H(125) General combination in the ATLAS experiment

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Higgs Hunting 2022

12-14/09/2022

Outline

- Global signal strength
- Production cross sections and Decay modes
- The couplings in the kappa framework
  - Fermions VS Bosons
  - Direct couplings to the SM particles and effective couplings to gluons and photons
- From the Global signal strength to the differential cross sections
  - Simplified cross sections
  - Differential cross sections to extract the Yukawa couplings

Based on Nature 607, 52–59 (2022) and CERN-EP-2022-143, sub. to JHEP.

Input analyses

A measurement based on a combined likelihood constructed from the latest ATLAS SM Higgs analyses, to get more sensitive and less model-dependent results on Higgs interactions:

- Nature 607, 52–59 (2022)
- Almost all measurements updated with the LHC full Run-2 dataset

Decay mode	Targeted production processes	$\mathcal{L}$ [fb^{-1}]
$H \to \gamma\gamma$	ggF, VBF, $WH, ZH, t\bar{t}H, tH$	139
$H \to ZZ$	ggF, VBF, $WH + ZH, t\bar{t}H + tH$	139
	$t\bar{t}H + tH$ (multilepton)	36.1
$H \to WW$	ggF, VBF	139
	WH, ZH	36.1
	$t\bar{t}H + tH$ (multilepton)	36.1
$H \to Z\gamma$	inclusive	139
$H \to b\bar{b}$	WH, ZH	139
	VBF	126
	$t\bar{t}H + tH$	139
	inclusive	139
$H \to \tau\tau$	ggF, VBF, $WH + ZH, t\bar{t}H + tH$	139
	$t\bar{t}H + tH$ (multilepton)	36.1
$H \to \mu\mu$	ggF $+ t\bar{t}H + tH$, VBF $+ WH + ZH$	139
$H \to c\bar{c}$	$WH + ZH$	139
$H \to$ invisible	VBF	139
	ZH	139

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Global signal strength

Considering all production and decay modes together:

$$\mu = \frac{\sigma \times \mathrm{B}}{(\sigma \times \mathrm{B})_{\mathrm{SM}}}$$

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

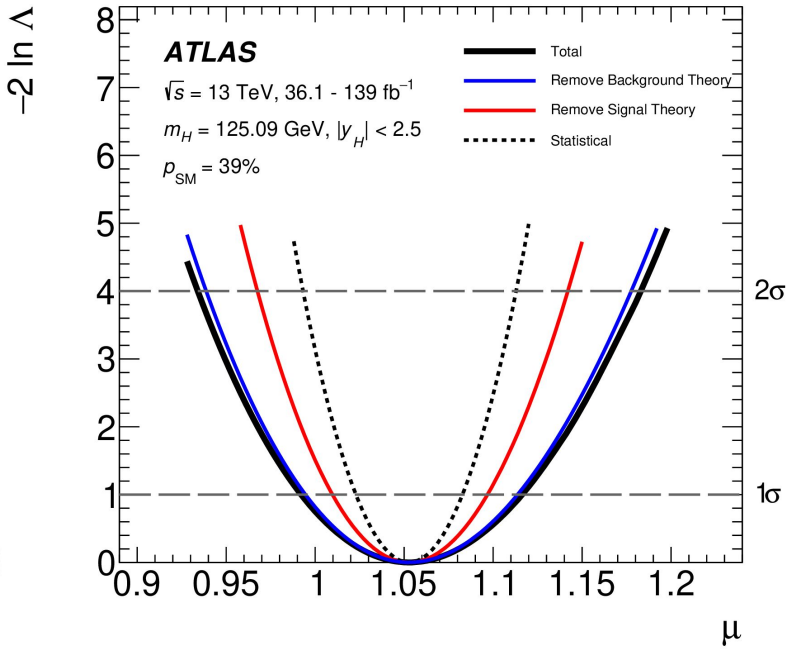
SM predictions following LHCHXSWG prescriptions

- SM compatibility (p-value): 39%

Experimental and theory uncertainties reduced by a factor of 2 wrt Run 1 result

- ATLAS+CMS (Run 1 combination):

$$1.09^{+0.11}_{-0.10} = 1.09^{+0.07}_{-0.07}(\text{stat.})^{+0.04}_{-0.04}(\text{exp.})^{+0.07}_{-0.06}(\text{sig. th.})^{+0.03}_{-0.03}(\text{bkg. th.})$$



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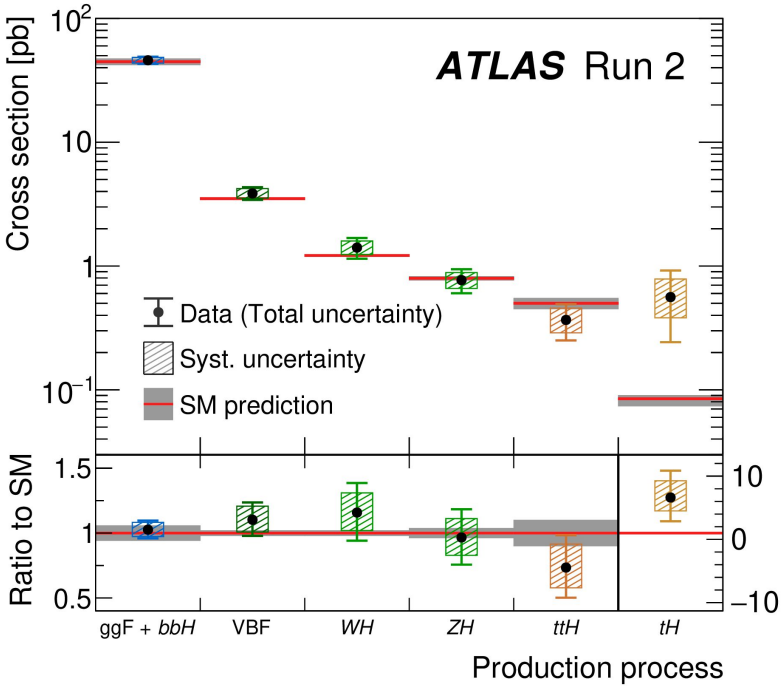
Production cross-sections



How: Branching ratios are assumed to be SM-like when combining processes and measurements

Highlights:

- SM compatibility (p-value): 65%
- ggF now at precision of 7%
- VBF now at precision of 12%

All major production have been observed:

- WH is observed with 5.8σ (5.1σ expected),
- ZH with 5.0σ (5.5σ)
- ttH+tH with 6.4σ (6.6σ)

Rare production mode:

- Upper limit on tH of 15(7) x SM at 95% C.L.
  - Strong correlation with ttH

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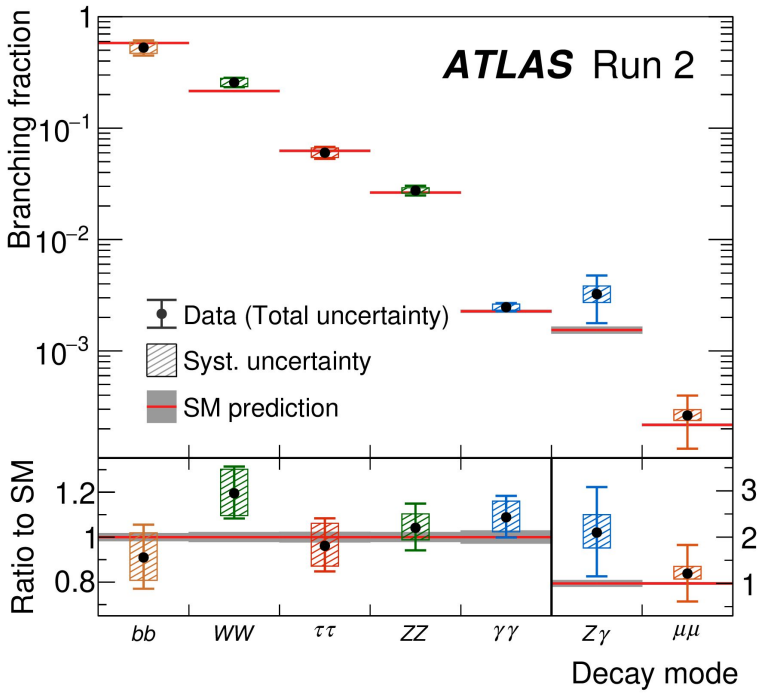
Decay Modes



