A detailed map of Higgs boson interactions by the ATLAS experiment ten years after the discovery

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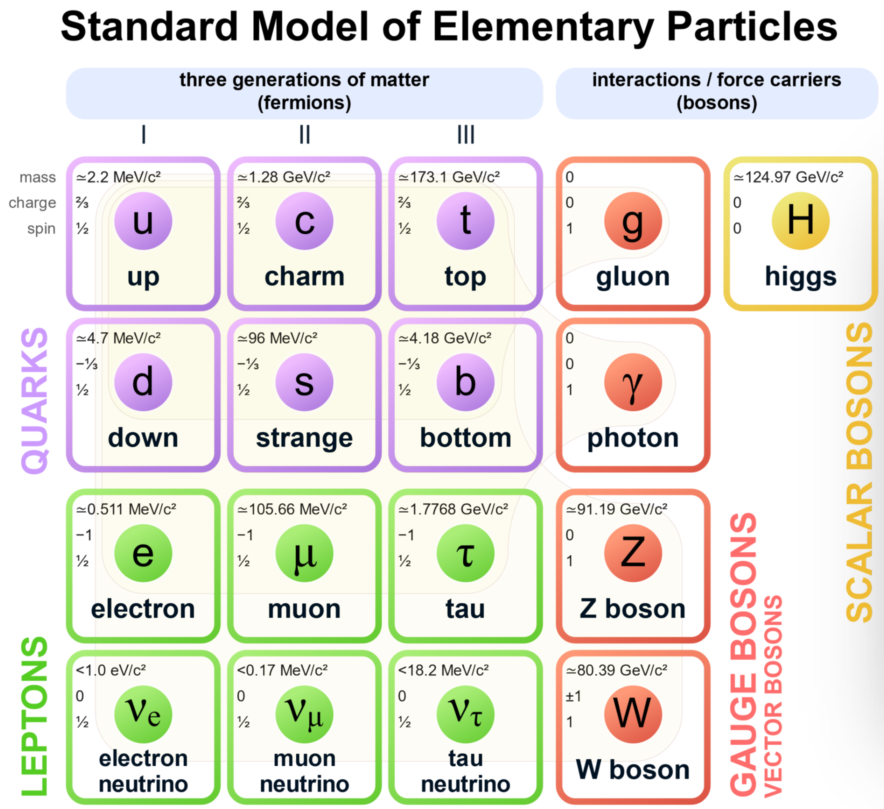
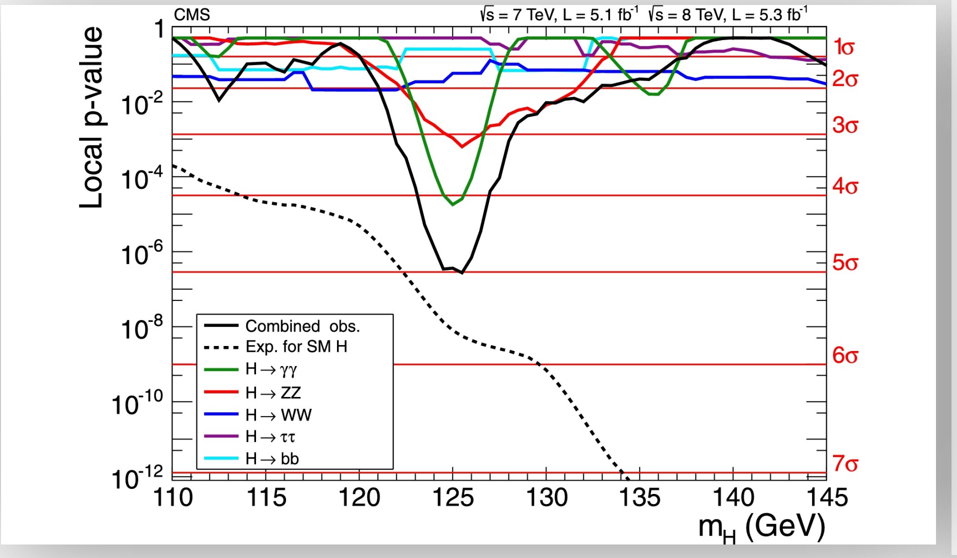
ATLAS EXPERIMENT

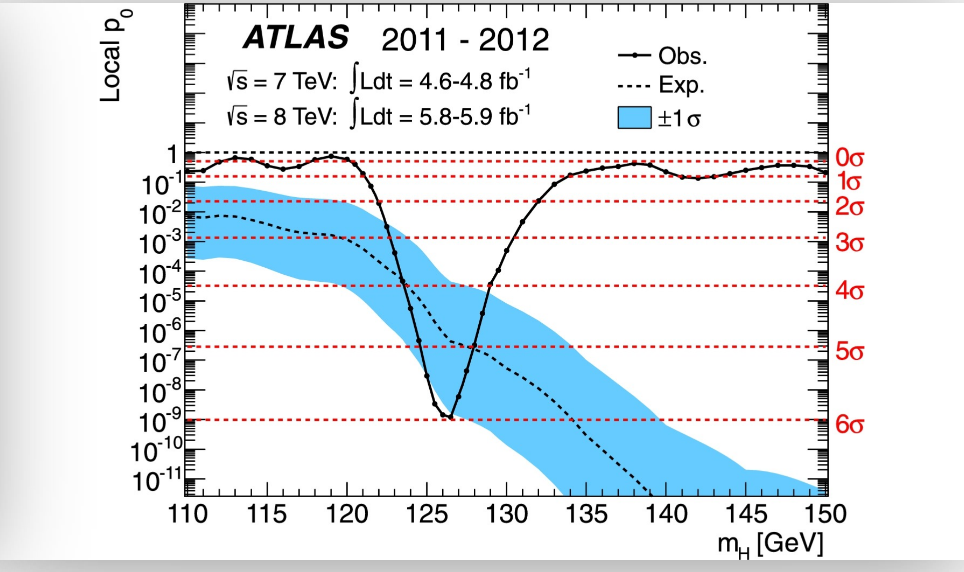
Higgs boson

◆ Higgs boson is responsible for the masses of elementary particles. One decade has passed since its discovery by ATLAS and CMS in 2012!

