

The Higgs Boson in ATLAS and CMS

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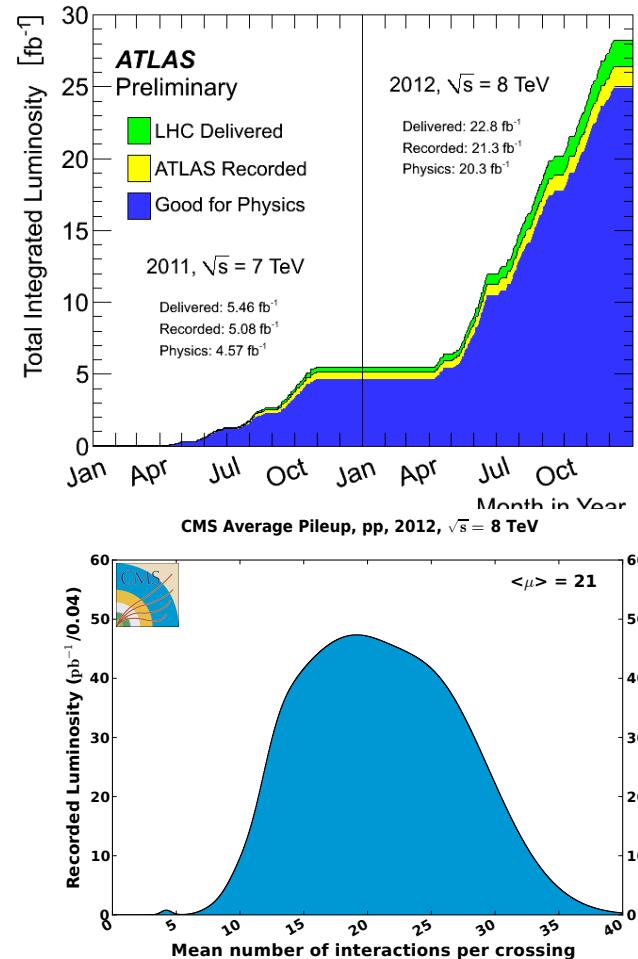
Laboratoire de physique nucléaire et des hautes énergies, Paris
on behalf of ATLAS and CMS collaborations



23 June 2014, XXX-th International Workshop on High Energy
Physics, Protvino, Russia

Machine and detector performance

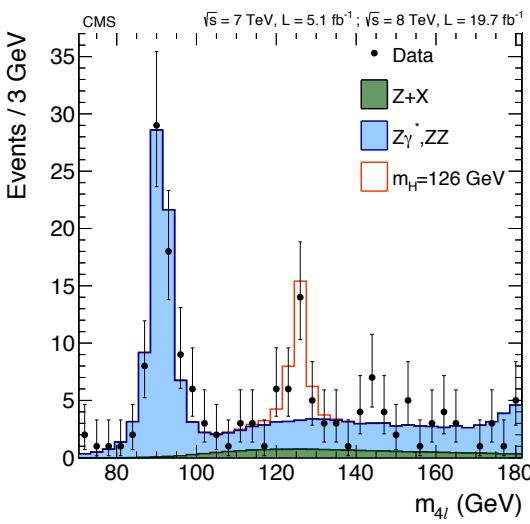
- The results presented here are obtained from LHC Run-1 pp collision data recorded by ATLAS and CMS:
 - 2011 @7 TeV
 - 2012 @8 TeV
- LHC has been extremely successful: **>28 fb⁻¹** delivered to both experiments
- The price for high luminosity is the large number of collisions per proton bunch crossing: $\langle\mu\rangle=21$, $\mu_{max}\sim 40$ (2012)
- High data taking efficiency in both experiments: 91-93%



Observation of the H \rightarrow di-boson decays

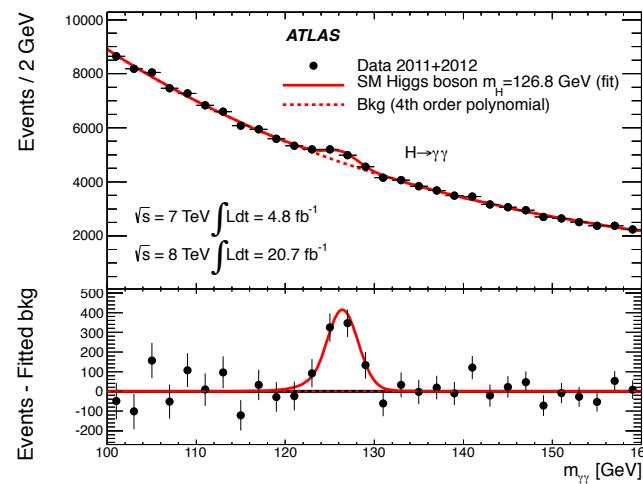
CMS, H \rightarrow ZZ \rightarrow 4l
6.8 σ @ m_H \sim 125.6 GeV

