Measurements of the Higgs boson properties and their interpretations with the ATLAS experiment

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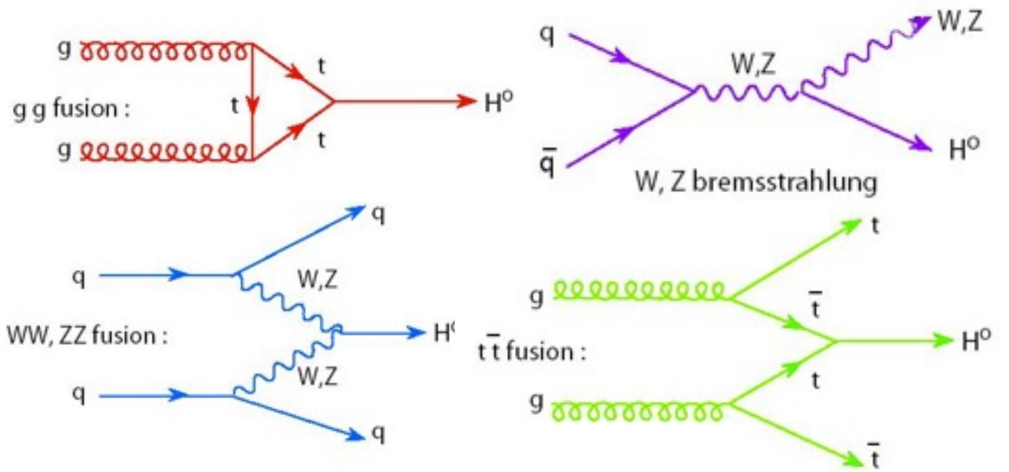
ATLAS is one of the multipurpose experiment working at the LHC at CERN

The Higgs production at LHC can occur through the following mechanisms:



ggF: is the dominant production mode, **$\sigma^{ggF}/\sigma^{TOT}$ = 87% @ 13 TeV.**

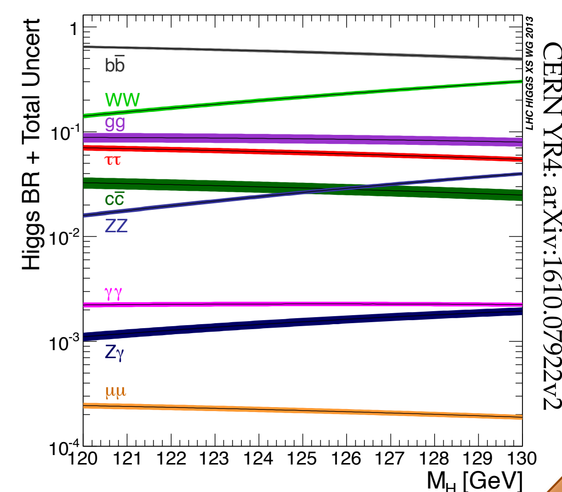
VBF: whose signature is characterized by H+2jet forward, **$\sigma^{VBF}/\sigma^{TOT}$ = 7% @ 13 TeV.**

VH: whose signature is composed by a H associated to a W or a Z boson, **σ^{VH}/σ^{TOT} = 4% @ 13 TeV.**

ttH-bbH: in which the H is associated to tt-bar/bb-bar pairs, **$\sigma^{ttH+bbH}/\sigma^{TOT}$ = 2% @ 13 TeV.**

Decay channels:

- H->ZZ*->4l: pure channel but very low statistics ($BR_{H\to ZZ^*\to 4l} \sim 2 \cdot 10^{-4}$)
- H->γγ : simple final state but low BR and large background
- H->WW*->lνlν: good sensitivity but low mass resolution
- H->bb-bar: huge bkg, best accesible via VH production
- H->ττ: very large bkg, best accesible via VBF and boosted H production
- H->Zγ & H->μμ: low BR



Introduction

In this presentation:

Run2: Higgs boson property measurements and their interpretations

- Production mode cross sections
- Simplified Template cross sections (STXS) analysis measures production in partitioned regions
- differential and fiducial cross sections analysis measures in a defined fiducial region that follows the experimental reconstructed signature
- combination and interpretations

More direct test of the SM ↑

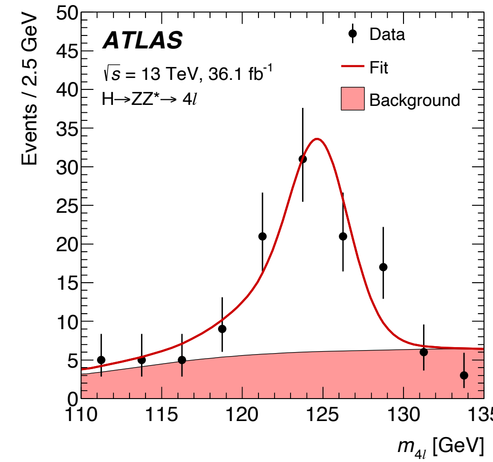
Couplings: μ_{ggF}, μ_{VBF}, … κ_g, κ_V, …

STXS: $\sigma_{ggF} \times BR(H \to \gamma\gamma)$ — Production mode separation

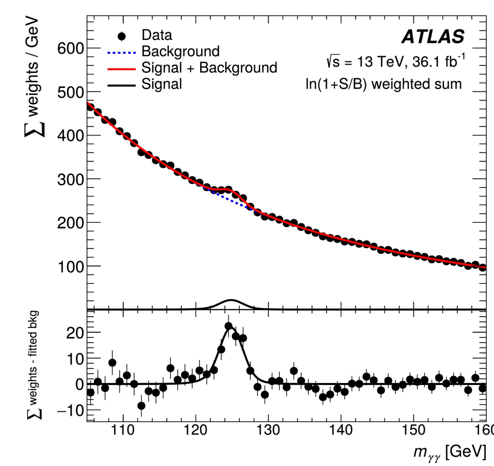
Fiducial xs: $\sigma_{incl} \times BR(H \to \gamma\gamma)$ — Inclusive in production mode

↓ Less assumptions

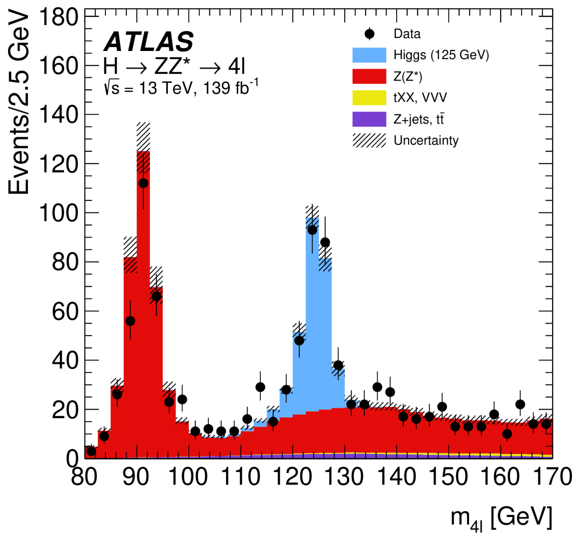
Run1+2 ATLAS Comb.
$m_H = 124.97 \pm 0.24$ GeV



$m_{ZZ^*} = 124.79 \pm 0.37$ GeV



$m_{\gamma\gamma} = 124.93 \pm 0.40$ GeV



Event selection (at most one quadruplet per event)

Mass requirements	50 GeV$< m_{12} <$ 106 GeV and 12 GeV $< m_{34} <$ 115 GeV
Lepton separation	$\Delta R(\ell_i, \ell_j) > 0.1$
J/ψ veto	$m(\ell_i, \ell_j) > 5$ GeV for all SFOS lepton pairs
Mass window	115 GeV $< m_{4\ell} <$ 130 GeV
If extra leptons with $p_T > 12$ GeV	Quadruplet with the largest ME
Rapidity	$\lvert y_H \rvert < 2.5$

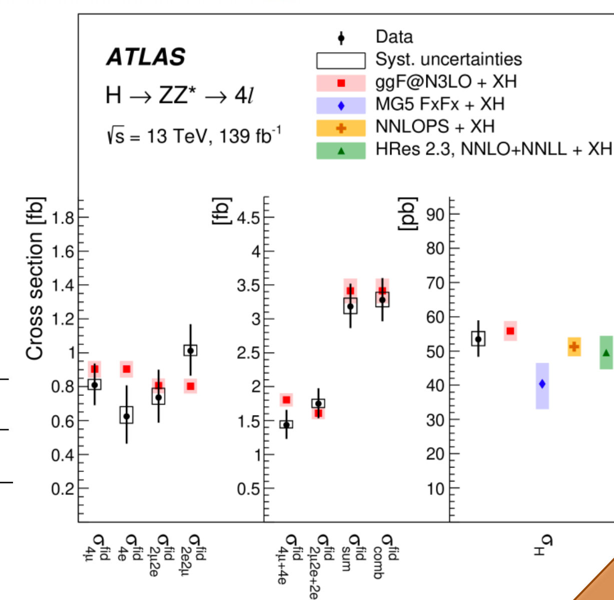
Signal extraction: Combined fit of the m_{4l} invariant mass distribution, bkg estimation from sidebands

Main systematics: Electron/muon reco and identification, efficiency and pileup uncertainties

$$\sigma \cdot \mathcal{B} \equiv \sigma \cdot \mathcal{B}(H \to ZZ^*) = 1.34 \pm 0.11(\text{stat.}) \pm 0.04(\text{exp.}) \pm 0.03(\text{th.})\ \text{pb} = 1.34 \pm 0.12\ \text{pb}$$

$$(\sigma \cdot \mathcal{B})_{\text{SM}} \equiv (\sigma \cdot \mathcal{B}(H \to ZZ^*))_{\text{SM}} = 1.33 \pm 0.08\ \text{pb}$$

$$\mu = 1.01 \pm 0.08(\text{stat.}) \pm 0.04(\text{exp.}) \pm 0.05(\text{th.}) = 1.01 \pm 0.11$$



The fiducial XS is extrapolated to the total phase space (no categorization):

Cross section [fb]	Data (± (stat.) ± (syst.))	Standard Model prediction	p-value [%]
σ_{tot} [pb]	53.5 ±4.9 ±2.1	55.7 ± 2.8	66