How: Production modes are assumed to be SM-like when combining processes and measurements

Highlights:

SM compatibility (p-value): 56%

All major decay modes have been observed:

- BR(bb) now at precision of 14%
- BR(ττ), BR(WW), BR(ZZ) and BR(γγ) now at precision of 10-12%

Rare production mode:

- Significance for H→μμ 2.0σ (1.7σ)
- Significance for H→Zγ 2.3σ (1.1σ)

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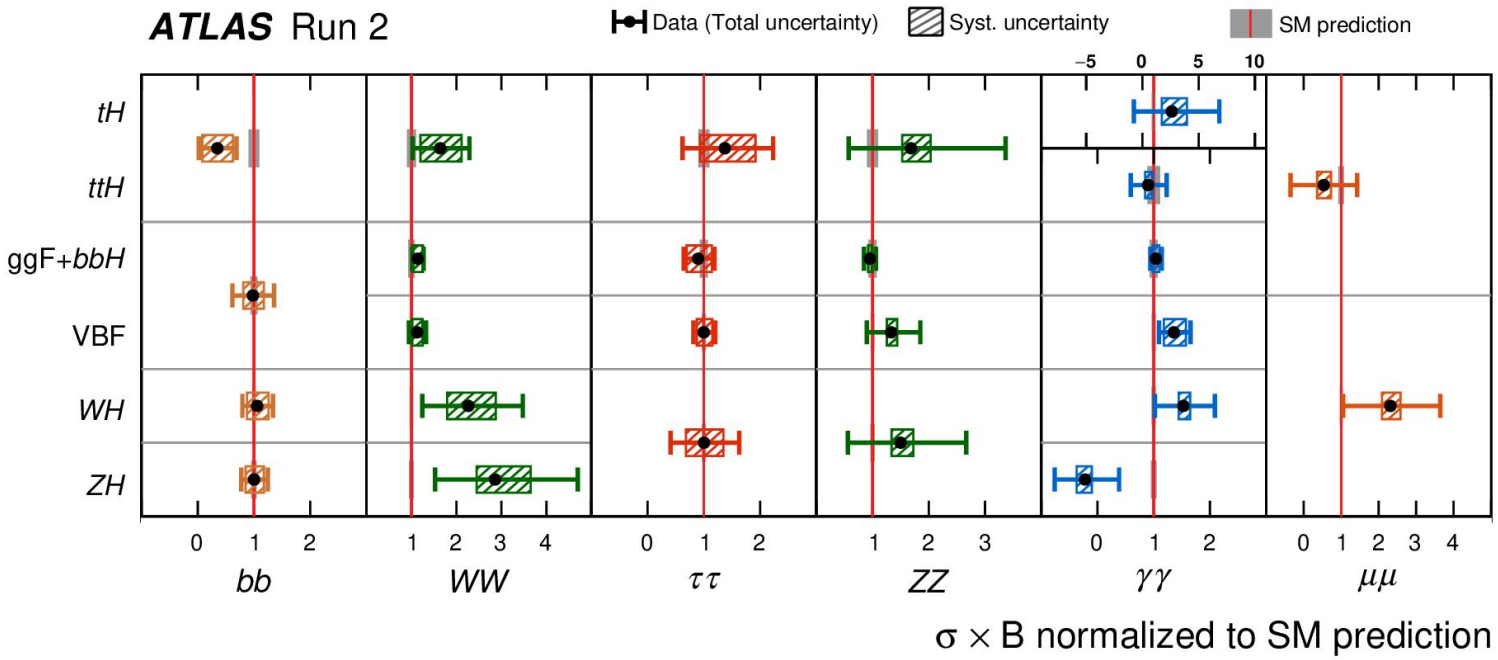
The complete portrait: Production and Decay

Measurements for all available cross sections and branching ratios

Assumptions on SM-BR relaxed - SM compatibility (p-value): 72%



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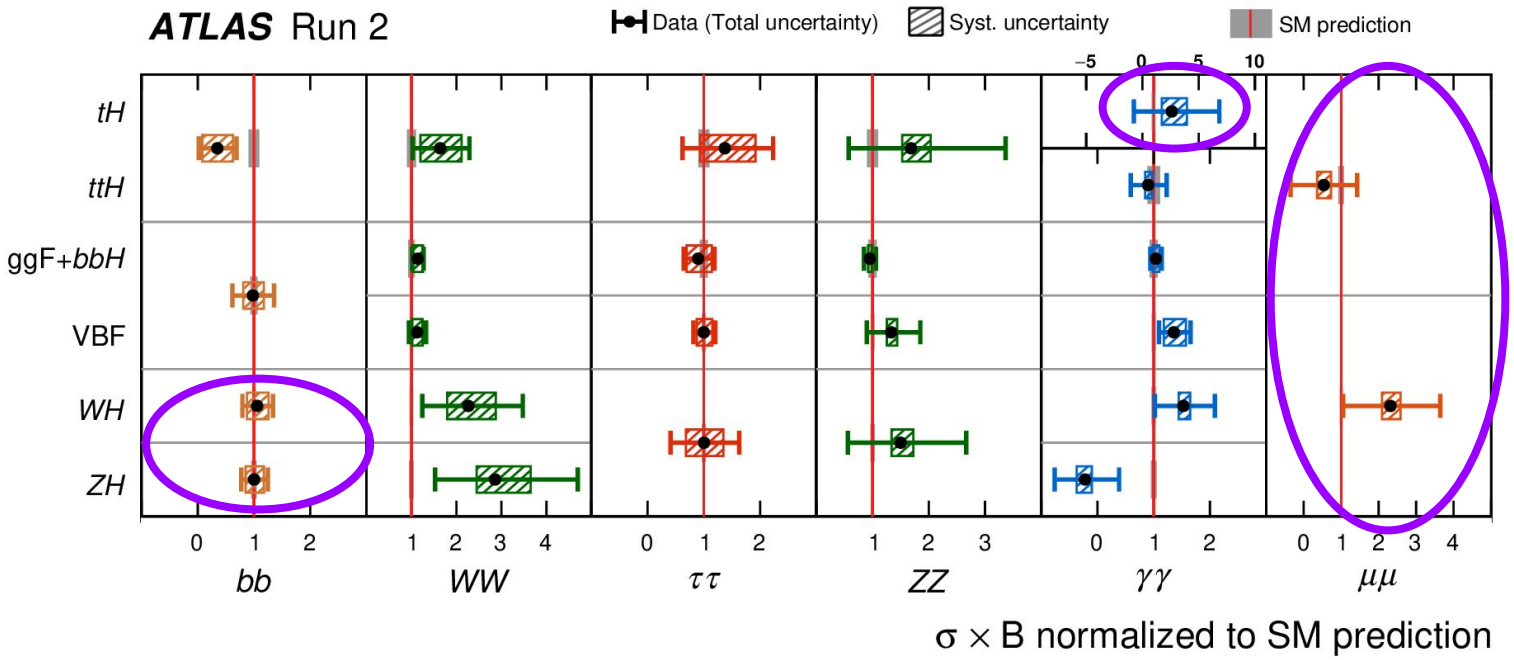

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“kappa” framework

Use the LO coupling modifier to probe for rate deviations from the SM.

