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ATLAS EXPERIMENT

MEASUREMENT OF CROSS SECTIONS AND COUPLINGS OF THE HIGGS BOSON

USING THE ATLAS DETECTOR

Bjarne Stugu

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Overview

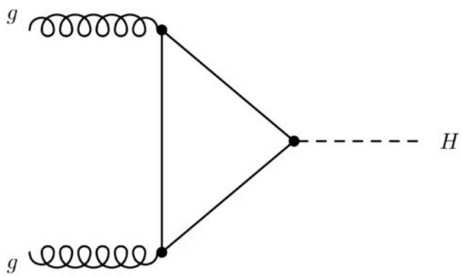
- Introduction
- Higgs production modes and decays
- Extracting signal strengths, μ, and coupling modifiers, κ.
- Analysis framework and published run-1 results
  - EUR Phys J C76 (2016) 6 and ATLAS+CMS combination JHEP08(2016)045
- Preliminary ATLAS run-2 results with 36.1 fb^{-1}
  - Results in 4l, μμ final states
    - + γγ and 4l+γγ combination 'hot off the press'
- Summary

INTRODUCTION

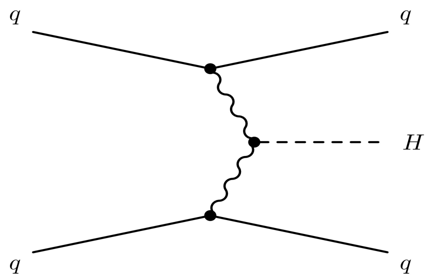
- Finding the Higgs boson is by far the most important discovery within particle physics during recent years
- Following discovery it is important to measure the properties of the Higgs boson to verify the SM and look for deviations that could present hints to new physics
- LHC: Access to a large number of production and decay modes (depending on luminosity)

Higgs production channels

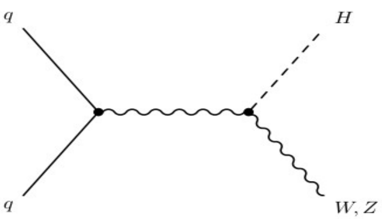
- Gluon-gluon fusion



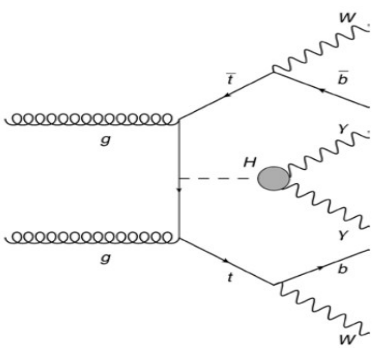
- Vector boson fusion



- V-H



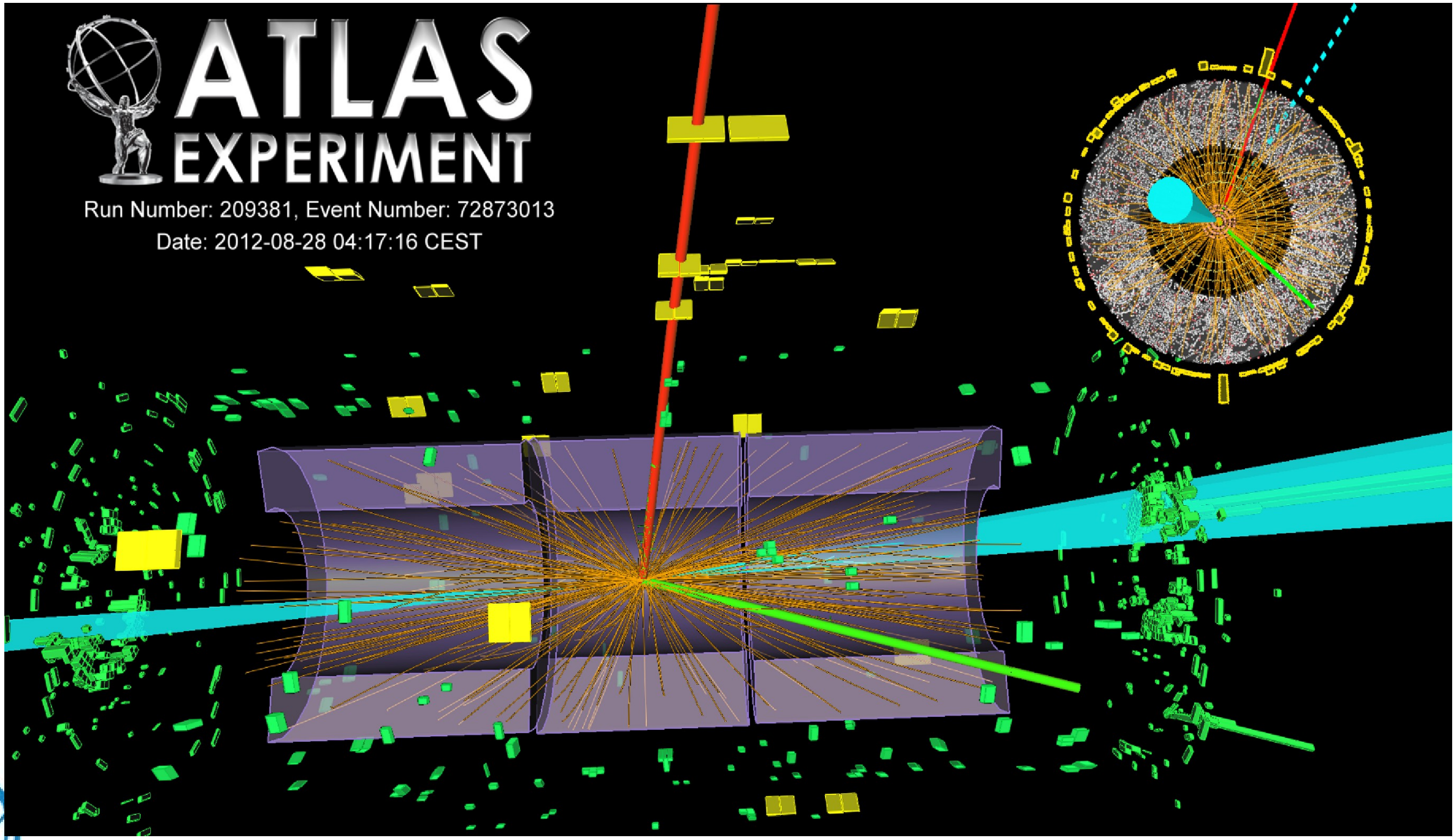
- ttH



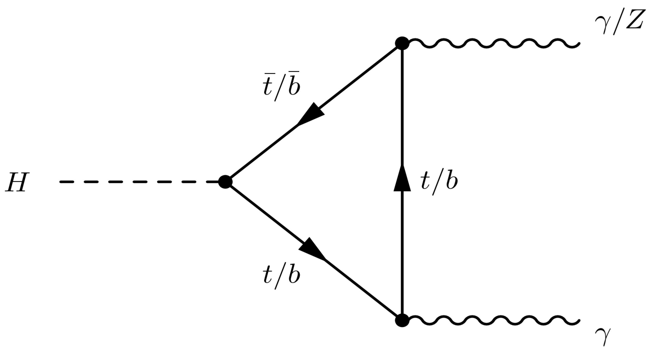
Production mode classification:

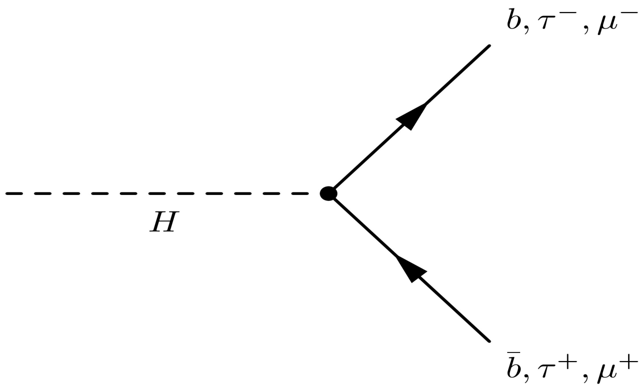
Below a Higgs to tau-tau candidate produced through Vector Boson Fusion

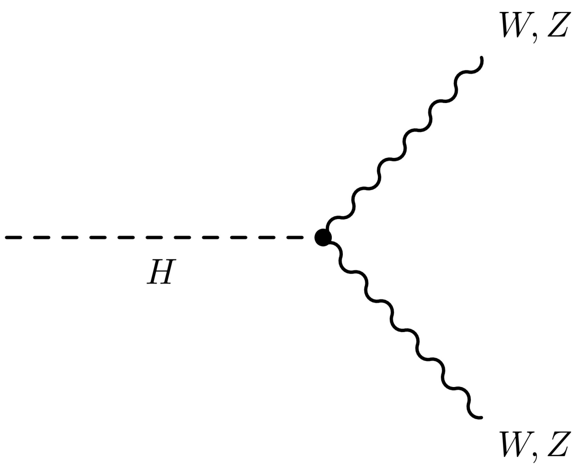
- Two forwards jets
- Higgs candidate is distinctly more transverse in VBF than in ggF



Higgs decay channels







A large number of combinations of production and decay modes

Fiducial cuts for particle identification
Requirements in H→4l and H→γγ analyses (run2)

- Muons:
  - $|\eta| < 2.7$; $p_T > 5$ GeV
- Electrons:
  - $|\eta| < 2.47$; $p_T > 7$ GeV
- Jets (for production mode tagging):
  - $|\eta| < 4.4$; $p_T > 30$ GeV
- Photons:
  - $|\eta| < 2.37$ (with $1.37\ |\eta| < 1.52$ excluded) ; $E_T > 25$ GeV