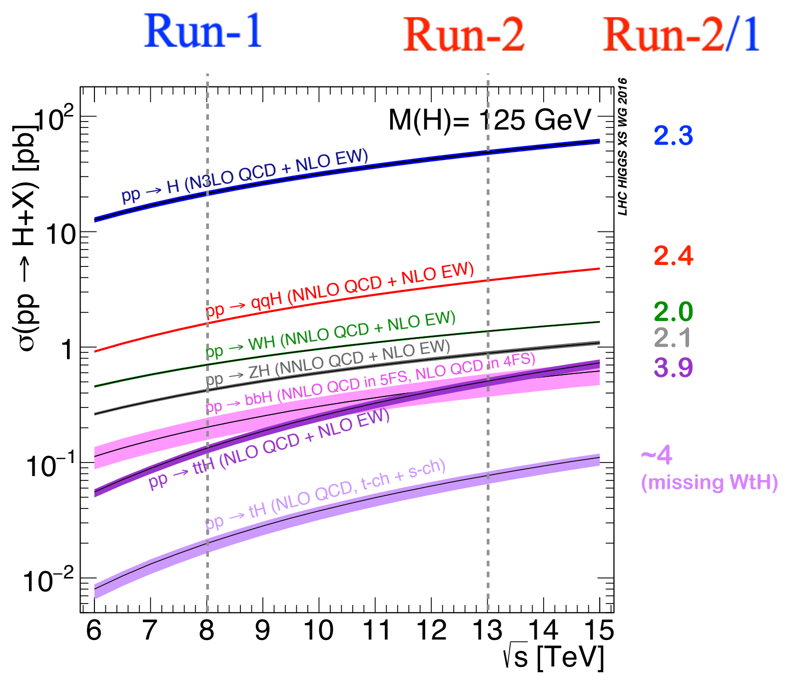


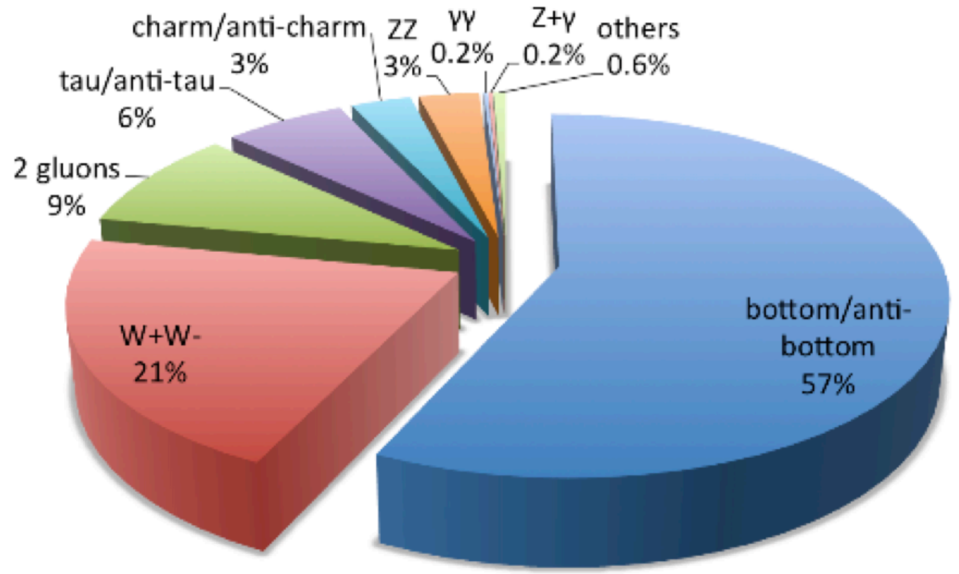
Discovery of Higgs boson opens a new era of particle physics —— measure propertied of Higgs precisely!

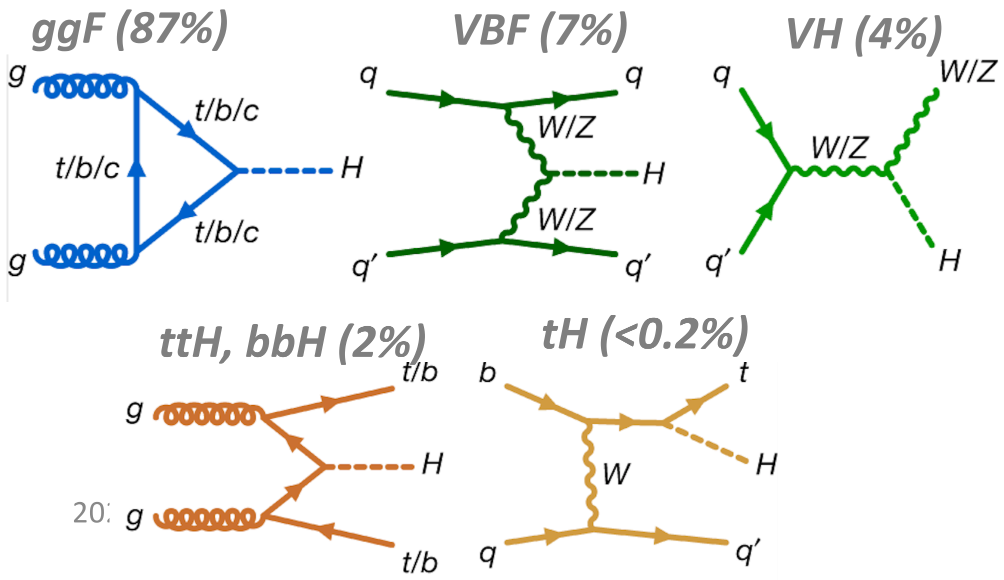




Productions and decays of Higgs boson







ZZ^* and $\gamma\gamma^*$: high resolution and precise differential measurements

WW^*: high BR but low mass resolution

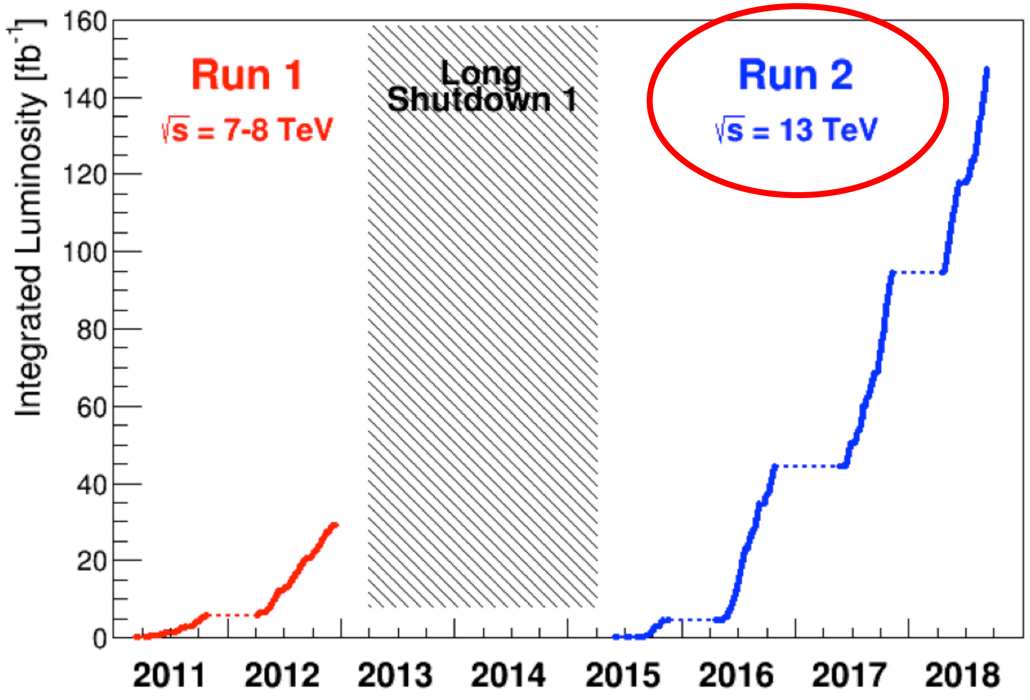
$\tau\tau$ and bb: high BR but low S/B, important to directly probe Yukawa coupling with 3rd generation fermions

