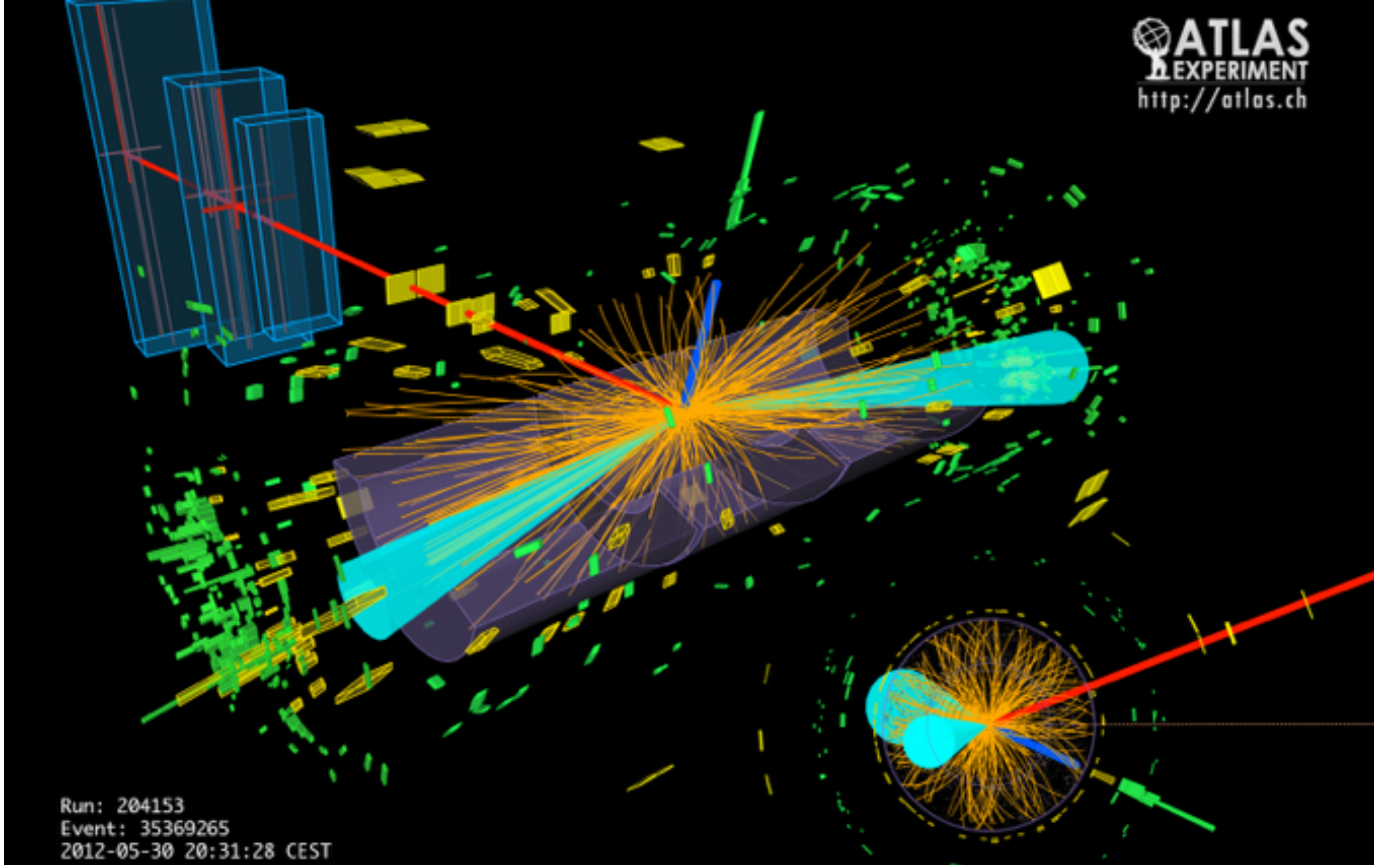

h(125) BOSON MEASUREMENTS IN ATLAS: RUN-1 LECACY AND EARLY RUN-2 RESULTS.

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On behalf of the ATLAS experiment

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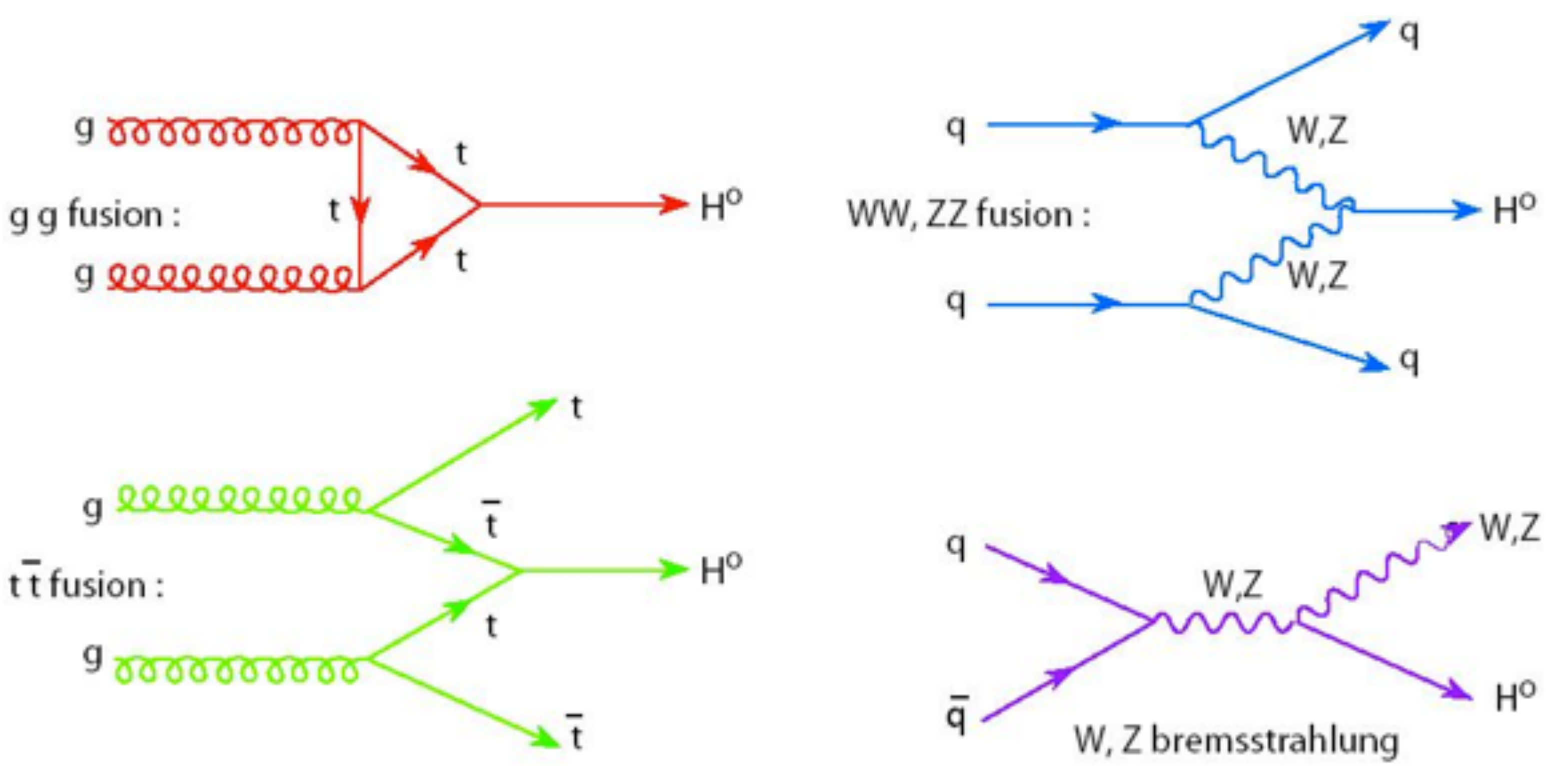
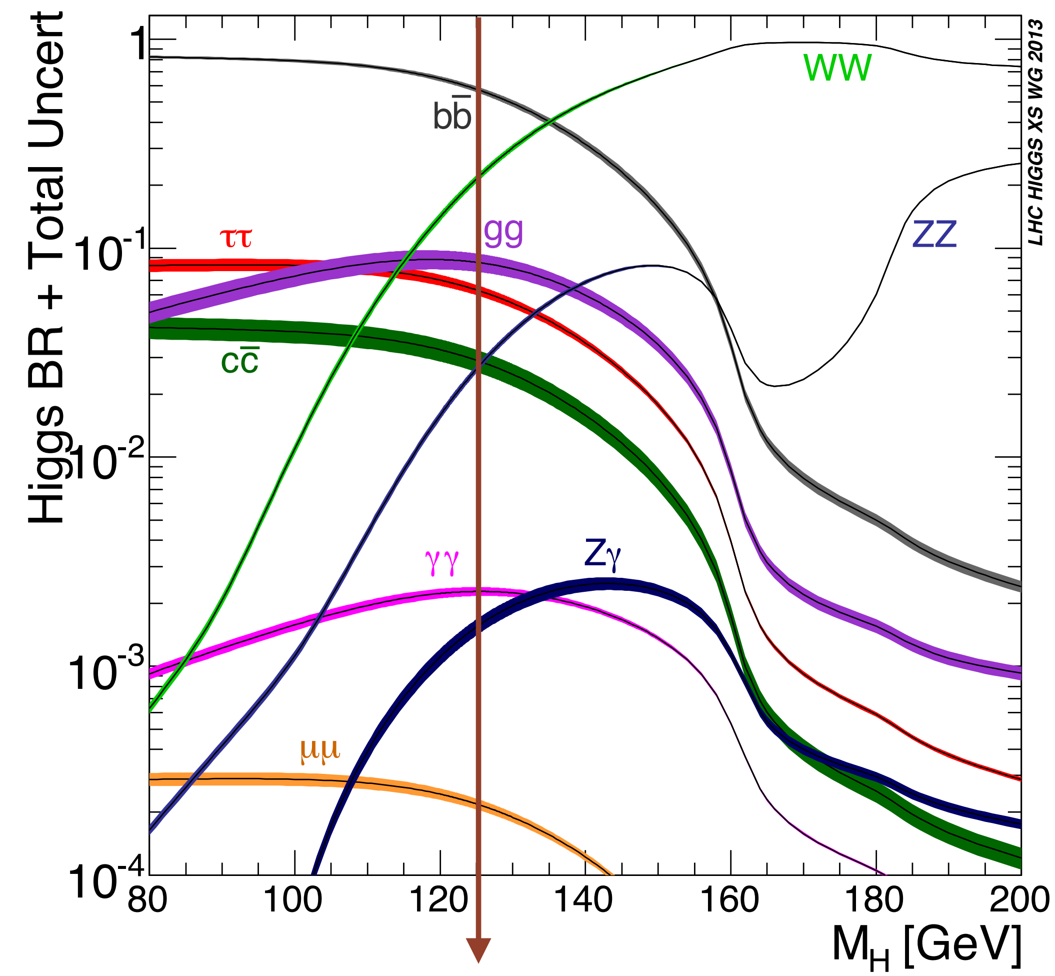
LLWI2016

INTRODUCTION

- Following the Higgs boson discovery in 2012, the task was to measure the properties of this new boson:
  - Mass
  - Width
  - Spin/parity
  - Couplings
  - Search for "non-standard" decay modes
- In this talk, I will review the latest ATLAS run-1 measurements (20+5 fb^{-1} at $\sqrt{s}$ = 8 and 7 TeV) including some ATLAS+CMS combinations (couplings).
- I will also mention some of the first run-2 ATLAS results (3.2 fb^{-1} of data at $\sqrt{s}$=13 TeV collected in 2015).

SM HIGGS BOSON PRODUCTION AT THE LHC





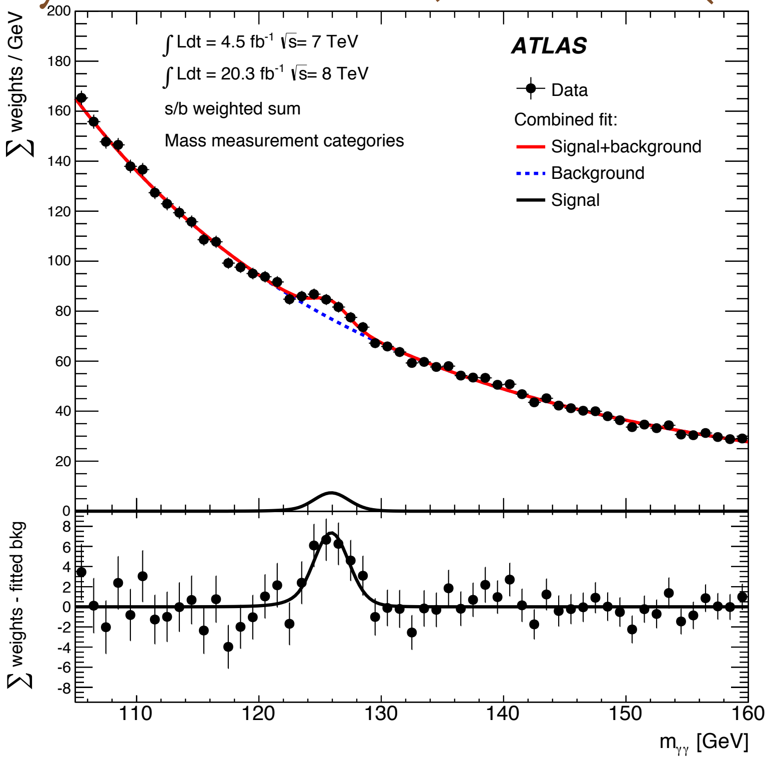
Production process	Cross section [pb] $\sqrt{s} = 7$ TeV	$\sqrt{s} = 8$ TeV	Order of calculation
ggF	15.0 ± 1.6	19.2 ± 2.0	NNLO(QCD)+NLO(EW)
VBF	1.22 ± 0.03	1.58 ± 0.04	NLO(QCD+EW)+~NNLO(QCD)
WH	0.577 ± 0.016	0.703 ± 0.018	NNLO(QCD)+NLO(EW)
ZH	0.334 ± 0.013	0.414 ± 0.016	NNLO(QCD)+NLO(EW)
$[ggZH]$	0.023 ± 0.007	0.032 ± 0.010	NLO(QCD)
bbH	0.156 ± 0.021	0.203 ± 0.028	5FS NNLO(QCD) + 4FS NLO(QCD)
ttH	0.086 ± 0.009	0.129 ± 0.014	NLO(QCD)
tH	0.012 ± 0.001	0.018 ± 0.001	NLO(QCD)
Total	17.4 ± 1.6	22.3 ± 2.0	

Decay channel	Branching ratio [%]
$H \to bb$	57.5 ± 1.9
$H \to WW$	21.6 ± 0.9
$H \to gg$	8.56 ± 0.86
$H \to \tau\tau$	6.30 ± 0.36
$H \to cc$	2.90 ± 0.35
$H \to ZZ$	2.67 ± 0.11
$H \to \gamma\gamma$	0.228 ± 0.011
$H \to Z\gamma$	0.155 ± 0.014
$H \to \mu\mu$	0.022 ± 0.001