$\eta = -\ln(\tan(\theta/2))$

Measurements in single decay channels

- We define ***signal strengths*** relative to the SM predictions: μ

$$\mu_i^f = \frac{\sigma_i \times \mathrm{BR}_f}{(\sigma_i \times \mathrm{BR}_f)_{\mathrm{SM}}} \equiv \mu_i \times \mu_f, \quad \text{with} \quad \mu_i = \frac{\sigma_i}{(\sigma_i)_{\mathrm{SM}}} \quad \text{and} \quad \mu_f = \frac{\mathrm{BR}_f}{(\mathrm{BR}_f)_{\mathrm{SM}}}.$$

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Always in combination

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Always in combination

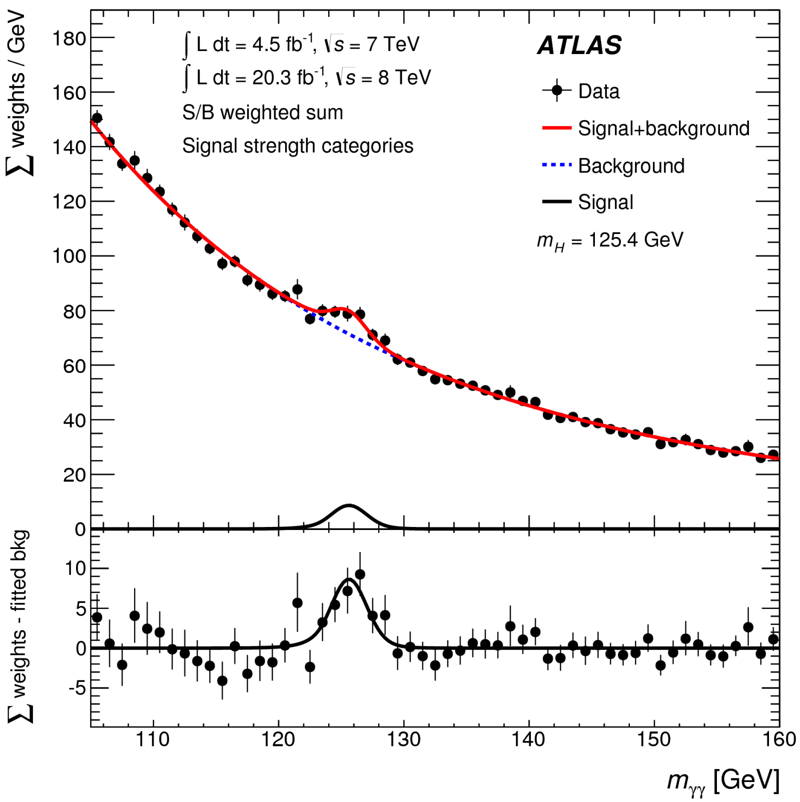
- Real life of experimental event selections:

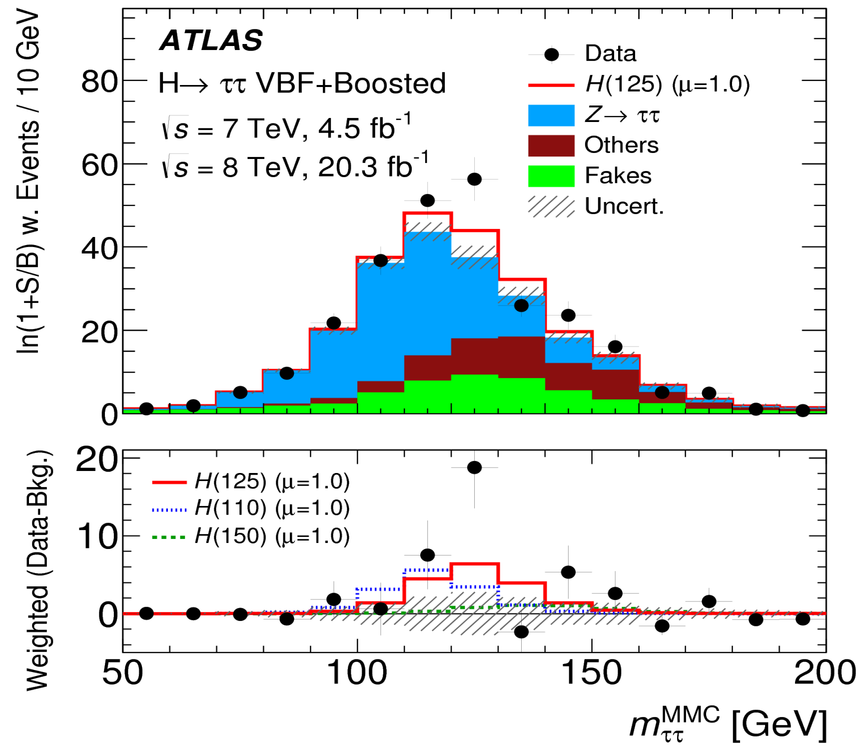
$$n_s^c = \sum_i \sum_f \mu_i (\sigma_i)_{\mathrm{SM}} \times \mu_f (\mathrm{BR}_f)_{\mathrm{SM}} \times A_{if}^c \times \varepsilon_{if}^c \times \mathcal{L}^c$$

Events are divided into ***categories***

with significant cross-talk

Input data 7+8 TeV , γγ and ττ





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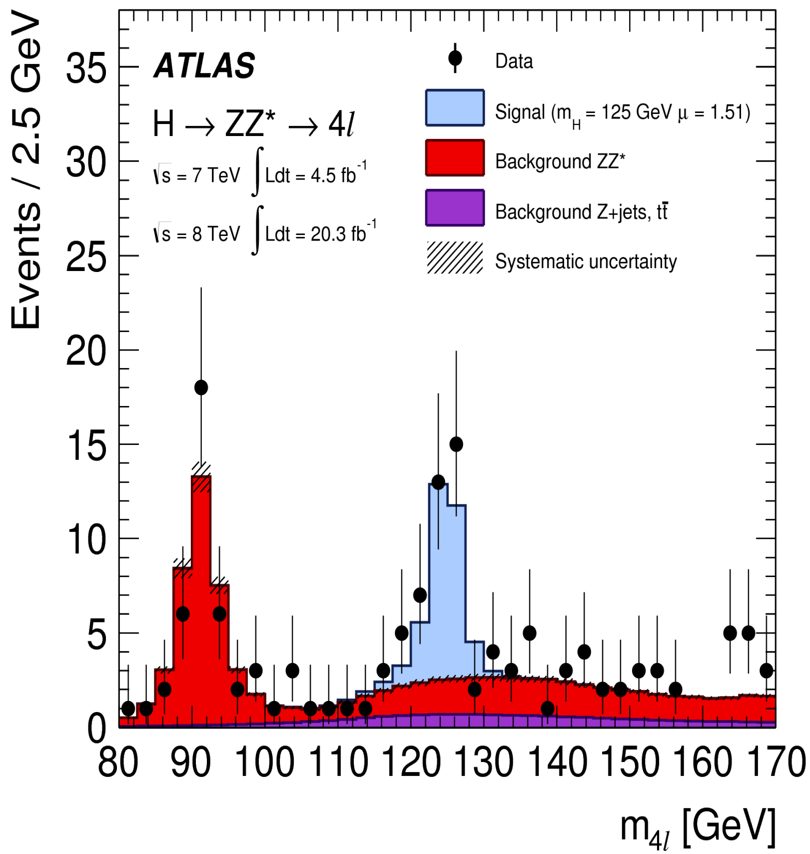
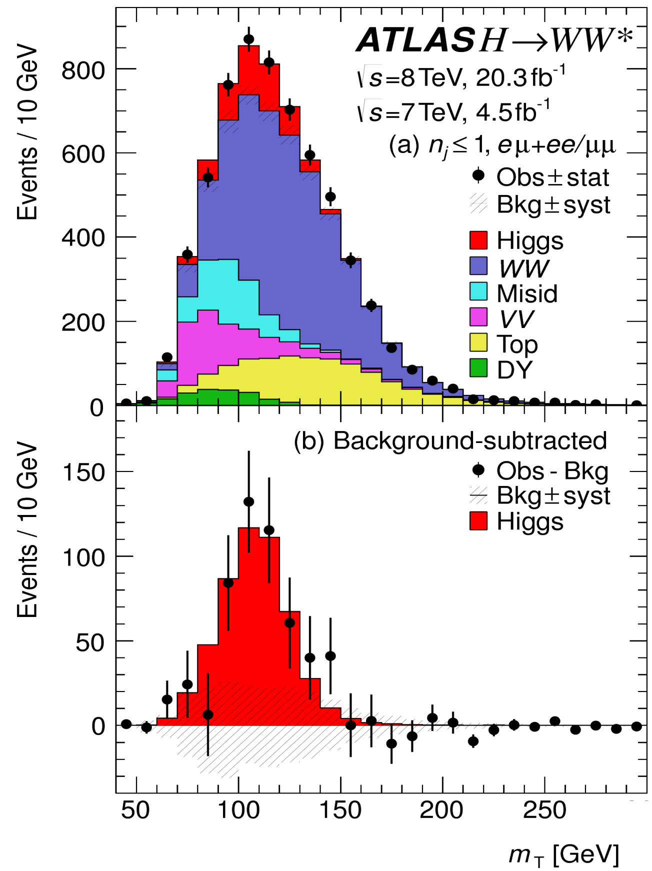
Input data 7+8 TeV (VB couplings)





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Theoretical production and decay rates used in the ATLAS run-1 study (m_{Higgs}= 125.36 GeV)