$\mu\mu$ and cc: small BR but access to Yukawa coupling with 2nd generation fermions

Invisible channel: probe the phase space sensitive to BSM

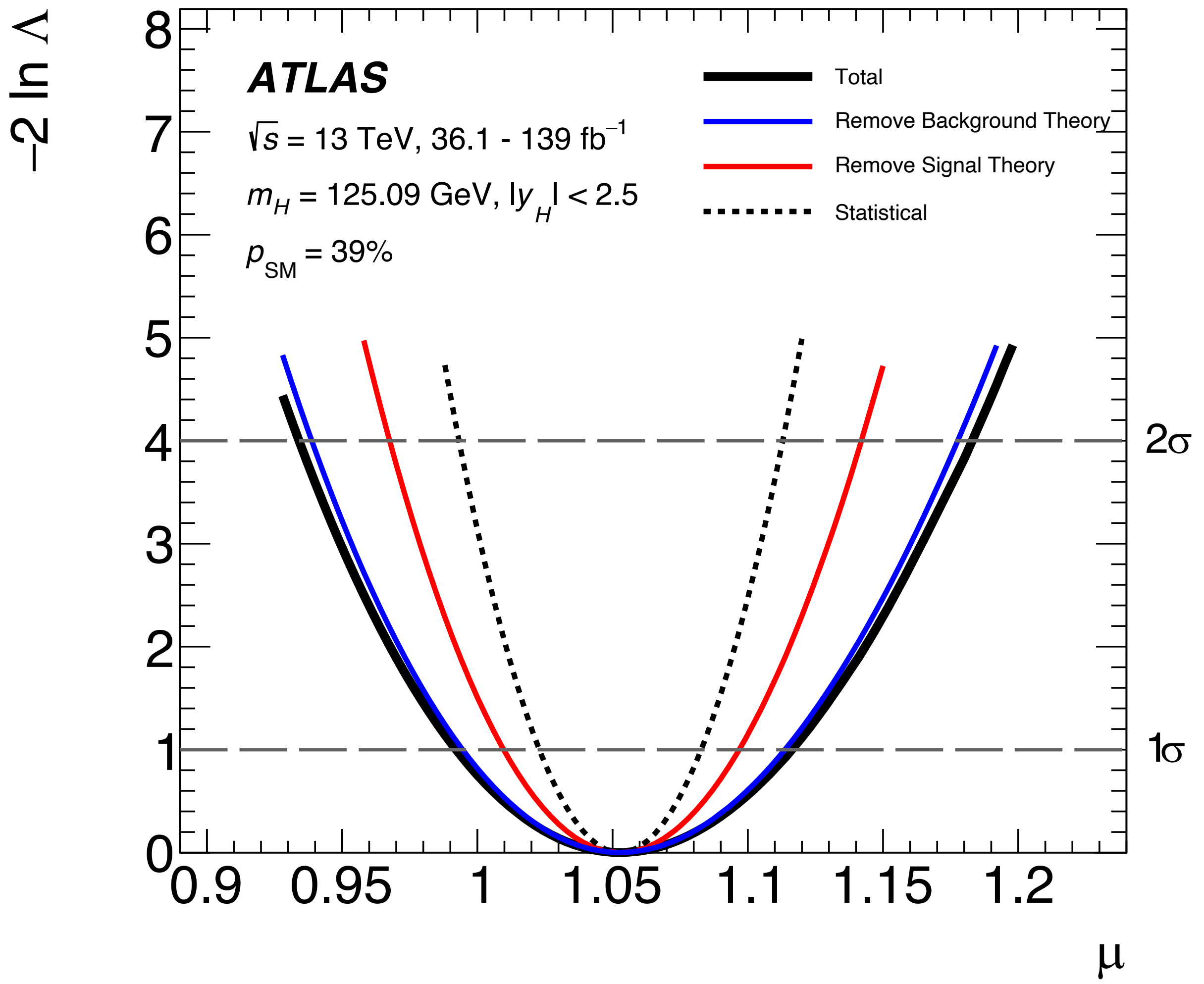
Input analyses

Decay mode	Targeted production processes	$\mathcal{L}$ [fb^{-1}]	Fits deployed in
$H \to \gamma\gamma$	ggF, VBF, WH, ZH, $t\bar{t}H$, tH	139	All
$H \to ZZ$	ggF, VBF, $WH + ZH$, $t\bar{t}H + tH$	139	All
	$t\bar{t}H + tH$ (multilepton)	36.1	All but fit of kinematics
$H \to WW$	ggF, VBF	139	All
	WH, ZH	36.1	All but fit of kinematics
	$t\bar{t}H + tH$ (multilepton)	36.1	All but fit of kinematics
$H \to Z\gamma$	inclusive	139	All but fit of kinematics
$H \to b\bar{b}$	WH, ZH	139	All
	VBF	126	All
	$t\bar{t}H + tH$	139	All
	inclusive	139	Only for fit of kinematics
$H \to \tau\tau$	ggF, VBF, $WH + ZH$, $t\bar{t}H + tH$	139	All
	$t\bar{t}H + tH$ (multilepton)	36.1	All but fit of kinematics
$H \to \mu\mu$	ggF + $t\bar{t}H + tH$, VBF + $WH + ZH$	139	All but fit of kinematics
$H \to c\bar{c}$	$WH + ZH$	139	Only for free-floating κ_c
$H \to$ invisible	VBF	139	κ models with $B_{\mathrm{u.}}$ & $B_{\mathrm{inv.}}$
	ZH	139	κ models with $B_{\mathrm{u.}}$ & $B_{\mathrm{inv.}}$



- **An unprecedented number of production and decay processes included**. Almost all the measurements upgraded to full Run2 luminosity.
- **All input Higgs analyses** combined statistically via profile-likelihood method to perform precise measurements of properties and couplings of Higgs boson

Global signal strength



- For a specific production process i and decay mode f, a signal strength is defined as