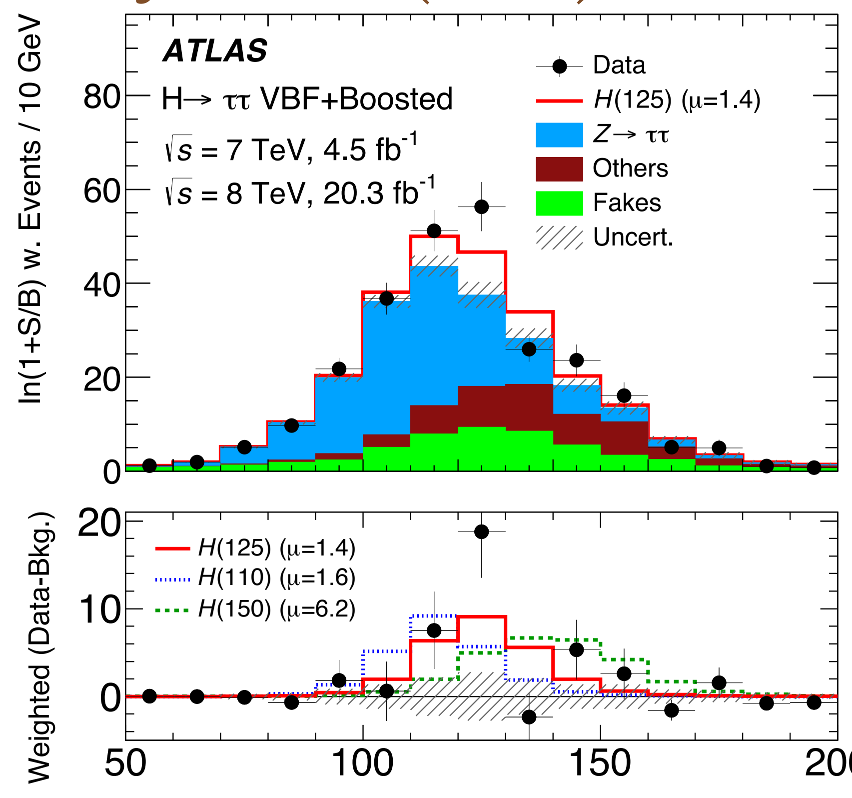
Tables from arXiv:1507.04548

HIGGS BOSON DISCOVERY BY DECAY CHANNELS

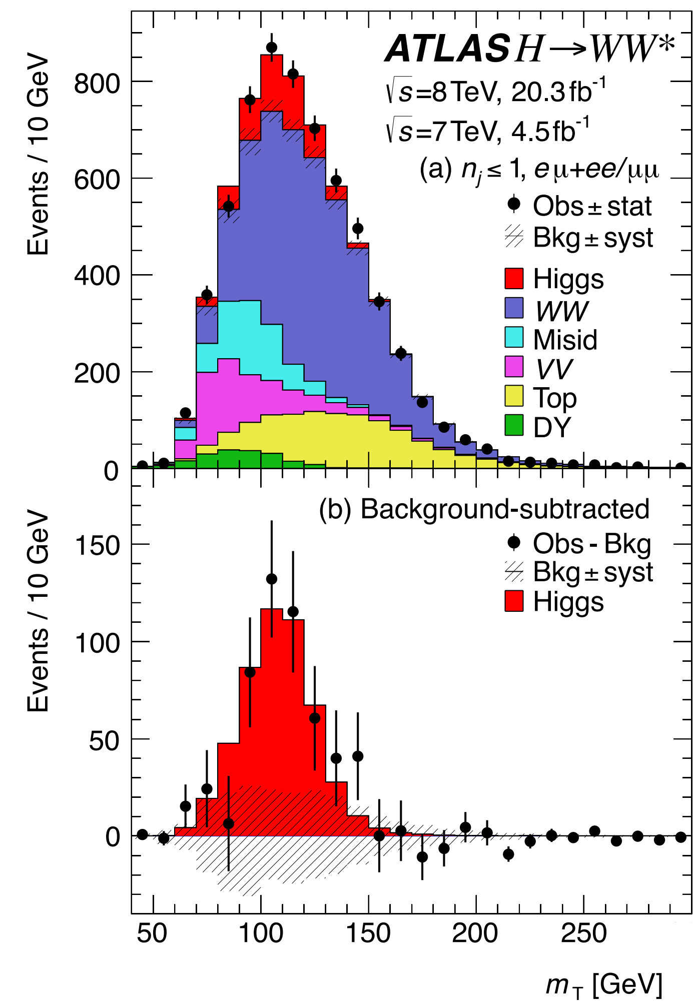
Phys. Rev. D. 90, 052004(2014)



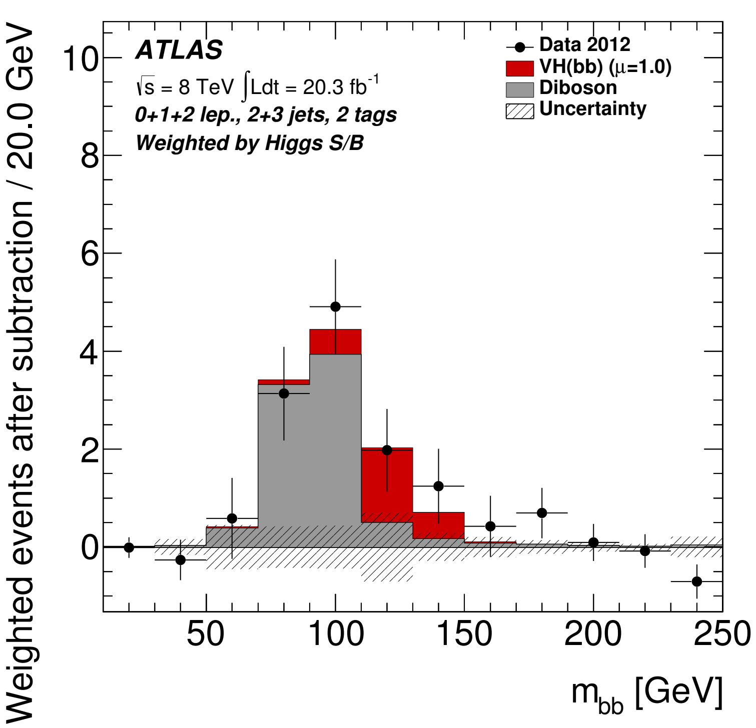
JHEP 04 (2015) 117



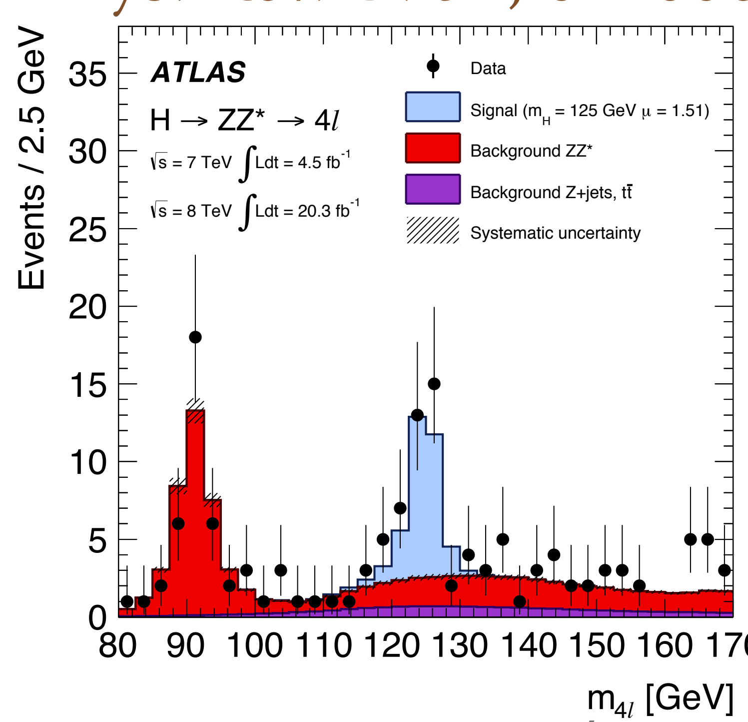
Phys. Rev. D 92, 012006(2015)



JHEP01(2015)069



Phys. Rev. D. 91, 012006(2015)



Significance of each production mode: ggF>5σ

Process	VBF	ttH	WH	ZH	VH
Observed	4.3	2.5	2.1	0.9	2.6
Expected	3.8	1.5	2.0	2.1	3.1

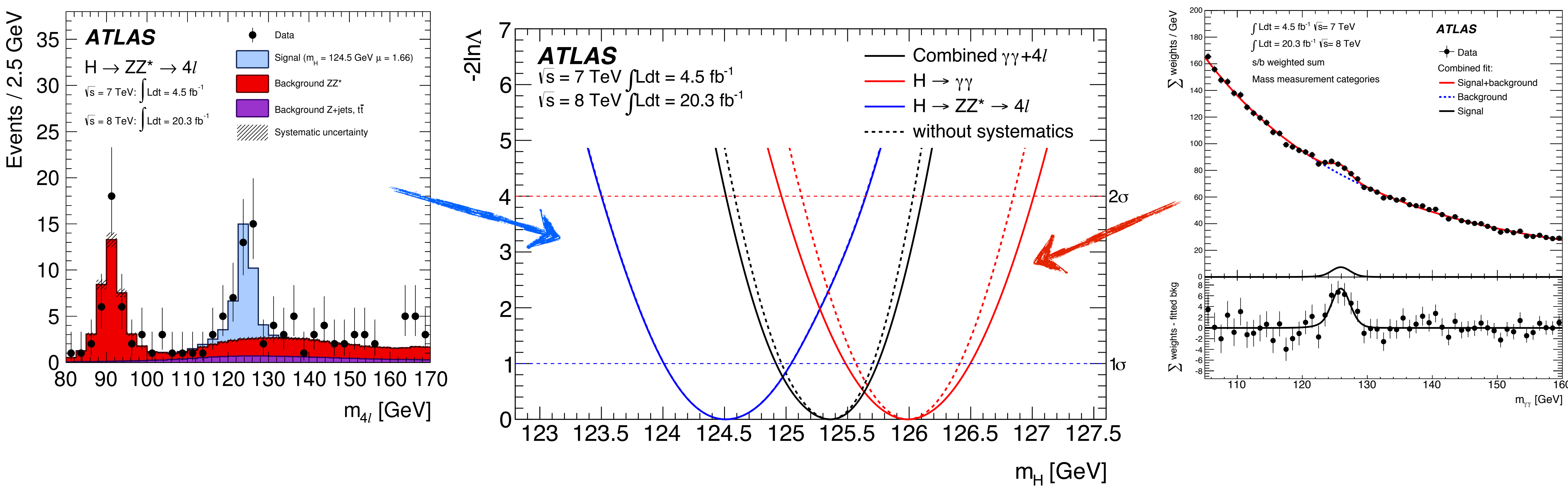
arXiv:1507.04548

MASS MEASUREMENT

- Precise measurement of m_H from channels with the best mass resolution: $H \to \gamma\gamma$, $H \to ZZ$ (<2%)

- Dominant uncertainties: photon energy scale ($H \to \gamma\gamma$), lepton energy and momentum scale, statistics ($H \to 4l$)

Phys. Rev. D. 90.052004(2014)



Combined mass: $m_H = 125.36 \pm 0.37(stat) + 0.18(sys)$ GeV

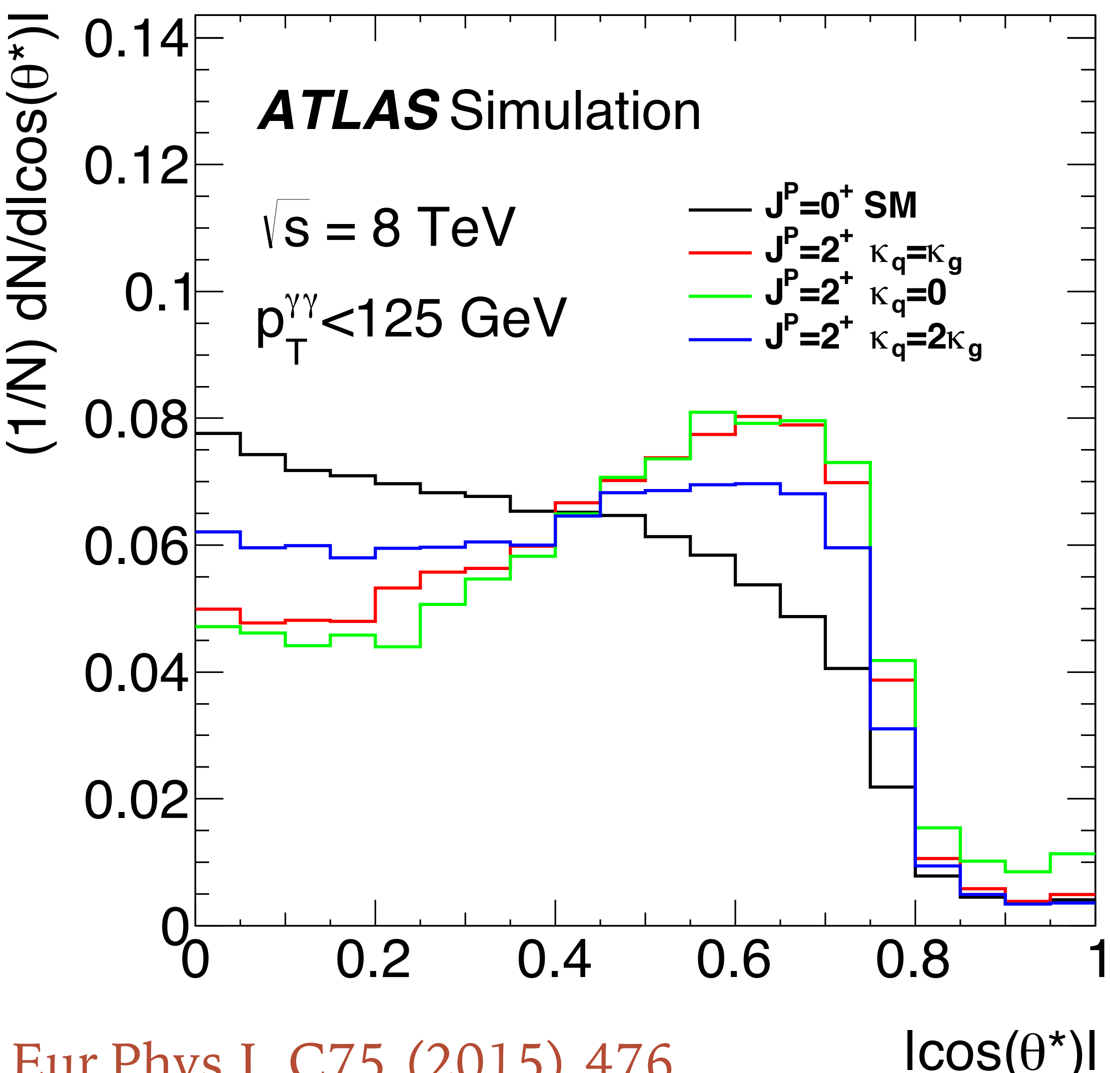
Mass difference 2.0 σ (p-value 4.8%).

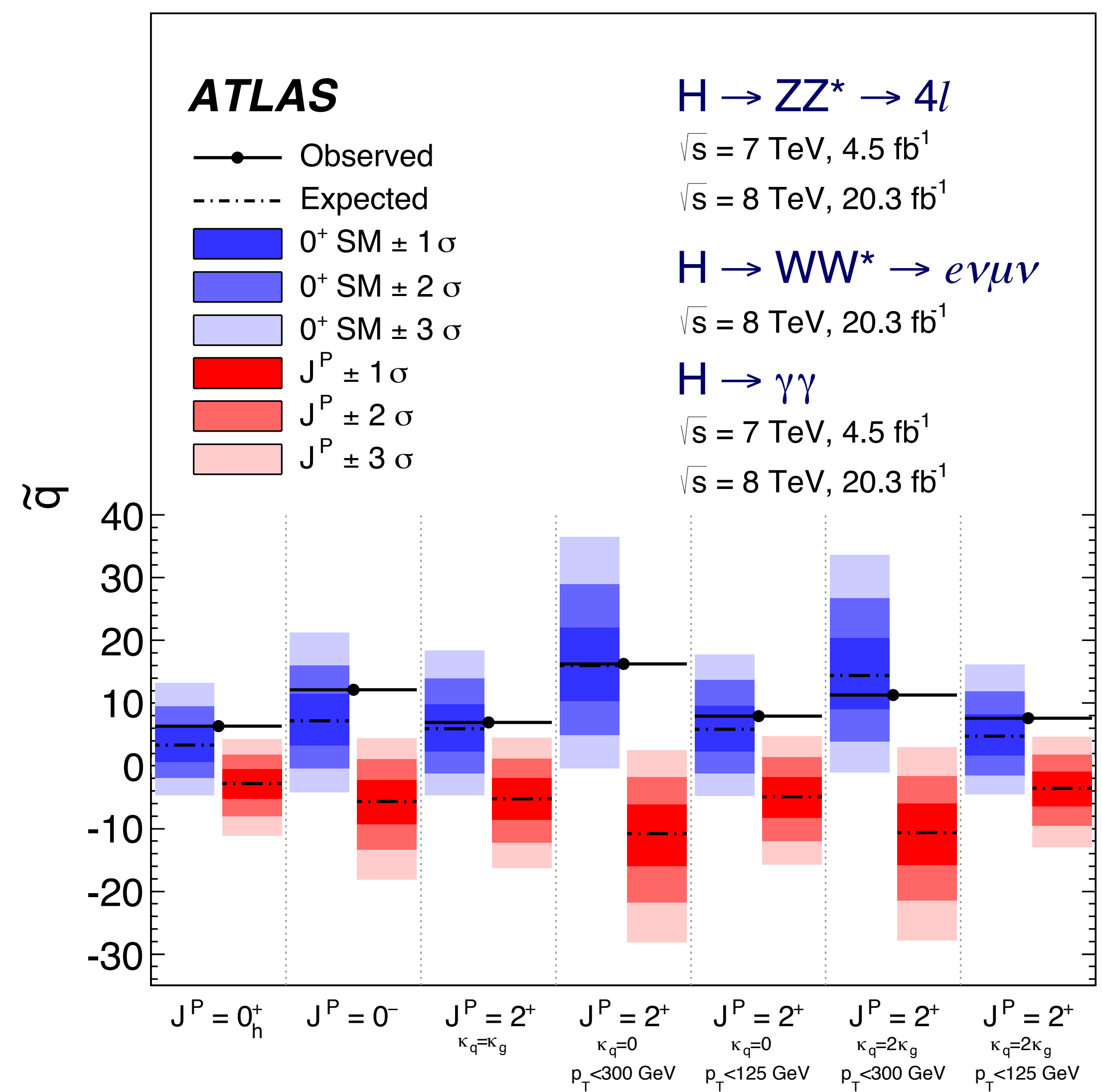
See ATLAS+CMS combined results in M. Machet talk!