Production process	Cross section [pb] $\sqrt{s} = 7$ TeV	Cross section [pb] $\sqrt{s} = 8$ TeV
ggF	15.0 ± 1.6	19.2 ± 2.0
VBF	1.22 ± 0.03	1.57 ± 0.04
WH	0.573 ± 0.016	0.698 ± 0.018
ZH	0.332 ± 0.013	0.412 ± 0.013
bbH	0.155 ± 0.021	0.202 ± 0.028
ttH	0.086 ± 0.009	0.128 ± 0.014
tH	0.012 ± 0.001	0.018 ± 0.001
Total	17.4 ± 1.6	22.3 ± 2.0

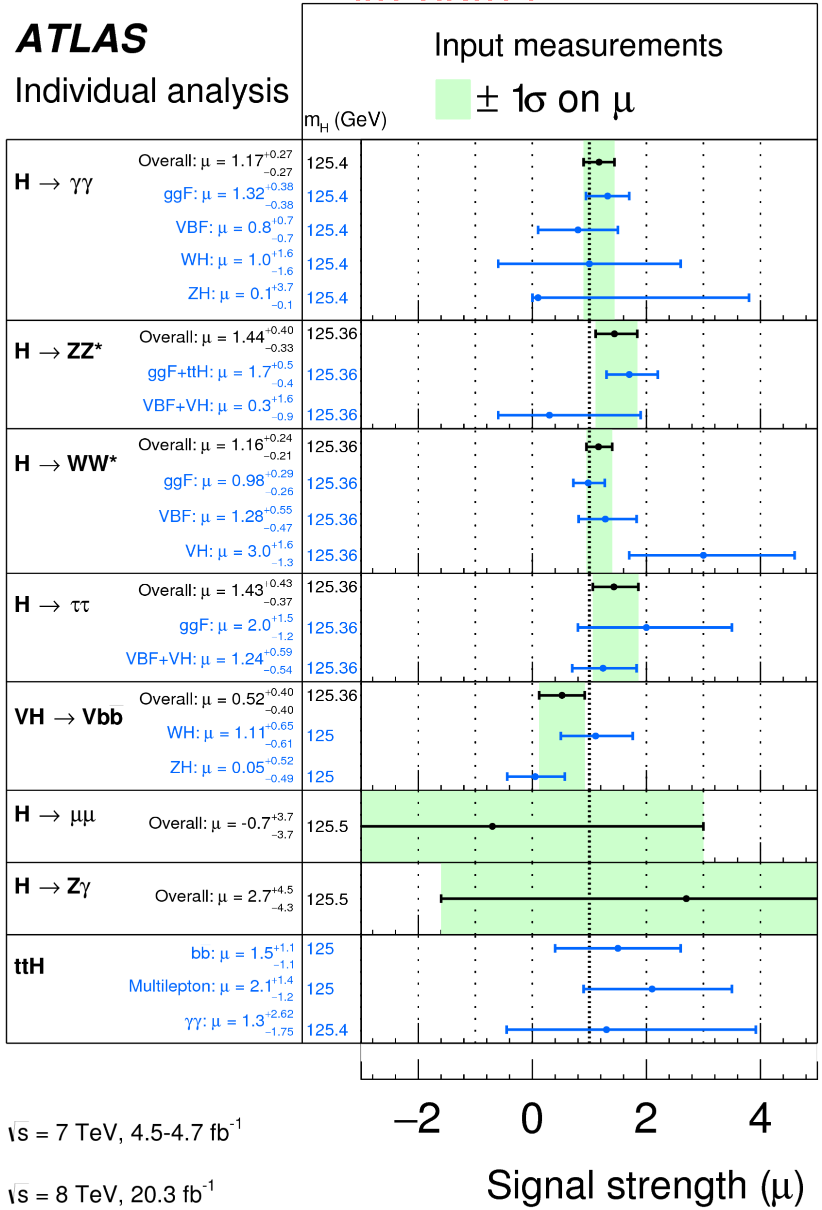
Decay channel	Branching ratio [%]
$H \to b\bar{b}$	57.1 ± 1.9
$H \to WW^*$	22.0 ± 0.9
$H \to gg$	8.53 ± 0.85
$H \to \tau\tau$	6.26 ± 0.35
$H \to c\bar{c}$	2.88 ± 0.35
$H \to ZZ^*$	2.73 ± 0.11
$H \to \gamma\gamma$	0.228 ± 0.011
$H \to Z\gamma$	0.157 ± 0.014
$H \to \mu\mu$	0.022 ± 0.001

The Higgs working group

S Heinemeyer et al., Handbook of LHC Higgs Cross Sections: 3. Higgs Properties (2013), arXiv:1307.1347 [hep-ph]

(except tH cross-section, from Alwall et al: JHEP 1407 (2014) 079)

The individual measurements to be reorganised to find production mode strengths



Each final state is produced in the different production modes, in analysis dependent proportions

Parameter estimation scheme

- Must take the production contributions of the different final state analyses and estimate overall cross-sections in the different modes

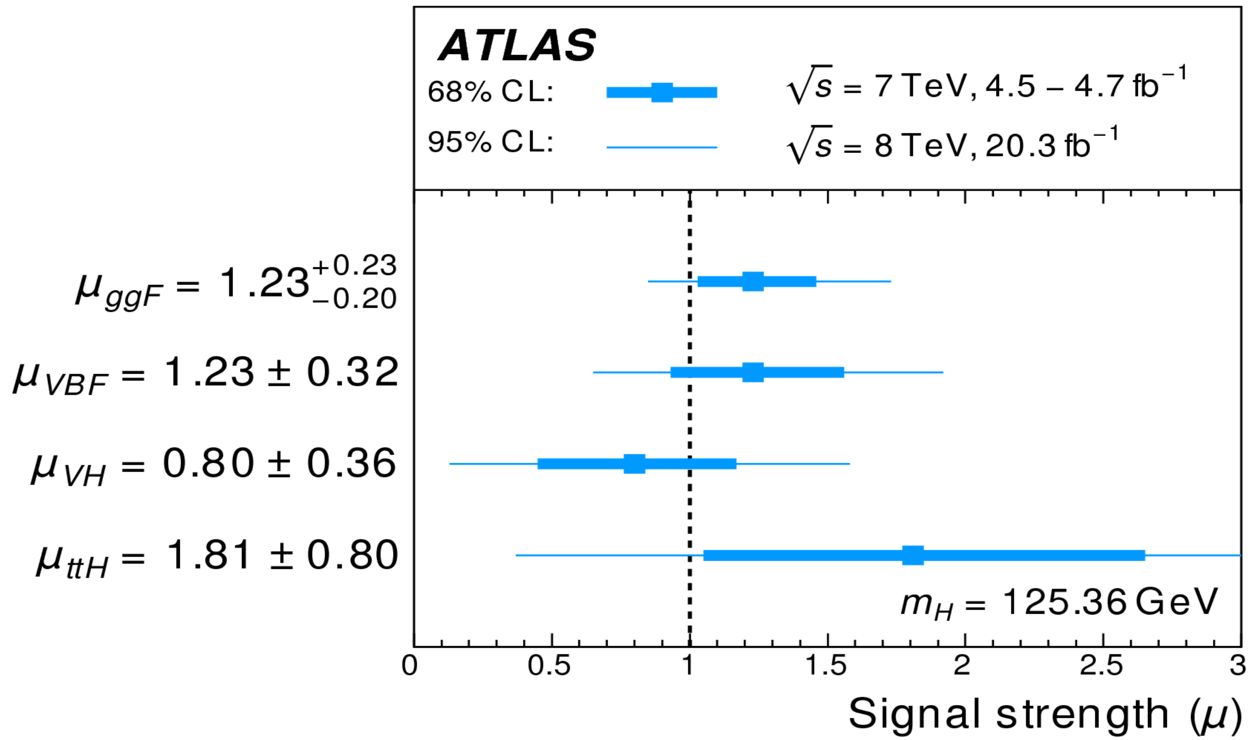
$$\Lambda(\alpha) = \frac{L(\alpha\,,\,\hat{\hat{\theta}}(\alpha))}{L(\hat{\alpha},\hat{\theta})}.$$

G. Cowan et al.
Eur. Phys. J. C71 (2011) 1554

Build a profile likelihood ratio in order to construct confidence intervals

- α is the vector of parameters of interest: (μ_i..,κ_i..).
- $\theta(\alpha)$ are nuisance parameters
- Denominator is most likely estimate
- Scan to get the confindence intervals of parameters of interest

Combinaton result: Strengths of the different production modes



Cross-sections for Higgs production at 7 and 8 TeV

$$\sigma_H(7\,\text{TeV}) = 22.1\,^{+7.4}_{-6.0}\,\text{pb} = 22.1\,^{+6.7}_{-5.3}\,(\text{stat.})\,^{+2.7}_{-2.3}\,(\text{syst.})\,^{+1.9}_{-1.4}\,(\text{theo.})\,\text{pb}, \text{ and}$$

$$\sigma_H(8\,\text{TeV}) = 27.7 \pm 3.7\,\text{pb} = 27.7 \pm 3.0\,(\text{stat.})\,^{+2.0}_{-1.7}\,(\text{syst.})\,^{+1.2}_{-0.9}\,(\text{theo.})\,\text{pb},$$

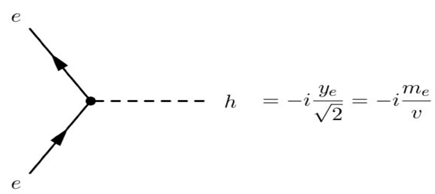
A little higher than than the theoretical predictions quoted (17.4±1.6 pb and 22.3 ±2.0 pb).