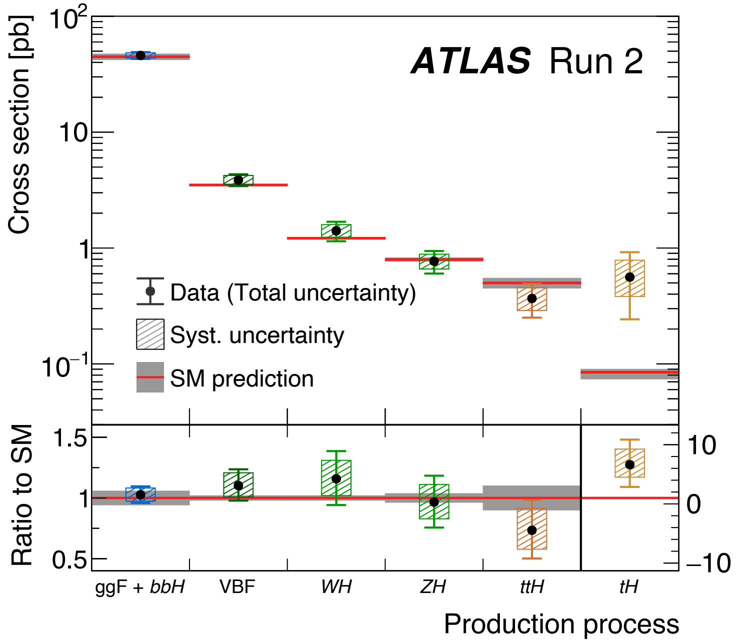
$$\mu_{if} = \left(\frac{\sigma_i}{\sigma_i^{SM}}\right)(B_f/B_f^{SM})$$

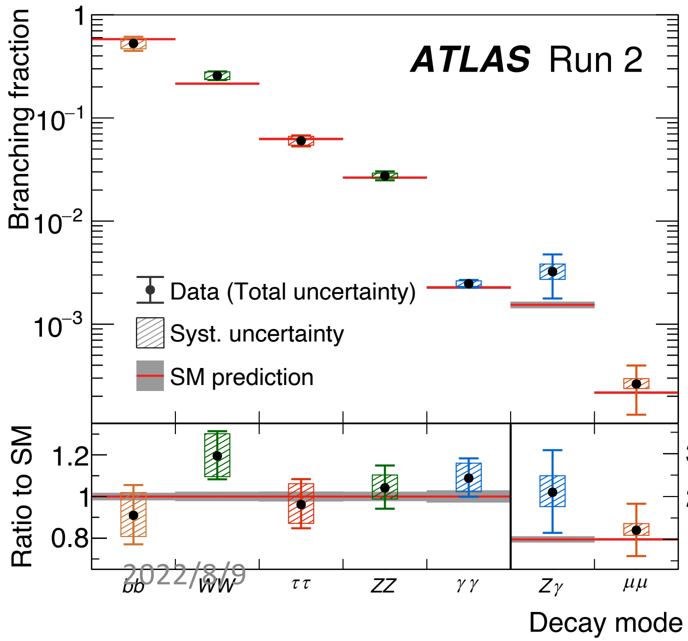
assuming a global $\mu =$ all μ_{if}, measured to be

$$\mu = 1.05 \pm 0.06$$
$$= 1.05 \pm 0.03(\text{stat.}) \pm 0.03(\text{exp.}) \pm 0.04(\text{sig. th.}) \pm 0.02(\text{bkg. th.}).$$

- The precision reaches to **6%**, improved by **~30%** compared with 79.8 fb^{-1} partial Run2 dataset ($\mu = 1.11^{+0.09}_{-0.08}$) Phys. Rev. D 101, 012002 (2020)
- Experimental and theoretical uncertainties almost a factor of 2 lower than Run1

Production cross-sections and BRs





- **All measured XS and BRs compatible with SM predictions.**

  p-value of SM compatibility is 65% for cross-sections, 56% for BRs.

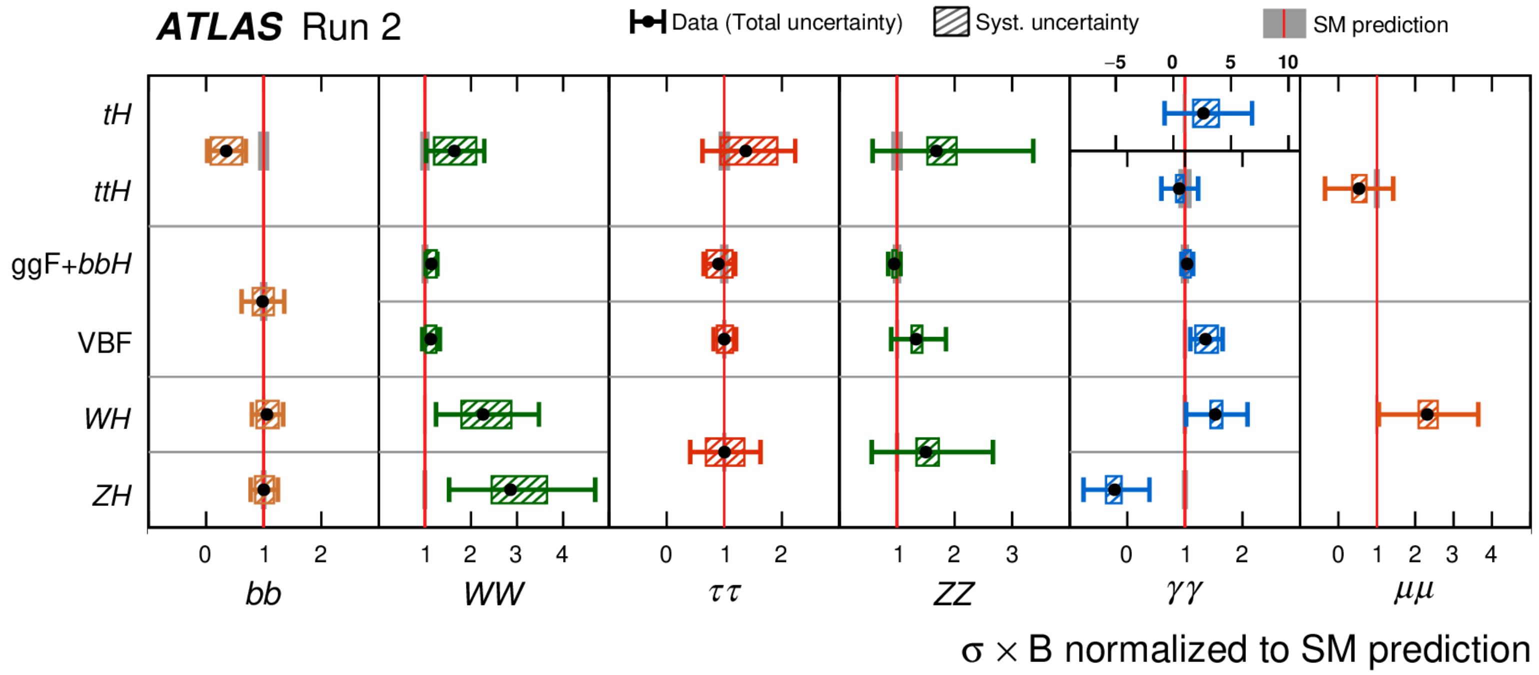
- **All major productions observed with significance over 5σ**

  WH observed with **5.8 (5.1)σ**, **ZH** observed with **5.0(5.5) σ**, **ttH+tH** with **6.4(6.6)σ**.