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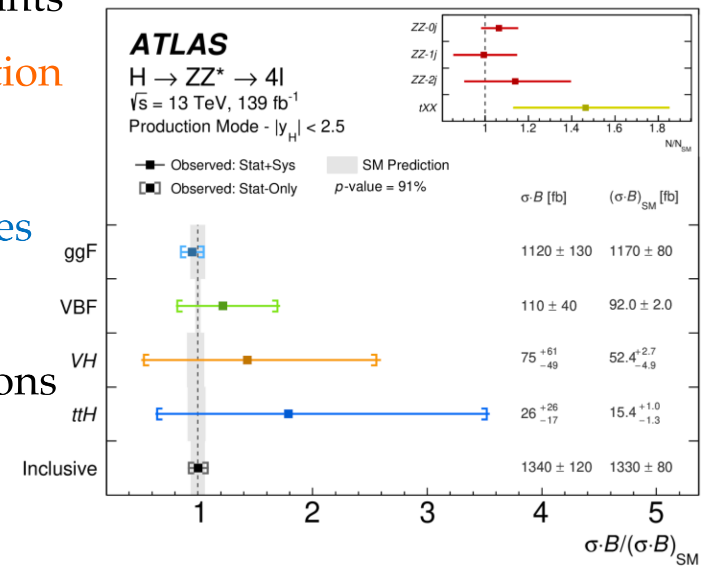
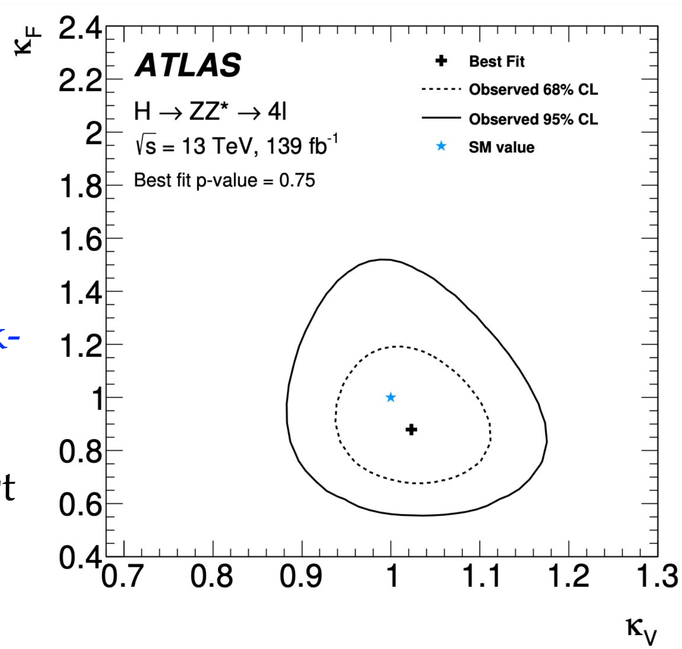
Additional reconstructed event categories and discriminants are used to enhance the sensitivity to the various production modes and BSM effects.

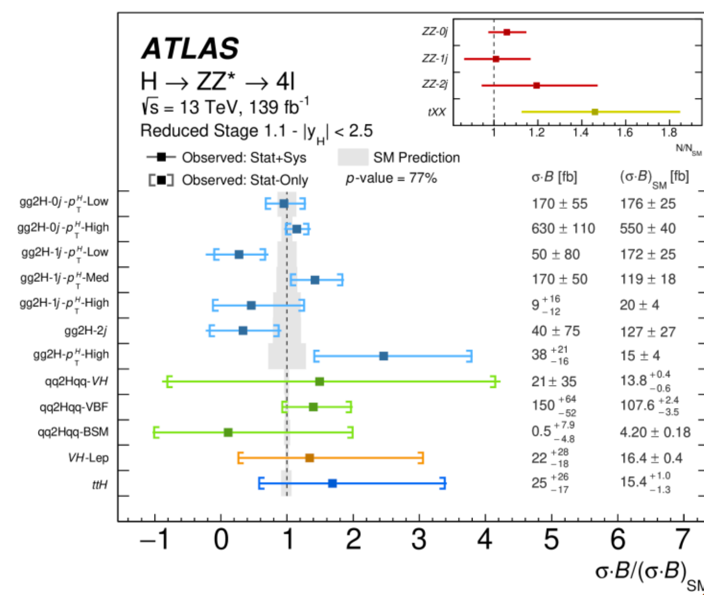
ggF XS: theoretical predictions and measured uncertainties are of the same order!

Production XS measurements agree with the SM predictions for the Higgs, within 1σ level.



Prod and decay couplings of the Higgs to fermions and bosons can be investigated with k-factors (ratio of BR and decay rates wrt SM predictions)





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Diff. XS are measured for variables sensitive to Higgs boson production and decay

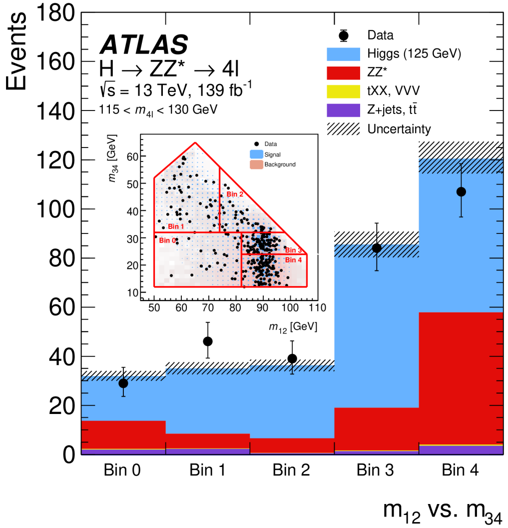
The measured differential fiducial cross sections can be used to probe possible effects of physics BSM

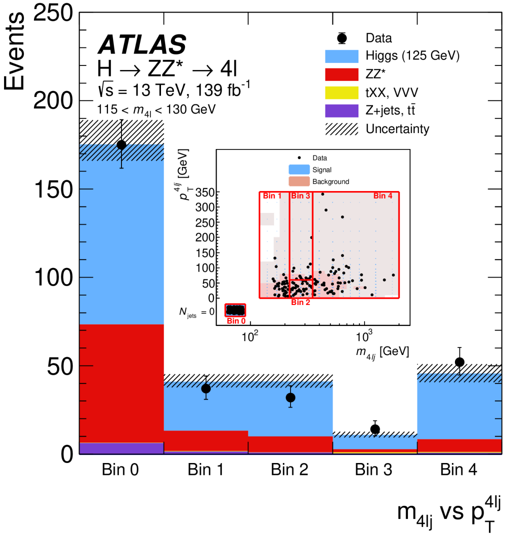
The ***m12×m34* differential XS** is used to interpret the measurement as a function of pseudo-observables

- sensitive to higher-order electroweak corrections to the Higgs boson decay
- sensitive to BSM contributions

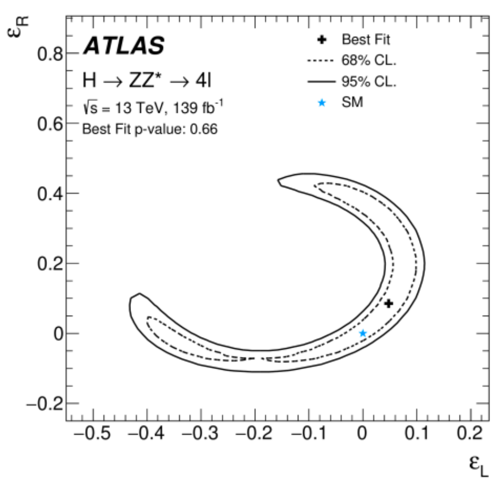
The ***pT4ℓ* differential XS** is used to constrain the Yukawa couplings of the Higgs boson to *b* and *c*-quarks

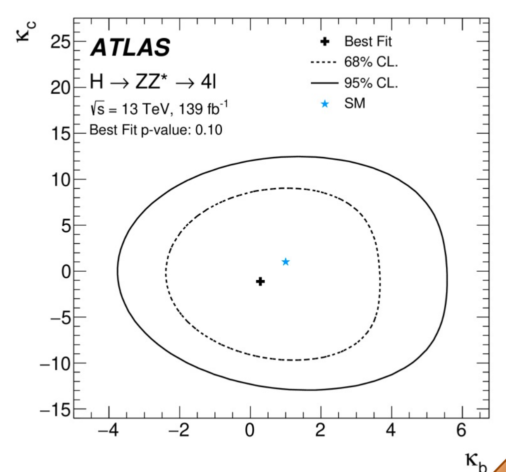
- sensitive to higher order QCD corrections to Higgs boson production
- sensitive to charm and bottom Yukawa couplings