However:

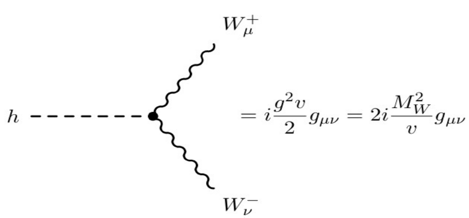
Newest calculations of the Higgs WG predict 10% larger ggF contributions to the cross-section (volume 4 of handbook)

Higgs couplings

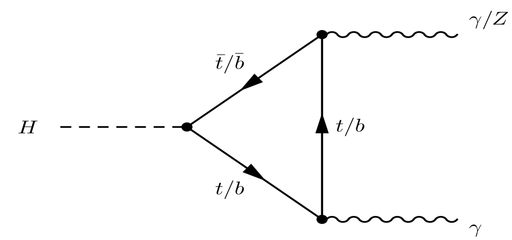
- The Higgs couples to *mass*
  - *Fermionic*



  - *Two gauge bosons:*



  - *Loops*



- The 'higgs working group' has proposed the 'kappa framework' for experimental tests

Coupling strengths: The 'κ' framework

developed by the Higgs working group to study deviations from the SM

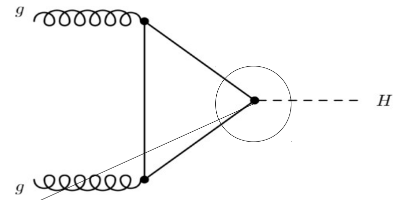
- Individual coupling modifiers: κ tied to a specific particle type
  - A given production mode is identified in several final states
  - Can define 'effective scale factors', κ, that should be equal to unity if the cross-sections agree with the SM

$$\sigma(i \to H \to f) = \frac{\sigma_i(\kappa_j) \cdot \Gamma_f(\kappa_j)}{\Gamma_H(\kappa_j)}$$

$$\Gamma_H(\kappa_j) = \kappa_H^2(\kappa_j) \cdot \Gamma_H^{\mathrm{SM}}$$

- 'Zero width' approximation

Parametrisations of couplings



Production	Loops	Interference	Expression in fundamental coupling-strength scale factors
$\sigma(\text{ggF})$	✓	b–t	$\kappa_g^2 \sim 1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$
$\sigma(\text{VBF})$	-	-	$\sim 0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	-	-	$\sim \kappa_W^2$
$\sigma(q\bar{q} \rightarrow ZH)$	-	-	$\sim \kappa_Z^2$
$\sigma(gg \rightarrow ZH)$	✓	Z–t	$\kappa_{ggZH}^2 \sim 2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t$
$\sigma(bbH)$	-	-	$\sim \kappa_b^2$
$\sigma(ttH)$	-	-	$\sim \kappa_t^2$
$\sigma(gb \rightarrow WtH)$	-	W–t	$\sim 1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t \kappa_W$
$\sigma(qb \rightarrow tHq')$	-	W–t	$\sim 3.4 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t \kappa_W$
Partial decay width			
$\Gamma_{b\bar{b}}$	-	-	$\sim \kappa_b^2$
Γ_{WW}	-	-	$\sim \kappa_W^2$
Γ_{ZZ}	-	-	$\sim \kappa_Z^2$
$\Gamma_{\tau\tau}$	-	-	$\sim \kappa_\tau^2$
$\Gamma_{\mu\mu}$	-	-	$\sim \kappa_\mu^2$
$\Gamma_{\gamma\gamma}$	✓	W–t	$\kappa_\gamma^2 \sim 1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$
$\Gamma_{Z\gamma}$	✓	W–t	$\kappa_{Z\gamma}^2 \sim 1.12 \cdot \kappa_W^2 + 0.00035 \cdot \kappa_t^2 - 0.12 \cdot \kappa_W \kappa_t$
Total decay width			
Γ_H	✓	$W - t$ $b - t$	$\kappa_H^2 \sim 0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 +$ $0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 +$ $0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{Z\gamma}^2 + 0.00022 \cdot \kappa_\mu^2$

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Fermion vs Vector Boson coupling strength

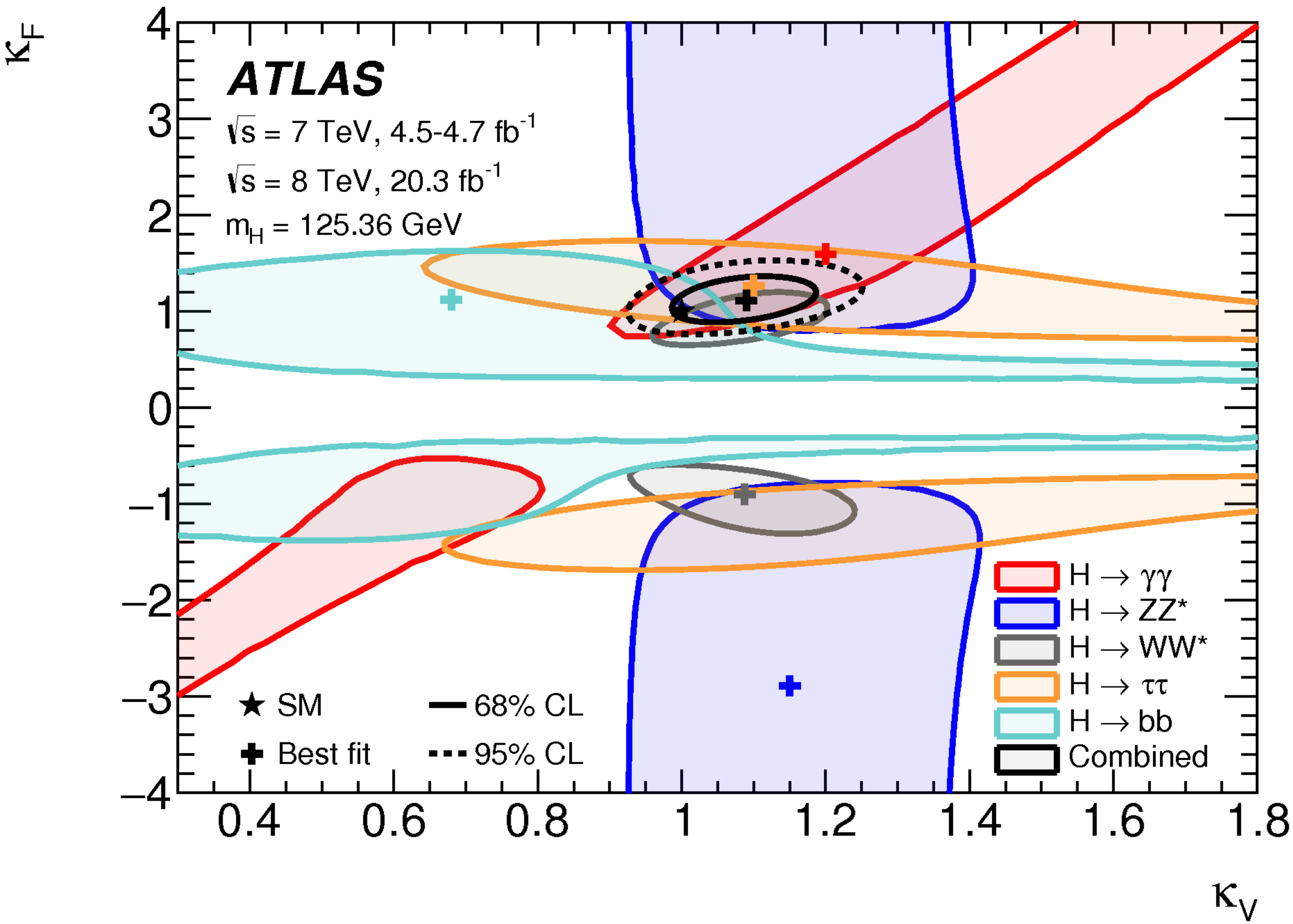
- Assume

$$\kappa_V = \kappa_W = \kappa_Z$$
$$\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_g = \kappa_\mu .$$