SPIN PARITY MEASUREMENT

- Test various options ($J^P=0^-, 0^+, 1^-, 1^+, 2^+$) to verify compatibility with SM hypothesis $J^P = 0^+$ using angular and kinematic distributions in diboson decay modes:
  - $H \to \gamma\gamma$ (sensitivity to 2+, excludes spin 1)
  - $H \to ZZ^* \to 4l$ (sensitivity to all spin/parity)
  - $H \to WW^* \to l\nu l\nu$ (sensitivity to spin 1 and spin 2)

All alternative hypotheses to SM rejected at >99.9% CL.



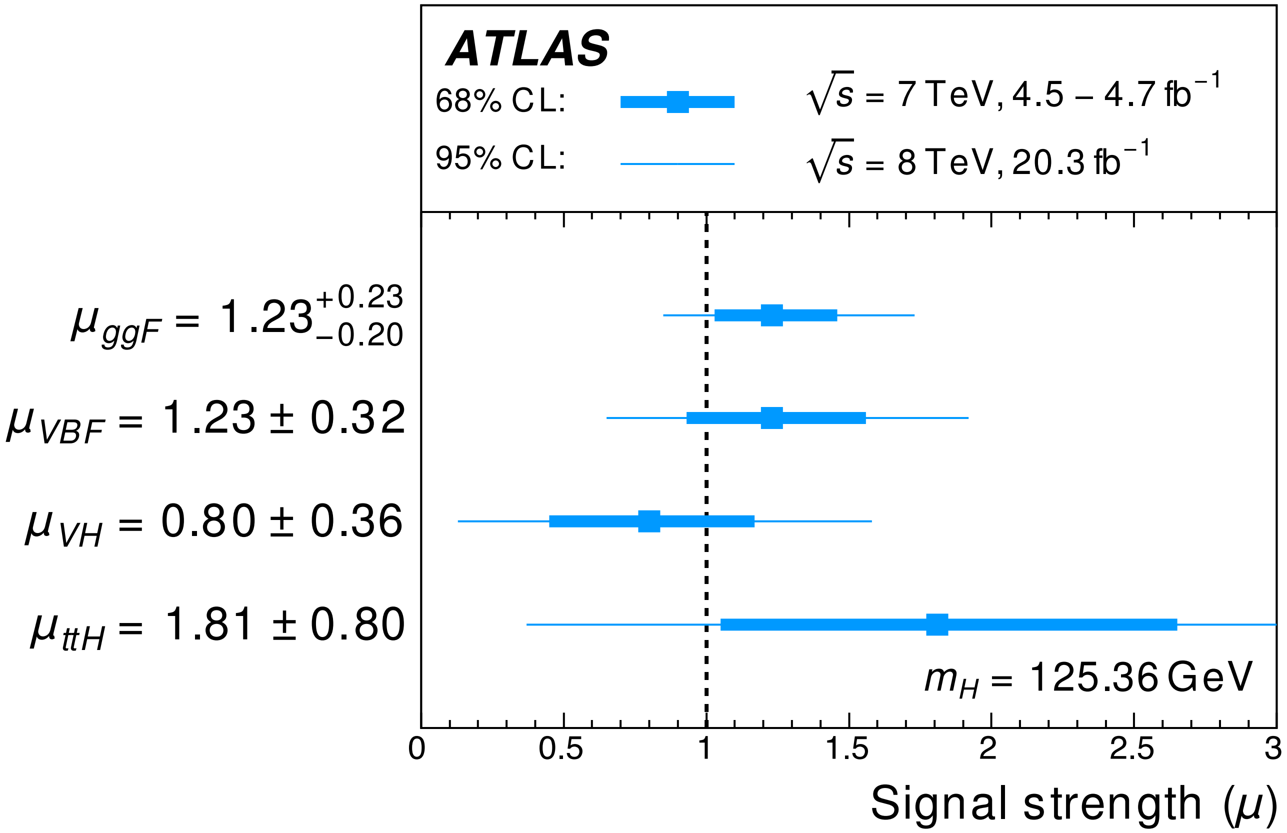


Eur.Phys.J. C75 (2015) 476

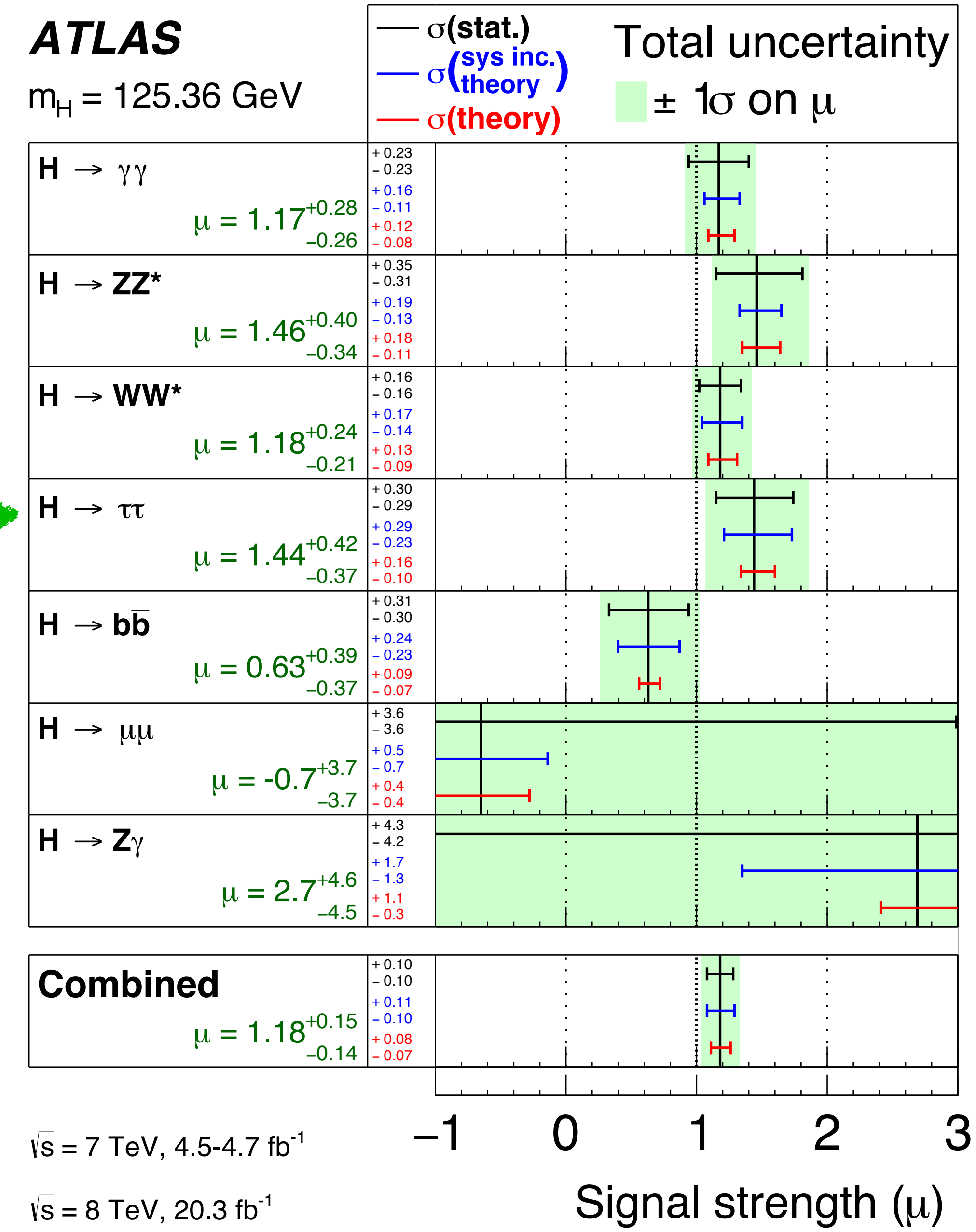
PRODUCTION AND DECAY STRENGTH

Measure the ratio between observed rate and SM Higgs boson expectation:

$$\mu_i = \frac{\sigma_i}{(\sigma_i)_{SM}} \quad \text{and} \quad \mu_f = \frac{BR_f}{(BR_f)_{SM}}$$



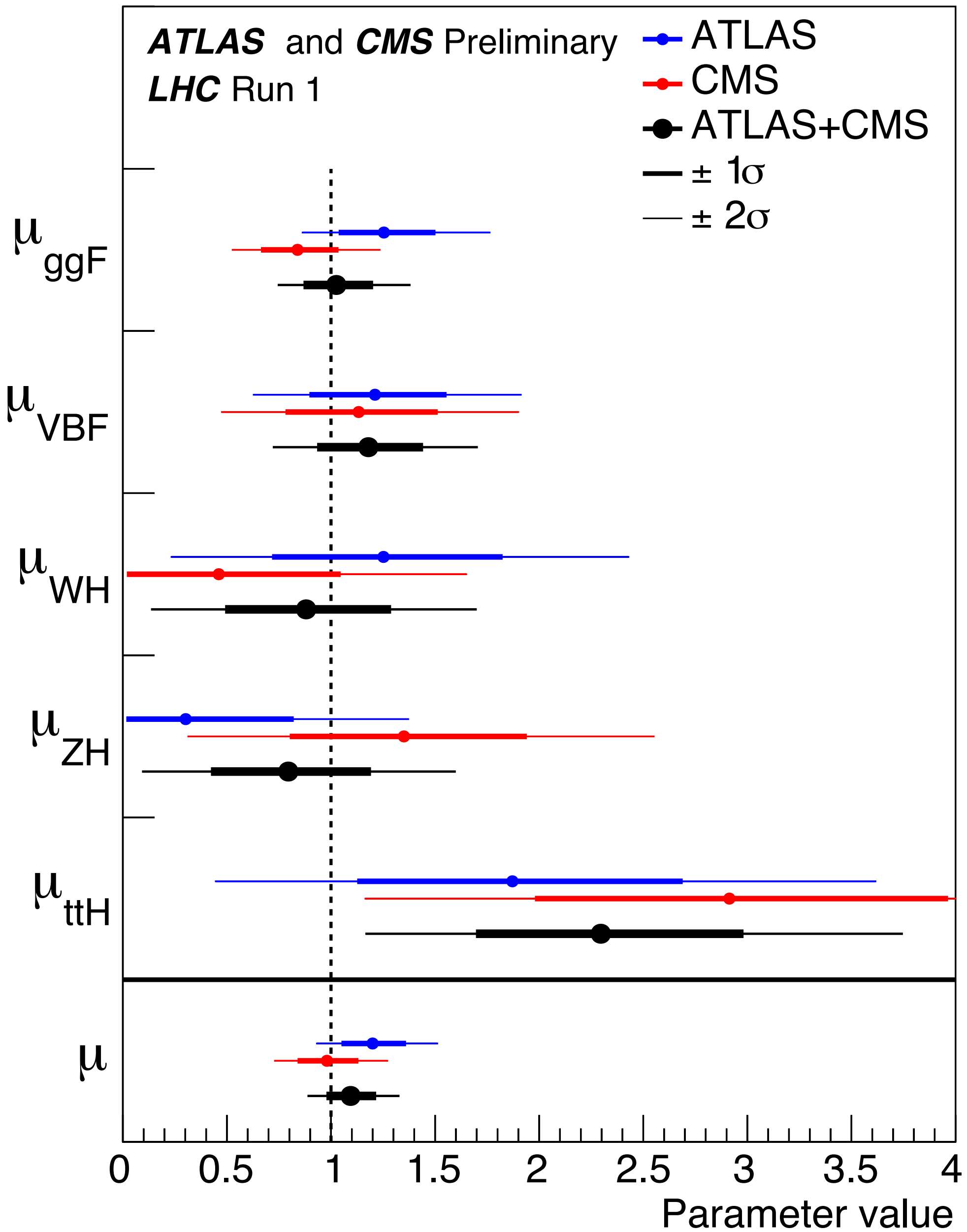
arXiv:1507.04548

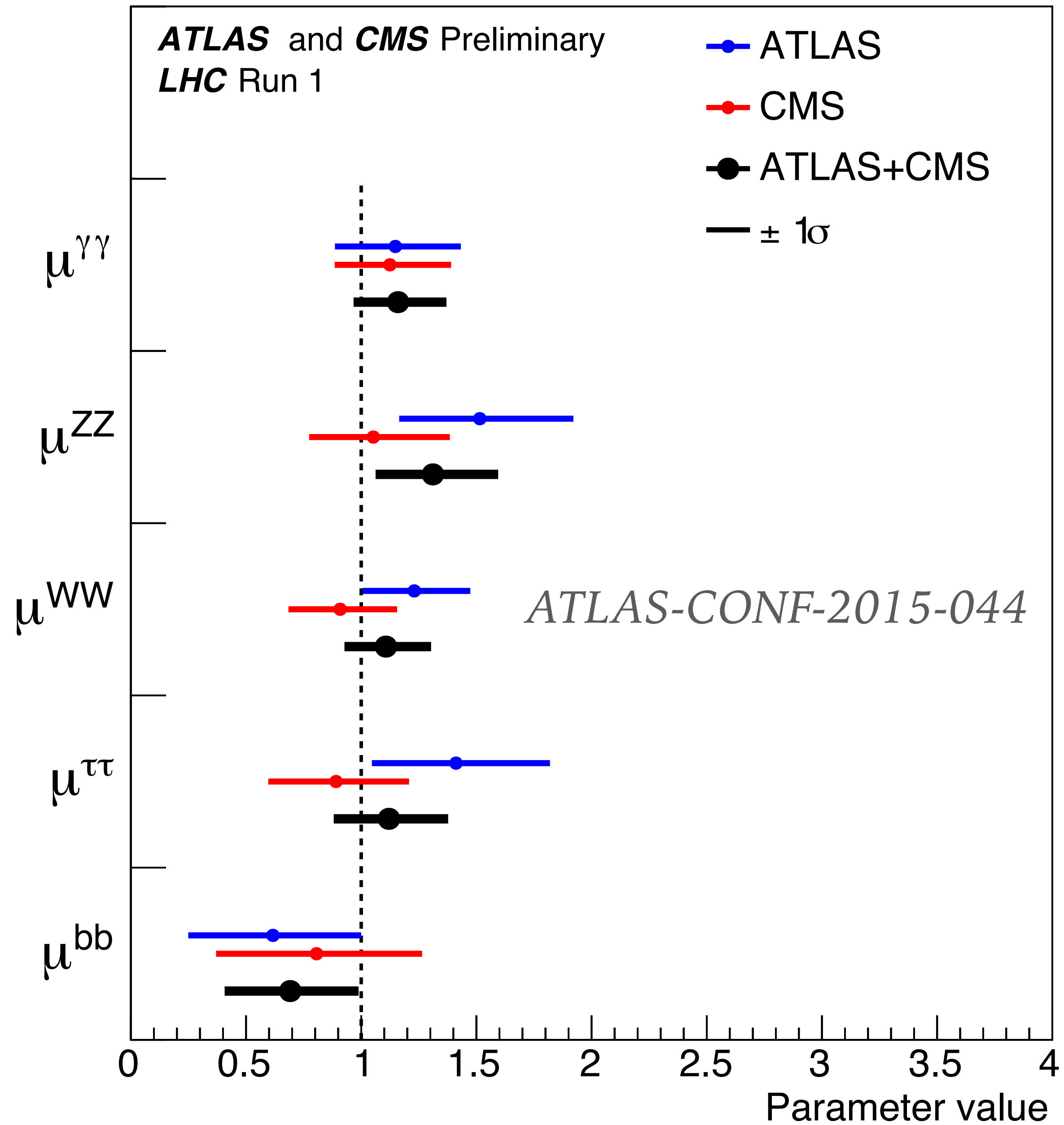


Results are SM like (all μ's ~ 1)

Decay: no sensitivity yet to μμ, Zγ

PRODUCTION AND DECAY STRENGTH: ATLAS + CMS





Signal strength $\mu = (\sigma_i.BR_f)_{meas} / (\sigma_i.BR_f)_{theo} = \mu_i \cdot \mu_f$

Global signal strength assuming SM ratio for all production and decay:

$\mu = 1.09 \pm 0.07$ stat ± 0.04 exp syst. ± 0.03 th. bkg $+0.07-0.06$ th. signal.