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

Introduce one scale factor κ per SM particle with observable "Higgs coupling” at the LHC: κ_W, κ_Z, κ_t, κ_b, κ_τ, etc.

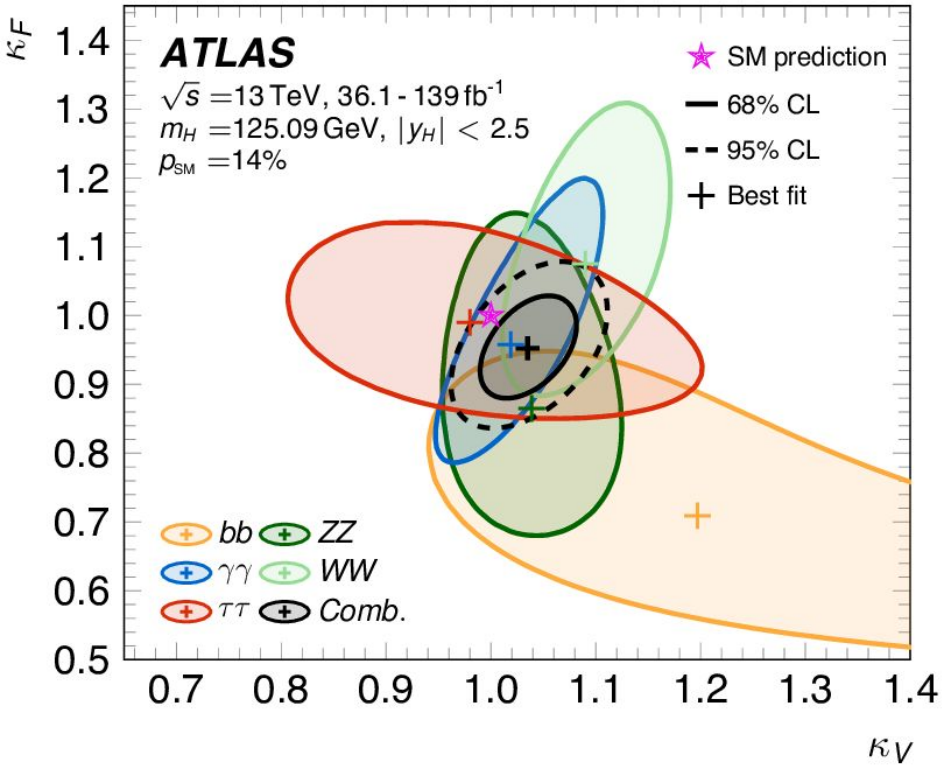
First Model:

A single coupling modifier for vector bosons κ_V and another for fermions κ_F

Loop processes resolved according to the SM particles that contribute to them

Highlights:

SM compatibility (p-value): 14%



$$\kappa_V = 1.035^{+0.031}_{-0.031}$$

$$\kappa_F = 0.95^{+0.05}_{-0.05}$$

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Effective coupling of loop contributions

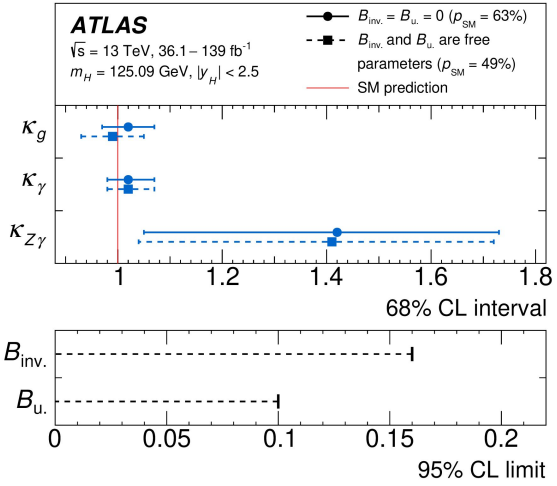
Capture all loop contributions to the Higgs interaction with gluons and photons

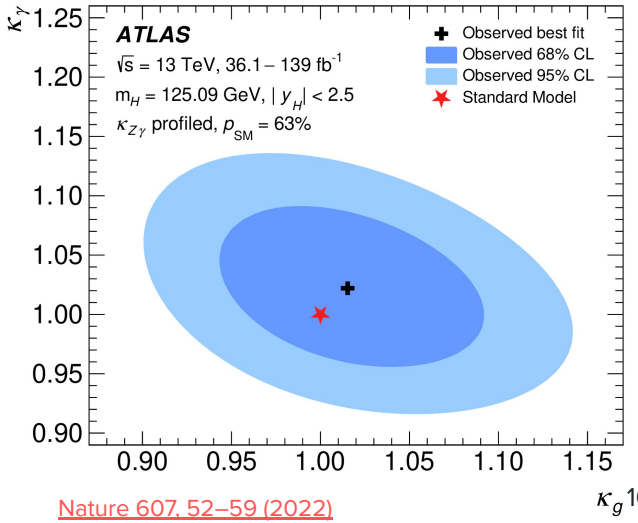
How: Assign coupling modifiers of ggF (κ_g), H→γγ (κ_γ) and H→Zγ ($\kappa_{Z\gamma}$)

Two scenarios: with and without invisible and undetected non-SM Higgs decays.

Highlights:

- SM compatibility (p-value): 63% ($B_{inv} = B_u = 0$)
- Upper limits on B_{inv} of 0.16 (0.09) and B_u of 0.10 (0.18) at 95% CL





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Coupling to each particle

How:

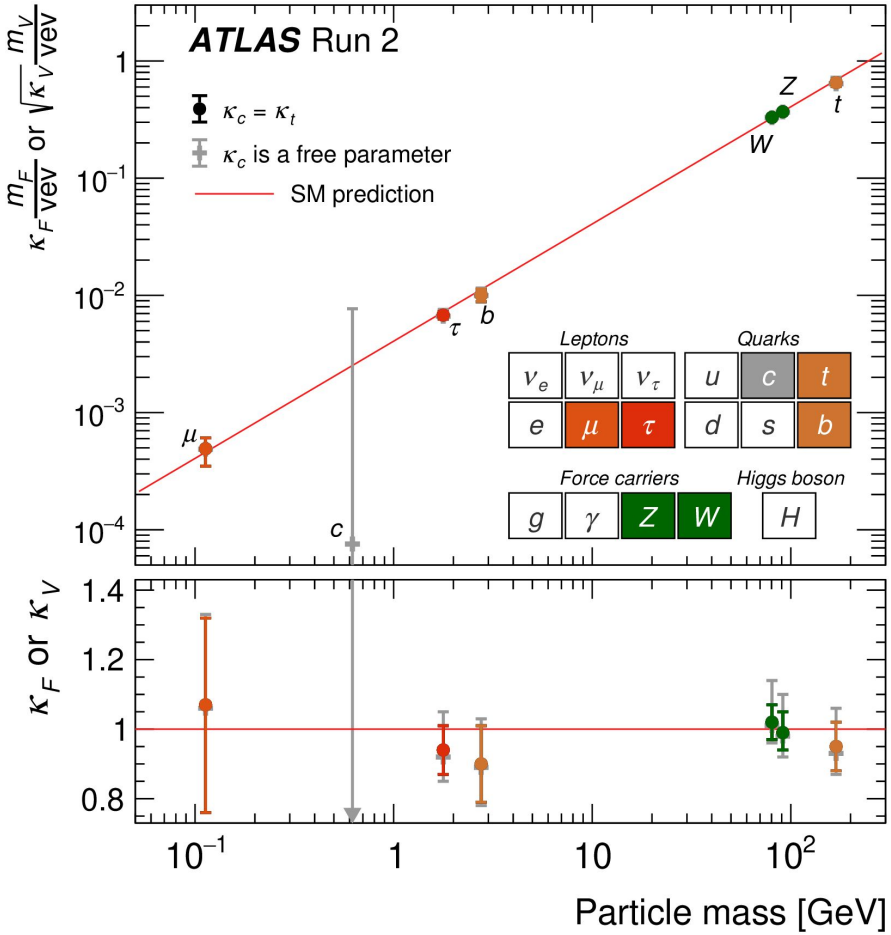
- All modifiers assumed to be positive
- Only SM particles in loop processes
- No invisible or undetected non-SM Higgs decays
- Two setups: with and without κc to cope with low sensitivity