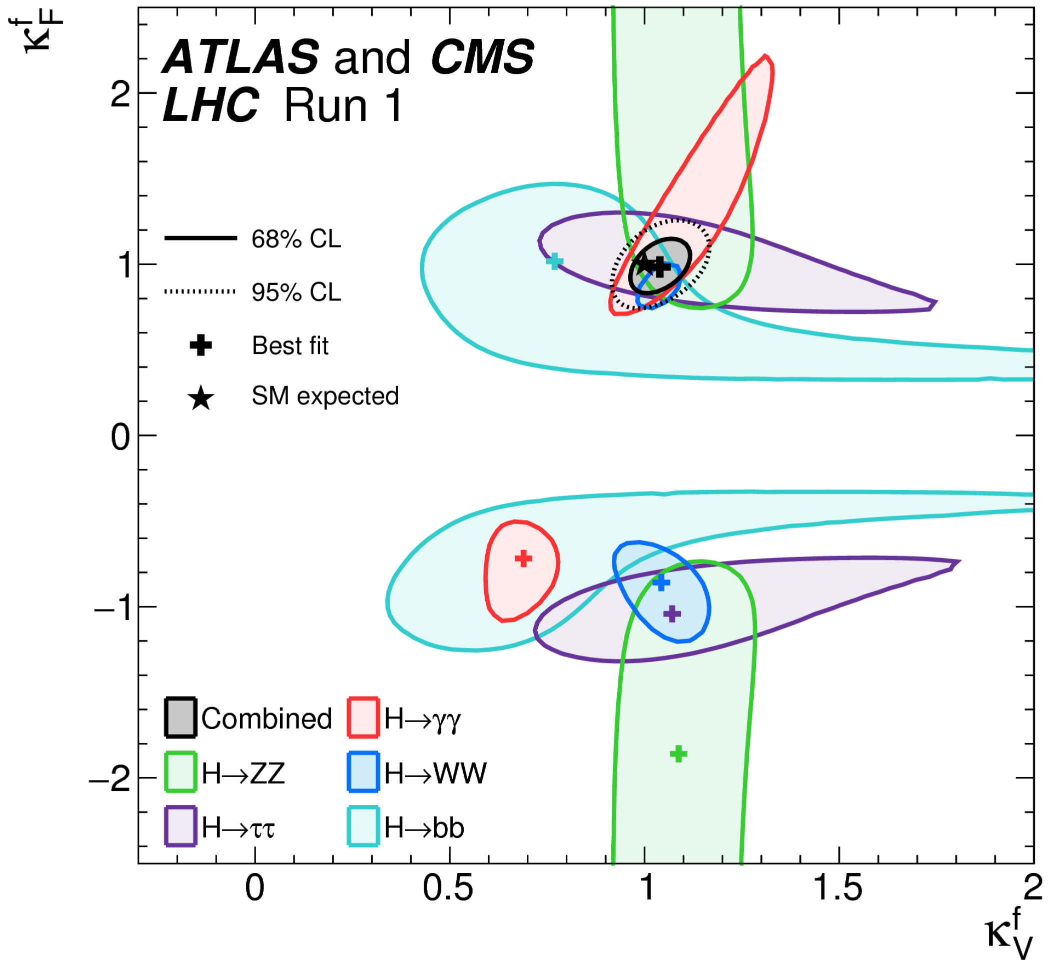
- and only SM couplings
- Run1 result

$$\kappa_V = 1.09 \pm 0.07 \left[{}^{+0.05}_{-0.05}(\text{stat.}) \, {}^{+0.03}_{-0.03}(\text{syst.}) \, {}^{+0.04}_{-0.03}(\text{theo.}) \right]$$
$$\kappa_F = 1.11 \pm 0.16 \left[{}^{+0.12}_{-0.11}(\text{stat.}) \, {}^{+0.10}_{-0.09}(\text{syst.}) \, {}^{+0.06}_{-0.05}(\text{theo.}) \right]$$

Result visualised



ATLAS and CMS **combined** Run1 measurements



Note:

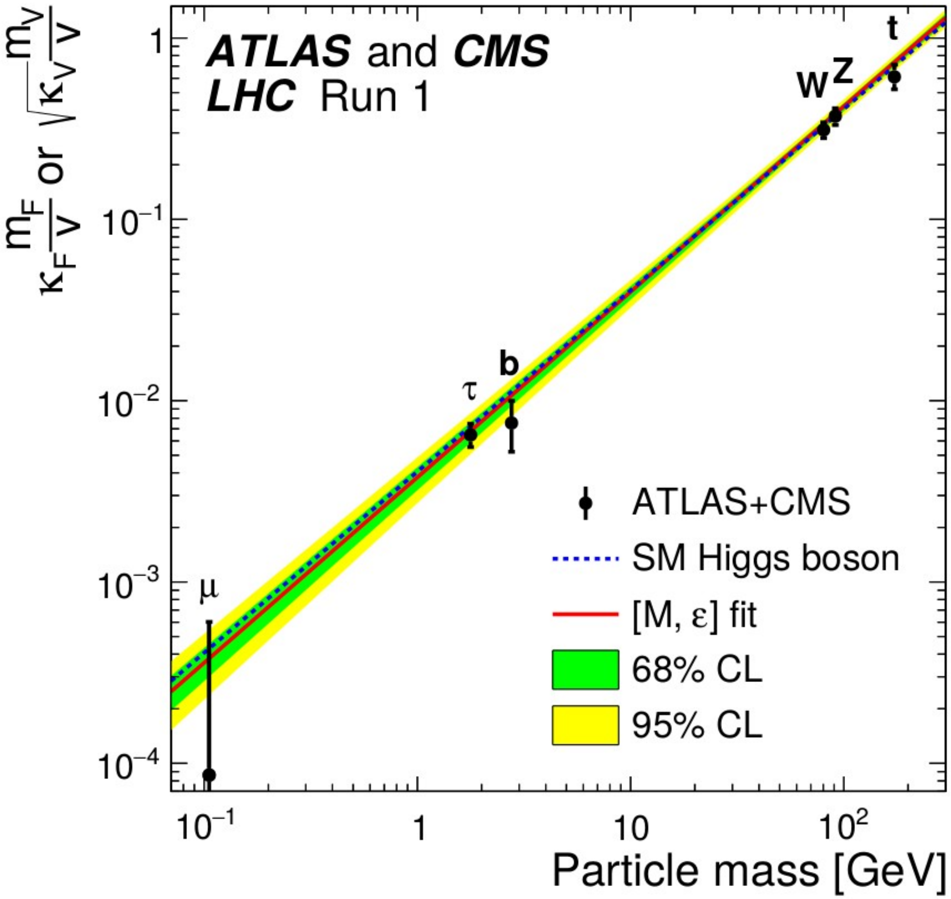
H→ZZ,WW constrains κ_V

H→ττ constrains κ_F

Sensitivity to sign of κ_F through Wt interference

JHEP08(2016)045

Summarizing RUN1 couplings vs mass



A variety of scenarios are probed

- Allow invisible or undetected contributions
- No assumtions on total width
- Compare up-type and down-type fermions
- Compare W to Z coupling
- Quark-lepton symmetry
- BSM contributions

- All consistent with SM

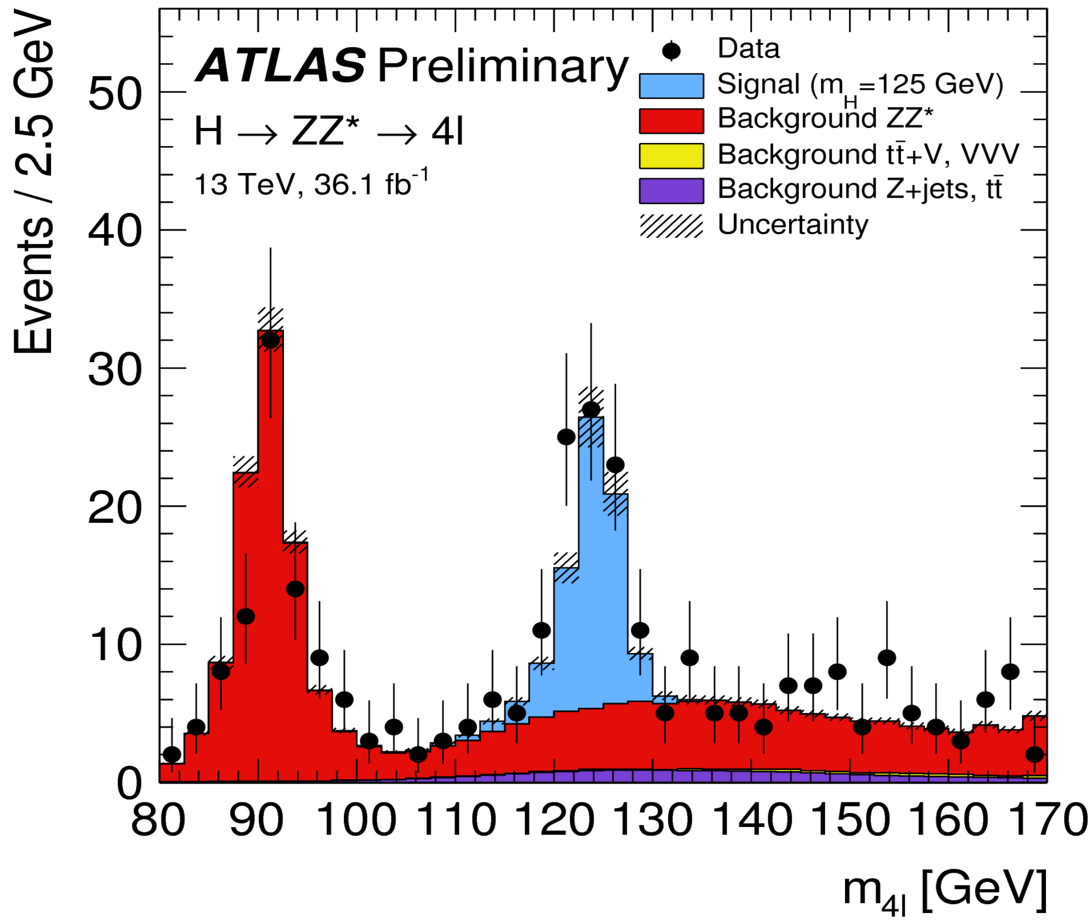
RUN-II (13 TeV) updates

- Preliminary results are available with 36.1/fb for
  - $H \rightarrow 4$ leptons
  - $H \rightarrow \gamma\gamma$
  - $H \rightarrow \mu\mu$ (limit, published)

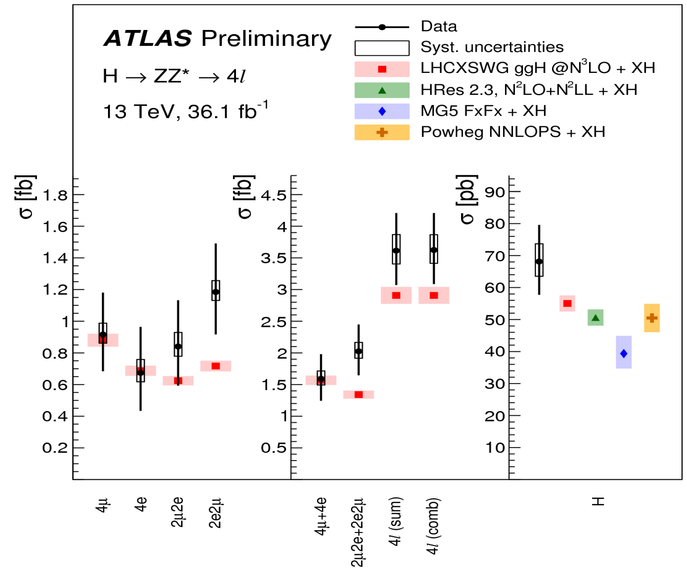
- ...and more is coming

The Higgs to four leptons signal at 13 TeV

- $H \rightarrow ZZ^{*} \rightarrow 4l$ (ATL-CONF-2017-032)