COUPLINGS MEASUREMENT: THE K FRAMEWORK

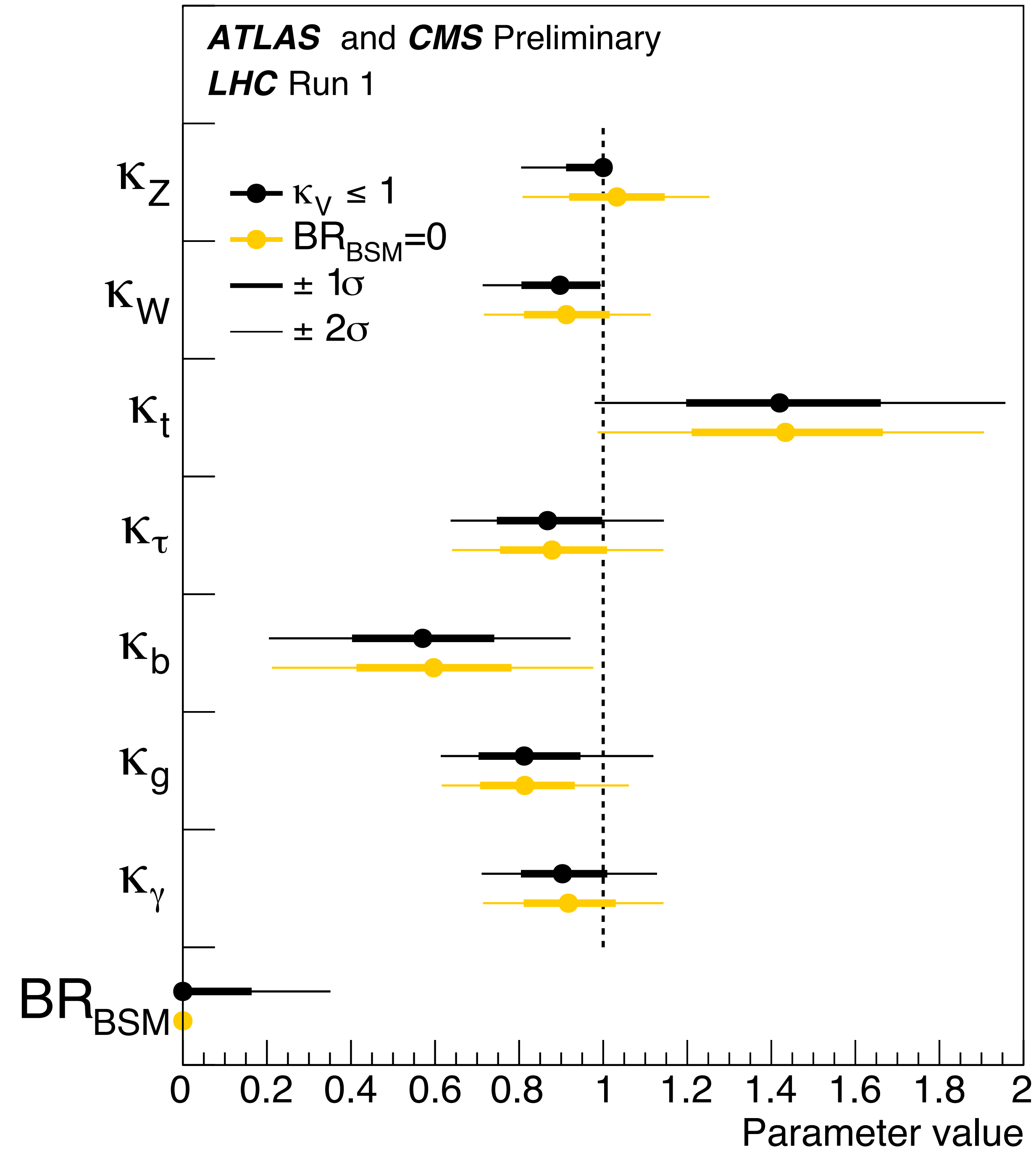
- Use couplings modifier:

  $\sigma_i = \kappa_i^2 * \sigma_i(SM)$

  $\Gamma_f = \kappa_f^2 * \Gamma_f(SM) \Rightarrow \mu_{fi} = \kappa_i^2 . \kappa_f^2 / (\Gamma_H / \Gamma_H(SM))$

- Loops (g and γ):
  - use SM interference (assuming no other particles)
  - or write as effective $\kappa g, \kappa\gamma$
- Total width:
  - Assume no BSM contribution
  - or allow additional BSM contribution to the width
- Assumes exactly same coupling structure as SM: **only account for rates!**

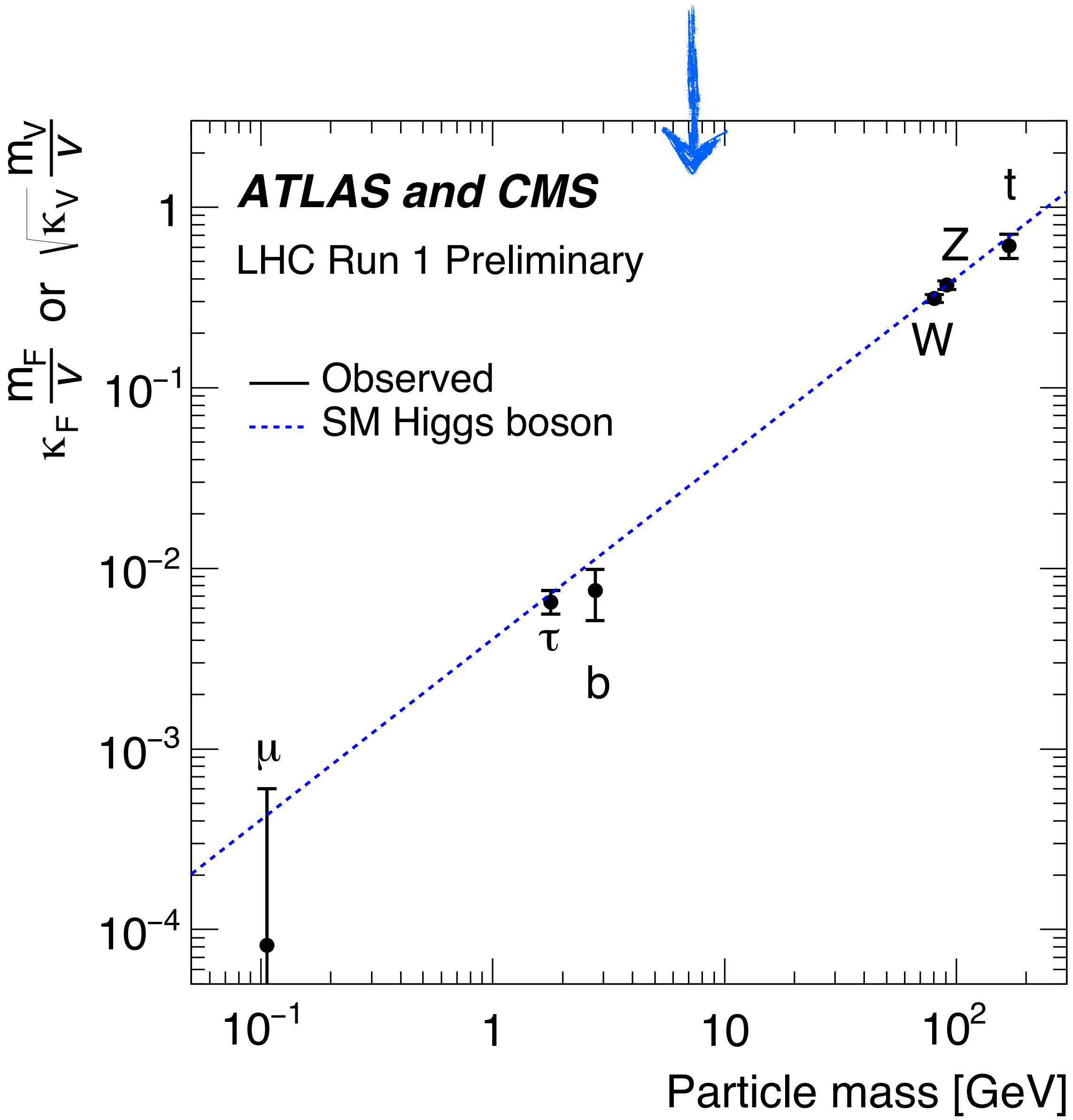
Allow BSM particles in loops and total width:



ATLAS-CONF-2015-044

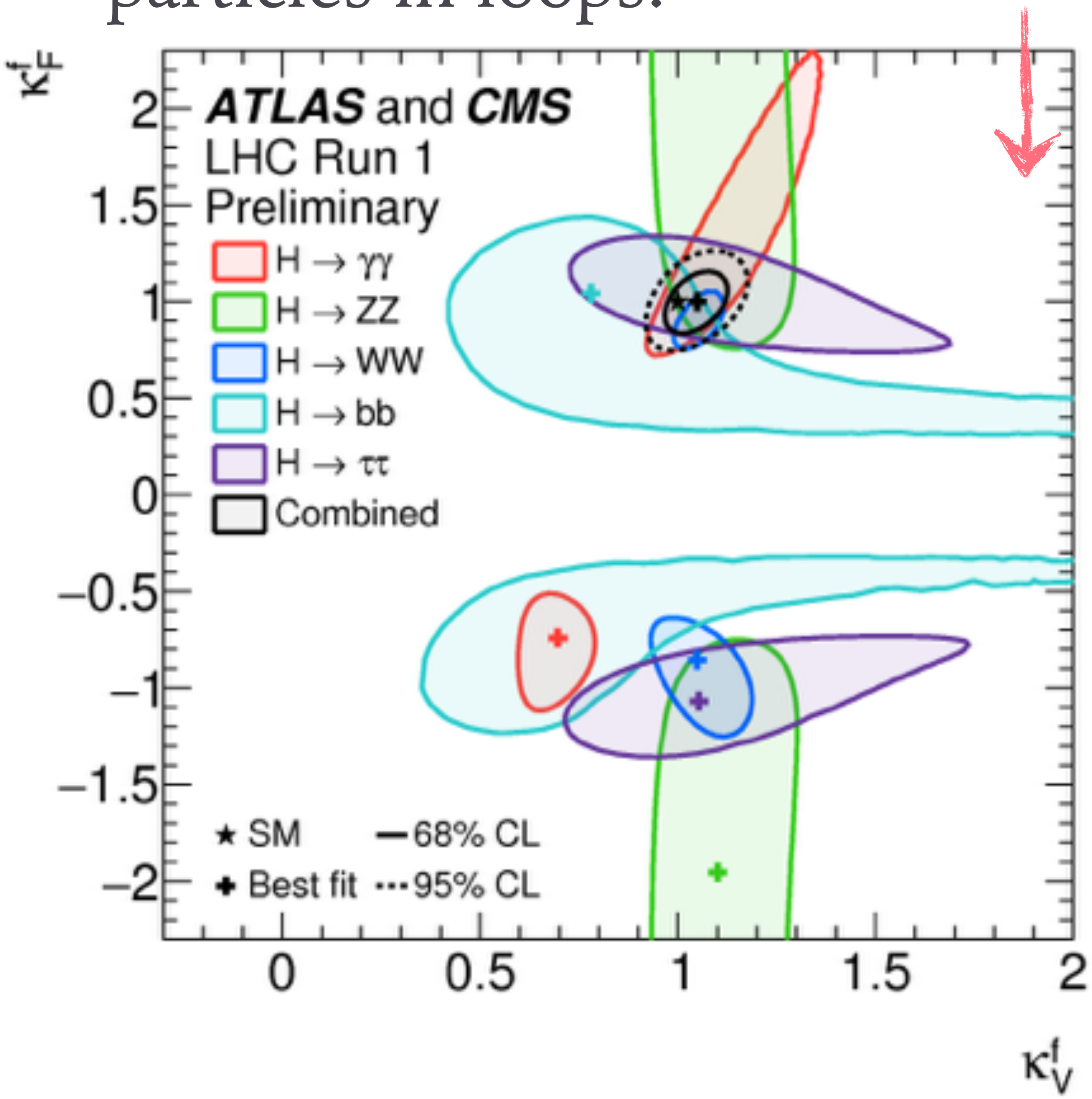
COUPLINGS: ATLAS+CMS COMBINATION

$BR_{BSM} = 0$ => Measure couplings to the SM particles



-Universal κ_F for fermions and κ_V for vector bosons

- No invisible decay mode or new particles in loops.



Interference effects (like in H→γγ decays) allow to probe the relative sign of κ_V and κ_F

ATLAS-CONF-2015-044

WIDTH STUDIES

(1) Phys. Rev. D. 90.052004(2014).
(2) ATLAS EPJ C75 (2015) 335.

In SM $\Gamma_H \sim 4.1$ MeV ($m_H = 125$ GeV) → Limited by exp. resolution (~1-2%)

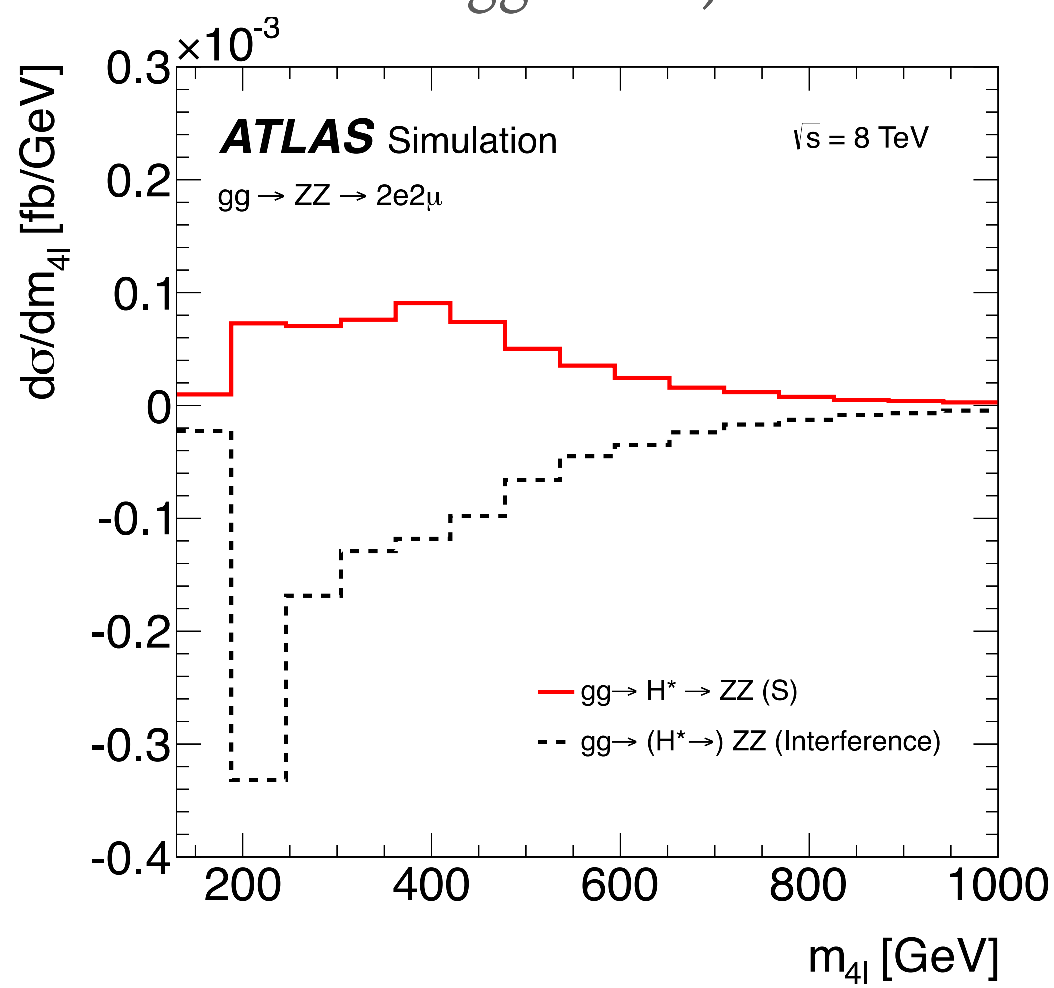
Direct measurement with m4l+mγγ spectra (assuming no interference with background processes): From H→ZZ→4l : $\Gamma_H < 2.6$ GeV at 95% CL (1).

Limit on Γ_H through off-shell production (with channels H→ WW→eνμν, H→ ZZ→4l, H→ ZZ→2l2ν):

- High mass region ($>2m_V$ with V=W,Z) is sensitive to the Higgs boson production through off-shell and background interference effects (negative interference with gg->ZZ:).