Highlights:

SM compatibility (p-value):
56% ($\kappa_c=\kappa_t$) and 65% (κ_c free-floating)

Coupling precision:

- Fermions (t, b, τ): 7% -12%
- Vector bosons (W, Z): 5%
- Upper limit on κc of 5.7 (7.6) x SM at 95% CL



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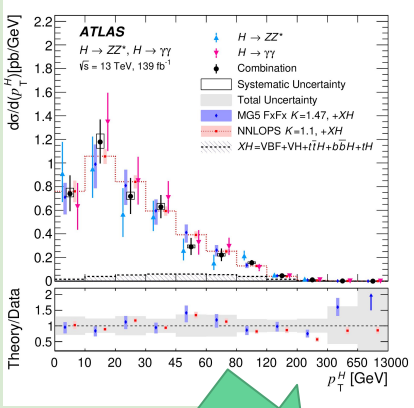
Constraints on b- and c-quark Yukawa couplings via p_T^H

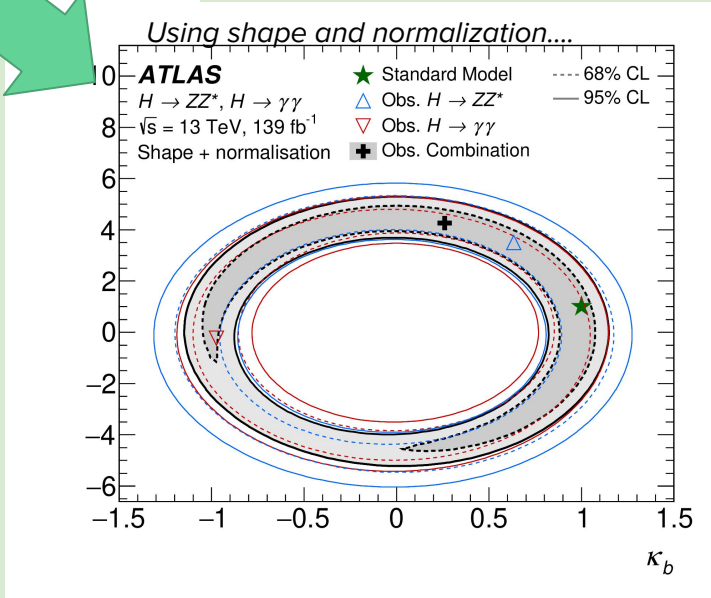
Heavy quark production can be enhanced at low p_T^H due to interference between ggF and quark-initiated production (1606.09253)

⇒Constrain Higgs couplings modifiers κ_c and κ_b with shape of the p_T^H distribution Limit extraction relies on accuracy of QCD radiation estimates!

Other tree-level couplings assumed to be SM



See Ruggero's talk for more details



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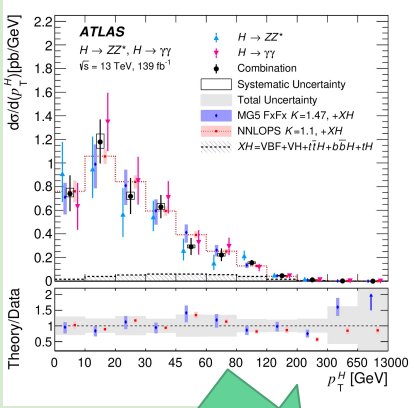
Other tree-level couplings assumed to be SM

Can combine with VH(→ bb, cc) measurements

(SM rate for c-quark is ~ 400 smaller than for b-quarks)



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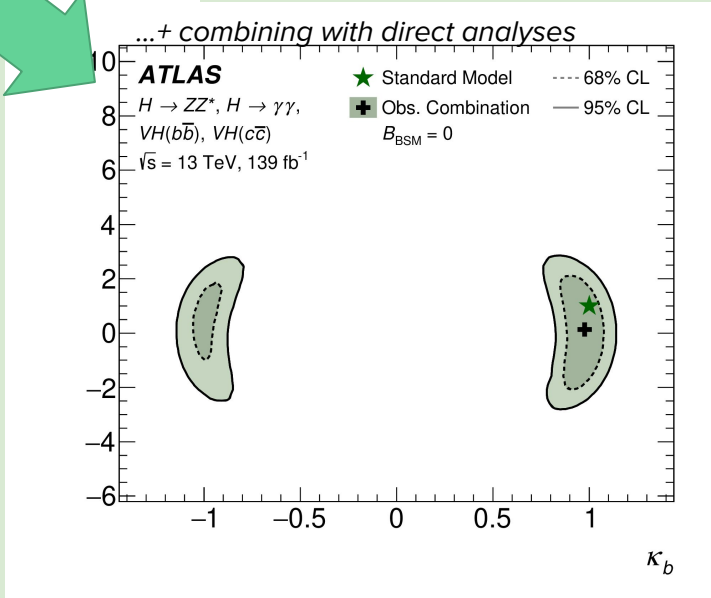

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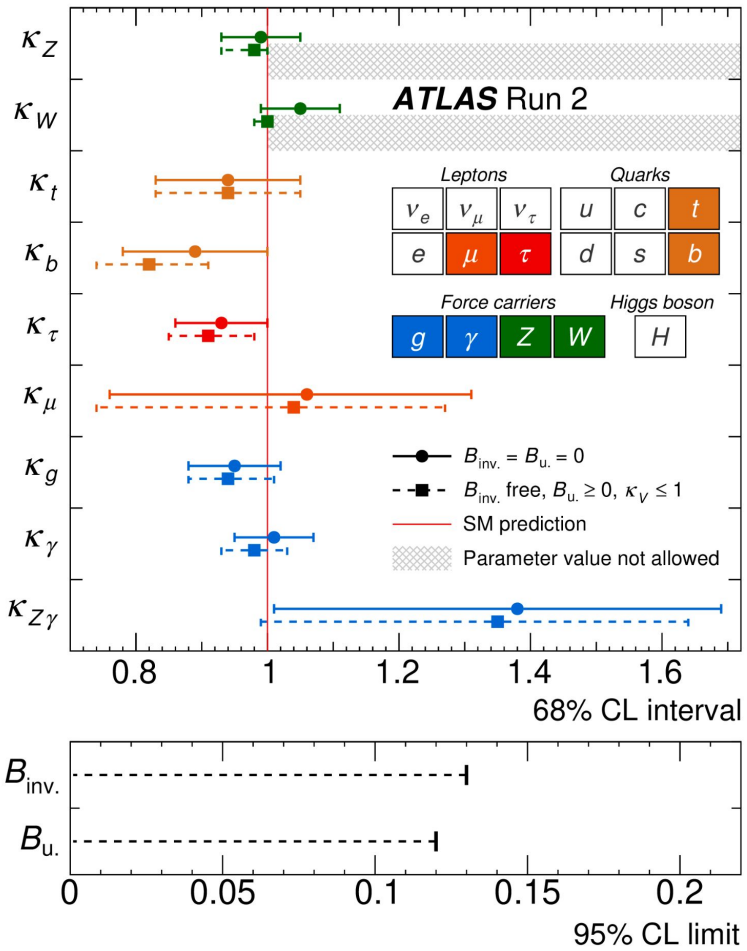
Generic coupling