Flavour-universal contact terms





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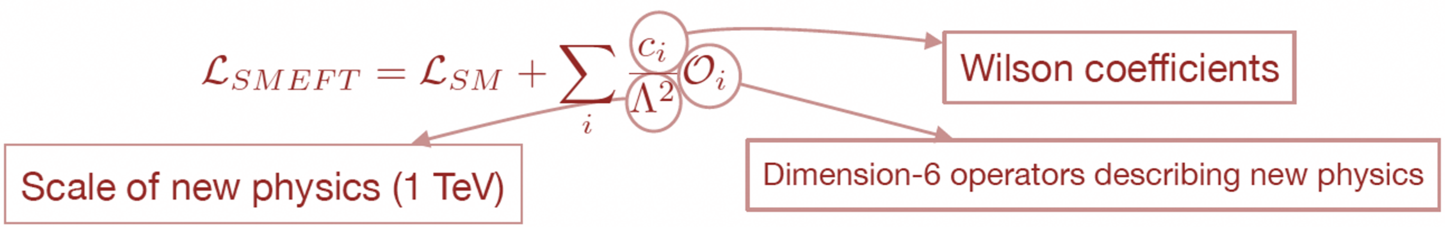
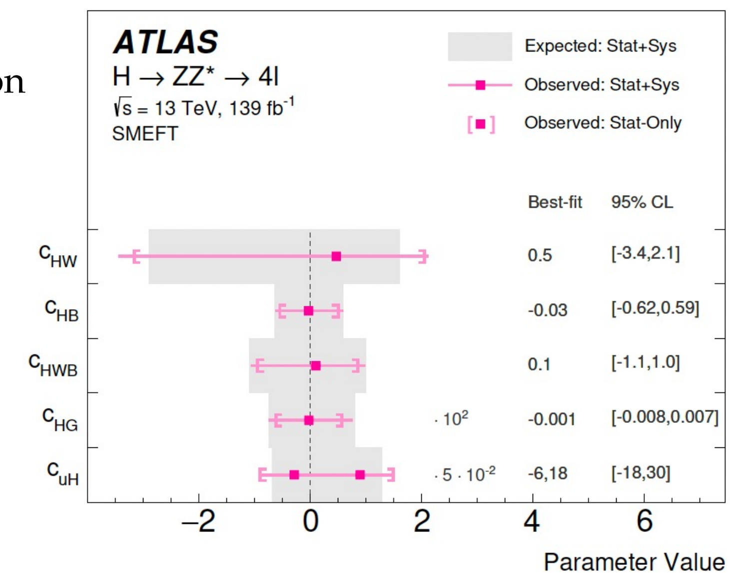
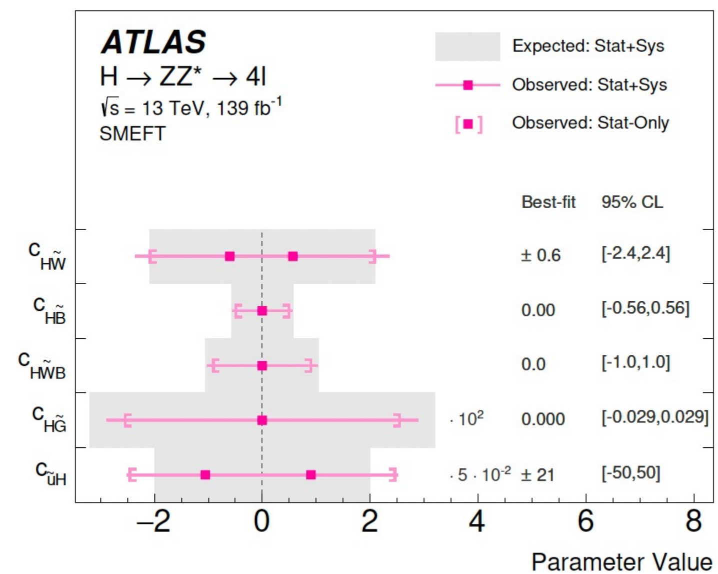
The strength and tensor structure of the Higgs-boson interactions are investigated following an effective field theory (EFT) approach in which additional CP-even and CP-odd interactions can change the event rates, the kinematic properties of the Higgs boson, and associated jet spectra, from those predicted by the SM. Contributions from New Physics in the differential cross sections are probed as non-zero values of the Wilson coefficients of the dimension-6 operators of an effective Langrangian.



Only one Wilson coefficient is fitted at a time while all others are set to zero.



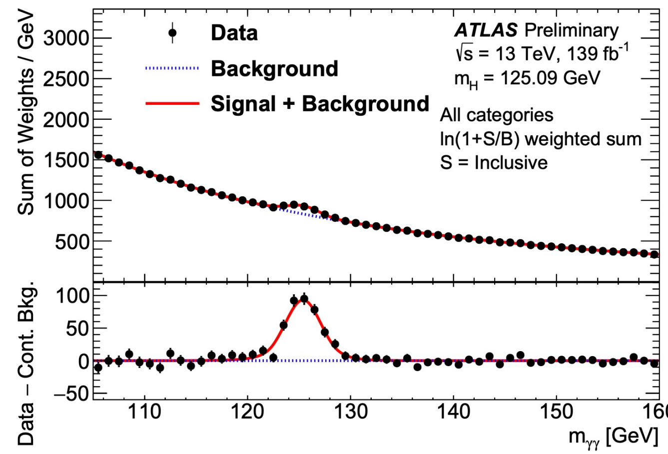


Selection:

- Photon isolation, $E_{T,1}>0.35m_{\gamma\gamma}$, $E_{T,2}>0.25m_{\gamma\gamma}$, $|\eta^{\gamma}| <1.37$ or $1.52<|\eta^{\gamma}| <2.37$
- Mass window $m_{\gamma\gamma}$ ϵ [105-160] GeV
- JET: $|y| < 4.4$ and $p_T > 30$ GeV (25 GeV in STXS)

Signal extraction: Continuous bkg with a mass fit, bkg estimation from data

Syst: bkg modelling (dominant), signal modelling, exp. systs.



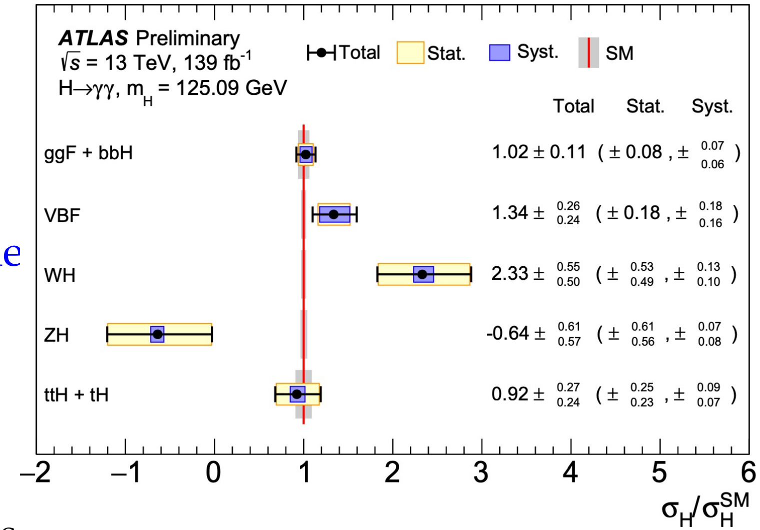
Fiducial inclusive XS:

$$(\sigma \times B_{\gamma\gamma})_{obs} = 127 \pm 10\,\text{fb} = 127 \pm 7\,(\text{stat.}) \pm 7\,(\text{syst.})\,\text{fb}$$

$$(\sigma \times B_{\gamma\gamma})_{exp} = 116 \pm 5\,\text{fb}$$

STXS -> 27 categories based on the reconstructed event properties, to target the different production modes and the different STXS regions

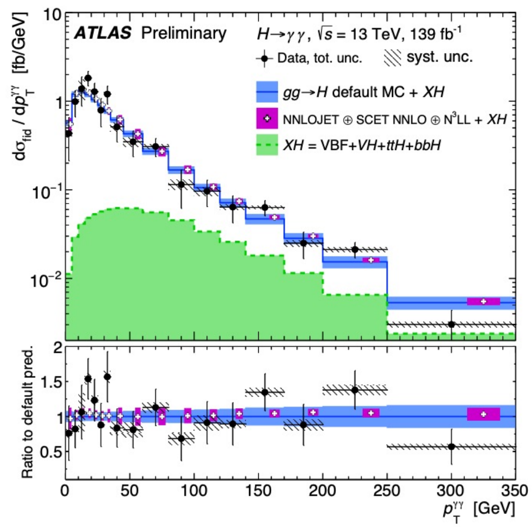
- Stage0: truth level splitting of the Higgs production processes
- Stage1: Additional splitting based on Higgs kinematics and associated particles to be measured when exp. sensitivity allows

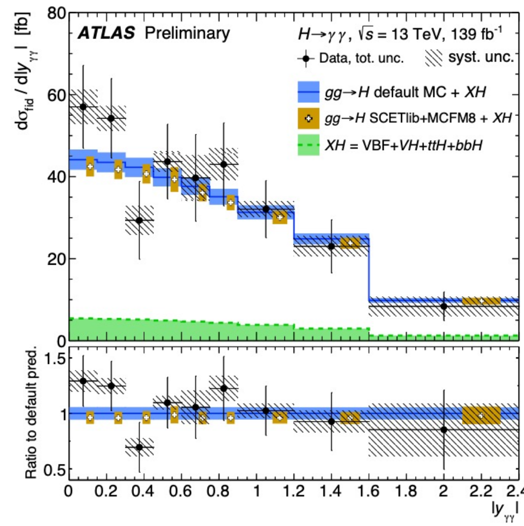


Differential fiducial XS:

Results are consistent with SM predictions

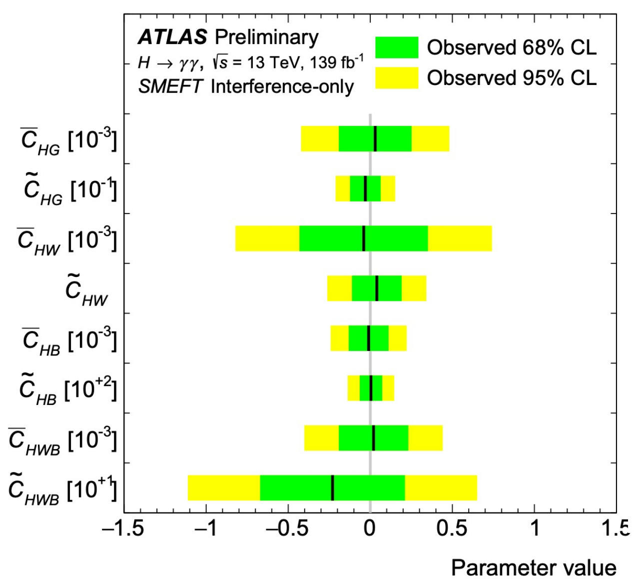
Distribution	$p(\chi^2)$ with Default MC Prediction
$p_T^{\gamma\gamma}$	44%
$\lvert y_{\gamma\gamma}\rvert$	68%
$p_T^{j_1}$	77%
N_{jets}	96%
$\Delta\phi_{jj}$	82%
m_{jj}	75%

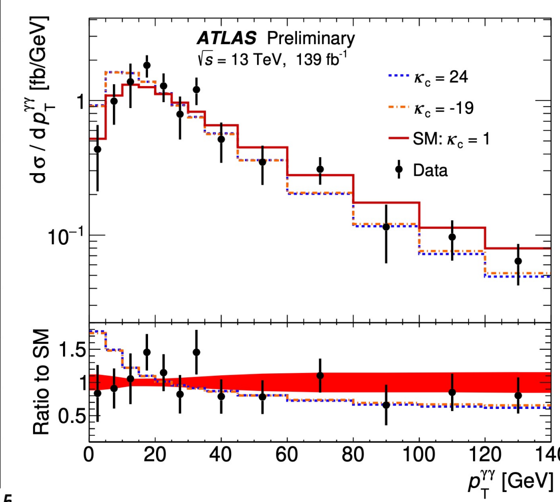




EFT approach with additional CP-even and CP-odd interactions to investigate possible BSM hints:

Higgs p_T spectrum is sensitive to the Yukawa couplings of the Higgs to the c and b quark: differential cross section for different values of κ_c corresponding to the upper and lower limits at 95% CL

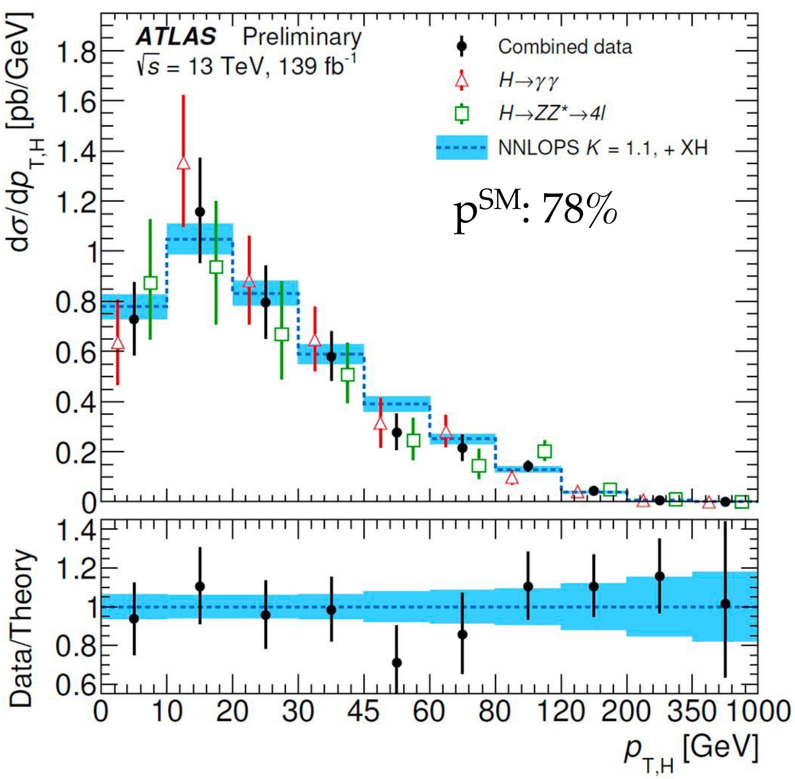


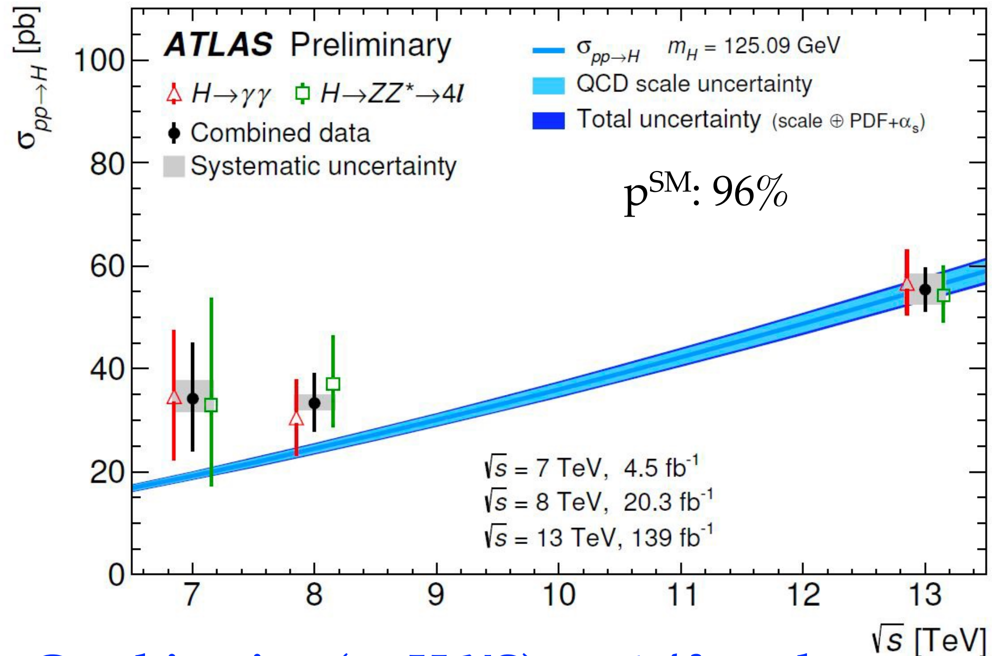


Higgs boson differential cross-section as function of p_T^H

~20% precision per bin (except highest bin)

-> Stat. unc. dominating





Combination (ppH XS): $55.4^{+4.3}_{-4.2}$ pb

- ~8% precision
- stat. and syst. unc. of the same order
- prediction: 55.6 ± 2.5 pb

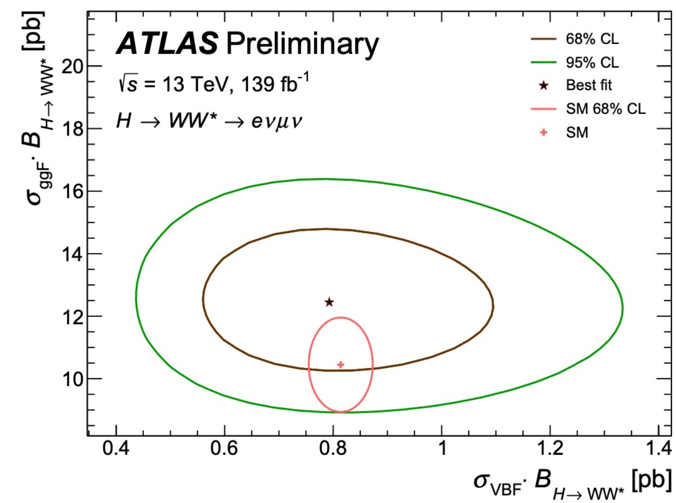
Higgs boson production cross-section results are in good agreement with each other and the SM prediction

The H->WW*->lνlν decay (1.5% of the overall final states)

Characterized by:

- the presence of 2 leptons with small opening angle
- requiring different flavor leptons (m_{ll} >10 GeV, p_T > 22/15 GeV)
- 2 neutrinos (MET, p_T^{Miss} > 20 GeV)

$$\sigma_{\text{ggF}} \cdot \mathcal{B}_{H\to WW^*} = 12.4 \pm 1.5 \text{ pb}$$
$$= 12.4 \pm 0.6 \text{ (stat.)} \pm 0.9 \text{ (exp syst.)} {}^{+0.7}_{-0.6} \text{ (sig theo.)} \pm 1.0 \text{ (bkg theo.) pb}$$
$$\sigma_{\text{VBF}} \cdot \mathcal{B}_{H\to WW^*} = 0.79 {}^{+0.19}_{-0.16} \text{ pb}$$
$$= 0.79 {}^{+0.11}_{-0.10} \text{ (stat.)} {}^{+0.06}_{-0.05} \text{ (exp syst.)} {}^{+0.13}_{-0.09} \text{ (sig theo.)} {}^{+0.08}_{-0.06} \text{ (bkg theo.) pb,}$$



-> SM predicted values of 10.4 ± 0.6 pb and 0.81 ± 0.02 pb for ggF and VBF, respectively

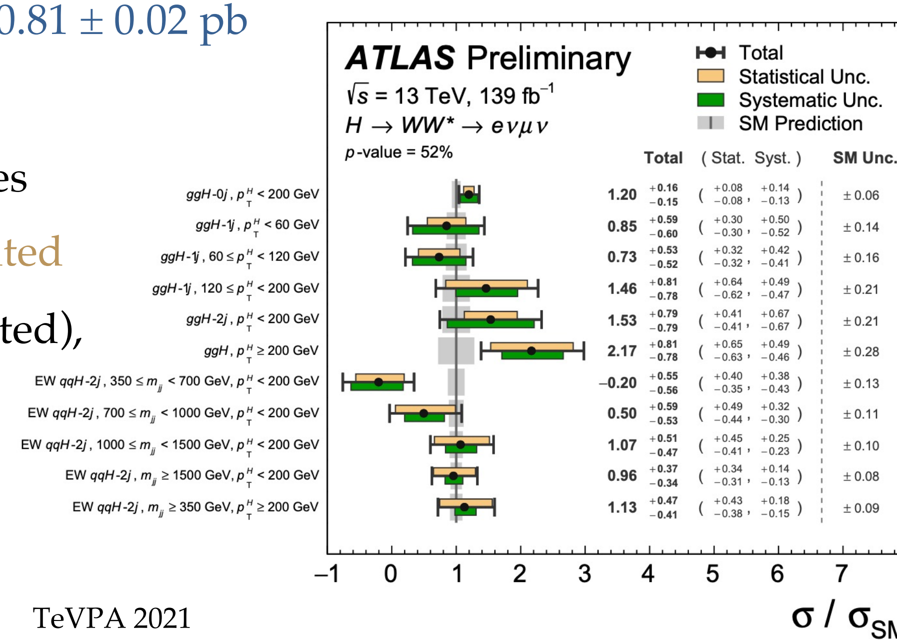
STXS cross-sections measured in 11 categories

Most analysis categories are statistically-limited

(high-p_T and high-m_{jj} categories are stat limited),

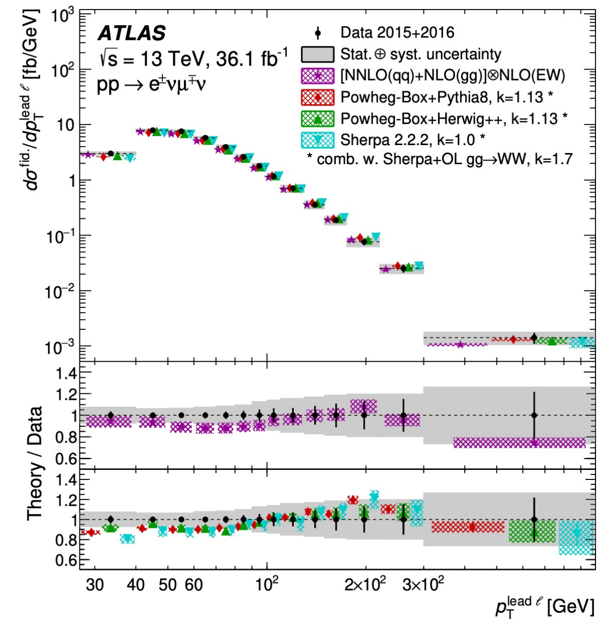
with some ggH modes affected

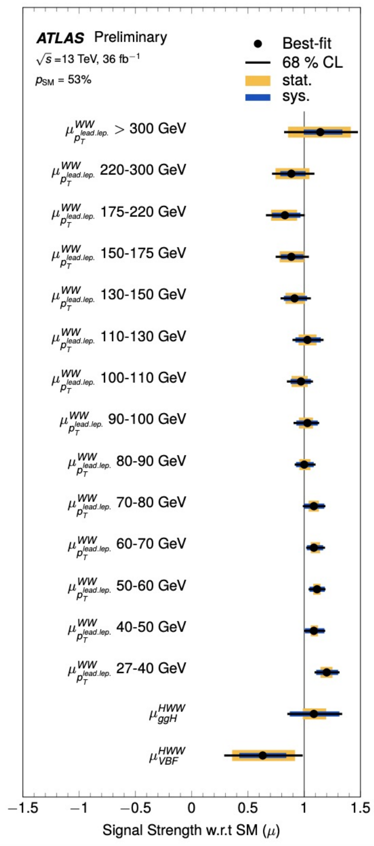
mostly by background theory uncertainties.