arXiv:1312.5353



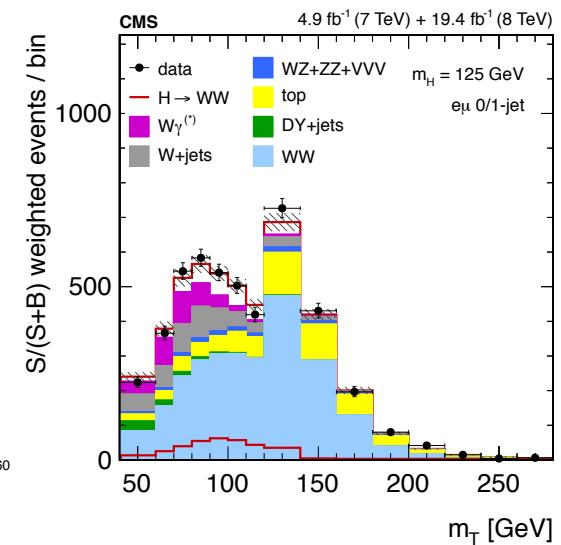
ATLAS, H \rightarrow $\gamma\gamma$
7.4 σ @ m_H \sim 126.5 GeV

arXiv:1307.1427



CMS, H \rightarrow WW
4.3 σ @ m_H \sim 125.6 GeV

arXiv:1312.1129

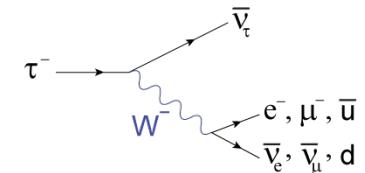


- The Higgs was discovered through its decays to di-bosons
- Now moving from discovery mode to precision measurements: mass, width, spin,..

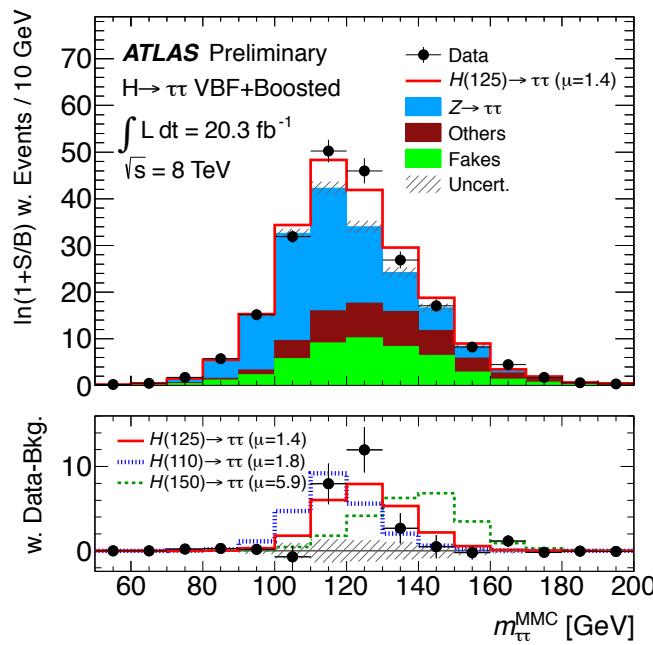
First direct evidence of Higgs coupling to fermions: $H \rightarrow \tau\tau$

Challenging analysis:

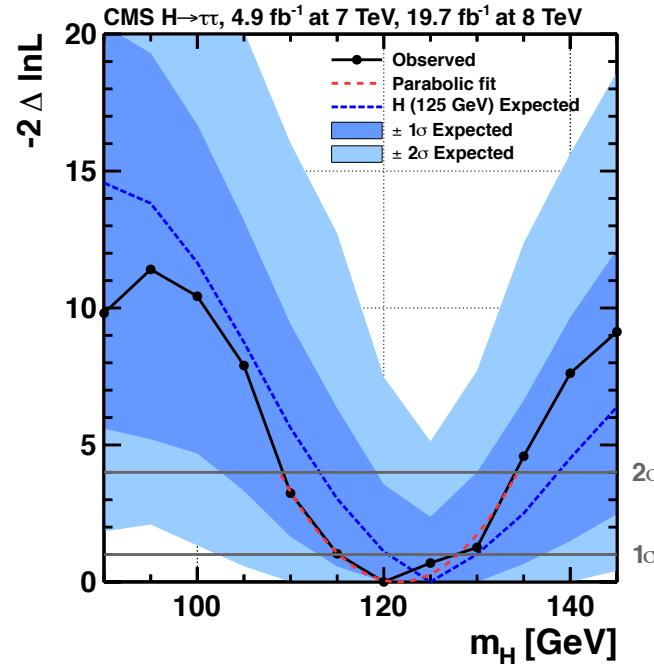
- huge background mainly from $Z \rightarrow \tau\tau$
- must achieve a good mass resolution despite the escaping neutrinos



ATLAS-CONF-2013-108



ATLAS: 4.1σ @ $m_H \sim 125.5$ GeV (3.2)