How: Similar to previous setup with this time allowing for non-SM particles in loop processes, with effective coupling strengths.

Two scenarios: with and without invisible and undetected non-SM Higgs decays.

Highlights:

- SM compatibility (p-value): 61% ($B_{inv} = B_u = 0$)
- Upper limits on B_{inv} of 0.13 (0.08) and B_u of 0.12 (0.21) at 95% CL
  - To include B_{inv} and B_u one has to add some extra constraint ($\kappa_V \leq 1$)



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Going beyond the complete portrait: STXS framework

STXS (Simplified Template Cross Sections)

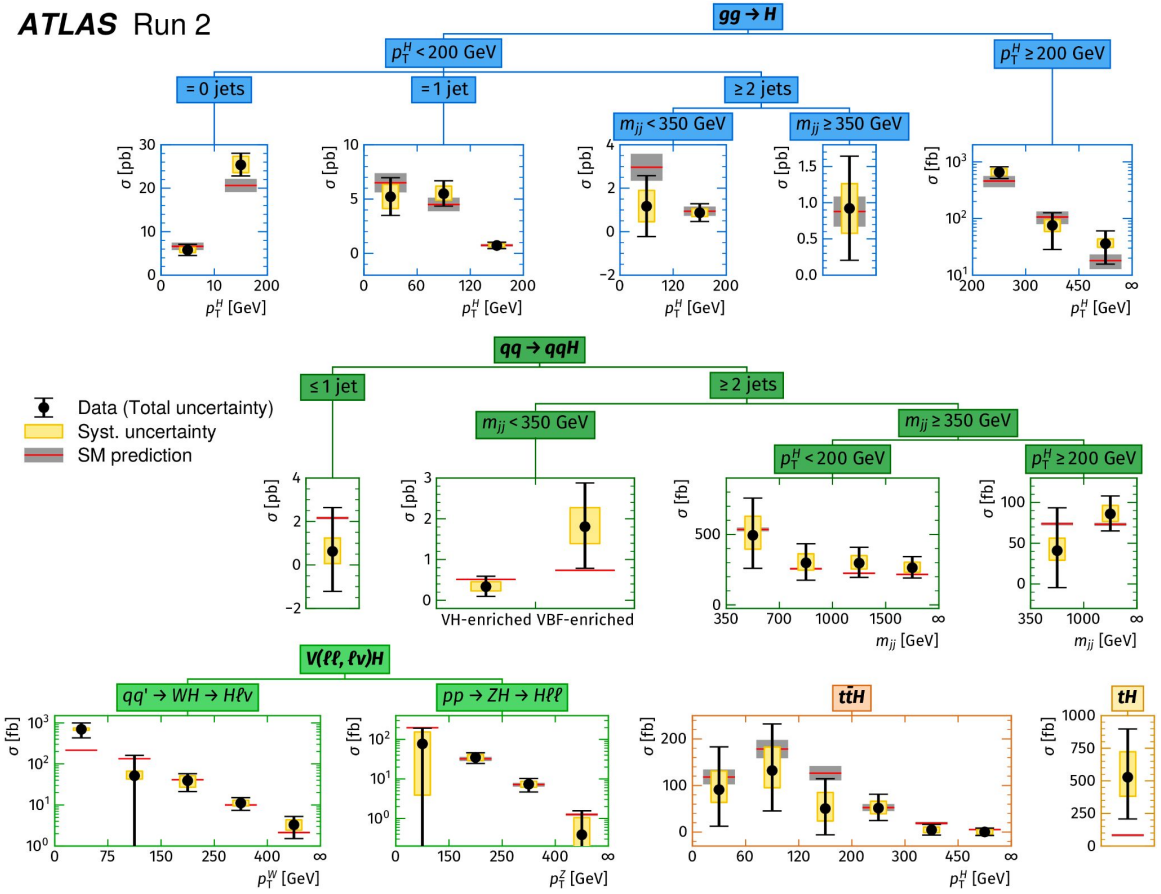
- Get sensitivity to BSM effects,
- Minimise acceptance extrapolations
- Avoid large theory uncertainties

How:

Split phase space of Higgs production processes into 36 kinematic regions

Branching ratios and kinematics of Higgs boson decays are assumed to be SM-like

Highlights: SM compatibility (p-value): 92%



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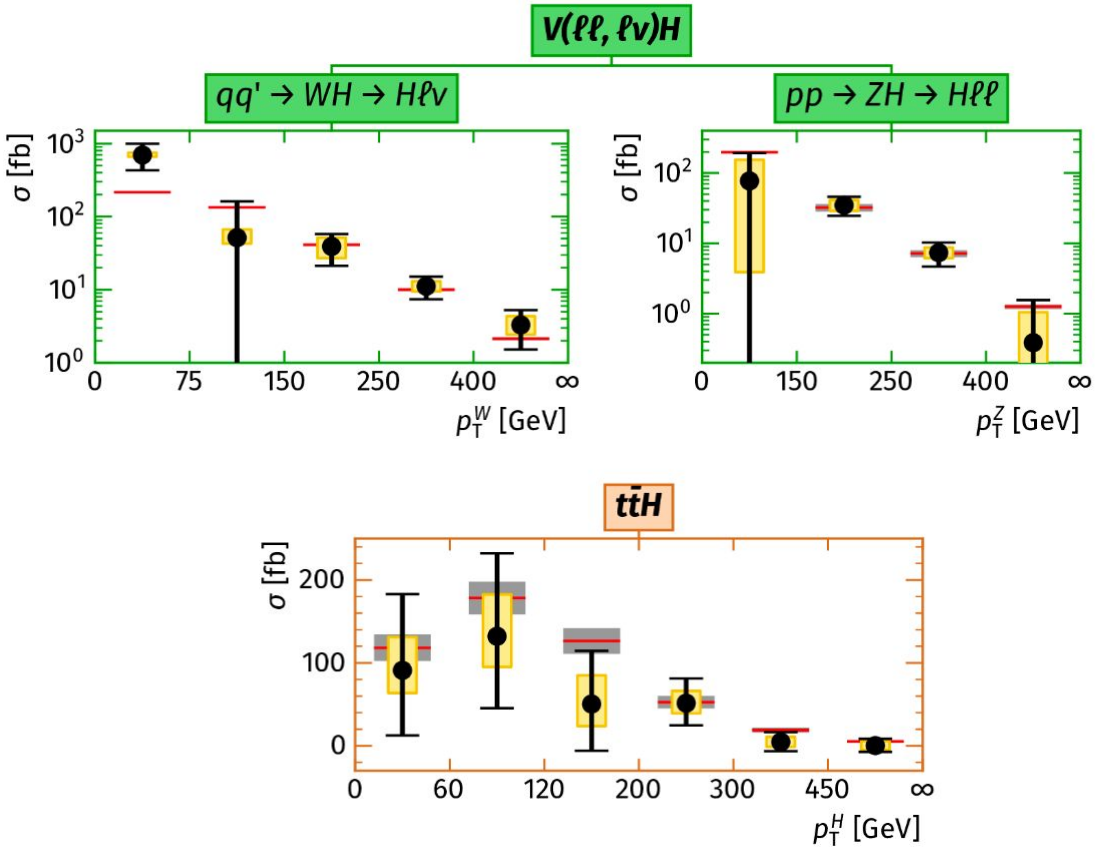

... a way to go differential for more complex and less abundant production modes...