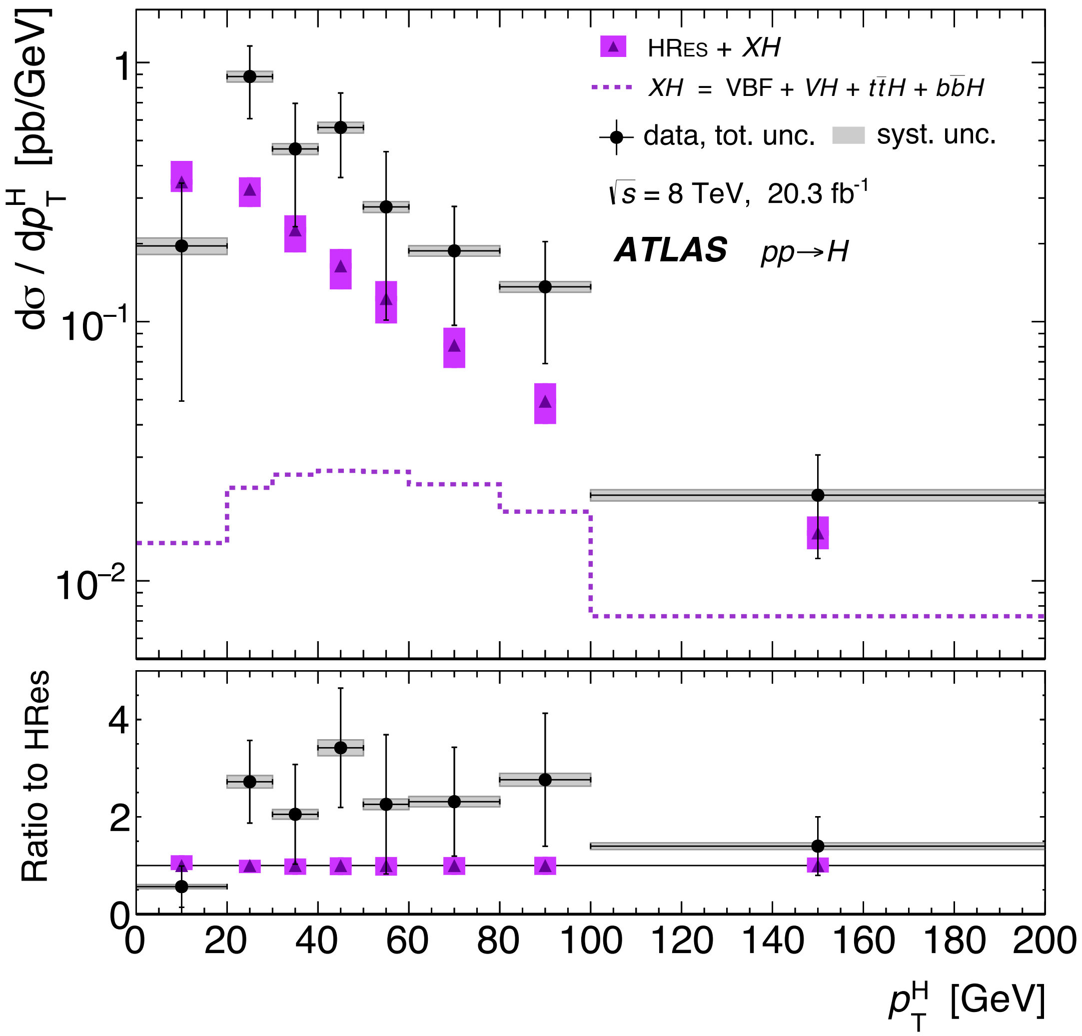
- Characterise the properties of the Higgs boson through off-shell signal strength/couplings. Assuming:
  - $q \sim m_H$ (on shell) → $\sigma_{onshell} \sim$ (couplings)/Γ_H
  - $q >> m_H$ (off shell) → $\sigma_{offshell} \sim$ (couplings)
  - Ratio ~ $\sigma_{onshell}/\sigma_{offshell} \sim \Gamma_H$

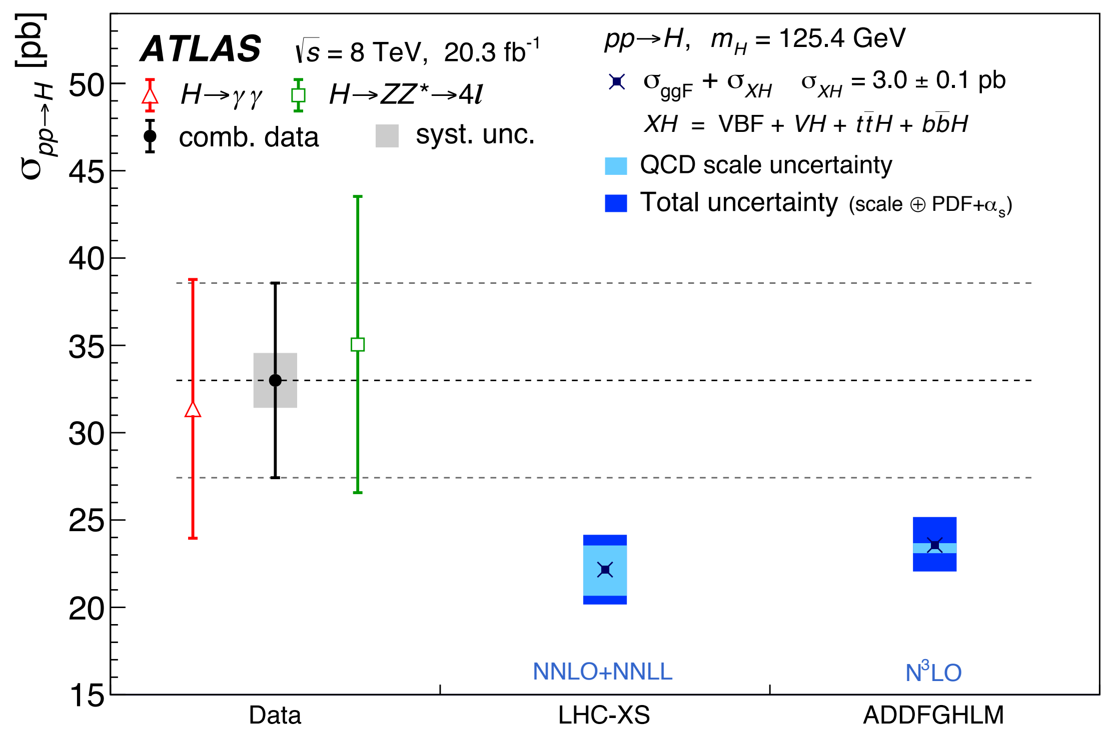
- Result: **$\Gamma_H < 22.7$ MeV** at 95% CL(2) →assuming no change in coupling and no new physics at high VV mass.



TOTAL AND DIFFERENTIAL CROSS SECTIONS

- Use γγ and 4l decay modes (can have inclusive selection with "simple" background subtraction procedure), and combine results.
- Measure differential cross-sections for quantities sensitive to various theoretical effects: pT(H),y(H) (QCD modelling in ggF) , number of jets (ratio in different production mechanism), etc..





Phys. Rev. Lett. 115 (2015) 091801

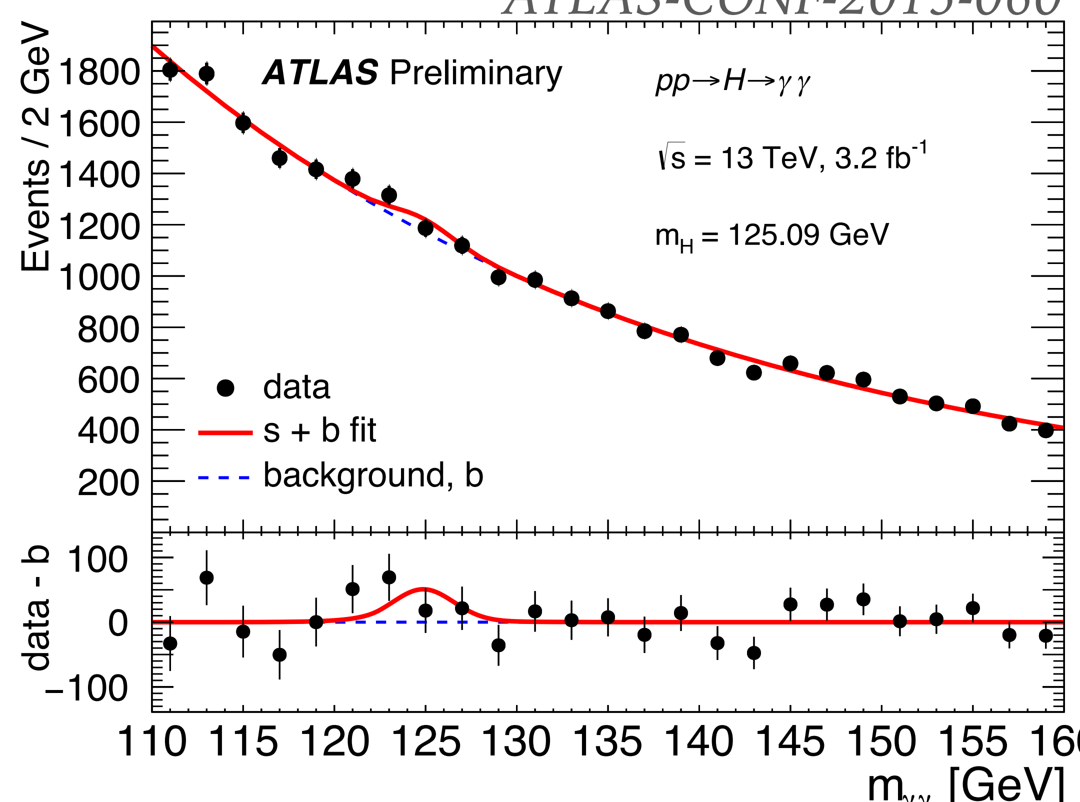
Total XS larger than SM, but shapes in good agreement with predictions (details in back-up).

Statistical uncertainties (23%-75%) dominate.

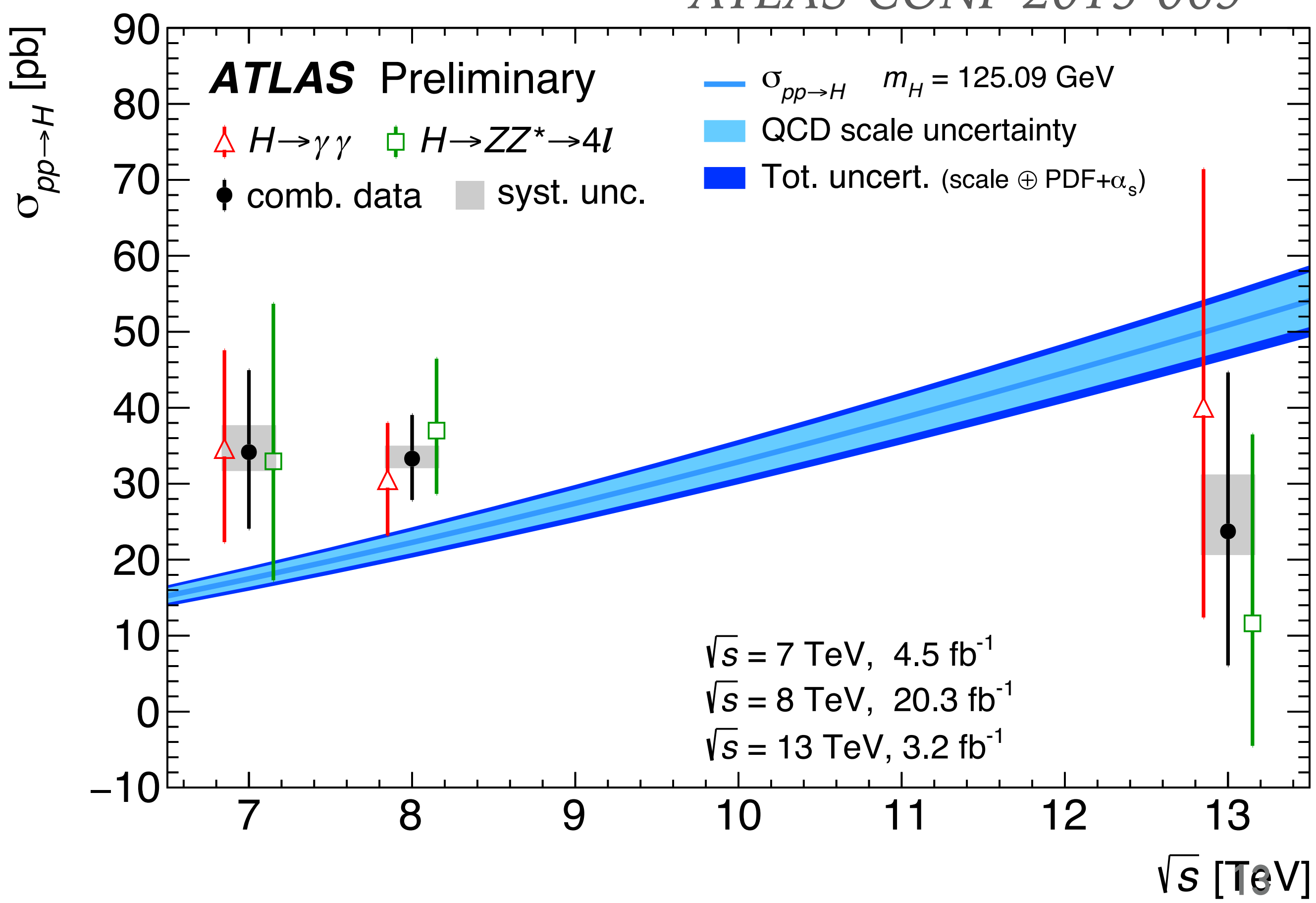
FIRST LOOK AT 13 TEV DATA FOR h(125)

- Luminosity of 3.2 fb^{-1} at 13 TeV not enough to reach run 1 sensitivity for h(125)
- ATLAS performed fiducial cross-section measurements in 4l and γγ channels (3.4σ combined sensitivity expected, 1.4σ observed)