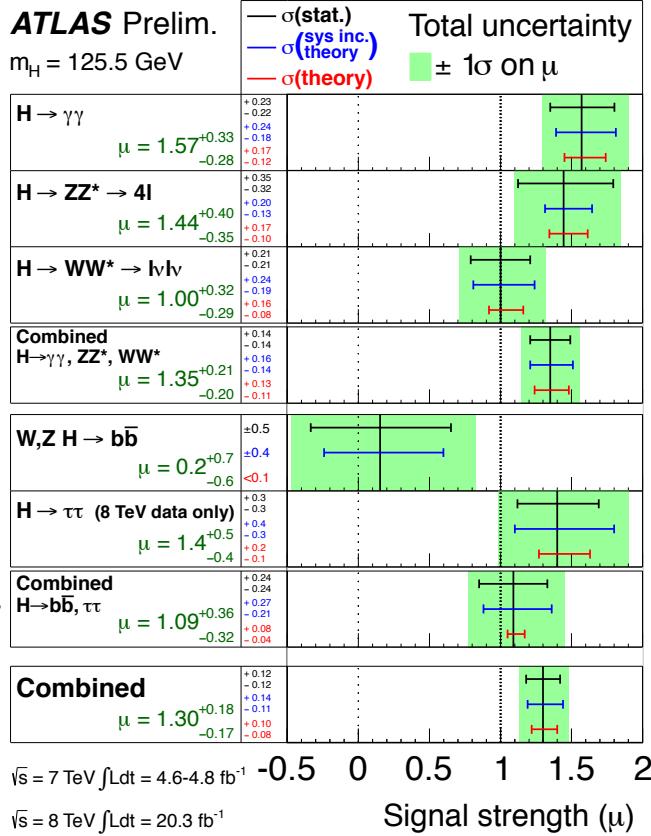


arXiv:1401.5041

CMS: 3.2σ @ $m_H \sim 125$ GeV (3.7)

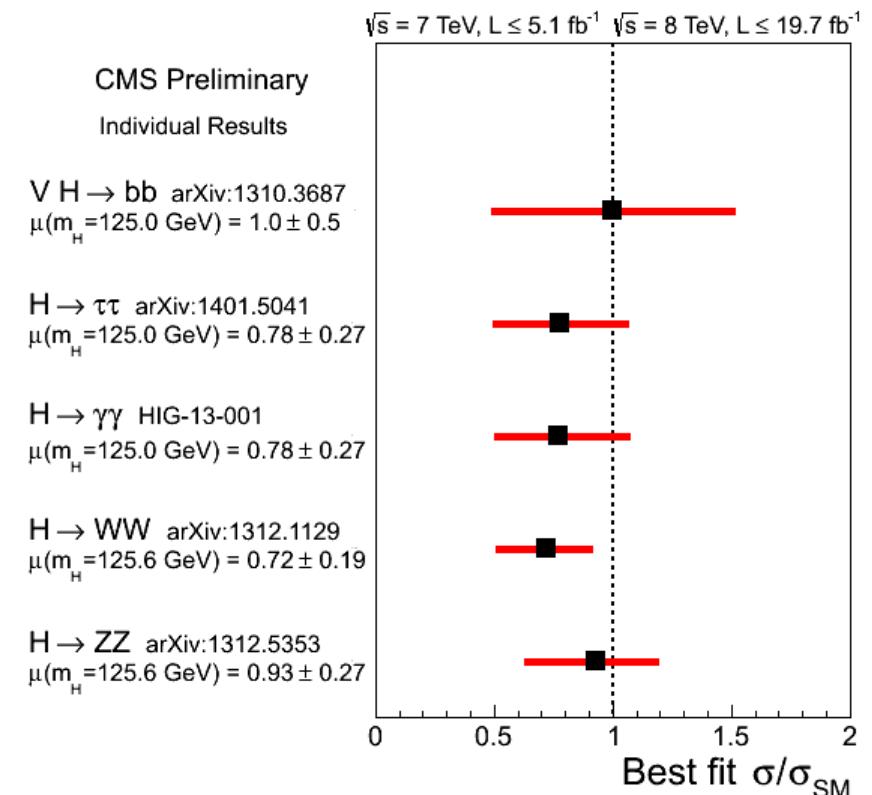
Higgs decay measurements

ATLAS-CONF-2014-009



ATLAS H \rightarrow fermions combination:

- 3.7σ evidence



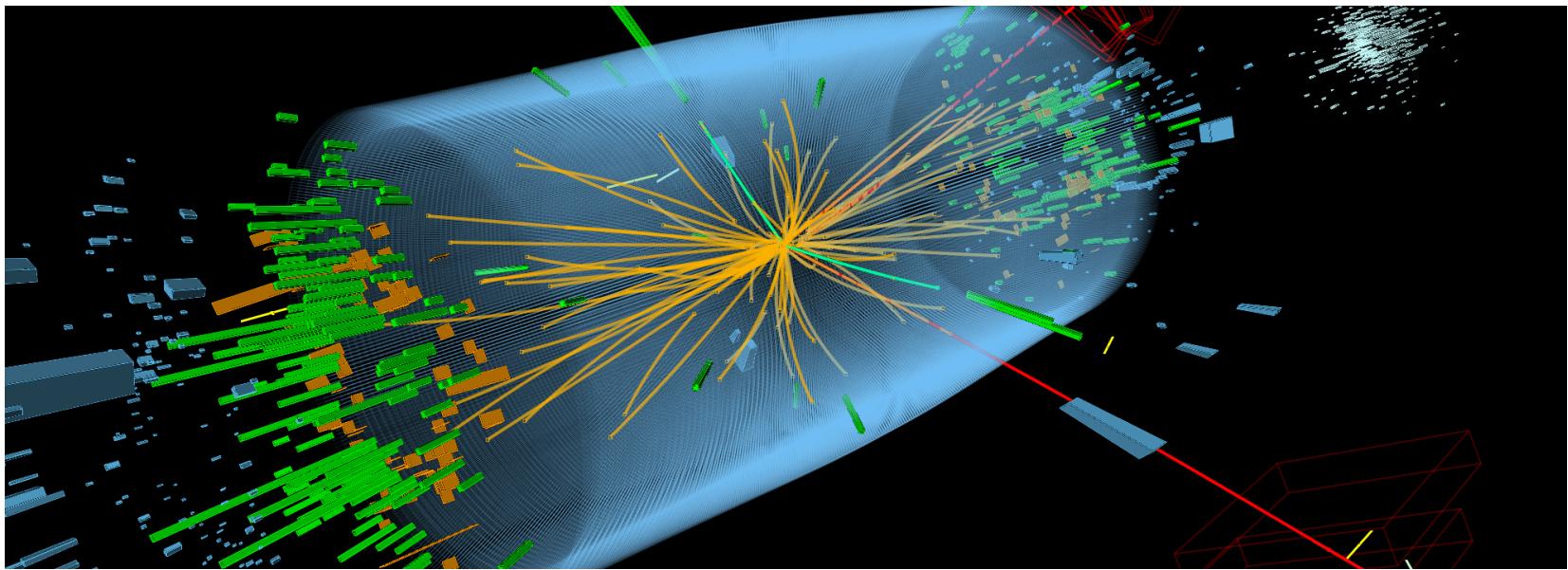
CMS H \rightarrow fermions combination:

- 3.8σ evidence (exp. 4.4)

Nature: 10.1038/nphys3005

Outline

- Higgs properties: mass, width, spin
- Test of the Higgs couplings
- Search for beyond the standard model physics in the Higgs sector



Properties of the new boson

Mass, width, spin

New ATLAS mass measurement

Performed on 2011 (7 TeV) and 2012 (8 TeV) data using $H \rightarrow ZZ \rightarrow 4\mu, 2e2\mu, 4e$ and $H \rightarrow \gamma\gamma$.
New calibration of muon and e/γ momentum and resolution.

$H \rightarrow \gamma\gamma$	$125.98 \pm 0.42 \pm 0.28$ GeV
$H \rightarrow 4l$	$124.51 \pm 0.52 \pm 0.06$ GeV
combined	$125.36 \pm 0.37 \pm 0.18$ GeV

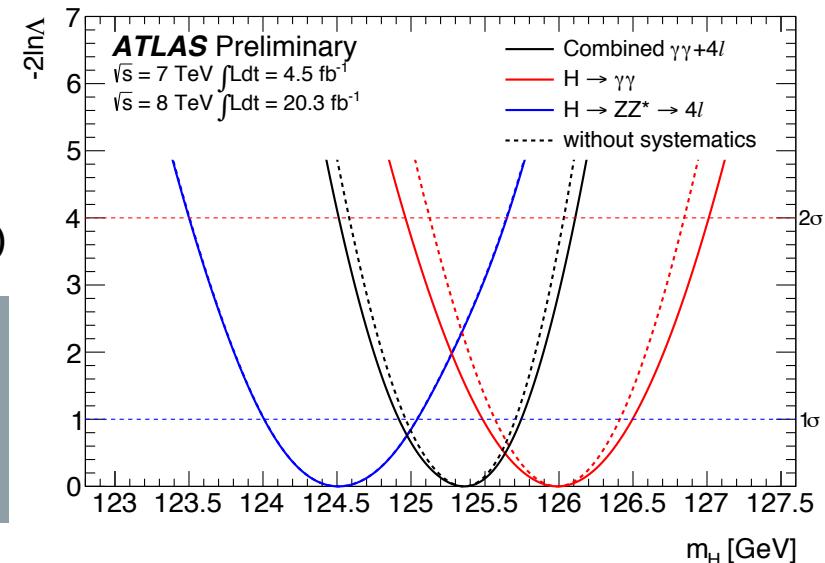
- Systematic uncertainty reduced by a factor 3!
- Increased statistical uncertainty mainly due to the reduced observed event yield in $H \rightarrow \gamma\gamma$
- Shift of central value in $H \rightarrow \gamma\gamma$: -0.8 GeV (-0.49 ± 0.35 GeV expected from new calibration)

Mass difference between the two channels:
 $\Delta m_H = 1.47 \pm 0.67 \pm 0.28$ GeV
compatibility at the 2.0σ level
(compared to 2.4σ previously)

previous result:

$$m_H = 125.5 \pm 0.2^{+0.5}_{-0.6} \text{ GeV}$$

(Phys. Lett. B726 (2013) 88–119)