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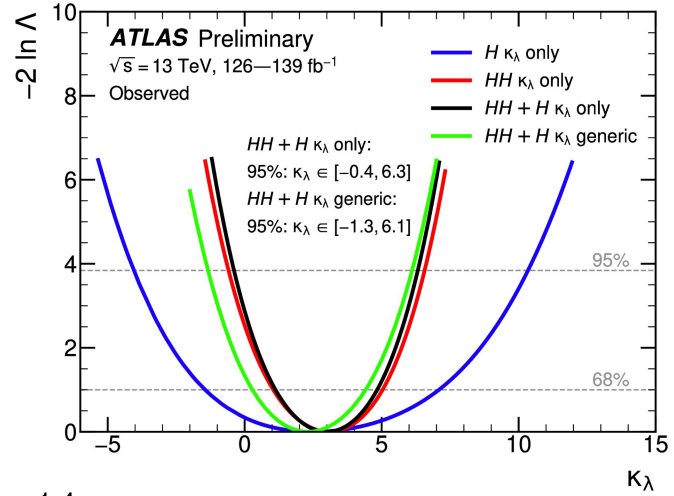
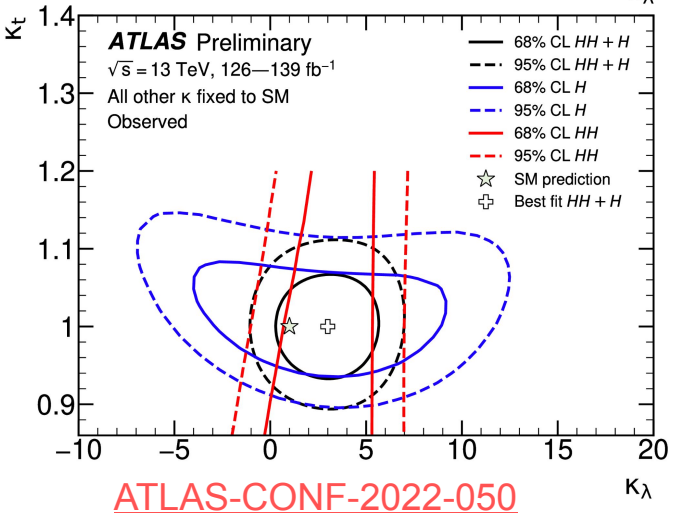
Summary

In the 10 years since the Higgs discovery, many measurements have been performed by the ATLAS collaboration, with confirmation that the properties of the Higgs Boson show good agreement with the SM.

- All main production and decay modes have been observed
- Hints of rare Higgs decays have been seen
- Total and differential cross sections have been presented and used to extract information on the Higgs couplings.
- Kinematic dependence of production cross sections has been studied across a wide range of phase space
  => Already used in the determination of Higgs self coupling.

Stay tuned for even better results from LHC Run 3!





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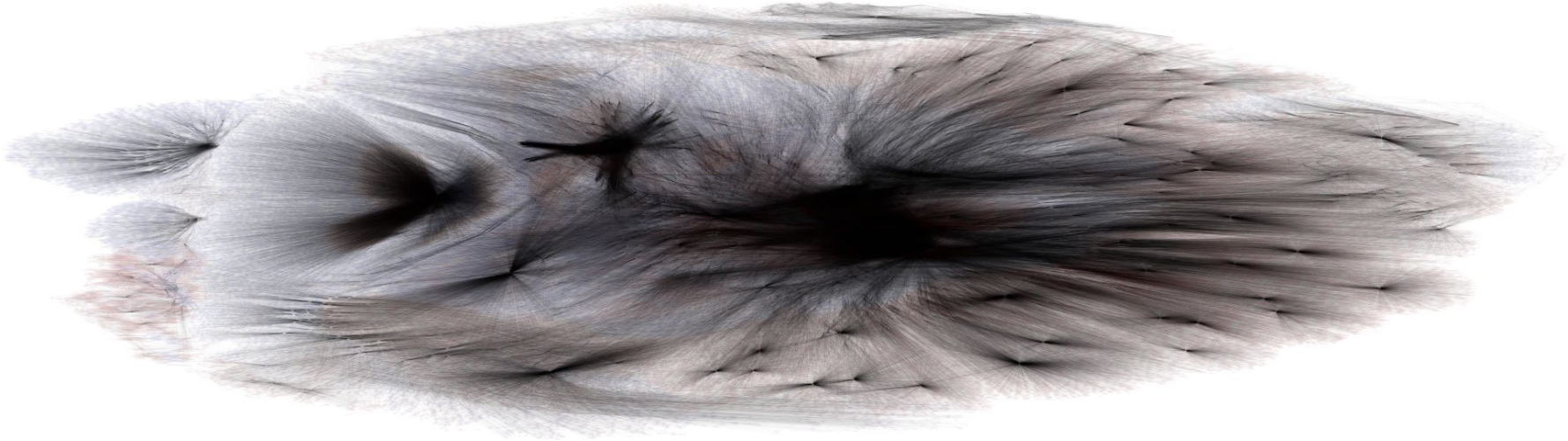
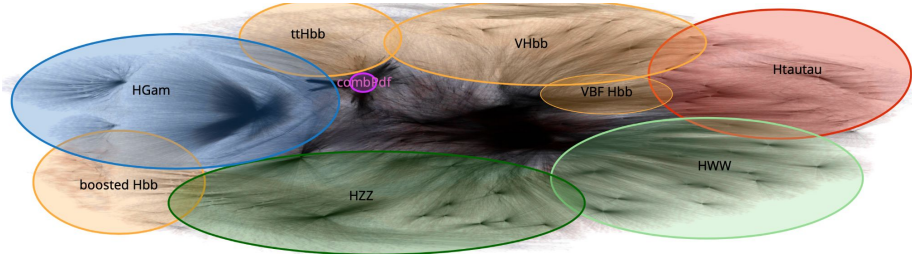
Thank you!



The Higgs Galaxy

Backup

The model



Measurement based on LR $\Lambda(\alpha) = \frac{L(\alpha, \hat{\hat{\theta}}(\alpha))}{L(\hat{\alpha}, \hat{\theta})}$,

In the asymptotic regime, $\lambda(\alpha) = -2\ln(\Lambda(\alpha))$ follows a χ^2 distribution.