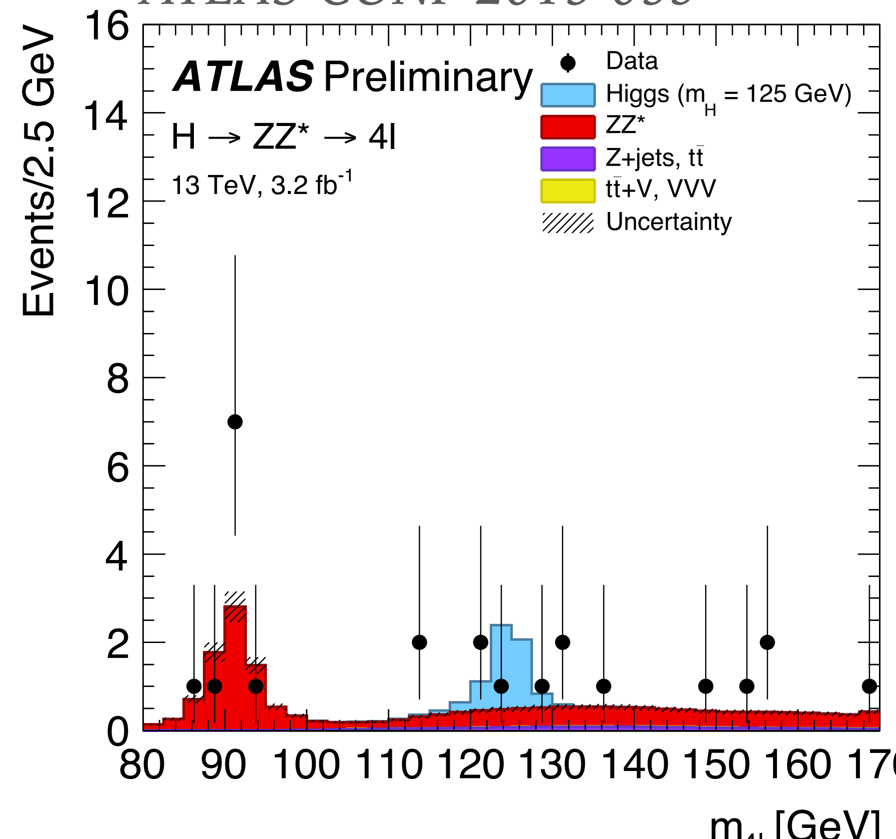
ATLAS-CONF-2015-060



ATLAS-CONF-2015-069



ATLAS-CONF-2015-059

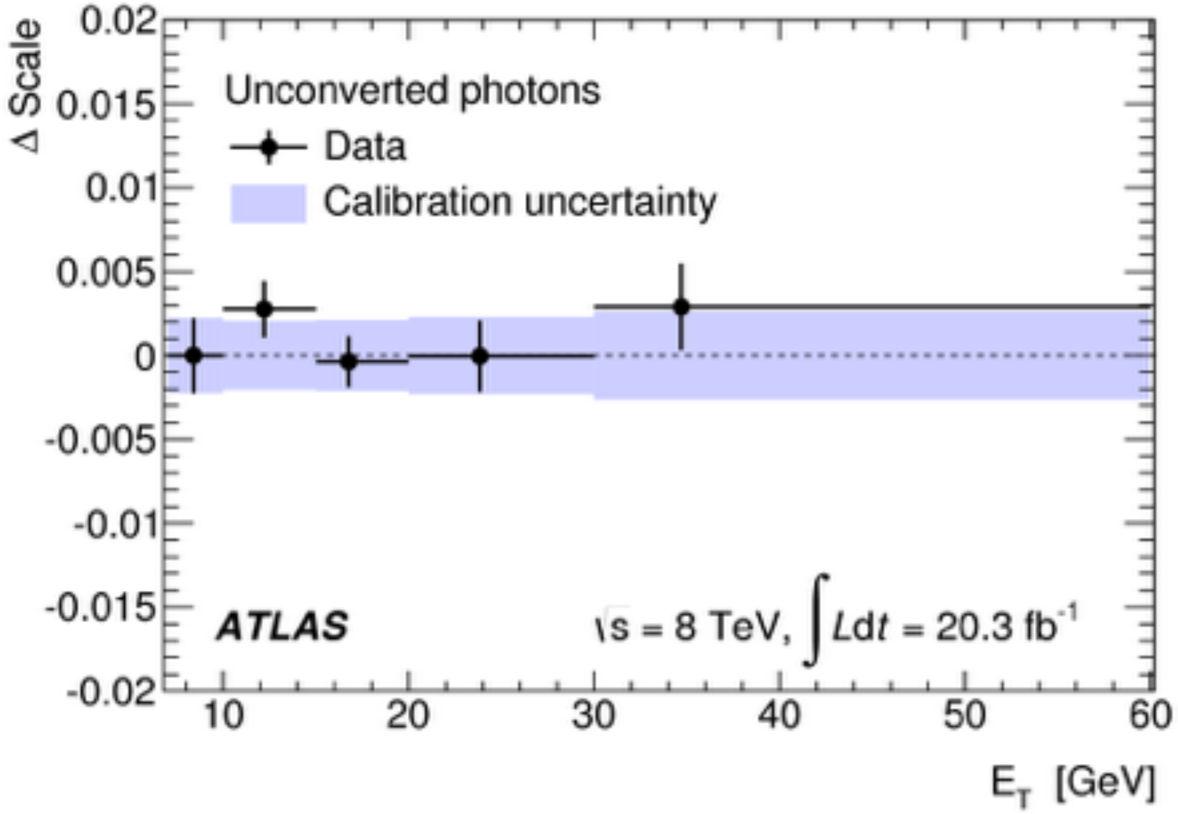


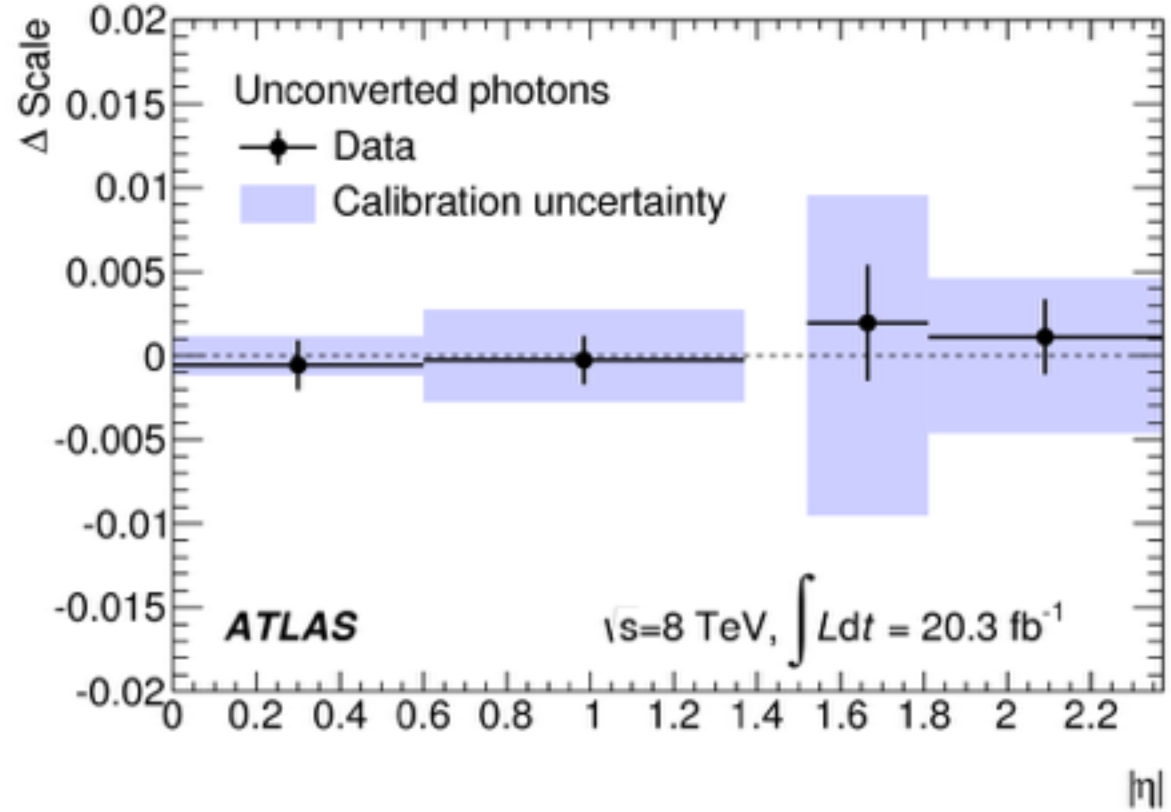
SUMMARY

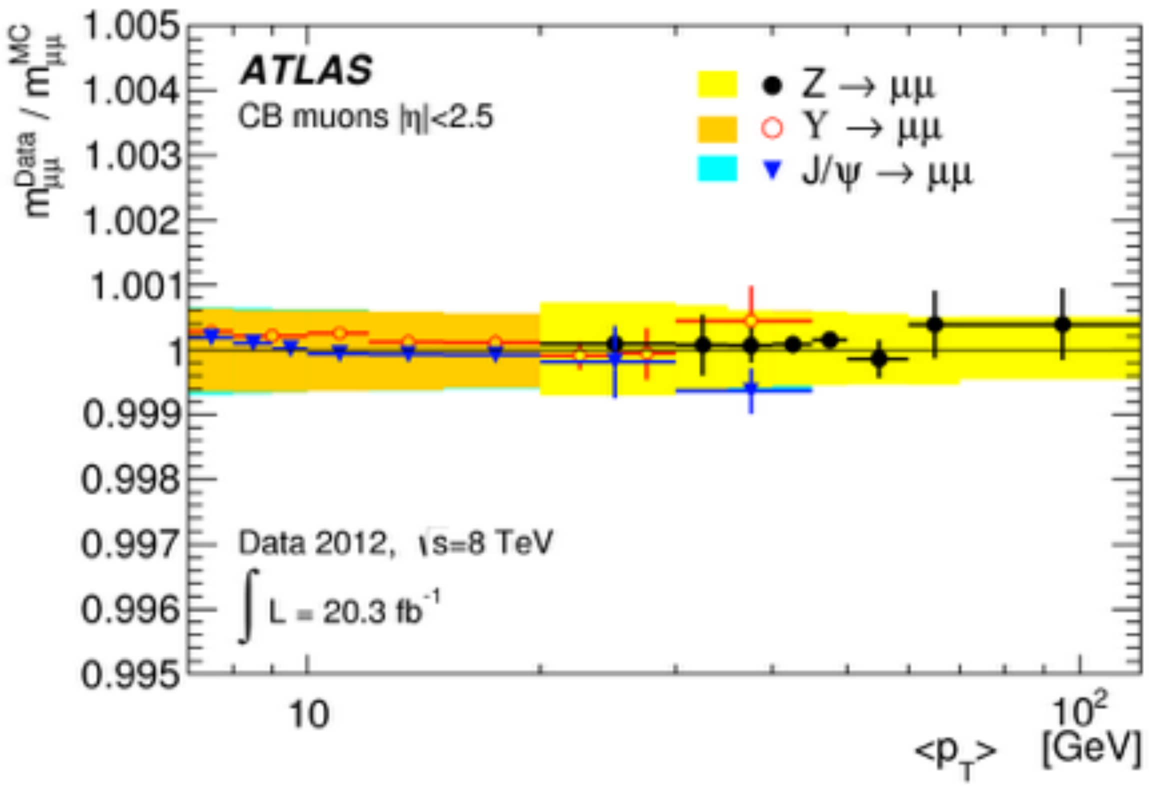
- From run I data, the properties of h(125) are consistent with SM predictions:
  - Combined mass measurement 125.36 ± 0.37(stat) +0.18(sys) GeV (ATLAS)
  - Combined signal strength μ = 1.09 ± 0.07 stat ±0.04 exp syst. ±0.03 th. bkg +0.07-0.06 th. signal. (ATLAS+CMS)
  - Any other spin than SM $J^P = 0^+$ is highly disfavoured
  - Direct evidence/observation in 4 decay modes
  - Coupling measurements with typical accuracy of ~10-20% (depending in scenario/assumptions), consistent with SM.
  - No BSM decay observed (see back-up).
- The 2015 is not as sensitive as run 1 data for h(125) but have been used by ATLAS to re-establish analysis for h(125) measurements.
- With 2016 data (~26 fb-1 expected) sensitivity will significantly improve over run 1.

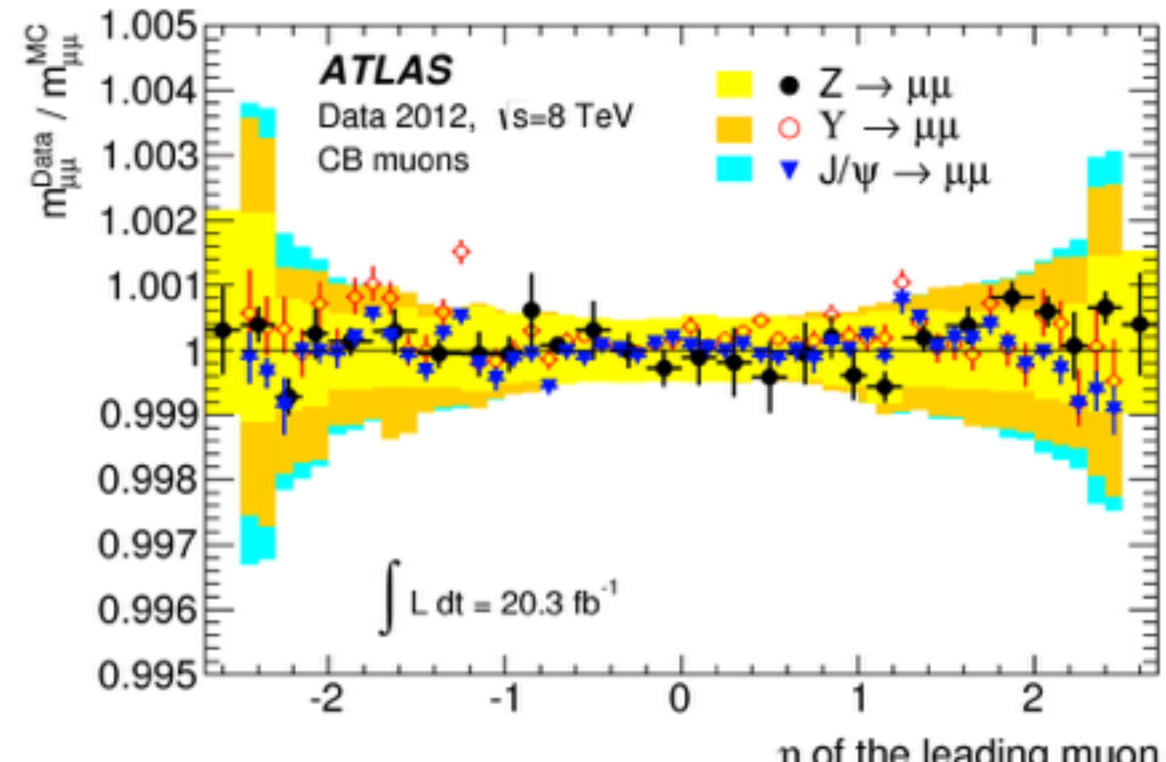
EXTRA MATERIAL

MASS MEASUREMENT UNCERTAINTIES









Analysis	Signal		$\int \mathcal{L}dt$ [fb^{-1}]	
Categorisation or final states	Strength μ	Significance [s.d.]	7 TeV	8 TeV
$H \to \gamma\gamma$ [12]	1.17 ± 0.27	5.2 (4.6)	4.5	20.3
ttH: leptonic, hadronic			✓	✓
VH: one-lepton, dilepton, E_T^{miss}, hadronic			✓	✓
VBF: tight, loose			✓	✓
ggF: 4 p_{Tt} categories			✓	✓
$H \to ZZ^* \to 4\ell$ [13]	$1.44^{+0.40}_{-0.33}$	8.1 (6.2)	4.5	20.3
VBF			✓	✓
VH: hadronic, leptonic			✓	✓
ggF			✓	✓
$H \to WW^*$ [14,15]	$1.16^{+0.24}_{-0.21}$	6.5 (5.9)	4.5	20.3
ggF: (0-jet, 1-jet) $\otimes$ ($ee + \mu\mu$, $e\mu$)			✓	✓
ggF: $\geq$ 2-jet and $e\mu$				✓
VBF: $\geq$ 2-jet $\otimes$ ($ee + \mu\mu$, $e\mu$)			✓	✓
VH: opposite-charge dilepton, three-lepton, four-lepton			✓	✓
VH: same-charge dilepton				✓
$H \to \tau\tau$ [17]	$1.43^{+0.43}_{-0.37}$	4.5 (3.4)	4.5	20.3
Boosted: $\tau_{lep}\tau_{lep}, \tau_{lep}\tau_{had}, \tau_{had}\tau_{had}$			✓	✓
VBF: $\tau_{lep}\tau_{lep}, \tau_{lep}\tau_{had}, \tau_{had}\tau_{had}$			✓	✓
$VH \to Vb\bar{b}$ [18]	0.52 ± 0.40	1.4 (2.6)	4.7	20.3
0ℓ ($ZH \to \nu\nu b\bar{b}$): $N_{jet} = 2, 3$, $N_{btag} = 1, 2$, $p_T^V \in$ 100-120 and $>$120 GeV			✓	✓
1ℓ ($WH \to \ell\nu b\bar{b}$): $N_{jet} = 2, 3$, $N_{btag} = 1, 2$, $p_T^V <$ and $>$120 GeV			✓	✓
2ℓ ($ZH \to \ell\ell b\bar{b}$): $N_{jet} = 2, 3$, $N_{btag} = 1, 2$, $p_T^V <$ and $>$120 GeV			✓	✓
		95% CL limit		
$H \to Z\gamma$ [19]		$\mu < 11$ (9)	4.5	20.3
10 categories based on $\Delta\eta_{Z\gamma}$ and p_{Tt}			✓	✓
$H \to \mu\mu$ [20]		$\mu < 7.0$ (7.2)	4.5	20.3
VBF and 6 other categories based on η_μ and $p_T^{\mu\mu}$			✓	✓
ttH production [21,22,23]			4.5	20.3
$H \to b\bar{b}$: single-lepton, dilepton		$\mu < 3.4$ (2.2)		✓
$ttH \to$multileptons: categories on lepton multiplicity		$\mu < 4.7$ (2.4)		✓
$H \to \gamma\gamma$: leptonic, hadronic		$\mu < 6.7$ (4.9)	✓	✓
Off-shell H^* production [24]		$\mu < 5.1 - 8.6$ ($6.7 - 11.0$)		20.3
$H^* \to ZZ \to 4\ell$				✓
$H^* \to ZZ \to 2\ell 2\nu$				✓
$H^* \to WW \to e\nu\mu\nu$				✓

K FRAMEWORK

Overview of Higgs boson production cross sections σi, partial decay widths Γf and total width ΓH. For each production or decay mode the scaling of the corresponding rate in terms of Higgs boson coupling-strength scale factors is given. For processes where multiple amplitudes contribute, the rate may depend on multiple Higgs boson coupling-strength scale factors, and interference terms may give rise to scalar product terms κiκj that allow the relative sign of the coupling-strength scale factors κi and κj to be determined.