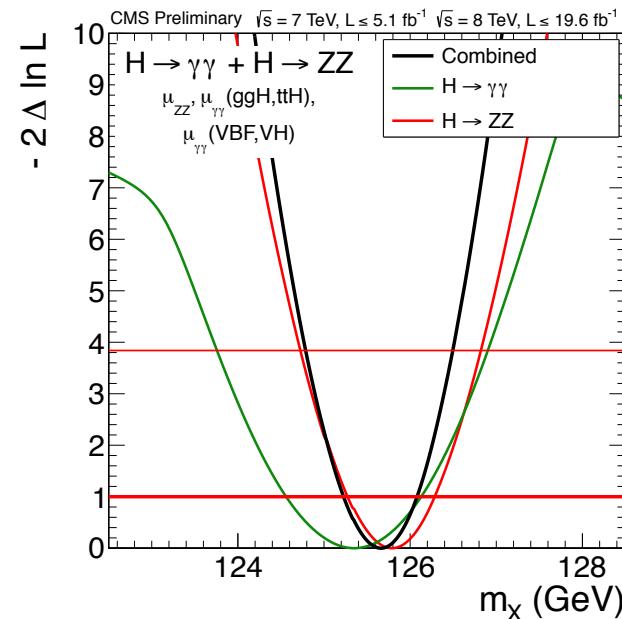
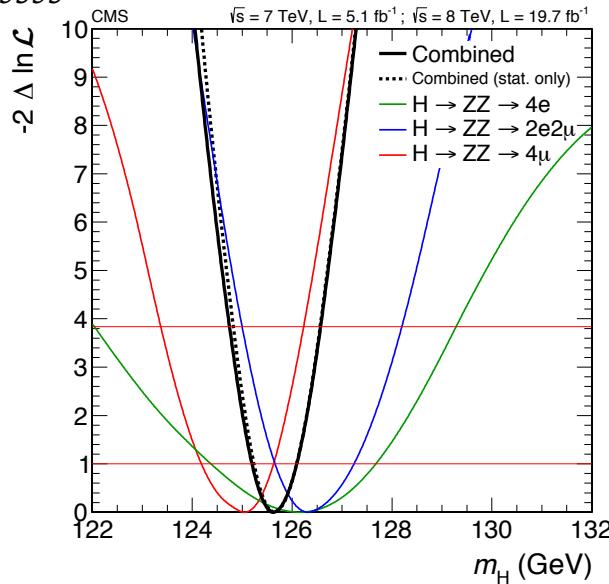


CMS mass measurement

Consistent measurements across $H \rightarrow 4l$ channels

$H \rightarrow 4e$	$126.2^{+1.5}_{-1.8}$ GeV
$H \rightarrow 2e2\mu$	$126.3^{+0.9}_{-0.7}$ GeV
$H \rightarrow 4\mu$	$125.1^{+0.6}_{-0.9}$ GeV
Combined	$125.6 \pm 0.4 \pm 0.2$ GeV

arXiv:1312.5353



and with $H \rightarrow \gamma\gamma$ (HIG-13-001):

$$m_H = 125.4 \pm 0.5 \pm 0.6 \text{ GeV}$$

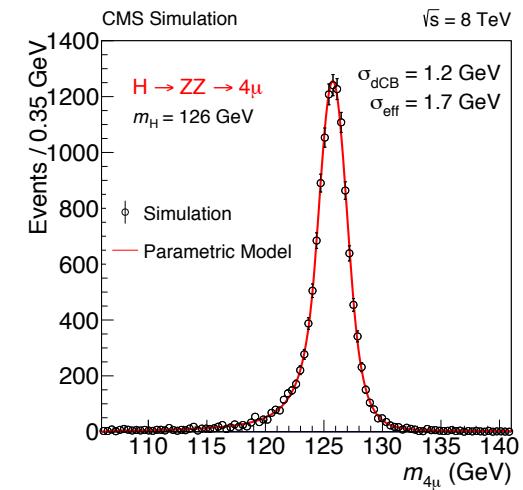
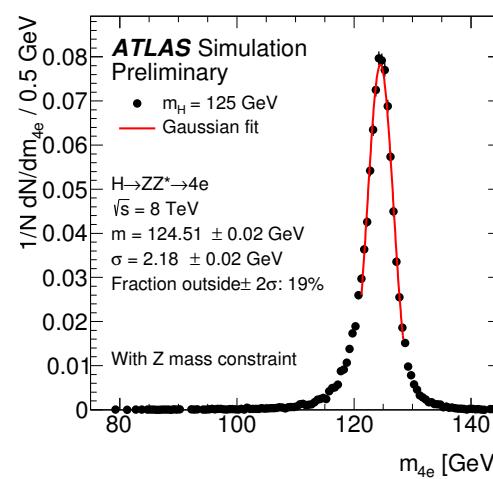
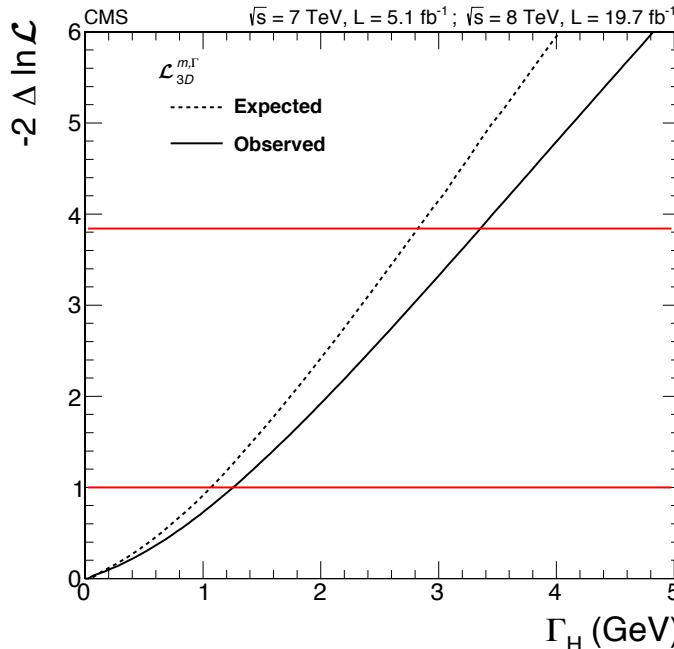
CMS $H \rightarrow 4l + H \rightarrow \gamma\gamma$ combined result:
 $m_H = 125.7 \pm 0.3 \pm 0.3$ GeV

HIG-13-005

Note: m_H from $H \rightarrow 4l$ was $125.8 \pm 0.5 \pm 0.2$ at the time of the combination.