- **Improved significance for rare decays**

  $H \rightarrow b\bar{b}$ observed with **7.0(7.7)σ**, $H \rightarrow \mu^+\mu^-$ with **2.0(1.7)σ**, $H \rightarrow Z\gamma$ with **2.3(1.1)σ**

Signal strength for different combination of production × decay



κ frameworks

Interpret cross-sections or decay width as function of kappa modifiers that represent Higgs coupling to various SM particles.

Kappa modifiers to different productions and decays

Production	Loops	Interference	Effective modifier	Resolved modifier
$\sigma(\text{ggF})$	✓	t–b	κ_g^2	$1.04\kappa_t^2 + 0.002\kappa_b^2 - 0.04\kappa_t\kappa_b$
$\sigma(\text{VBF})$	···	···	···	$0.73\kappa_W^2 + 0.27\kappa_Z^2$
$\sigma(qq/qg \to ZH)$	···	···	···	κ_Z^2
$\sigma(gg \to ZH)$	✓	t–Z	$\kappa_{(ggZH)}$	$2.46\kappa_Z^2 + 0.46\kappa_t^2 - 1.90\kappa_Z\kappa_t$
$\sigma(WH)$	···	···	···	κ_W^2
$\sigma(t\bar{t}H)$	···	···	···	κ_t^2
$\sigma(tHW)$	···	t–W	···	$2.91\kappa_t^2 + 2.31\kappa_W^2 - 4.22\kappa_t\kappa_W$
$\sigma(tHq)$	···	t–W	···	$2.63\kappa_t^2 + 3.58\kappa_W^2 - 5.21\kappa_t\kappa_W$
$\sigma(b\bar{b}H)$	···	···	···	κ_b^2
Partial decay width				
Γ^{bb}	···	···	···	κ_b^2
Γ^{WW}	···	···	···	κ_W^2
Γ^{gg}	✓	t–b	κ_g^2	$1.11\kappa_t^2 + 0.01\kappa_b^2 - 0.12\kappa_t\kappa_b$
$\Gamma^{\tau\tau}$	···	···	···	κ_τ^2
Γ^{ZZ}	···	···	···	κ_Z^2
Γ^{cc}	···	···	···	$\kappa_c^2 (= \kappa_t^2)$
$\Gamma^{\gamma\gamma}$	✓	t–W	κ_γ^2	$1.59\kappa_W^2 + 0.07\kappa_t^2 - 0.67\kappa_W\kappa_t$
$\Gamma^{Z\gamma}$	✓	t–W	$\kappa_{(Z\gamma)}^2$	$1.12\kappa_W^2 - 0.12\kappa_W\kappa_t$
Γ^{ss}	···	···	···	$\kappa_s^2 (= \kappa_b^2)$
$\Gamma^{\mu\mu}$	···	···	···	κ_μ^2
Total width ($B_{\text{inv}} = B_{\text{undet}} = 0$)				
Γ_H	✓	···	κ_H^2	$0.58\kappa_b^2 + 0.22\kappa_W^2 + 0.08\kappa_g^2 + 0.06\kappa_\tau^2 + 0.03\kappa_Z^2 + 0.03\kappa_c^2 + 0.0023\kappa_\gamma^2 + 0.0015\kappa_{(Z\gamma)}^2 + 0.0004\kappa_s^2 + 0.00022\kappa_\mu^2$

The effective couplings of loop-induced processes are resolved in terms of fundamental SM couplings.

$$\sigma(i \to H \to f) = \sigma_i B_f = \frac{\sigma_i(\kappa)\Gamma_f(\kappa)}{\Gamma_H(\kappa, B_{\text{inv.}}, B_{\text{u.}})},$$

partial width of decay mode f

BRs of **invisible ($ZZ^* \to 4\nu$, DM candidates $\chi\chi$)** and **undetected channels (light quarks, gluons…)**

Total decay width of Higgs boson

$$\Gamma_H(\kappa, B_{inv.}, B_{u.}) = \kappa_H^2(\kappa, B_{inv.}, B_{u.})\Gamma_H^{SM} = \frac{\sum_p B_p^{SM}\kappa_p^2}{(1 - B_{inv.} - B_{u.})}\Gamma_H^{SM}$$

Non-SM decays enter the parameterization via $B_{inv.}$ and $B_{u.}$

κ_V VS κ_F

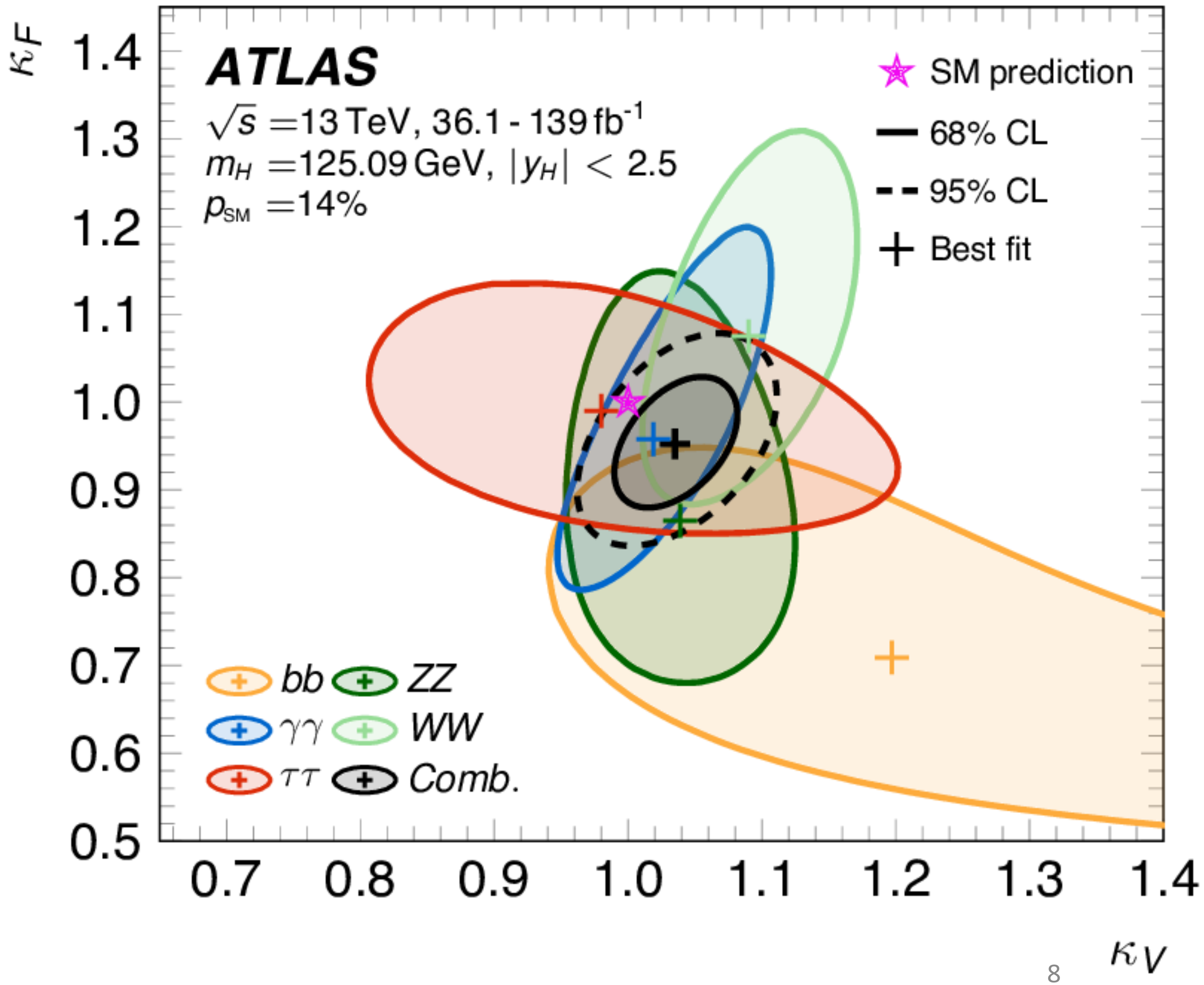
$\kappa_V = \kappa_W = \kappa_Z$, κ_F **applies to all fermions (leptons, quarks)**