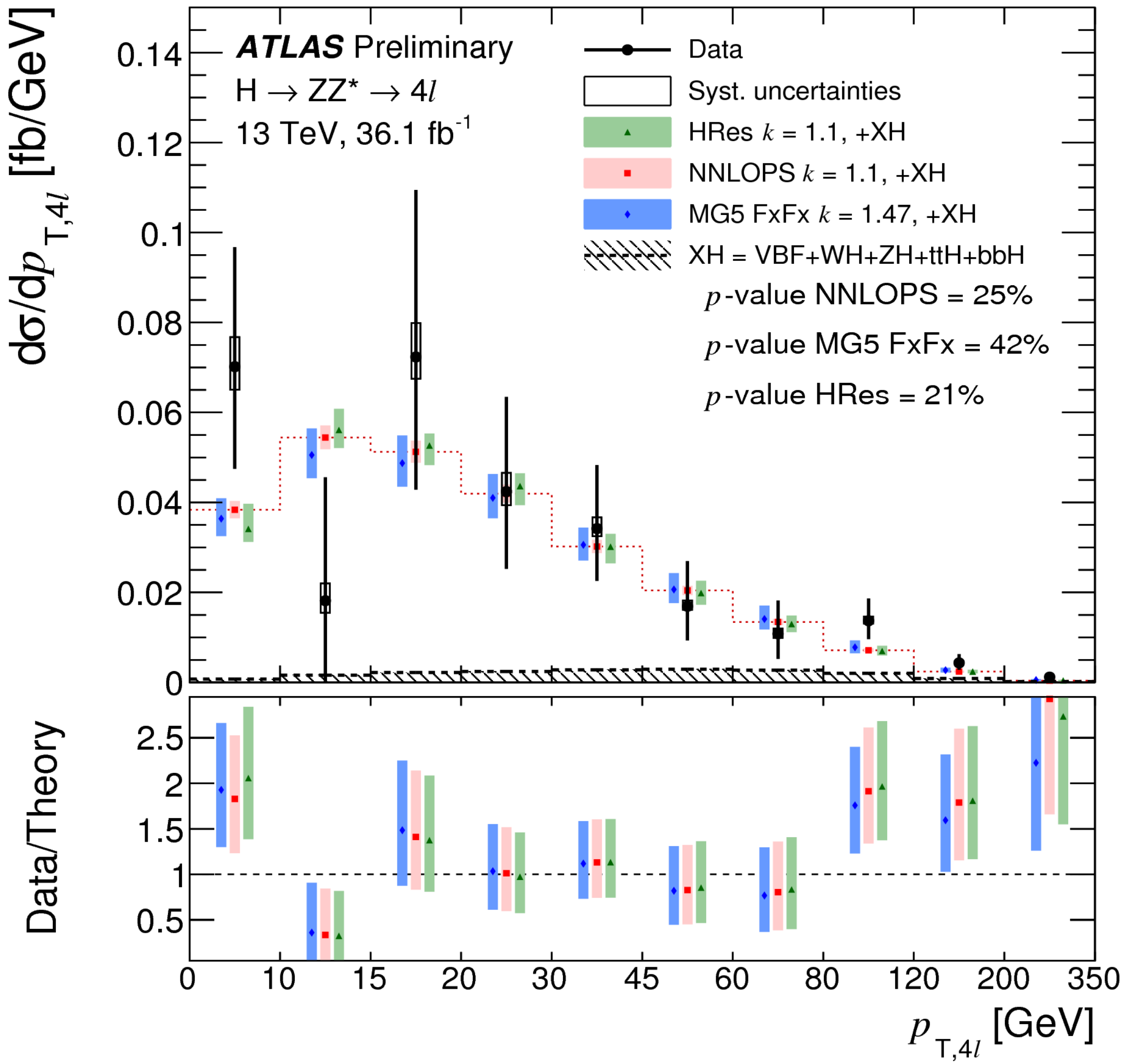
Fiducial and total cross-sections at 13TeV from H →4l



Summed contributions, or *combined* using SM BR-fractions of the Z

Cross section	Data (± (stat) ± (sys))	LHCXSWG prediction	p-value [%]
$\sigma_{4\mu}$ [fb]	$0.92\ {}^{+0.25}_{-0.23}\ {}^{+0.07}_{-0.05}$	0.880 ± 0.039	88
σ_{4e} [fb]	$0.67\ {}^{+0.28}_{-0.23}\ {}^{+0.08}_{-0.06}$	0.688 ± 0.031	96
$\sigma_{2\mu 2e}$ [fb]	$0.84\ {}^{+0.28}_{-0.24}\ {}^{+0.09}_{-0.06}$	0.625 ± 0.028	39
$\sigma_{2e2\mu}$ [fb]	$1.18\ {}^{+0.30}_{-0.26}\ {}^{+0.07}_{-0.05}$	0.717 ± 0.032	7
$\sigma_{4\mu+4e}$ [fb]	$1.59\ {}^{+0.37}_{-0.33}\ {}^{+0.12}_{-0.10}$	1.57 ± 0.07	65
$\sigma_{2\mu 2e+2e2\mu}$ [fb]	$2.02\ {}^{+0.40}_{-0.36}\ {}^{+0.14}_{-0.11}$	1.34 ± 0.06	6
σ_{sum} [fb]	$3.61\ {}^{+0.54}_{-0.50}\ {}^{+0.26}_{-0.21}$	2.91 ± 0.13	19
σ_{comb} [fb]	$3.62\ {}^{+0.53}_{-0.50}\ {}^{+0.25}_{-0.20}$	2.91 ± 0.13	18
σ_{tot} [pb]	$69\ {}^{+10}_{-9}\ \pm 5$	55.6 ± 2.5	19

Also Higgs Pt distribution in 4 lepton final state



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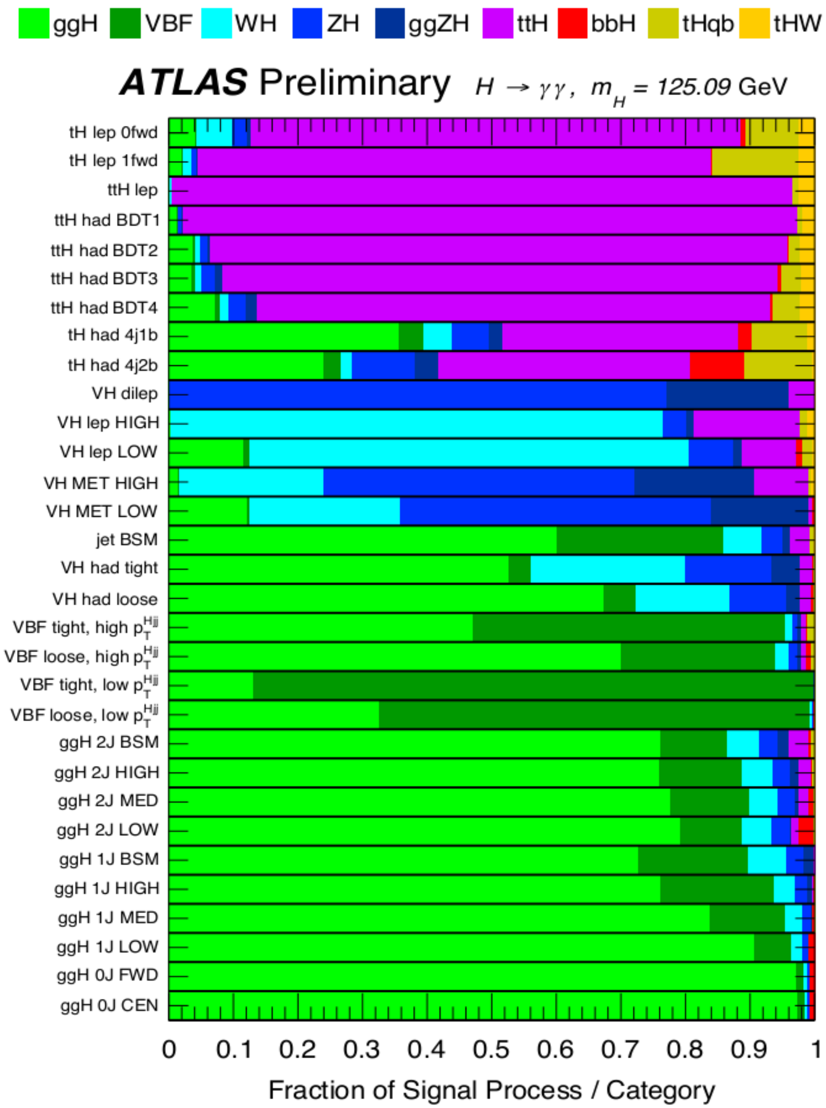
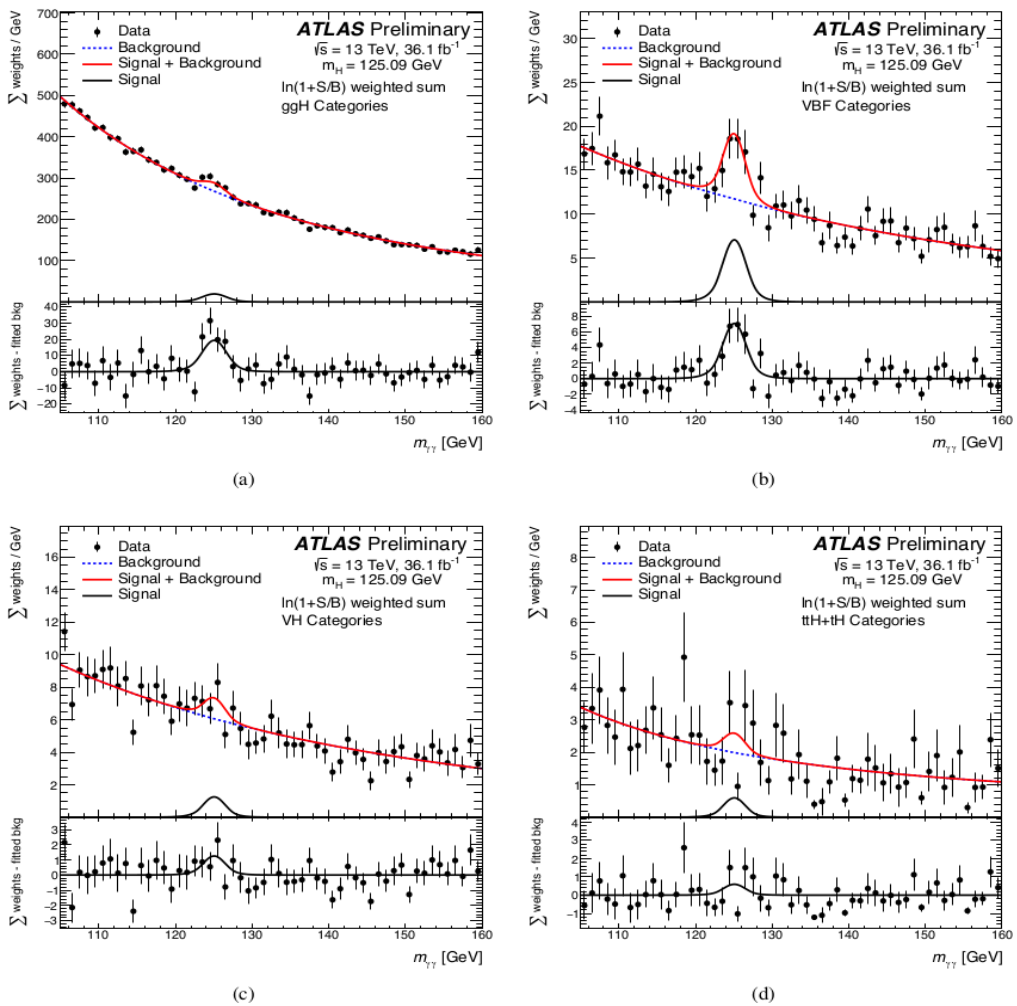
Details of event classification, Run2 H→γγ