Constraints on the Higgs width

The Higgs width predicted by the Standard Model is ~ 4 MeV. Beyond SM contributions may increase it significantly.



However, the direct determination is limited by the much larger detector resolution: 1-2 GeV

Limits at 95%CL:

CMS $H \rightarrow 4l$: $\Gamma_H \leq 3.4 \text{ GeV}$
 CMS $H \rightarrow \gamma\gamma$: $\Gamma_H \leq 6.9 \text{ GeV}$

arXiv:1312.5353
 HIG-13-016

ATLAS $H \rightarrow 4l$: $\Gamma_H \leq 2.6 \text{ GeV}$
 ATLAS $H \rightarrow \gamma\gamma$: $\Gamma_H \leq 4.4 \text{ GeV}$

arXiv:1406.3827

CMS limits from off-shell H \rightarrow ZZ analysis

Measurements of the on-shell and off-shell cross-sections give a direct constraint on the Higgs width:

$$\sigma_{gg \rightarrow H \rightarrow ZZ}^{\text{on-shell}} \sim \frac{g_{ggH}^2 g_{HZZ}^2}{m_H \Gamma_H} \quad \sigma_{gg \rightarrow H \rightarrow ZZ}^{\text{off-shell}} \sim \frac{g_{ggH}^2 g_{HZZ}^2}{(2m_Z)^2}$$

assuming the couplings remain unchanged.

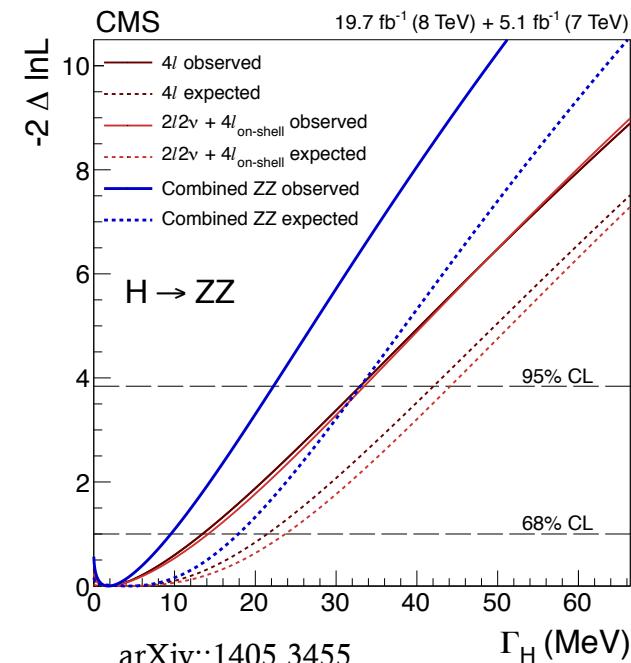
CMS measured the off-peak cross sections in

- H \rightarrow 4l, $m_{4l} > 220$ GeV: 11 events observed
- H \rightarrow 2l2v: $m_T > 180$ GeV: 91 events

$$m_T^2 = \left[\sqrt{p_{T,\ell\ell}^2 + m_{\ell\ell}^2} + \sqrt{E_T^{\text{miss}}^2 + m_{\ell\ell}^2} \right]^2 - \left[\vec{p}_{T,\ell\ell} + \vec{E}_T^{\text{miss}} \right]^2$$

On-peak cross section measured in the H \rightarrow 4l channel only ($105.6 < m_{4l} < 140.6$ GeV)

channel	Observed limit @95% CL (expected)
H \rightarrow 4l	33 MeV (42 MeV)
H \rightarrow 2l2v	33 MeV (44 MeV)
combined	22 MeV (33 MeV)