- κ_V and κ_F assumed to be positive. p-value of SM compatibility is **14%**
- **Large positive correlation 39% between them** due to most sensitive input measurements involving ggF production with decays into vector bosons

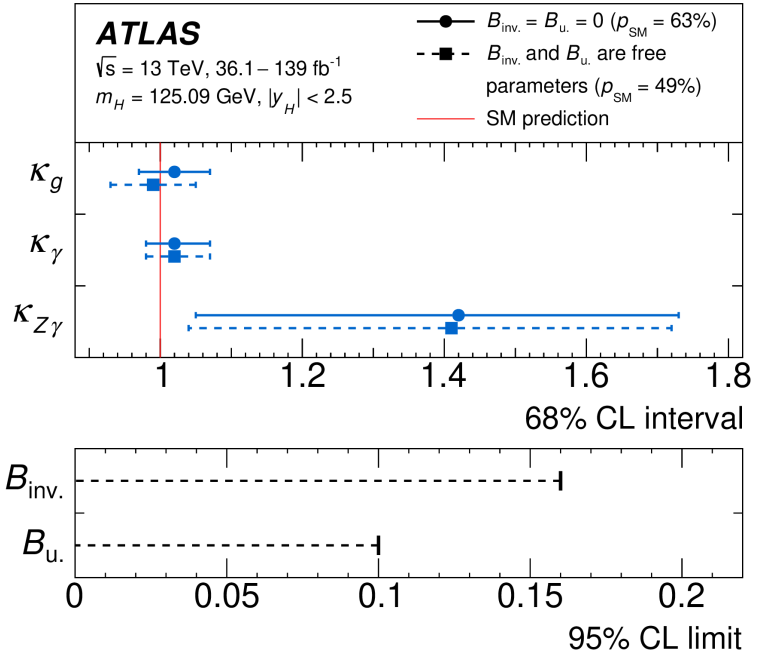
Combined result:

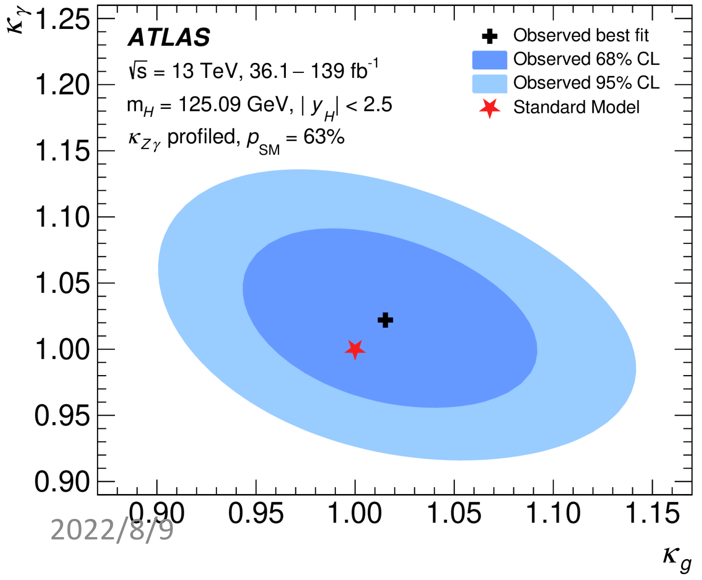
$\kappa_V = 1.035 \pm 0.031$

$\kappa_F = 0.95 \pm 0.05$



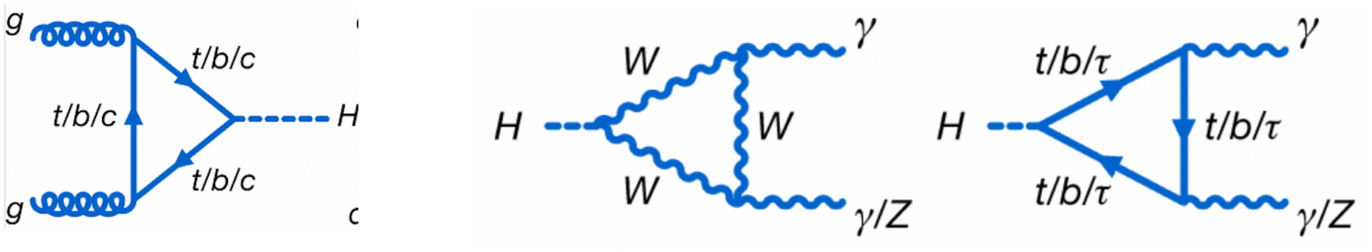
Effective couplings of loop contributions





Effective coupling modifiers of loop-induced production (**ggF**) and decays ($H \to gg, H \to \gamma\gamma, H \to Z\gamma$): $\kappa_g, \kappa_\gamma, \kappa_{Z\gamma}$

ggF $\quad\quad$ $\gamma\gamma, Z\gamma$



- ◆ $B_{inv.} = B_{u.} = 0$
  - ◆ SM compatibility (p_{SM}) is **63%**
- ◆ $B_{inv.}, B_{u.}$ **free-floating**
  - ◆ SM compatibility (p_{SM}) is **49%**
  - ◆ upper limits of $B_{inv.}$ is **0.16 (0.09)** and that of $B_{u.}$ is **0.10(0.18)** @ 95% CL