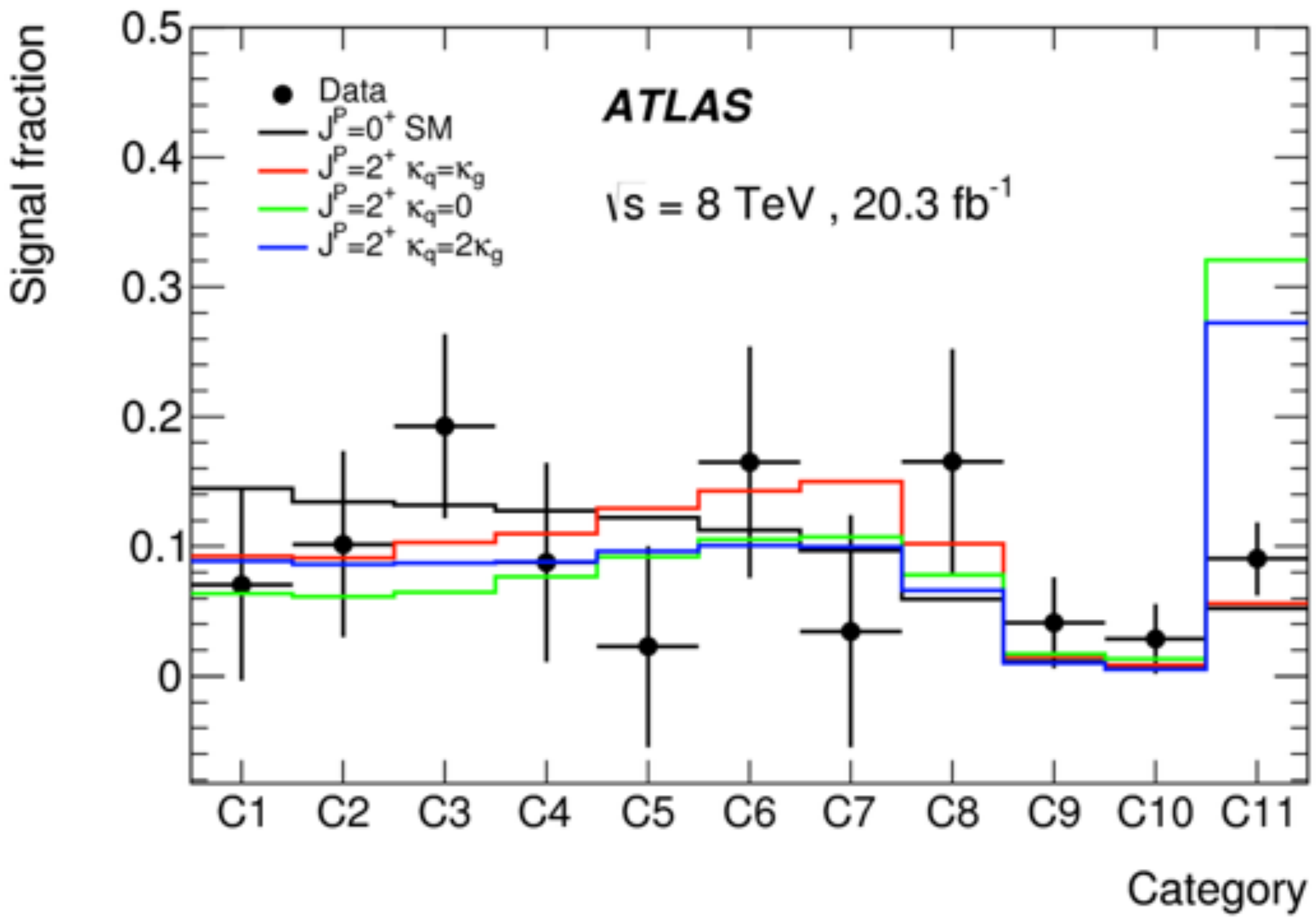
Production	Loops	Interference	Expression in fundamental coupling-strength scale factors	
$\sigma(ggF)$	✓	b–t	$\kappa_g^2 \sim$	$1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$
$\sigma(VBF)$	-	-	$\sim$	$0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	-	-	$\sim$	κ_W^2
$\sigma(q\bar{q} \to ZH)$	-	-	$\sim$	κ_Z^2
$\sigma(gg \to ZH)$	✓	Z–t	$\kappa_{ggZH}^2 \sim$	$2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t$
$\sigma(bbH)$	-	-	$\sim$	κ_b^2
$\sigma(ttH)$	-	-	$\sim$	κ_t^2
$\sigma(gb \to WtH)$	-	W–t	$\sim$	$1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t \kappa_W$
$\sigma(qb \to tHq')$	-	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				
$\Gamma_{b\bar{b}}$	-	-	$\sim$	κ_b^2
Γ_{WW}	-	-	$\sim$	κ_W^2
Γ_{ZZ}	-	-	$\sim$	κ_Z^2
$\Gamma_{\tau\tau}$	-	-	$\sim$	κ_τ^2
$\Gamma_{\mu\mu}$	-	-	$\sim$	κ_μ^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	✓	$W-t$ $b-t$	$\kappa_H^2 \sim$	$0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 +$ $0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 +$ $0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{Z\gamma}^2 + 0.00022 \cdot \kappa_\mu^2$

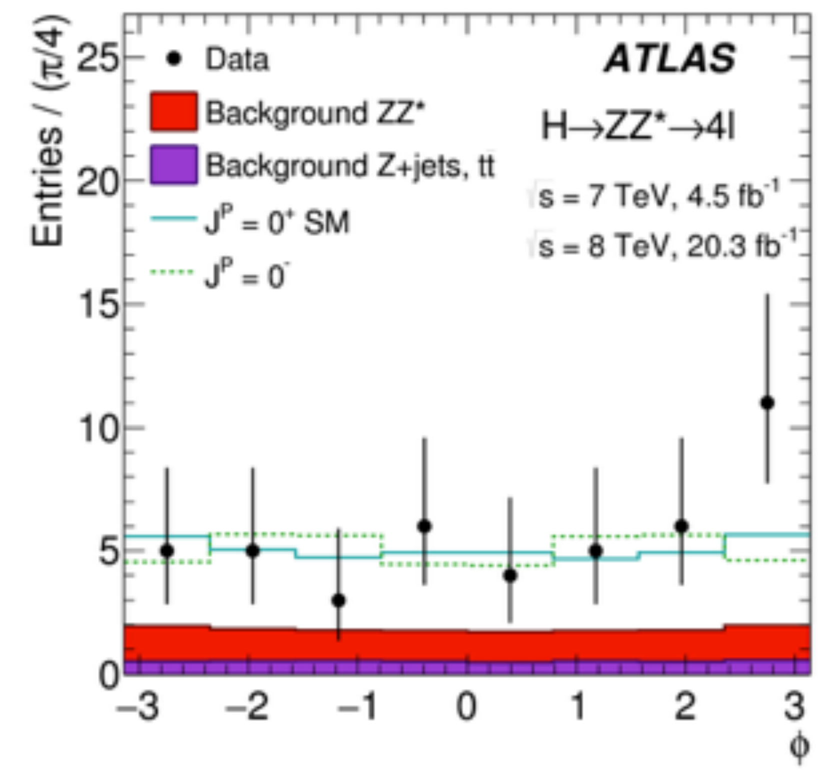
OVERVIEW RESULTS ATLAS AND CMS

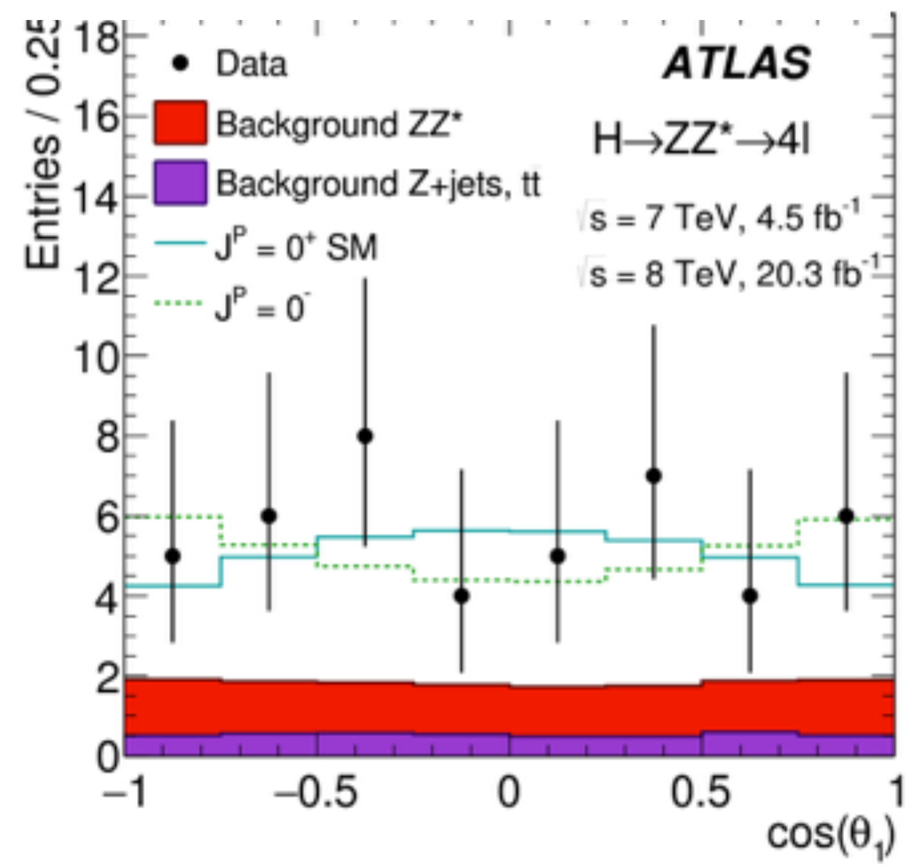
Channel	References for individual publications		Signal strength [μ] from results in this paper (Section 5.2)		Signal significance [σ]	
	ATLAS	CMS	ATLAS	CMS	ATLAS	CMS
$H \to \gamma\gamma$	[51]	[52]	$1.15^{+0.27}_{-0.25}$	$1.12^{+0.25}_{-0.23}$	5.0	5.6
			$\left(^{+0.26}_{-0.24}\right)$	$\left(^{+0.24}_{-0.22}\right)$	(4.6)	(5.1)
$H \to ZZ \to 4\ell$	[53]	[54]	$1.51^{+0.39}_{-0.34}$	$1.05^{+0.32}_{-0.27}$	6.6	7.0
			$\left(^{+0.33}_{-0.27}\right)$	$\left(^{+0.31}_{-0.26}\right)$	(5.5)	(6.8)
$H \to WW$	[55,56]	[57]	$1.23^{+0.23}_{-0.21}$	$0.91^{+0.24}_{-0.21}$	6.8	4.8
			$\left(^{+0.21}_{-0.20}\right)$	$\left(^{+0.23}_{-0.20}\right)$	(5.8)	(5.6)
$H \to \tau\tau$	[58]	[59]	$1.41^{+0.40}_{-0.35}$	$0.89^{+0.31}_{-0.28}$	4.4	3.4
			$\left(^{+0.37}_{-0.33}\right)$	$\left(^{+0.31}_{-0.29}\right)$	(3.3)	(3.7)
$H \to bb$	[38]	[39]	$0.62^{+0.37}_{-0.36}$	$0.81^{+0.45}_{-0.42}$	1.7	2.0
			$\left(^{+0.39}_{-0.37}\right)$	$\left(^{+0.45}_{-0.43}\right)$	(2.7)	(2.5)
$H \to \mu\mu$	[60]	[61]	-0.7 ± 3.6	0.8 ± 3.5		
			(± 3.6)	(± 3.5)		
ttH production	[28,62,63]	[65]	$1.9^{+0.8}_{-0.7}$	$2.9^{+1.0}_{-0.9}$	2.7	3.6
			$\left(^{+0.72}_{-0.66}\right)$	$\left(^{+0.88}_{-0.80}\right)$	(1.6)	(1.3)

SPIN-PARITY

10 categories (labelled from C1 to C10) collect events with pTγγ < 125 GeV, divided into 10 bins of equal size in | cosθ ∗|, while the 11th category (labelled C11) groups all events with pTγγ≥ 125 GeV.

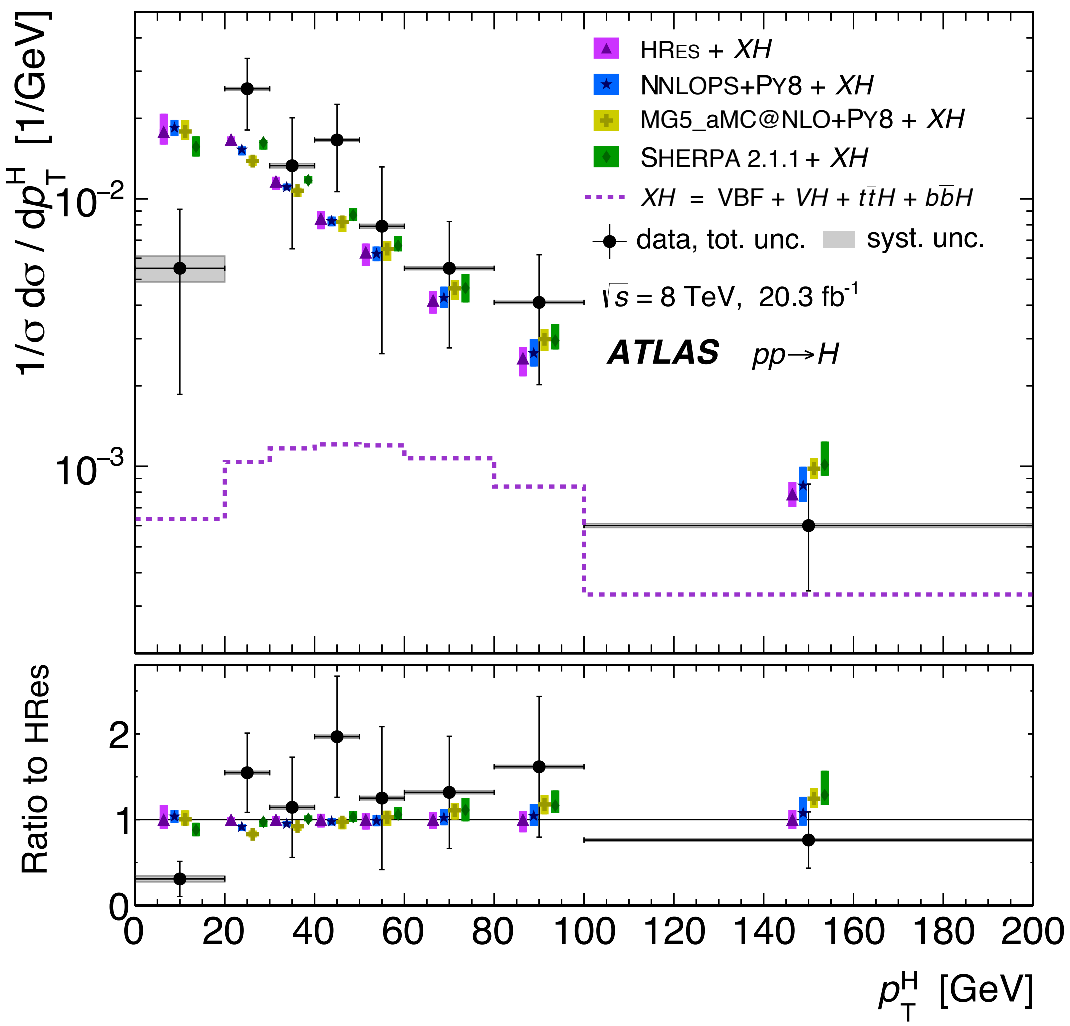


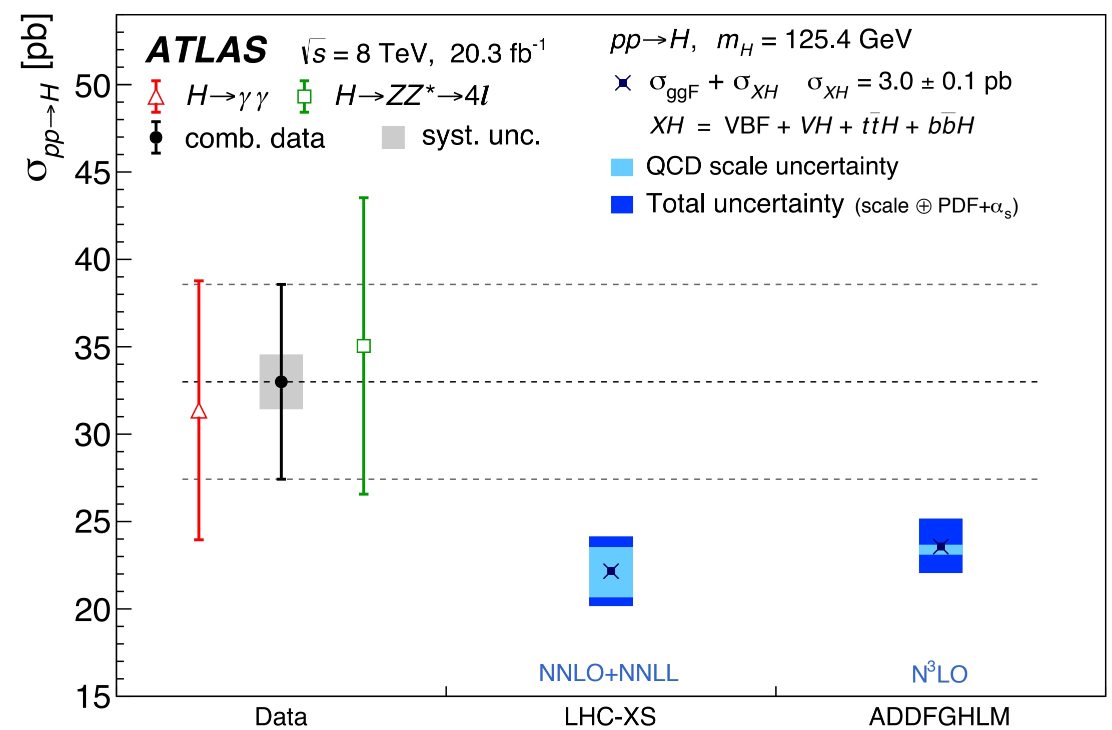




TOTAL AND DIFFERENTIAL CROSS SECTIONS

Total XS larger than SM, but normalised cross-section shapes in good agreement with predictions.