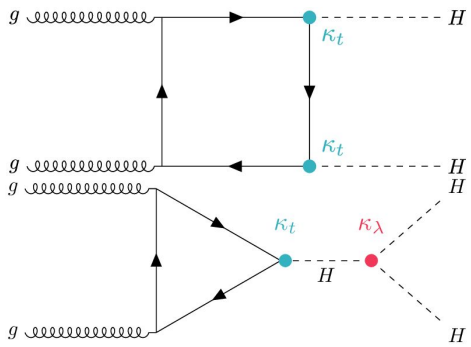
Over 2600 systematic uncertainties.

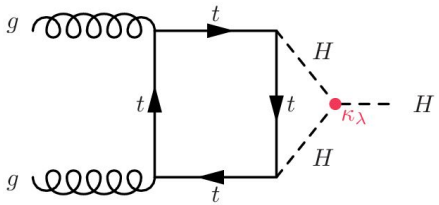
Main experimental systematics:

- Global signal strength:

- luminosity measurement (1.7%),
- electron (~1%)
- jet and b-jet reconstruction (~1%)
- data-driven background modelling (~1%)
- limited number of simulated events (~1%)

...and the self coupling?





- κ_λ mostly determined by the HH production.
- κ_t plays an important role in HH.
- H+HH allows a combined determination of the couplings.
- H measurements are sensitive to κ_λ too (NLO electroweak corrections)
  - kinematic dependence => STXS measurements are used

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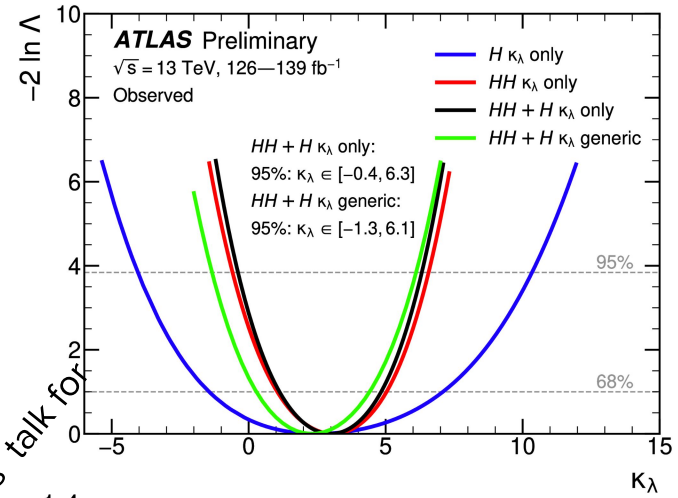
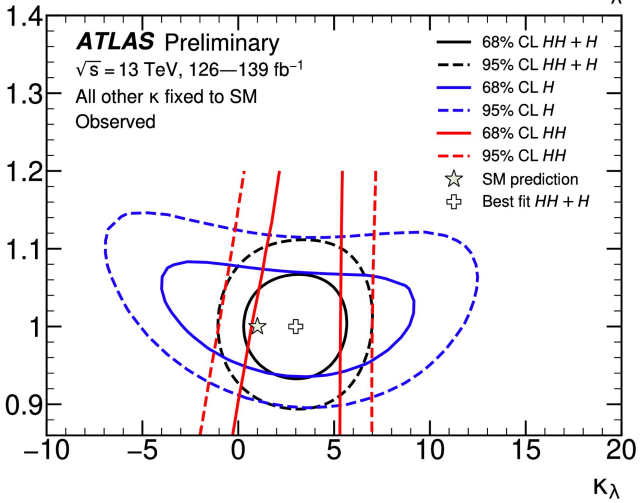
See Zhe Yang's talk for more details





Projection for HL-LHC

Precision foreseen for HL-LHC

- 2% error on κ for vector bosons
- 3-4% error on κ for fermions

In all the input channels, QCD scale and Parton Showers are leading systematics.

Experimental syst.:

In productions with jets (i.e. VBF), jet flavour composition among the leading systematics

Pile-up entering mostly in the isolation and identification of the objects.

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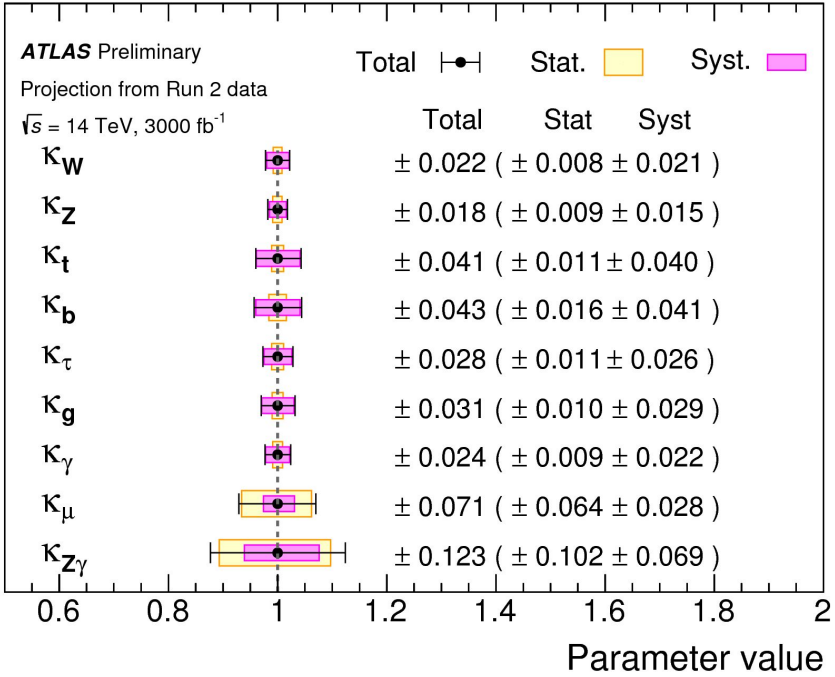


“kappa” framework

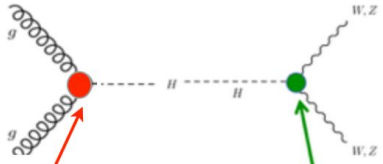
With known Higgs boson mass, the SM Higgs sector is fixed.

Use the LO coupling modifier to probe for rate deviations from the SM.

Introduce one scale factor κ per SM particle with observable "Higgs coupling” at the LHC: κ_W, κ_Z, κ_t, κ_b, κ_τ, etc.

Example: ggF→H→WW (or ZZ)

Effective κ

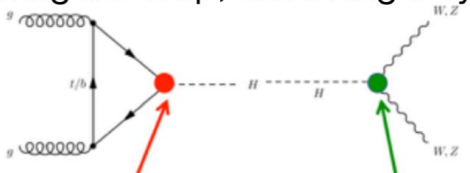


$\sigma_{ggF} = \kappa_g^2\ \sigma_{ggF}(SM)$

$\Gamma_{W,Z} = \kappa^2_{W,Z}\Gamma_{W,Z}(SM)$

or

Resolving the loop, assuming only SM



$\sigma_{ggF} = (1.06\ \kappa_t^2 + 0.01\kappa_b^2 - 0.07\kappa_b\kappa_t)\ \sigma_{ggF}(SM)$

$\Gamma_{W,Z} = \kappa^2_{W,Z}\Gamma_{W,Z}(SM)$

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Fiducial and differential measurements

Cross sections and kinematic distributions are measured in space defined by the detector acceptance

The strategy: Define fiducial regions that matches these spaces

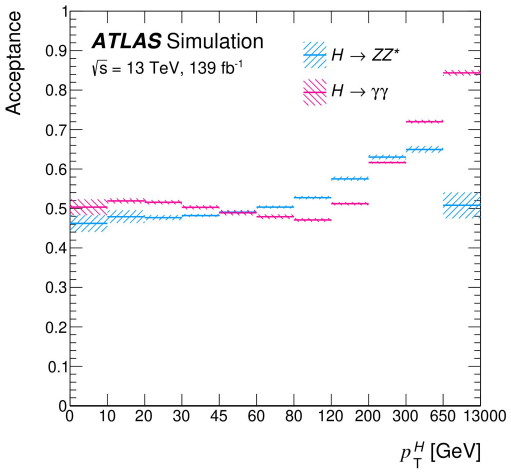
- it includes minimum physics assumptions in the measurement
- it allows for easy comparison of physics models today and in the future.