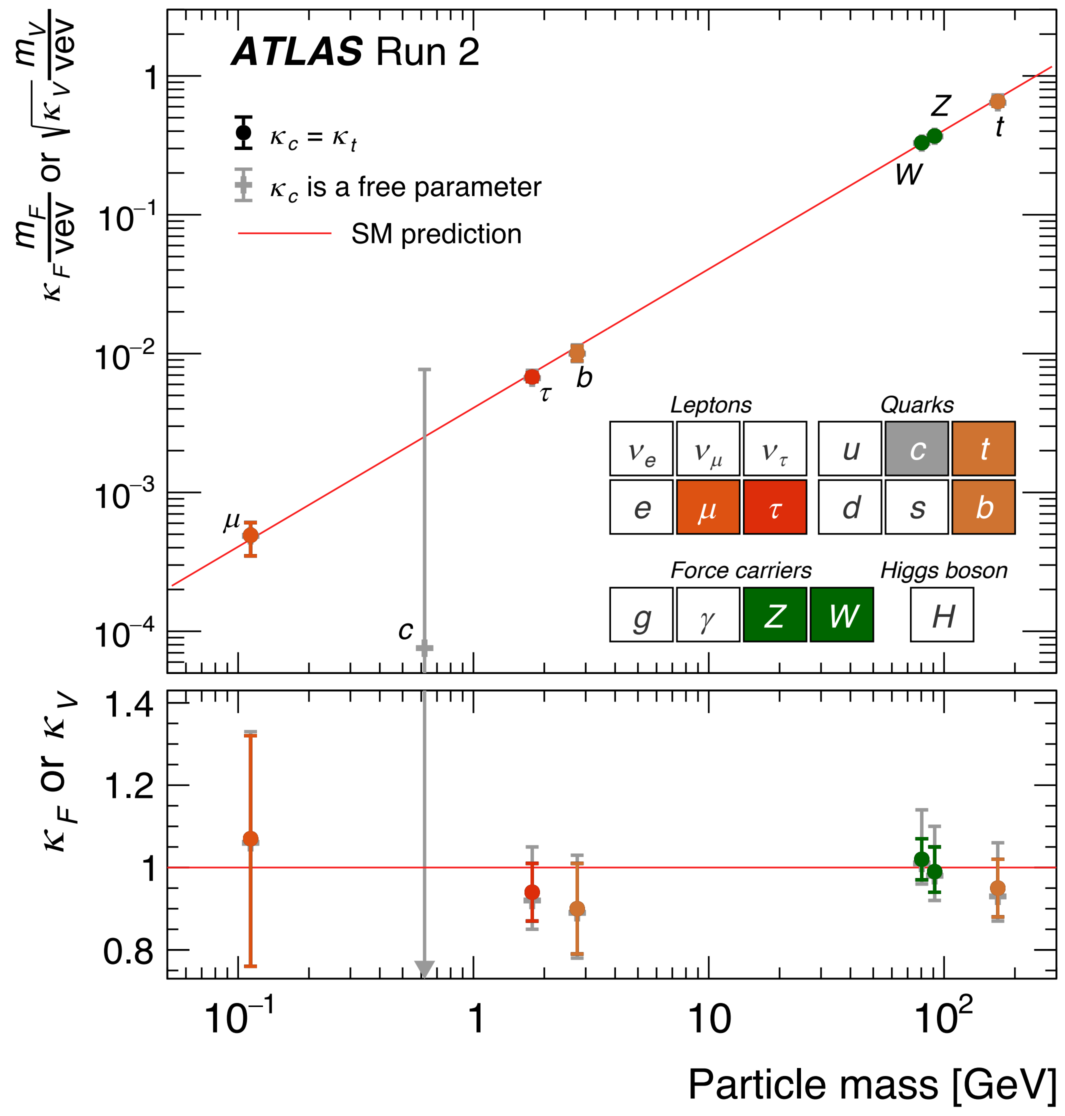
Direct couplings to SM particles

The coupling of Higgs to each SM particle treated independently: W, Z, t, b, c, μ, τ with following assumptions:

- All the modifiers are positive
- Only SM particles contribute to loop-induced processes
- Invisible and undetected decays not considered

- $\kappa_c = \kappa_t$, exclude κ_c to cope with its low sensitivity
  - Precision of fermions (t, b, τ) between **7%-12%,** while that of vector bosons (W, Z) around **5%**

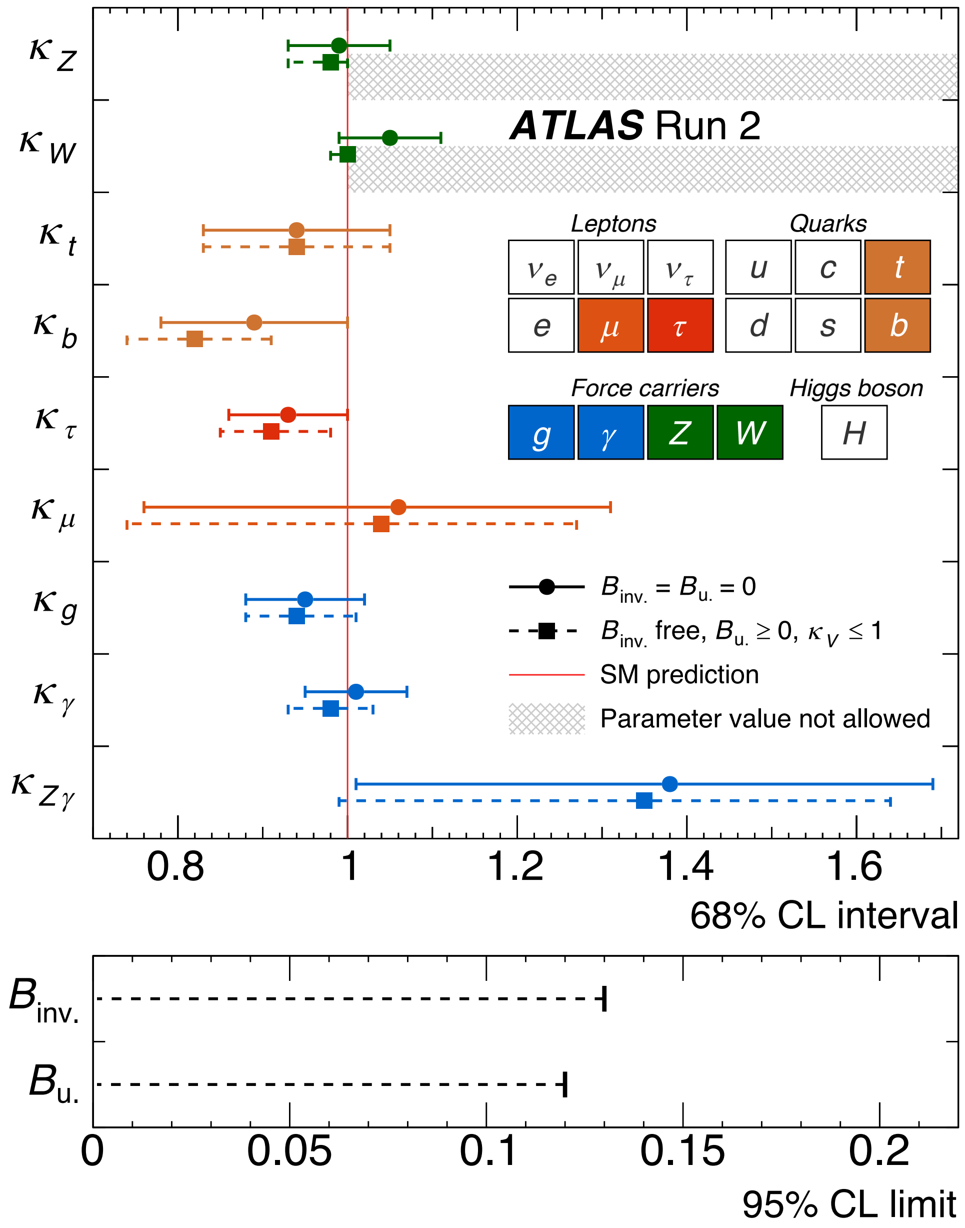
- **κ_c free-floating**, to study constraint on coupling to c quark
  - hint of constraint on κ_c observed with a upper limit of **5.7(7.6) x SM** @95% CL, largely improved w.r.t **8.5(12.4) x SM** in individual $H \to cc$