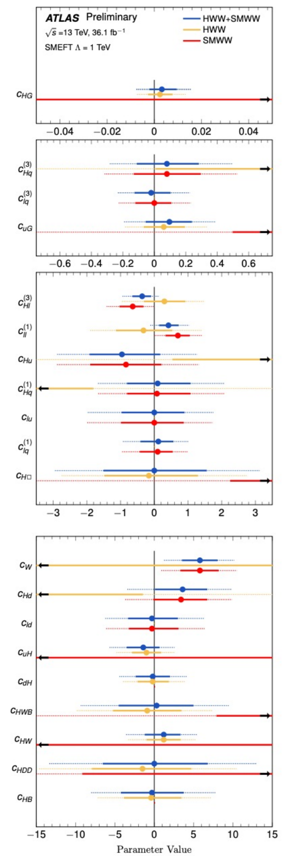


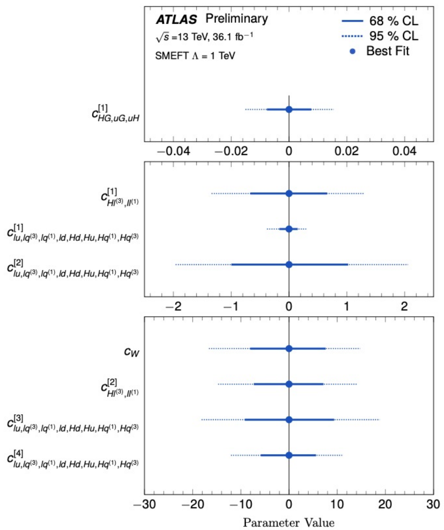
Fiducial and differential XSs SM pp->WW (36 fb^{-1})

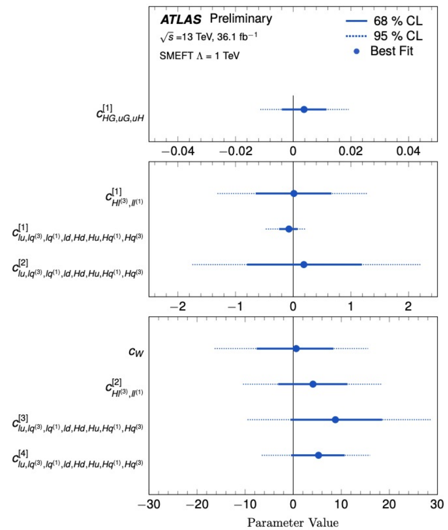
- p_T leading lepton is sensitive to SM_{EFT} operators
- impact of the SM_{EFT} operators on the μ modifiers and diff XS
- Resulting constraints agree with SM within 2σ or better







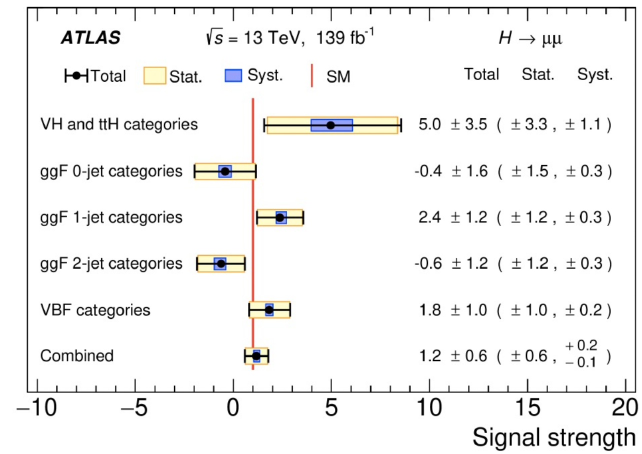




H -> μμ

The signal yield is obtained by a simultaneous binned maximum-likelihood fit to the $m_{\mu\mu}$ distributions of 20 categories in the range 110–160 GeV

μ =1.2 ±0.6, significance observed (expected)= 2.0σ (1.7σ)



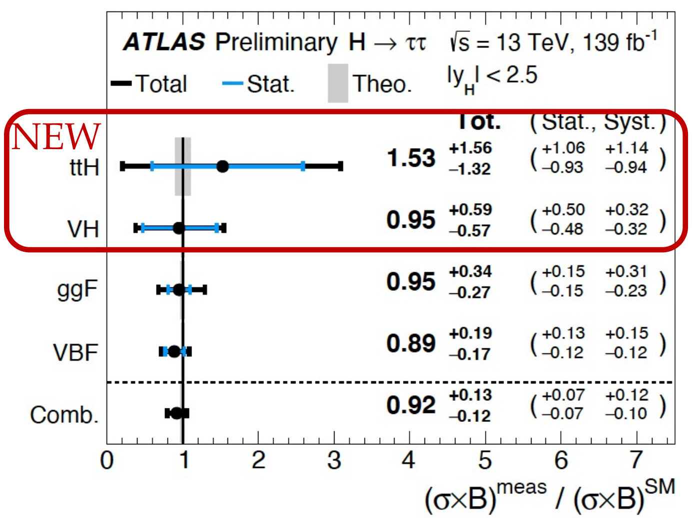
H -> ττ

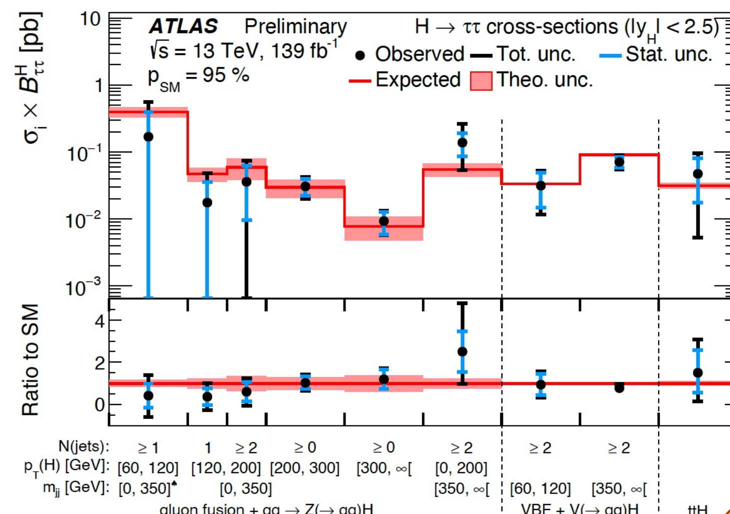
Signal region: 100 GeV < m_{MMC} < 150 GeV

At least two neutrinos in the final state -> Find most probable Higgs boson mass m_{MMC}

$$(\sigma \times BR)^{obs} = 2.90 \pm 0.21\,(stat)\,^{+0.37}_{-0.32}\,(syst)\,pb$$

- Strong constraints on VBF XS: observation of VBF process at 5.3 σ
- STXS in 9 categories
- Results in agreement with SM





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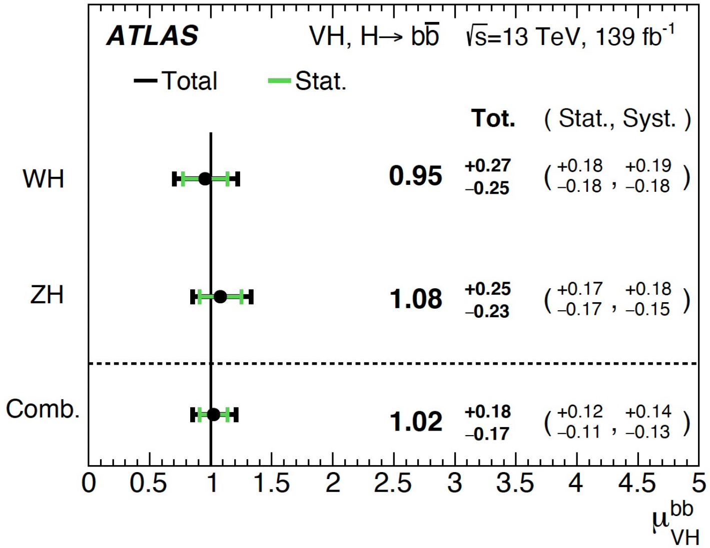
H ->bb Main challenge at the LHC: large QCD background

VH(V→ℓℓ, H→bb) resolved:

Higgs boson candidate: 2 small-radius R=0.4 b-tagged jets 2 e/μ **or** 1 e/μ+MET **or** MET from leptonic V decay (Z→νν, W→ℓν, Z→ℓℓ)

- **VH(V→ℓℓ, H→bb) measured at 6.7** (6.7) σ **obs.** (exp.)
- **observation** of **ZH(Z→ℓℓ,H→bb)** at 5.3 (5.1)σ obs. (exp.)
- **evidence** of **WH(W→ℓν,H→bb)** at 4.0 (4.1)σ obs. (exp.)