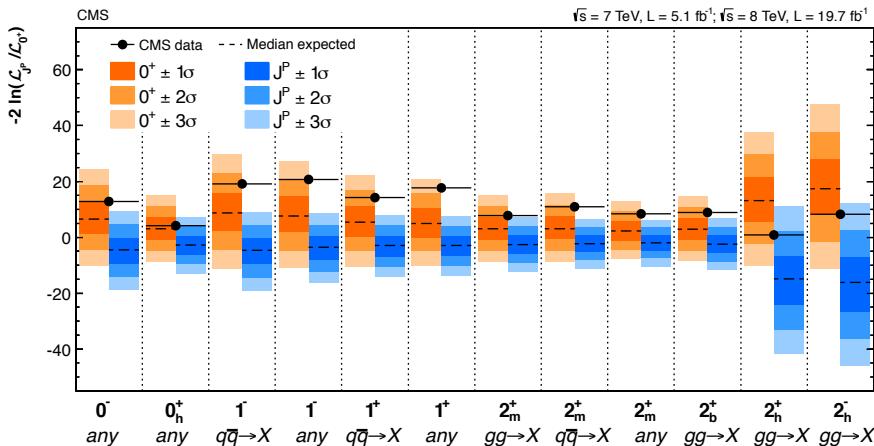


arXiv::1405.3455

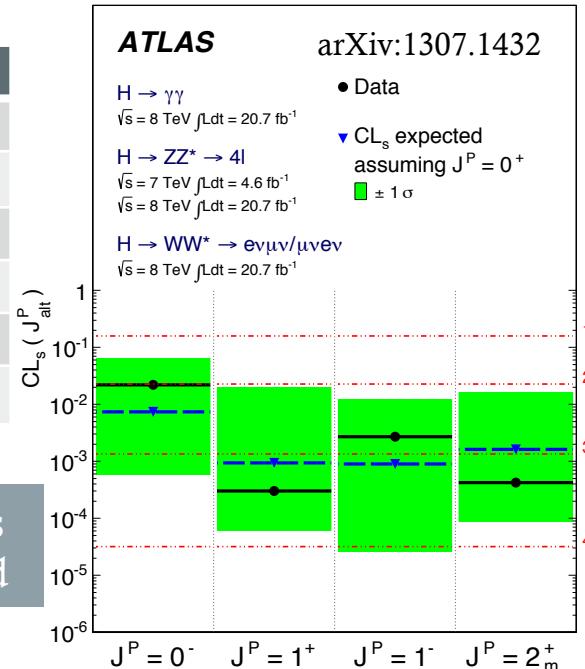
Spin and CP Analysis

CMS H \rightarrow ZZ \rightarrow 4l analysis arXiv:1312.5353

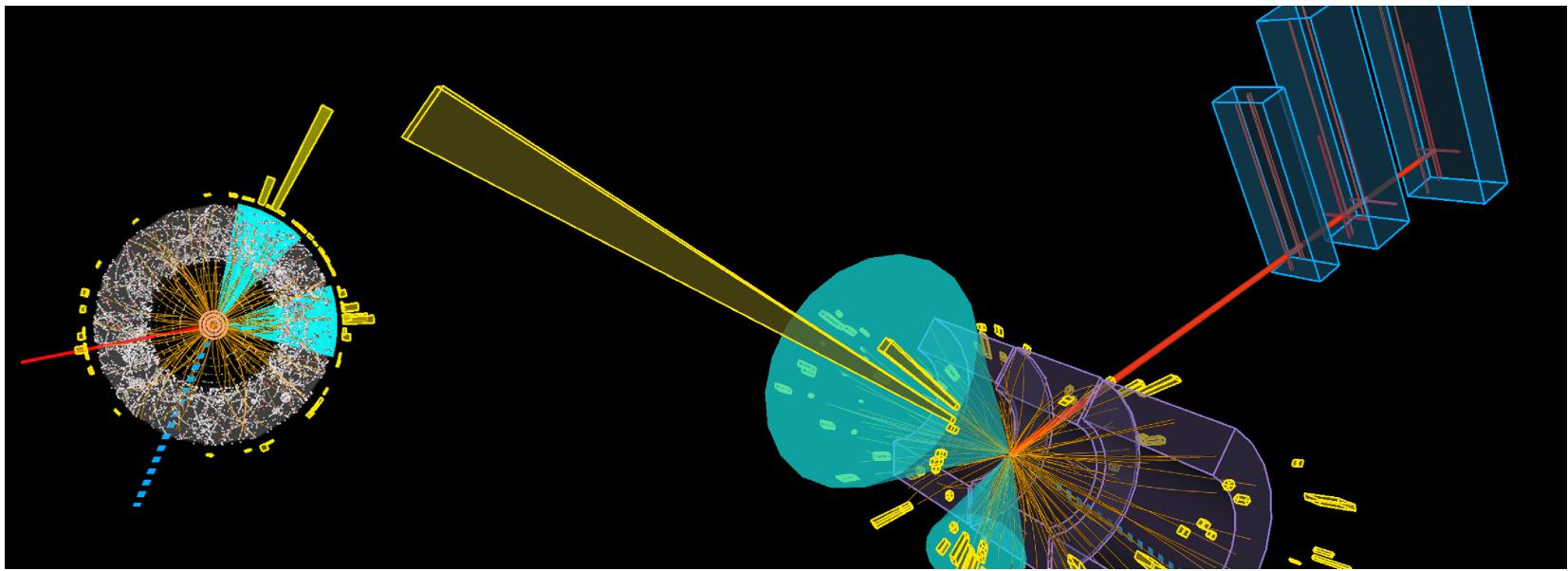
model	prod. mode	scenario	model	prod. mode	scenario
0 $^-$	any	pseudo-scalar	2 ^+_m	gg \rightarrow X	KK graviton
0 ^+_h	any	BSM scalar	2 ^+_m	any	KK graviton
1 $^-$	qq \rightarrow X	exotic vector	2 ^+_m	qq \rightarrow X	KK graviton
1 $^-$	any	exotic vector	2 ^+_b	gg \rightarrow X	KK G (bulk)
1 $^+$	qq \rightarrow X	exotic pseudo-vector	2 ^+_h	gg \rightarrow X	BSM tensor
1 $^+$	any	exotic pseudo-vector	2 ^-_h	gg \rightarrow X	BSM tensor