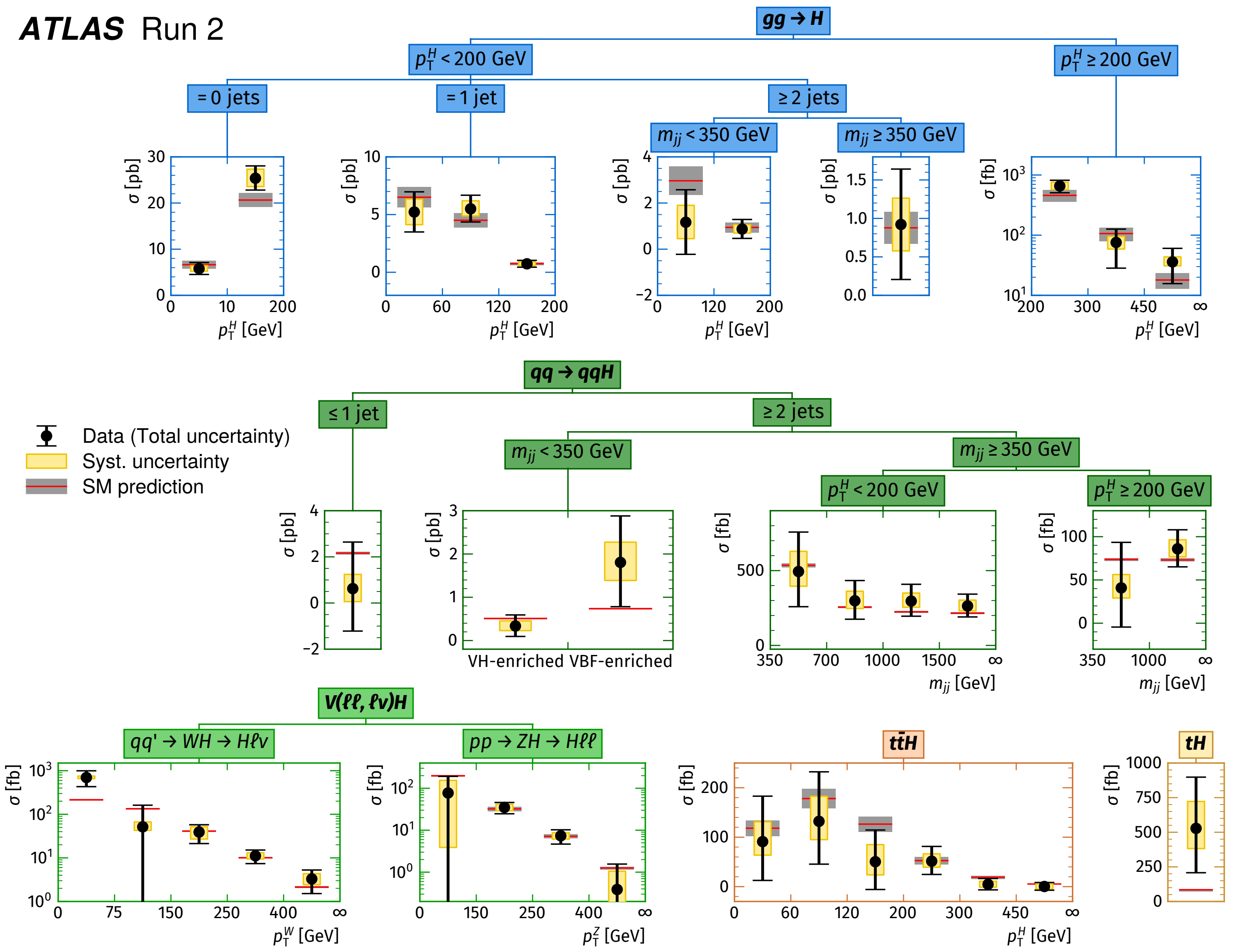
Generic kappa model

Besides the direct couplings to SM particles in the last model, the effective coupling modifiers of loop contributions treated independently as well

- $B_{inv.} = B_{u.} = 0$
  - p-value of SM compatibility is **61%**
- $B_{inv.}$ **free,** $B_{u.} \geq 0, \kappa_V \leq 1$
  - the assumption of $B_{u.} \geq 0, \kappa_V \leq 1$ raised to avoid degenerate solutions.
  - Upper limit of $B_{inv.}$ is **0.13(0.08)** and that of $B_{u.}$ is **0.12(0.21)** @ 95% CL, improved w.r.t $B_{inv.}$< **0.145(0.103)** from direct ATLAS searches



STXS measurements (36 kinematic regions)



- **Simplified template cross-sections (STXS)** partitions Higgs production phase space into a set of kinematic regions defined by properties of Higgs or associated jet, W/Z boson
- The goal is to **provide sensitivity to BSM effects, avoid large theory uncertainties** in these predictions, and **minimize the model-dependence** of acceptance extrapolations
- All the measurements compatible with SM predictions, with a p_{SM} of **94%**

Summary

- An unprecedented number of Higgs production and decay processes are combined, where almost all input measurements upgraded to full Run2 dataset. The measurements of Higgs properties and couplings show pretty good agreement with SM, with an unprecedented precision.

- Much progress made w.r.t Run1!
  - All major production modes and decays observed with larger significance.
  - Hints of rare Higgs productions and decays seen.
  - The coupling strength modifiers to SM particles measured with a higher precision, and the constraints on BR of non-SM decays improved significantly as well.

- Look forward to even more precise Higgs coupling measurements in LHC Run3!