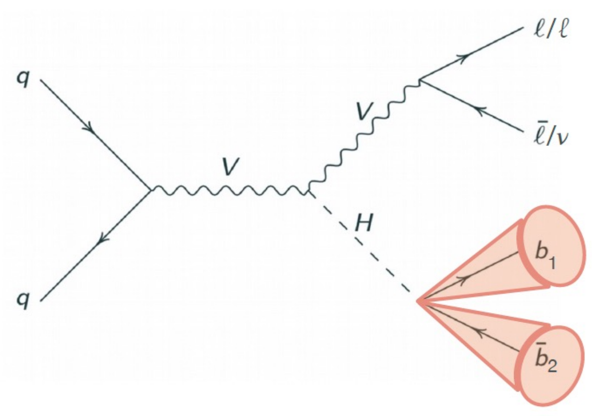
VH(V→ℓℓ, H→bb) boosted:

High-p_T "partner"of VH (V→ℓℓ, H→bb) resolved

- BSM scenarios predict **deviations from the SM** at **high p_T**
- simultaneous measurement of μ_{VH} and μ_{VZ}
- analysis is statistically limited:

  VH(V→ℓℓ, H→bb) measured at **2.1** (2.7) σ **obs.** (exp.)

  VZ(Z→ℓℓ,Z→bb) at 5.4 (5.7)σ obs. (exp.)



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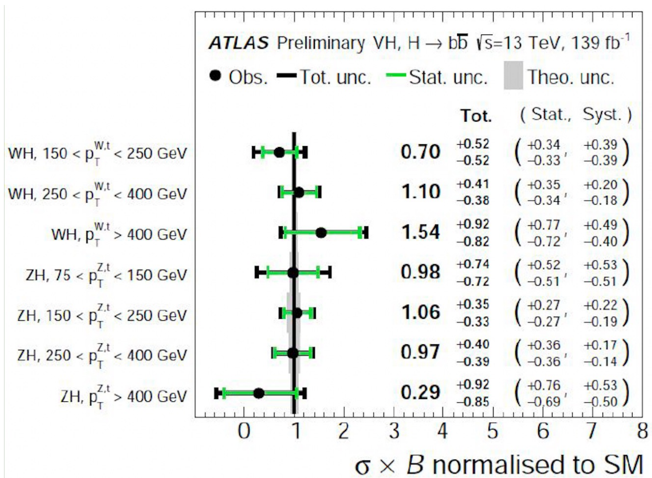
VH(V→ℓℓ, H→bb) combination of the resolved and boosted analyses

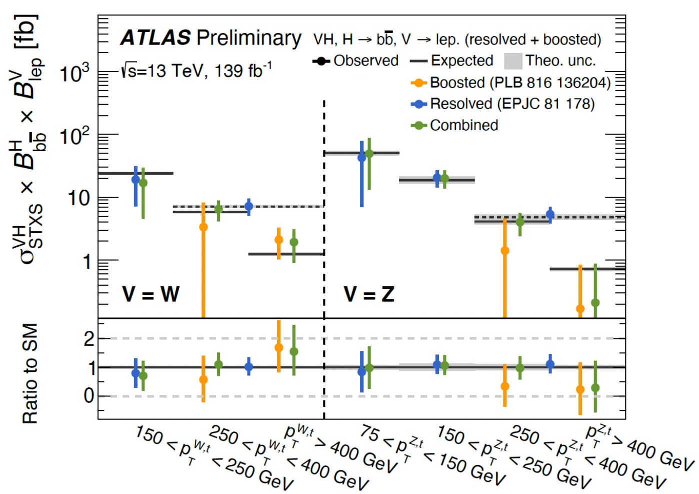
STXS meas. compatible with the SM expectations with uncertainties between 30% and 85%

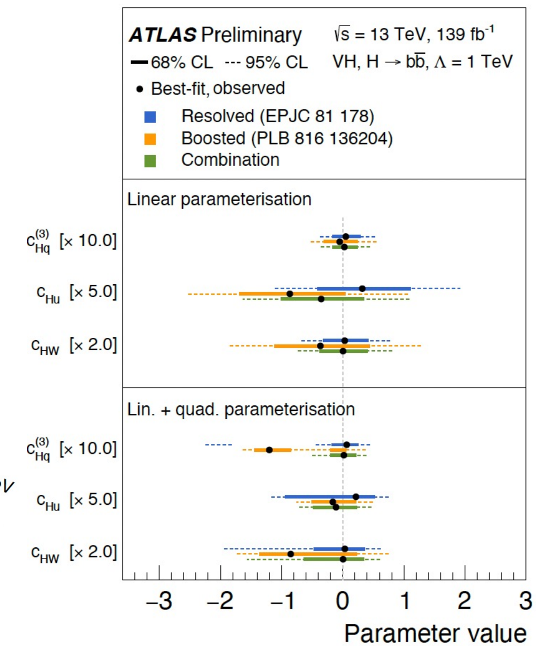
- statistical and systematic uncertainties of the same order of magnitude for p_{TV} < 400 GeV
- highest p_{TV} bins are limited in sensitivity by statistical uncertainties

Test presence of BSM physics via effective Lagrangian operators:

σ(qq→ZH), σ(qq→WH), BR(H→bb) parametrized as linear/quadratic polynomials in $\mathbf{c_i}$







VBF (H→bb) measured at 2.6 (2.8) σ obs. (exp.) :

$$\mu_{VBF,H\to b\bar{b}} = 0.95^{+0.32}_{-0.32}(\text{stat.})^{+0.20}_{-0.17}(\text{syst.})$$

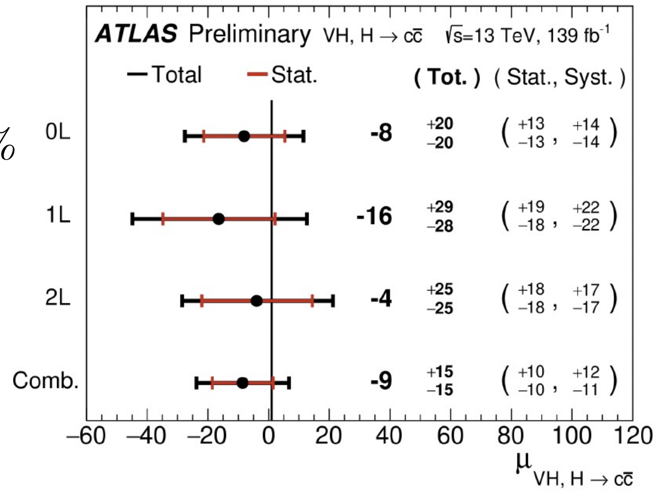
VH -> cc

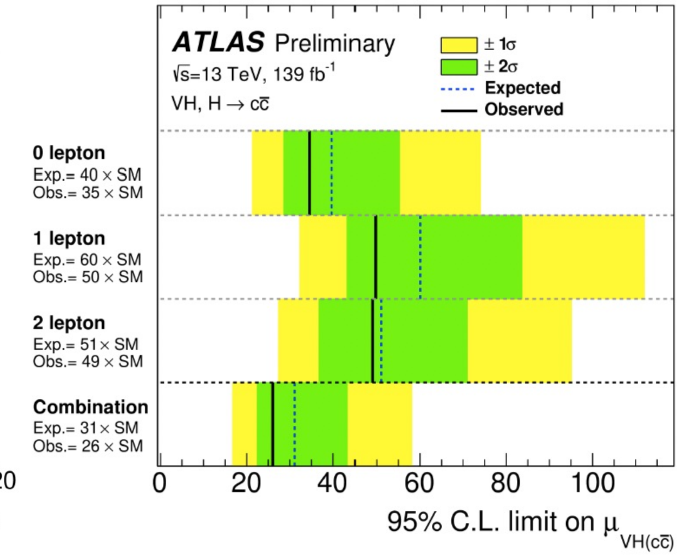
Best fit signal strength

$\mu_{VH(cc)} = -9 \pm 15$

compatibility with SM: 83.9%

- Stat and syst uncert. of similar size
- leading syst: V+jets/top modelling and flavour tagging

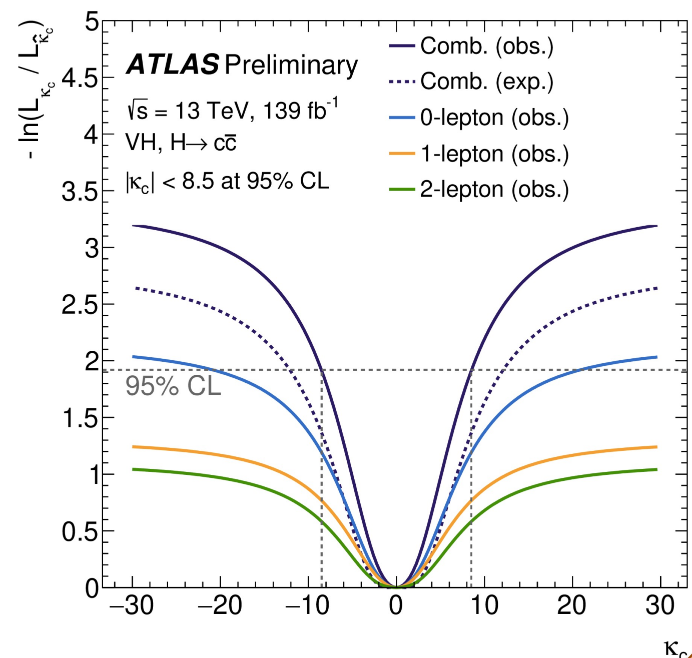




Signal strength parametrisation as a function of κ_c :

$$\mu(\kappa_i) = \frac{\kappa_c^2}{B(H \to c\bar{c})\kappa_c^2 + (1 - B(H \to c\bar{c}))}$$

- Expected limit on κ_c at 95% CL in combined fit $|\kappa_c| < 12.4$
- observed best fit $\kappa_c = 0$
- first direct limit on κ_c @ 95%CL with $|\kappa_c| < 8.5$ -> complementary and compatible with indirect constraint from H->ZZ*->4l