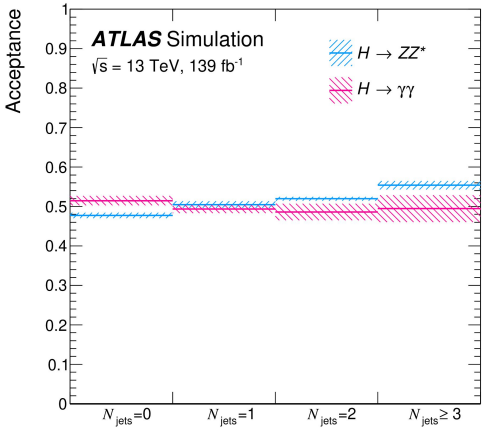
Measurements are corrected for detector response with an unfolding procedure.

This approach is used for H→γγ and H→4l measurements. When combining, one must "correct"/"unfold" to the full phase space since fiducial regions are different.

Combined measurements in CERN-EP-2022-143, sub. to JHEP:

- Higgs: p_T, $|y|$, p_T vs $|y|$, Jets: N_{jets}, p_T^{j1}



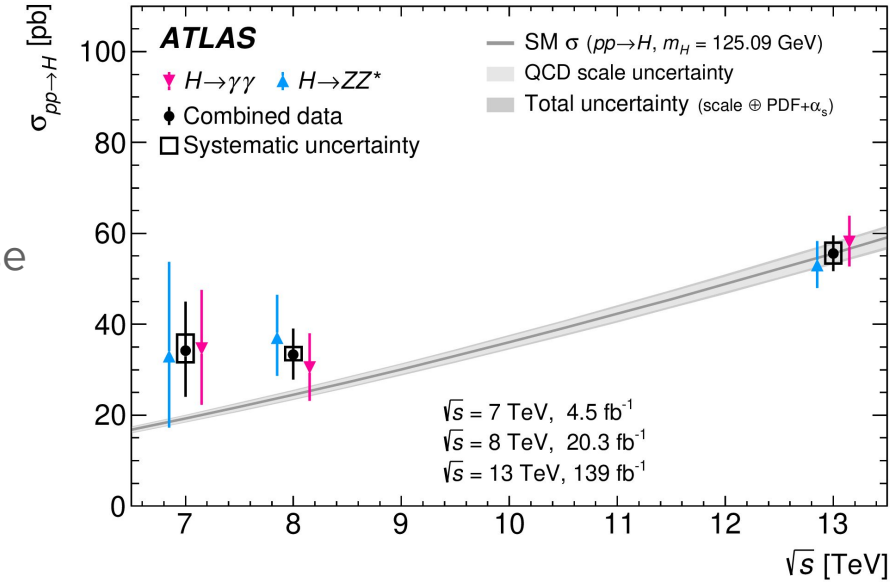


CERN-EP-2022-143, sub. to JHEP

Total cross section

- Total x-sec for H→4l and H→γγ in fiducial phase space
- Total combined x-sec is full phase space

Note: BR(γγ) ~ 19 BR(4l) Similar precision due to different background S/B



13 TeV x-sec	Obs	uncert	SM	uncert	Obs/SM
H4l fid (fb)	3.28 ± 0.32	10 %	3.41 ± 0.18	5 %	0.96 ± 0.11
Hγγ fid (fb)	67 ± 6	9 %	64 ± 4	6 %	1.05 ± 0.11
Comb tot (pb)	$55.5^{+4.0}_{-3.8}$	7 %	55.6 ± 2.8	5 %	1.00 ± 0.09

CERN-EP-2022-143, sub. to JHEP

Differential cross section

Why: Higgs p_T probes the QCD modeling of the ggF production mechanism:

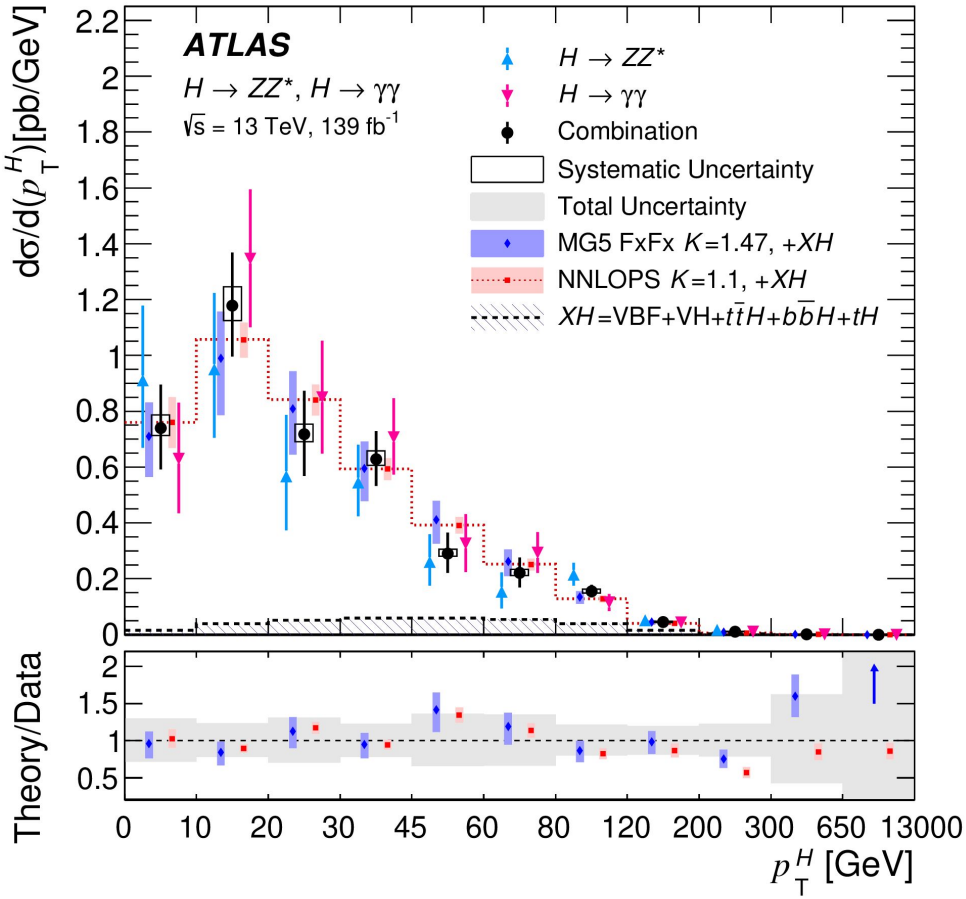
- low p_T: soft/collinear QCD emission (resummation) + **see next slide**
- high p_T: H + ≥1 jet (Fixed order calc) can expect BSM effects at high p_T

Highlights:

p-values: H→4l VS H→γγ: 20 %

p-values: Data VS MG5 FxFx: 73%

p-values: Data VS NNLOPS: 91%



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