Events are classified according to their assumed production mode and other discriminants.
The production mode content in each class is subsequently estimated

The Run-2 H→γγ signal in different categories



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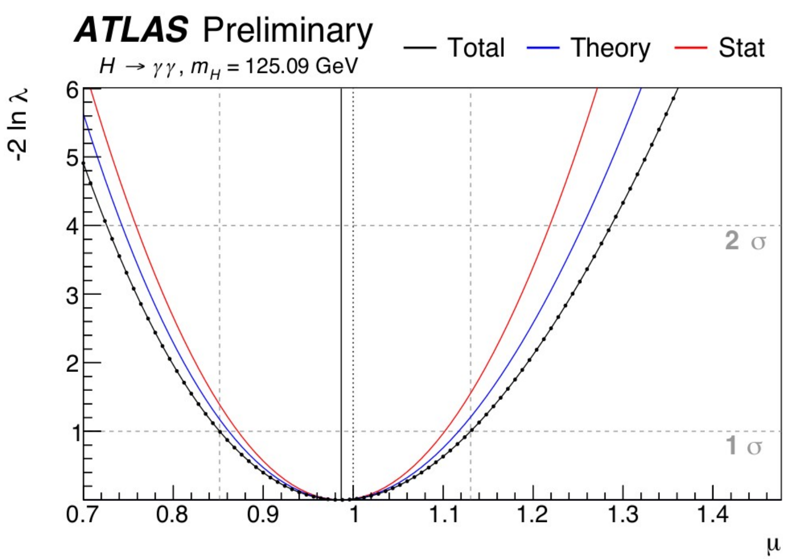
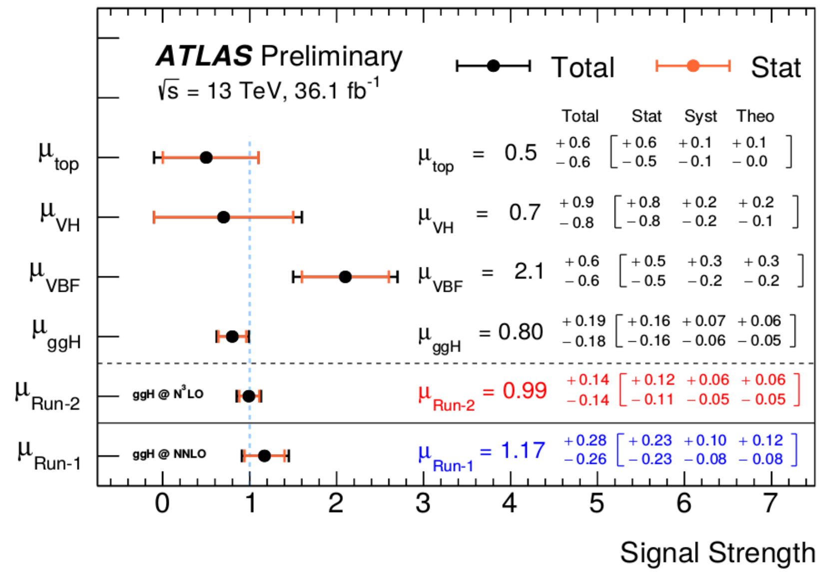
Higgs signal strengths at 13 TeV using the $\gamma\gamma$ final state

$$\mu = 0.99\,^{+0.14}_{-0.13} = 0.99\,^{+0.12}_{-0.11}\,(\text{stat.})\,^{+0.05}_{-0.04}\,(\text{exp.})\,^{+0.07}_{-0.06}\,(\text{theory})$$

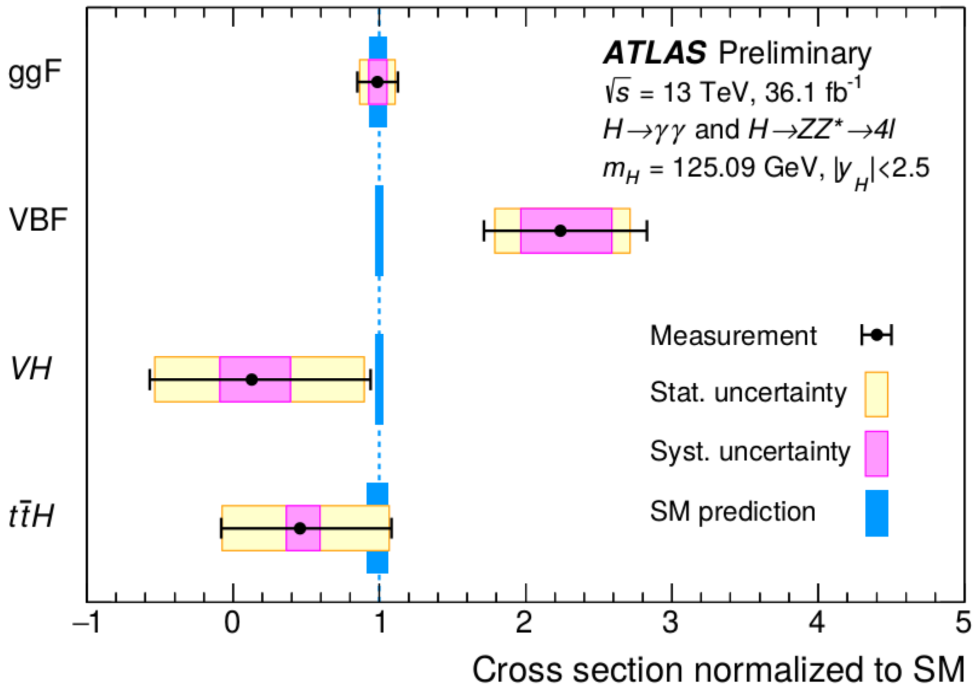




Note improvement over run 1

Combined *4l* and $\gamma\gamma$ signal strengths at 13 TeV

$$\mu = 1.09 \pm 0.12 = 1.09 \pm 0.09\ (\text{stat.})\ ^{+0.06}_{-0.05}\ (\text{syst.})\ ^{+0.06}_{-0.05}\ (\text{th.})$$



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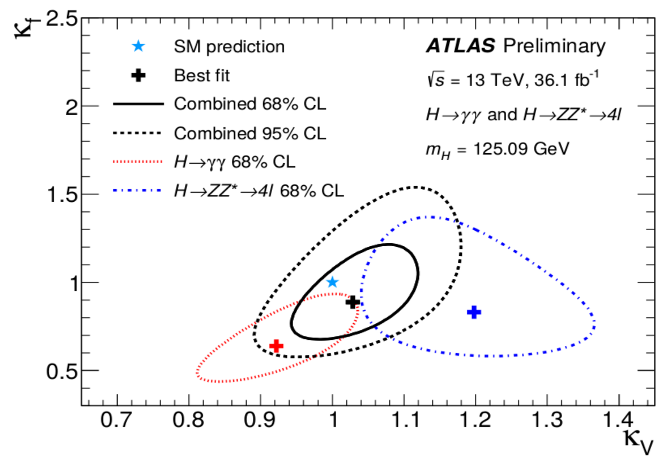
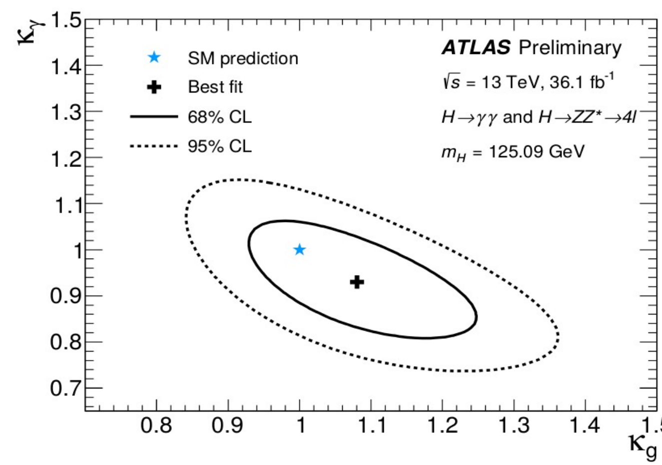
Couplings at 13 TeV from γγ and 4l combination