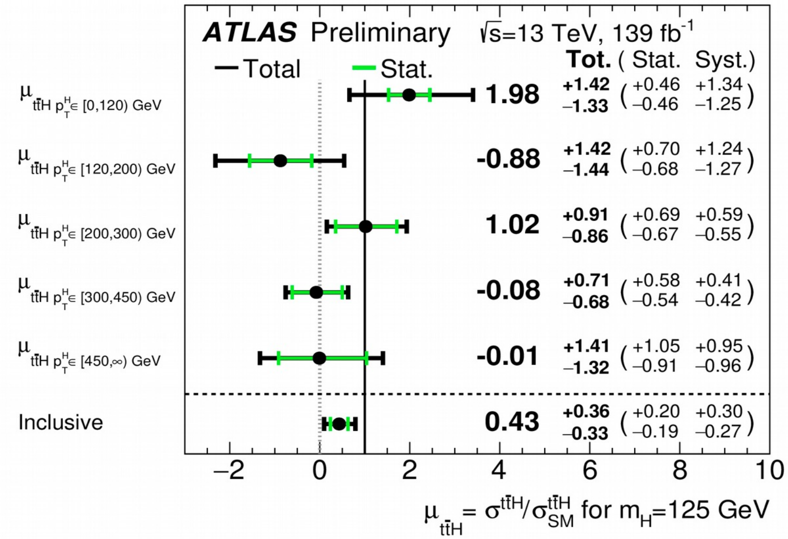
ATLAS-CONF-2020-058, ATLAS-CONF-2019-045

ttH (H->bb) Most common decay mode, but challenging final state due to combinatorics from many bjets

$$\mu_{ttH} = \sigma/\sigma_{SM} = 0.43$$

observed/expected significance of 1.3σ/3.0σ

- Measurement performed in STXS bins of p_{TH}
  - high statistics and boosted category allow probe the high p_T regime
- results limited by theoretical uncertainty on ttbar+hf(b/c) background as well as data statistics

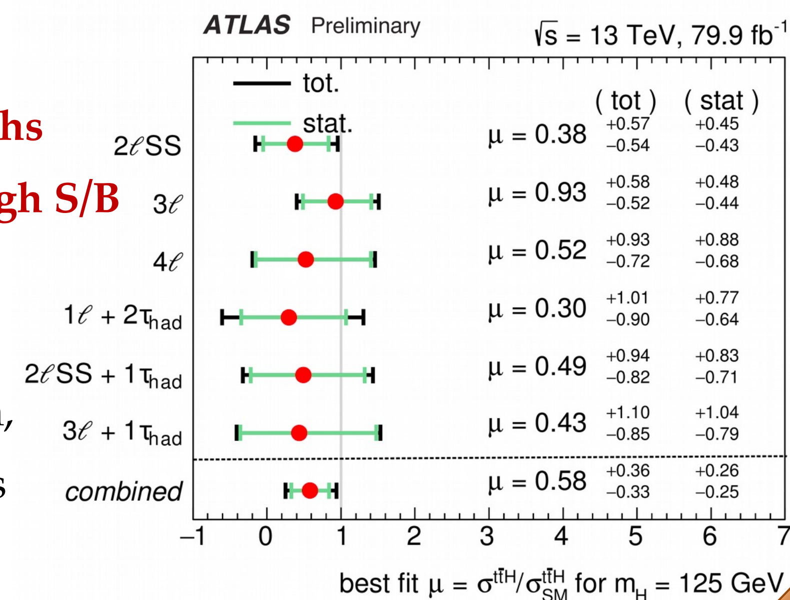


ttH Multilepton (H → WW*, ττ, ZZ*): many decay paths possible. Divide by final state, focus on those with high S/B

$$\mu_{ttH} = 0.58$$

observed/expected significance of 1.8σ/3.1σ

- ttW normalization pulled higher than SM prediction, consistent among regions and other ATLAS analyses
- largest uncertainty from data statistics



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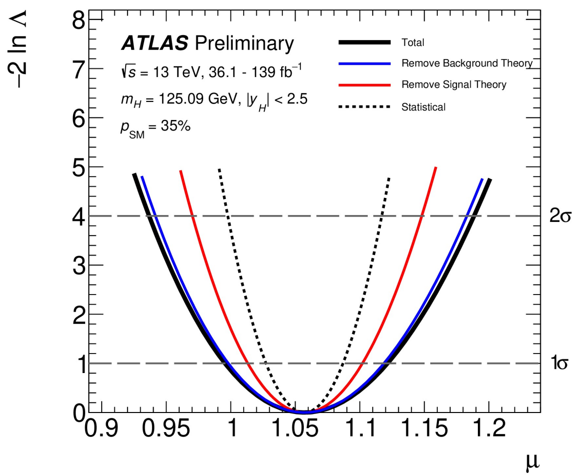
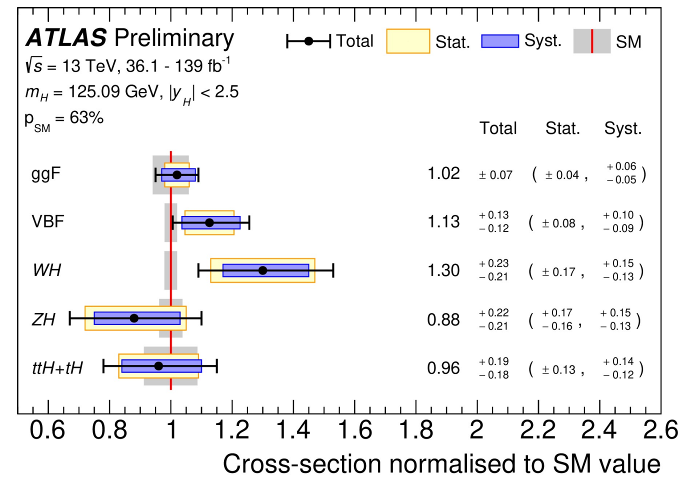
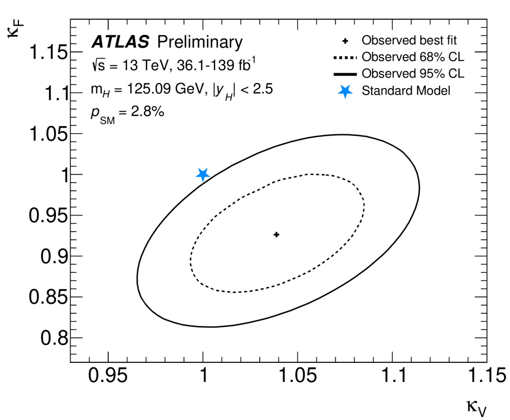
Signal strength: $\mu = 1.06 \pm 0.06 = 1.06 \pm 0.03\,(\text{stat.}) \pm 0.03\,(\text{exp.}) \pm 0.04\,(\text{sig. th.}) \pm 0.02\,(\text{bkg. th.})$

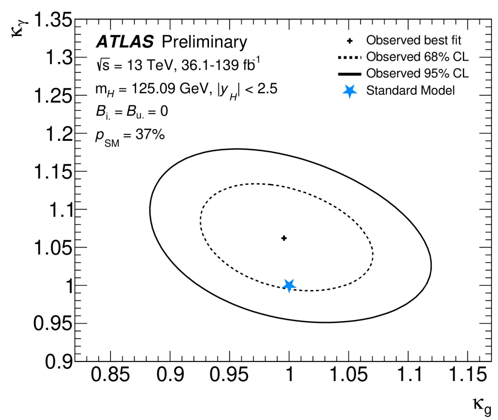


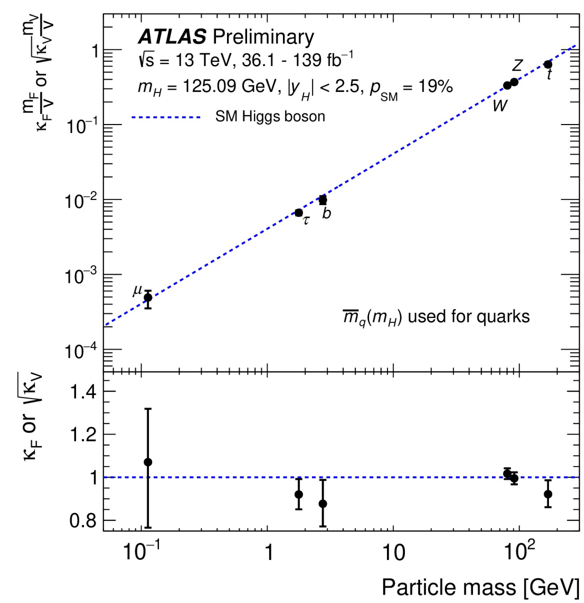
XS per production mode: XSs are normalised to their SM predictions, measured assuming SM values for the decay branching fractions