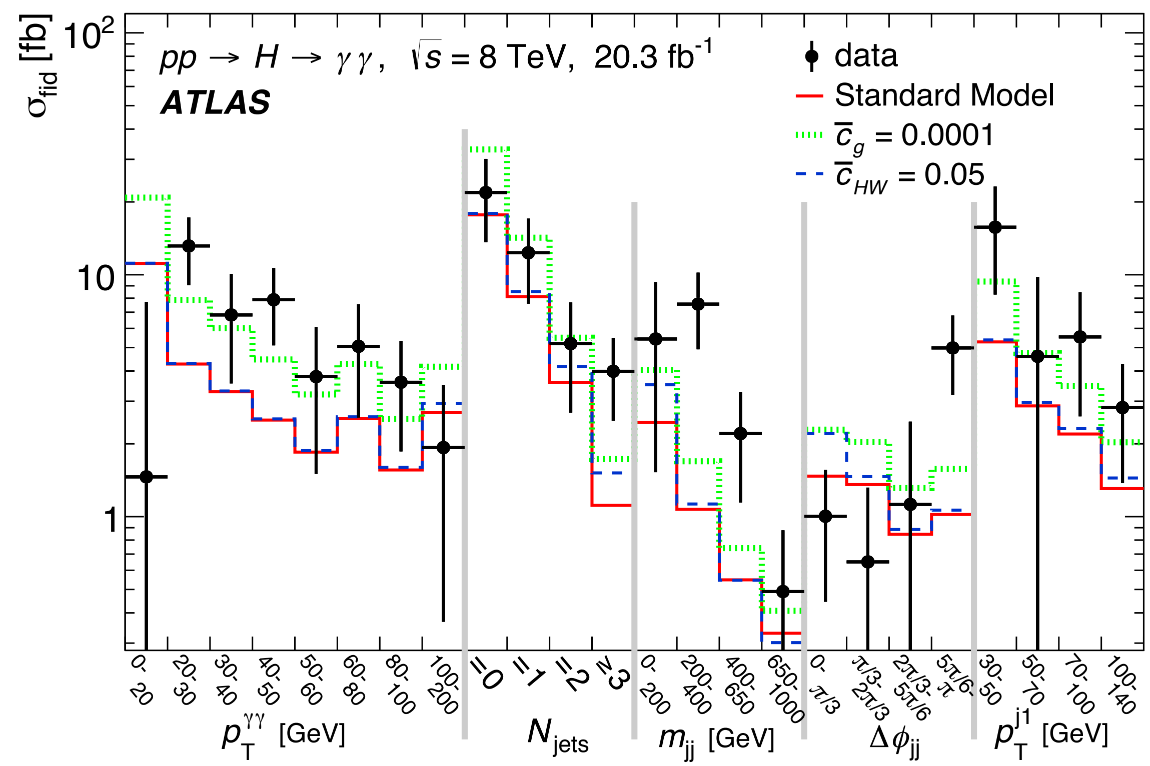
Phys. Rev. Lett. 115 (2015) 091801

EFT STUDY WITH DIFFERENTIAL CROSS-SECTIONS

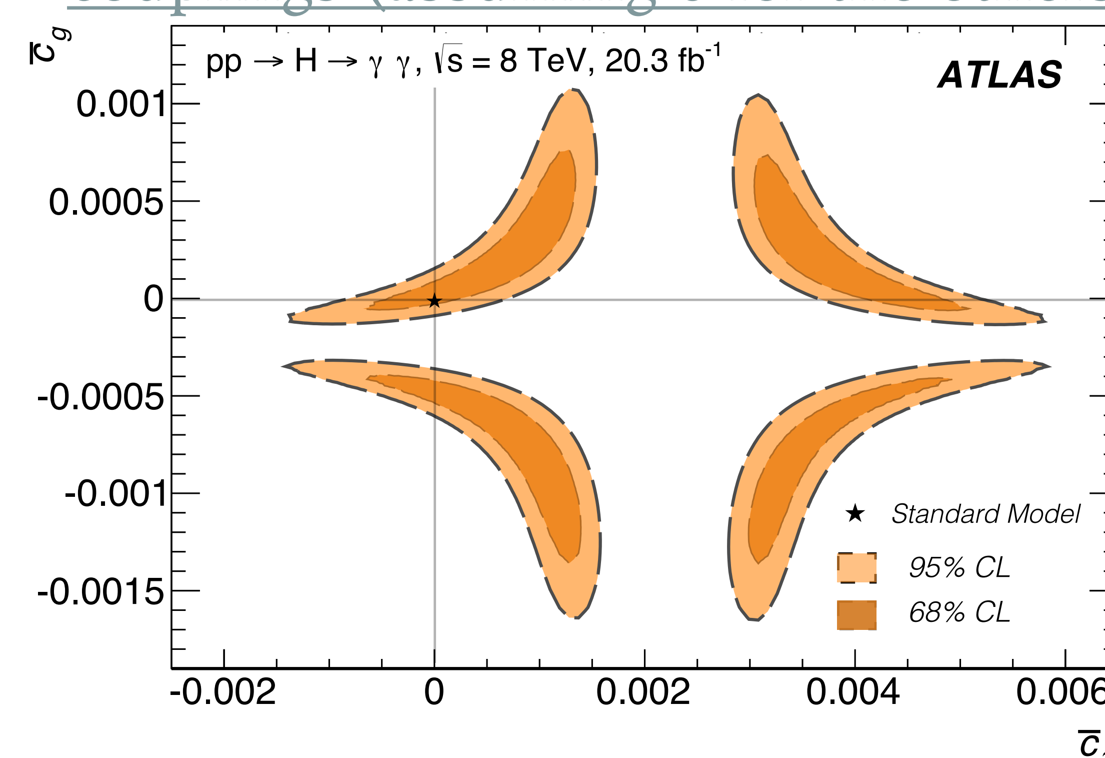
- Using an effective Lagrangian, which introduces additional CP-even and CP-odd interactions:
  - Changes in the kinematic properties of the Higgs boson wrt SM.
  - Modifying couplings to photons, gluons and vector bosons.
- The parameters are probed by a simultaneous fit of 5 differential XS previously measured in H→γγ at @8TeV.
  - Statistical correlations between bins of different distributions are estimated with “boostrapping” technique and included in the fit (details in back-up).

No significant deviations from SM are observed.

Phys.Lett. B753 (2016) 69-85

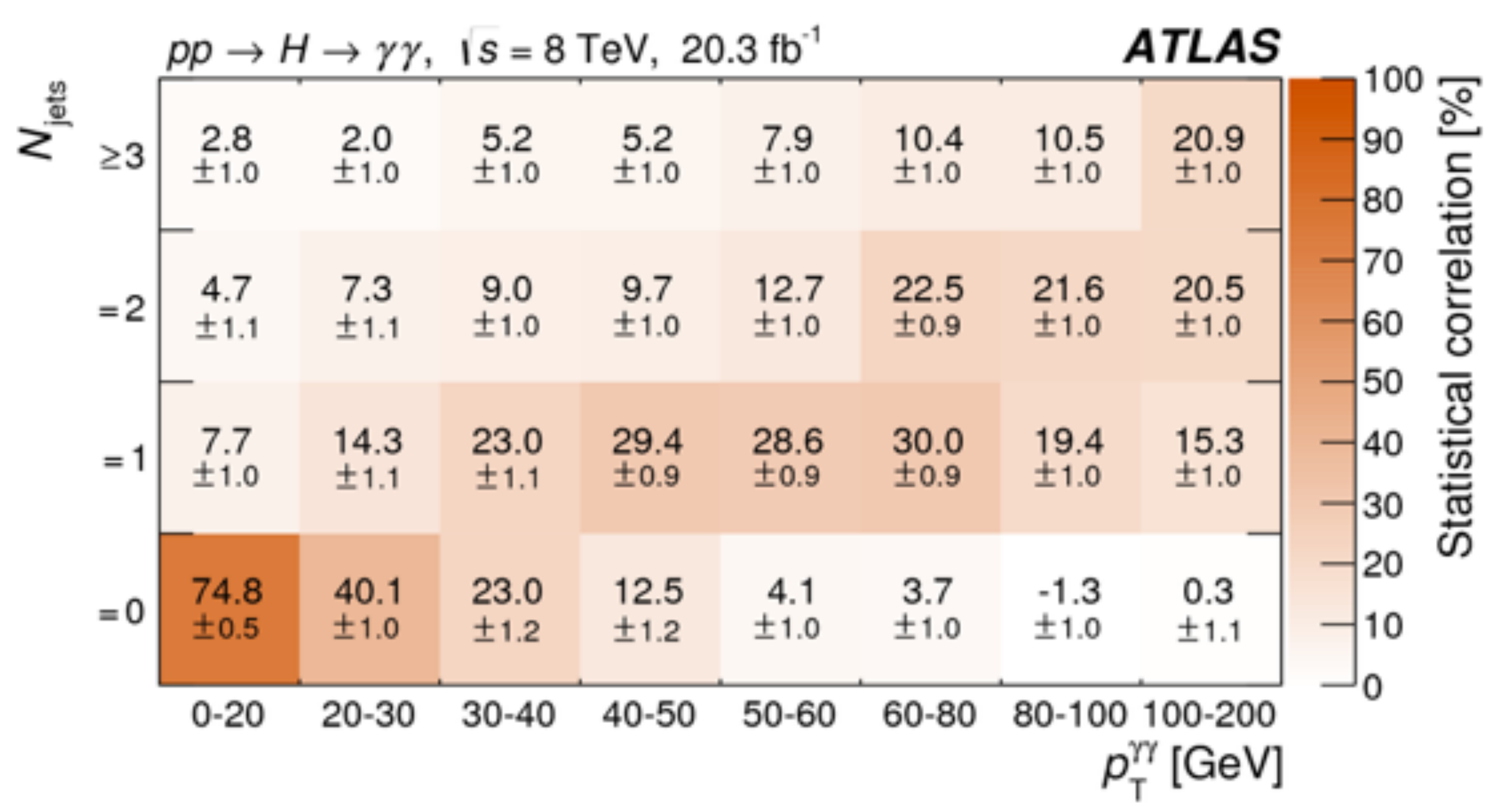


Example: limit on 2 anomalous couplings (assuming 0 for the others).



EFT STUDY: “BOOTSTRAPPING’”

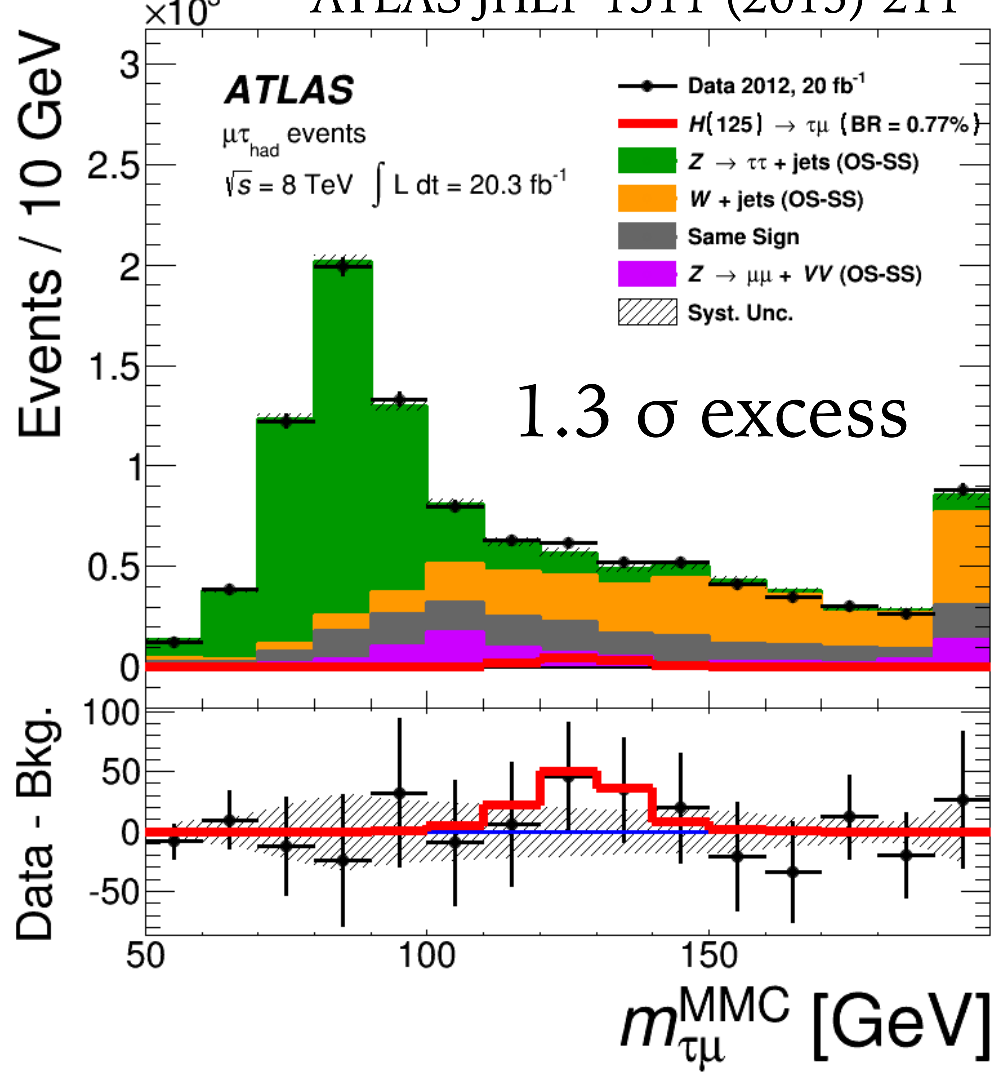
- Statistical correlations between the measured XS of different distributions are obtained with a ’bootstrapping’ method .
- Bootstrapped event samples are constructed from data by **assigning each event a weight pulled from a Poisson distribution with unit mean**.
- The five differential distributions are then reconstructed using the weighted events, and the signal yields in each bin of a differential distribution are determined using an unbinned maximum-likelihood fit of the diphoton invariant mass spectrum.
- The procedure is done 10 000 times with statistically independent weights and the correlation between two bins of different distributions is determined from the scatter graph of the corresponding extracted cross sections.
- Observed correlations between bins of the measured pTγγ and Njets XS:



RARE BSM h(125) DECAY

- Probe **lepton flavor violation** in decay looking for H→τμ (or τe or eμ)
- BR(τμ)<1.85% (exp 1.24%)

ATLAS JHEP 1511 (2015) 211



- **h(125) to invisible searches** combined: *JHEP11(2015)206*
- Invisible Higgs boson decay search using "tagged" production modes. Most sensitive is VBF production

Channels	Upper limit on BR($h \to$ inv.) at the 95% CL					
	Obs.	−2 std. dev.	−1 std. dev.	Exp.	+1 std. dev.	+2 std. dev.
VBF h	0.28	0.17	0.23	0.31	0.44	0.60
$Z(\to \ell\ell)h$	0.75	0.33	0.45	0.62	0.86	1.19
$V(\to jj)h$	0.78	0.46	0.62	0.86	1.19	1.60
Combined Results	0.25	0.14	0.19	0.27	0.37	0.50