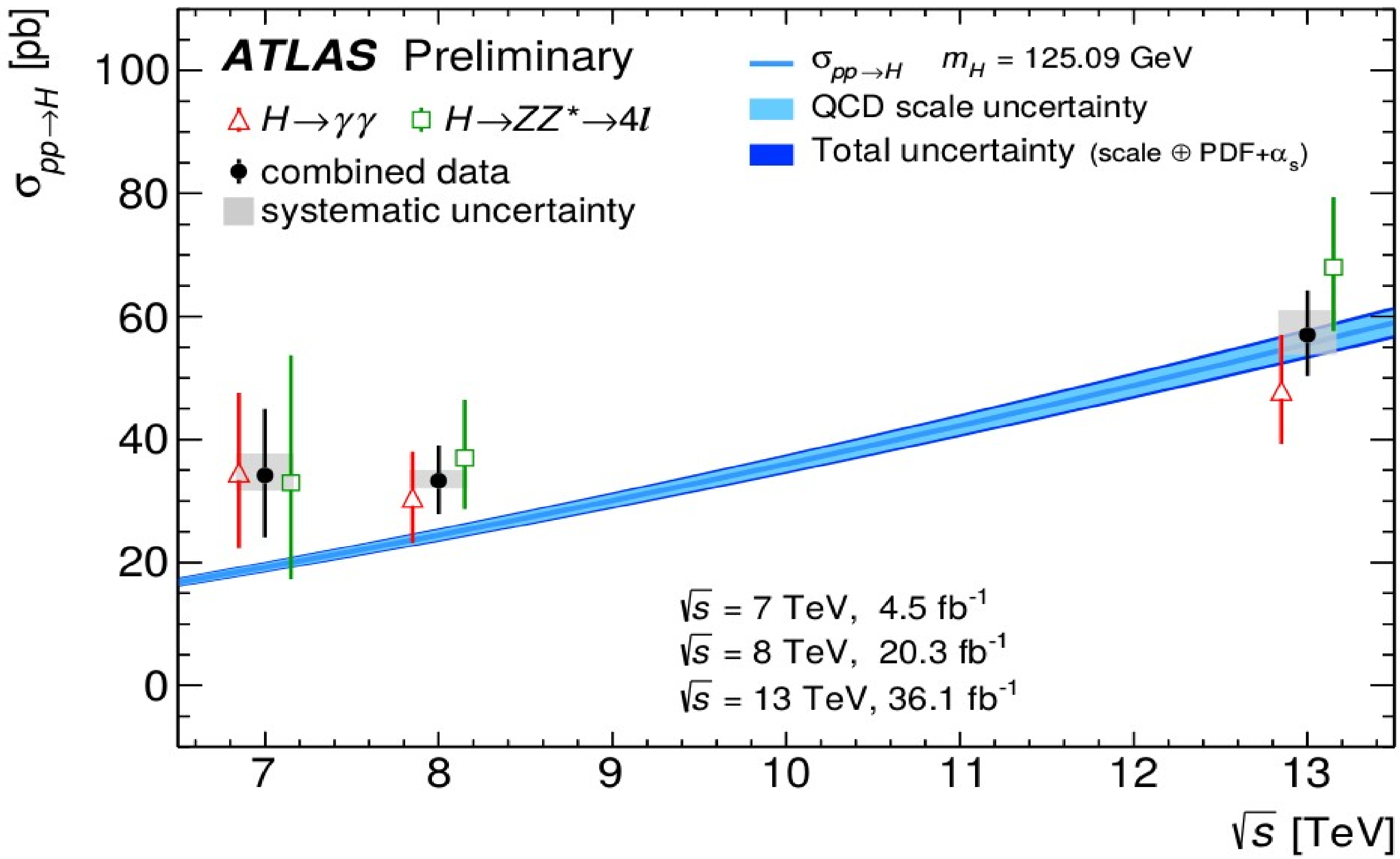
- Negative κ_F can be excluded at 95% C.L.
- $\kappa_V = 1.03 \pm 0.06$, $\kappa_f = 0.88^{+0.19}_{-0.15}$



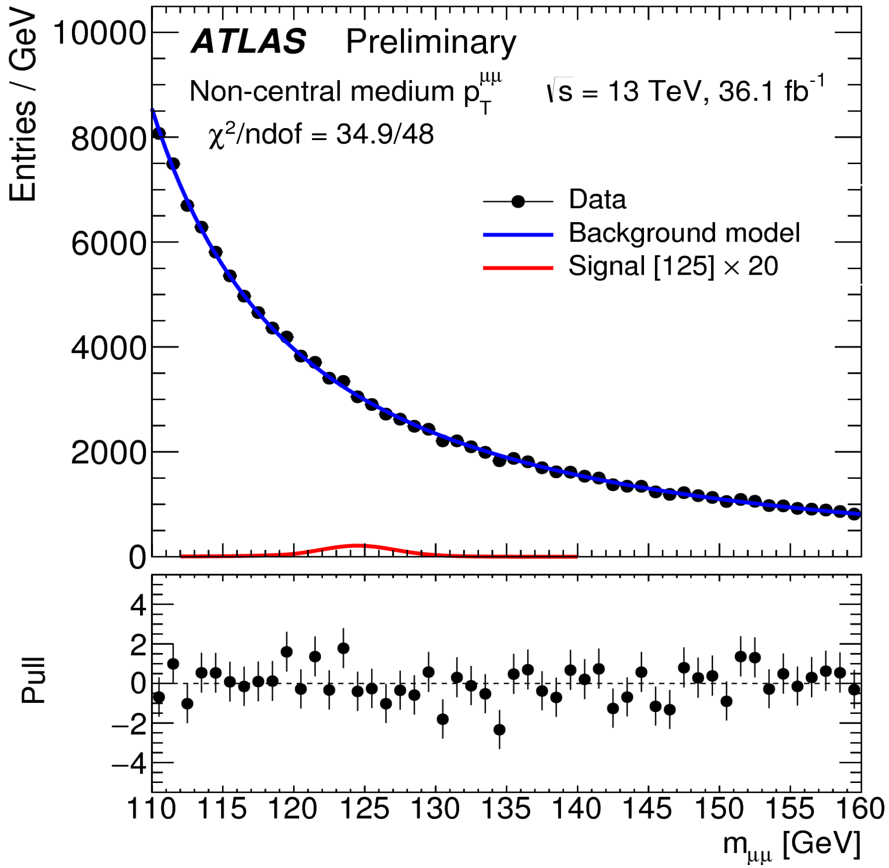
- Fit without assumptions on γγ and *gg* vertices:
- $\kappa_g = 1.08^{+0.11}_{-0.10}$, $\kappa_\gamma = 0.93^{+0.09}_{-0.08}$



Higgs Cross-section results 7, 8 and 13 TeV



The sensitivity to H →μμ is getting interesting



Signal strength
μ < 2.8 (95% c.l.)

Plot shows just one of the categories

Conclusions

- Higgs physics at the LHC has moved to a vigorous measurement phase with access to
  - Cross-sections
  - Individual couplings
- Precision is around or approaching 10% for many of the estimates performed
- No deviations from the Standard Model at this precision
- ATLAS results for 13 TeV 2015+2016 data are close to completion for most Higgs analyses
  - Some channels missing
  - ttH results are coming up
  - Full combination study to be performed
- Next milestone:
  - Collect good data in 2017-2018 and analyse the full RUN2 dataset

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Theoretical cross-sections, 13 TeV

Table 1: Summary of event generators and PDF sets used to model the signal and the main background processes. The SM cross sections σ for the Higgs production processes with $m_H = 125.09$ GeV are also given separately for $\sqrt{s} = 13$ TeV, together with the orders of the calculations.

Process	Generator	Showering	PDF set	Order of calculation	σ[pb] $\sqrt{s} = 13$ TeV
ggH	Powheg NNLOPS	Pythia8	PDF4LHC15	N3LO(QCD)+NLO(EW)	48.52
VBF	Powheg Box	Pythia8	PDF4LHC15	NNLO(QCD)+NLO(EW)	3.78
WH	Powheg Box	Pythia8	PDF4LHC15	NNLO(QCD)+NLO(EW)	1.37
$qq \to ZH$	Powheg Box	Pythia8	PDF4LHC15	NNLO(QCD)+NLO(EW)	0.76
$gg \to ZH$	Powheg Box	Pythia8	PDF4LHC15	NNLO(QCD)+NLO(EW)	0.12
$t\bar{t}H$	MadGraph5_aMC@NLO	Pythia8	NNPDF3.0	NLO(QCD)+NLO(EW)	0.51
$b\bar{b}H$	MadGraph5_aMC@NLO	Pythia8	CT10	5FS(NNLO)+4FS(NLO)	0.49
$tHqb$	MadGraph5_aMC@NLO	Pythia8	CT10	5FS(NLO)	0.07
tHW	MadGraph5_aMC@NLO	Herwig++	CT10	5FS(NLO)	0.02