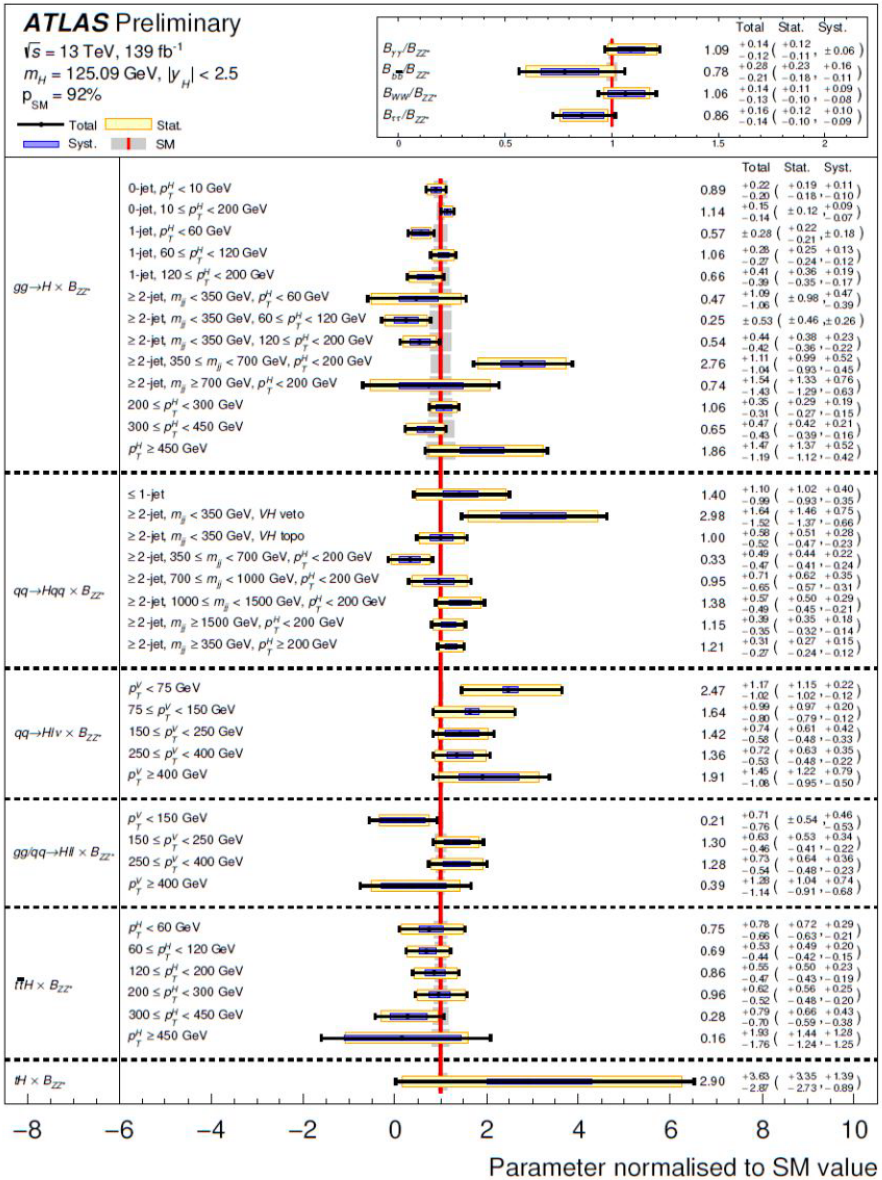


Couplings of the Higgs boson to SM particles are investigated within the kappa framework





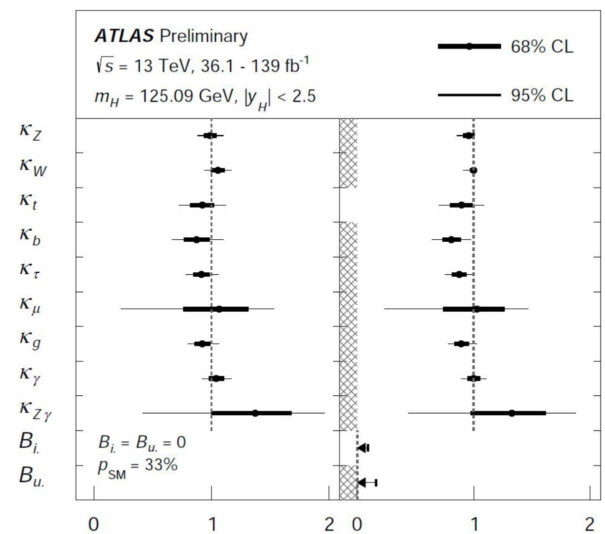




STXS Combination: most granular, simultaneous measurement to date (41 POI fit!)

- inclusion of new data and improved analyses
- for all bins stat. unc. dominating
- only in few bins syst. unc. start to matter (e.g. ggF 0 jet)
- very good agreement with SM prediction

Probing BSM contributions via effective coupling stregths (k)



Conclusions

- We are studying the main production processes of the Higgs boson with precision up to the level of 10%
- Results from Run1+Run2 with up to 139 fb^{-1} indicate that measurements of the properties of the H(125) show consistency with the Higgs Boson predicted by the SM
- EFT approaches to test possible BSM contributions to the Higgs boson properties have been extensively investigated
- Most of our measurements are still statistically dominated in the most sensitive channels

We are entering the precision era:

looking for possible hints of New Physics behind the corner!

Thanks for your attention!

Backup

In BSM theories, the Higgs boson properties may not be determined only via a simple scaling of couplings: kinematic distributions in production and decay modes may be sensitively modified by BSM (incl. EFT) effects.

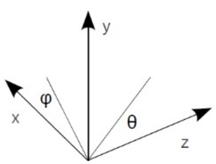
Simplified template cross sections (STXS) developed to:

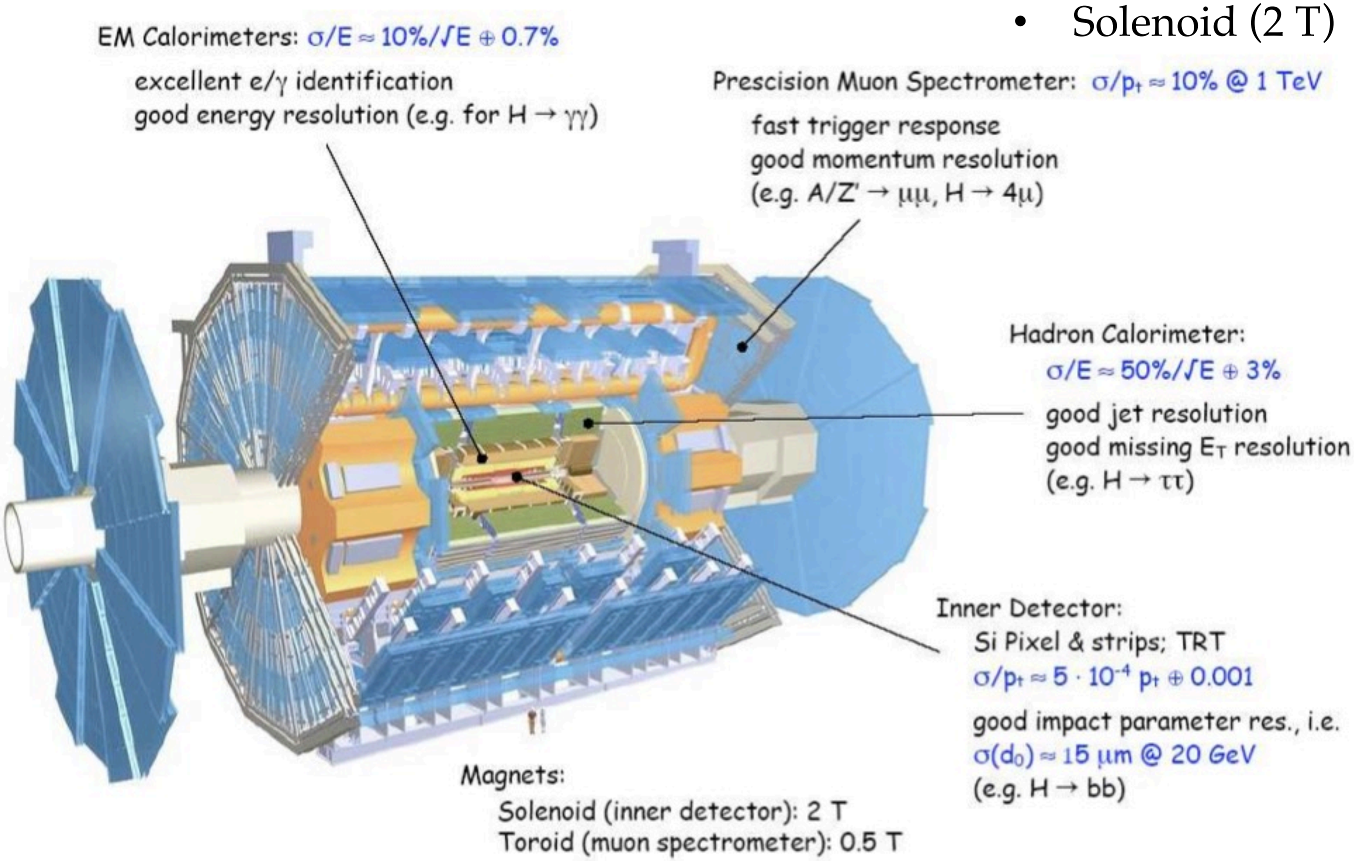
- separate measurement and interpretation steps to reduce in a systematic fashion the theory dependencies folded into the measurements (dependence on theoretical uncertainties and on the underlying physics model)
- provide more finely-grained measurements (and hence more information for theoretical interpretations) while at the same time allowing and benefiting from the global combination of the measurements in all decay channels

Fiducial cross sections, i.e. cross sections for specific states within the phase space defined by experimental selection and acceptance cuts, provide:

- largely model-independent way to test for deviations in kinematic distributions
- differential fiducial XS are a powerful for scrutinizing the SM Lagrangian structure of the Higgs boson interactions

A Thoroidal LHC ApparatuS





Inner Detector:

- Silicon trackers (pixel and microstrip)
- Gas trackers (with measurement of the transition radiation, TRT)
- Solenoid (2 T)

Electromagnetic Calorimeter:

- Sampling Pb+LAr

Hadronic Calorimeter:

- Fe+scintillator
- LAr technology

Muon System:

- Superconducting thoroids
- Precision tracking chambers
- Trigger chambers

Analyses in RunI have been optimized for the discovery

- Observed boson compatible, within the uncertainties, with the Higgs predicted by the SM -> deviations are small

Measurements of:

- **Fiducial Cross Sections and Differential Cross Sections** in variables sensitive to the quantum numbers of the Higgs boson (spin, CP), production modes, proton PDFs and perturbative QCD effects

Interpretations in terms of:

- **Signal strenght**: defined as the ratio of the XS • BR with respect to the SM (more model dependent): $\mu = (\sigma\, BR)_{obs}/(\sigma\, BR)_{SM}$
- **Coupling modifiers (k_j)**: parametrizing production and decay, coupling modifiers as multiplicative factors, narrow width approximation

$$\sigma_i \cdot \mathrm{BR}^f = \frac{\sigma_i(\vec{\kappa}) \cdot \Gamma^f(\vec{\kappa})}{\Gamma_\mathrm{H}}$$

where $\kappa_j^2 = \Gamma^j / \Gamma^j_{\mathrm{SM}}$, $\kappa_j^2 = \sigma_j / \sigma_j^{\mathrm{SM}}$

-> k_j=1 refers to the Standard Model case (SM)

maybe you can add backup slides showing
- one of the (theory) plots showing how the pT Higgs spectrum varies with different values of kappa
- mention the assumptions going into the kappa_c/b interpretation (also for H→gammagamma)
- H→ZZ* is the only analysis so far (if I am not mistaken) that considers acceptance effects in the EFT interpretation, so maybe this is worth mentioning and having a backup slide on it? -> ok
- I think it'd be good to be prepared to answer why the constraint on cHG tilde is much less than on cHG -> ok