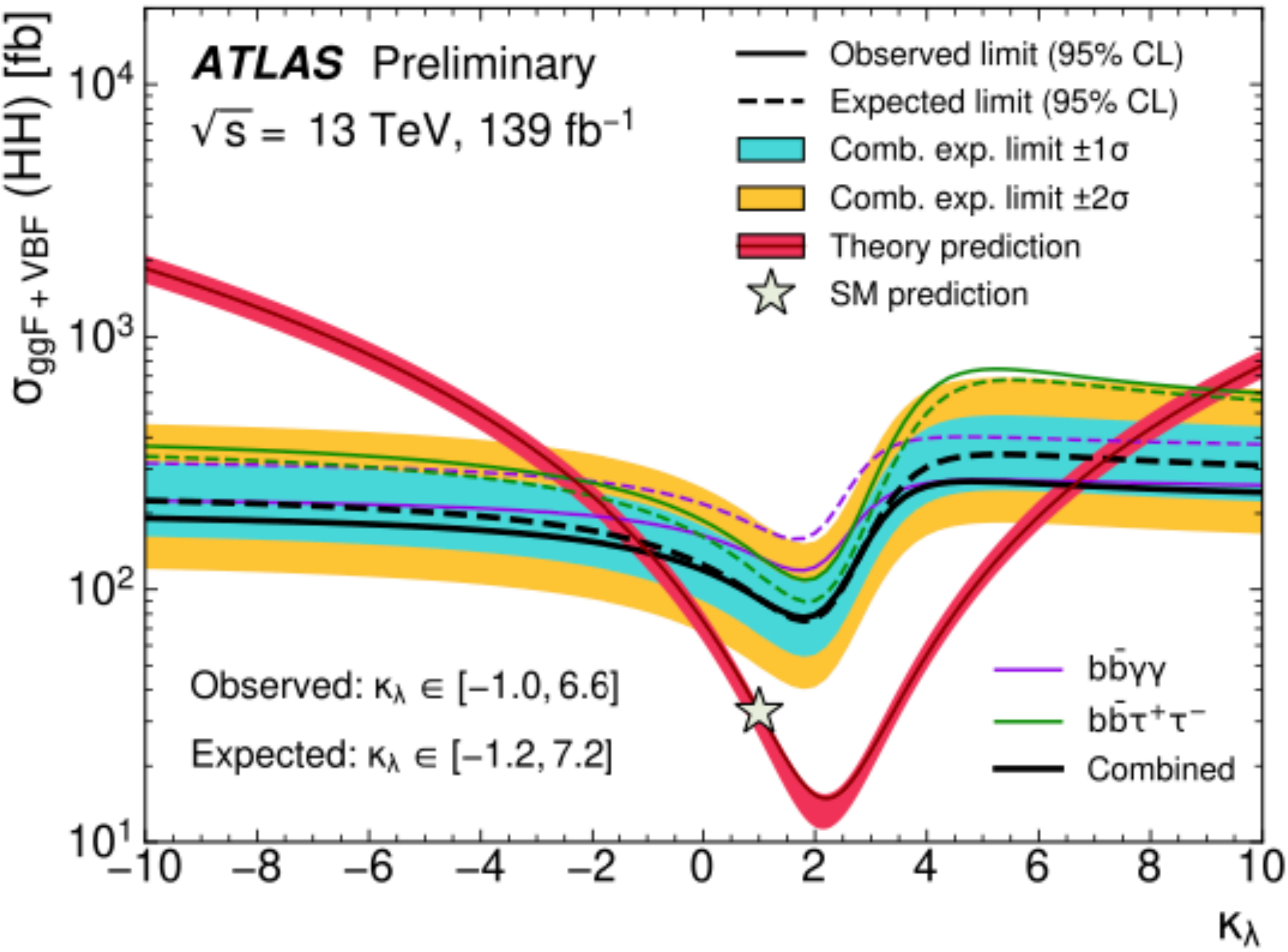

ATLAS Preliminary
√s = 13 TeV, 36.1 - 139 fb-1
mH = 125.09 GeV
pSM = 79%
Total
Stat.
Syst.
SM
Total Stat. Syst.
ggF γγ 1.02 +0.11 −0.11 (+0.08 −0.08 , +0.07 −0.07)
ggF ZZ 0.95 +0.11 −0.11 (+0.10 −0.10 , +0.04 −0.03)
ggF WW 1.13 +0.13 −0.12 (+0.06 −0.06 , +0.12 −0.10)
ggF ττ 0.87 +0.28 −0.25 (+0.15 −0.15 , +0.23 −0.20)
ggF+ttH μμ 0.52 +0.91 −0.88 (+0.77 −0.79 , +0.49 −0.38)
VBF γγ 1.47 +0.27 −0.24 (+0.21 −0.20 , +0.17 −0.14)
VBF ZZ 1.31 +0.51 −0.42 (+0.50 −0.42 , +0.11 −0.06)
VBF WW 1.09 +0.19 −0.17 (+0.15 −0.14 , +0.11 −0.10)
VBF ττ 0.99 +0.20 −0.18 (+0.14 −0.14 , +0.15 −0.12)
VBF+ggF bb 0.98 +0.38 −0.36 (+0.31 −0.33 , +0.21 −0.15)
VBF+VH μμ 2.33 +1.34 −1.26 (+1.32 −1.24 , +0.20 −0.23)
VH γγ 1.33 +0.33 −0.31 (+0.32 −0.30 , +0.10 −0.08)
VH ZZ 1.51 +1.17 −0.94 (+1.14 −0.93 , +0.24 −0.16)
VH ττ 0.98 +0.59 −0.57 (+0.49 −0.49 , +0.33 −0.29)
WH bb 1.04 +0.28 −0.26 (+0.19 −0.19 , +0.20 −0.18)
ZH bb 1.00 +0.24 −0.22 (+0.17 −0.17 , +0.17 −0.14)
ttH+tH γγ 0.93 +0.27 −0.25 (+0.26 −0.24 , +0.08 −0.06)
ttH+tH WW 1.64 +0.65 −0.61 (+0.44 −0.43 , +0.48 −0.43)
ttH+tH ZZ 1.69 +1.69 −1.10 (+1.65 −1.09 , +0.37 −0.16)
ttH+tH ττ 1.39 +0.86 −0.76 (+0.66 −0.62 , +0.54 −0.44)
ttH+tH bb 0.35 +0.34 −0.33 (+0.20 −0.20 , +0.28 −0.27)
−4 −2 0 2 4 6 8
σ × B normalised to SM

Figure 2



ATLAS Preliminary
√s = 13 TeV, 139 fb⁻¹
Observed limit (95% CL)
Expected limit (95% CL)
Comb. exp. limit ±1σ
Comb. exp. limit ±2σ
Theory prediction
SM prediction
Observed: κλ ∈ [−1.0, 6.6]
Expected: κλ ∈ [−1.2, 7.2]
bb̄γγ
bb̄τ⁺τ⁻
Combined
σggF + VBF (HH) [fb]
κλ