J $P=0^+$ hypothesis strongly favoured

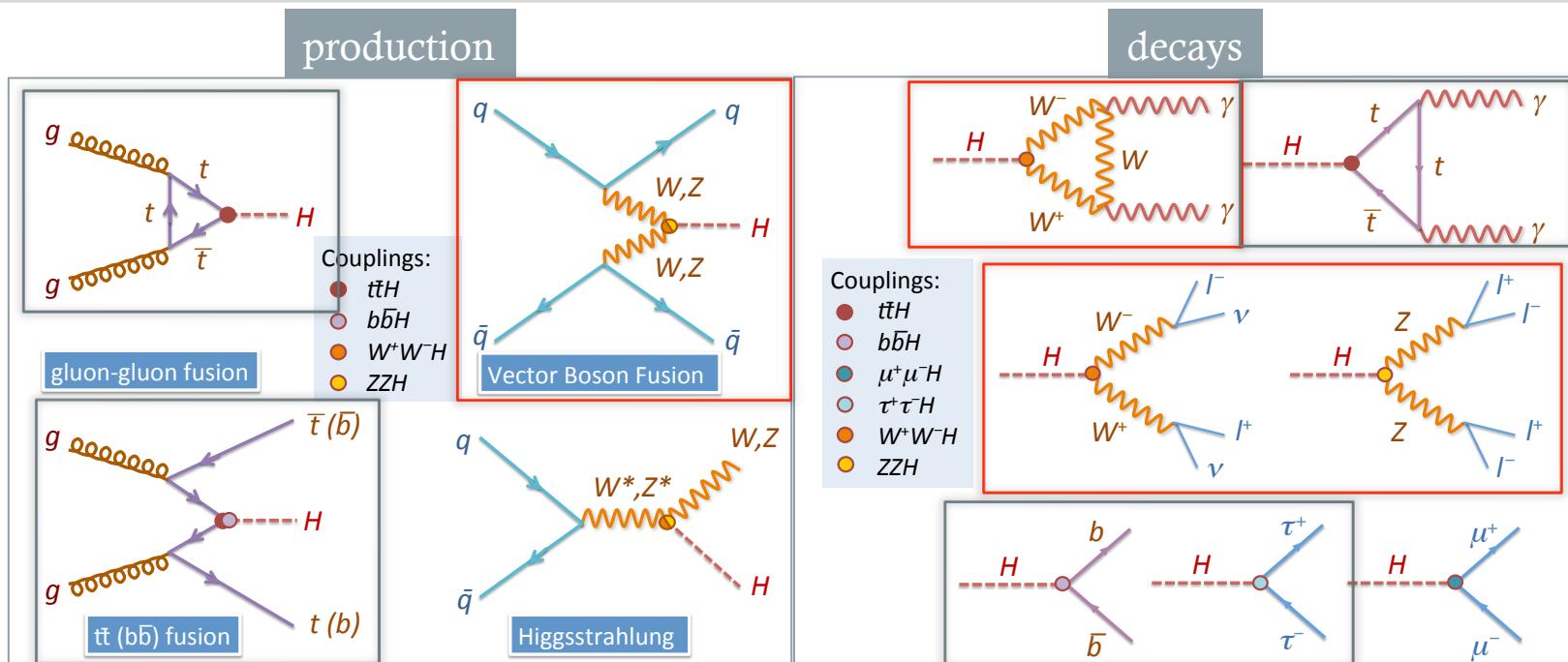


ATLAS: 0 $^-, 1^+, 1^-, 2^+$ excluded >97.8% CL
 CMS: 0 $^-,$ spin 1 excluded at 99.9%, spin 2 >95%
 CMS: CP-odd fraction to ZZ amplitude:
 $f_{a3} = 0.00^{+0.17}_{-0.00}$



Probing the Higgs couplings

Higgs couplings



Discovery of the Higgs: indirect proof of gluon-gluon fusion production mode

Observation of the decays to WW and ZZ

Observation of the decay to $\gamma\gamma$: check SM prediction for W and t loop contributions

Evidence for the decay to fermions

Evidence for vector boson fusion production mode

No evidence yet for $t\bar{t}H$ production mode

Search for deviations from the SM prediction of couplings

- Are the measurements in agreement with the predicted couplings of Higgs to SM particles?
- Measure $(\sigma \cdot \text{BR})(ii \rightarrow H \rightarrow ff)$ and test deviations on σ_{ii} , Γ_{ff} and Γ_H :

$$(\sigma \cdot \text{BR}) (ii \rightarrow H \rightarrow ff) = \frac{\sigma_{ii} \cdot \Gamma_{ff}}{\Gamma_H}$$

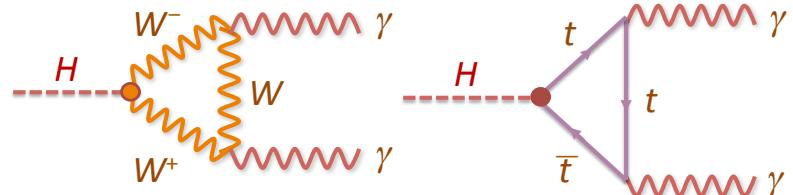
- Assumption: one single, narrow, CP-even scalar resonance near 125 GeV, with the same coupling structure as for the SM Higgs
- Parametrise possible deviations with individual coupling scale factors κ_i :

For example:

$$(\sigma \cdot \text{BR}) (\text{gg} \rightarrow H \rightarrow \gamma\gamma) = \sigma_{\text{SM}}(\text{gg} \rightarrow H) \cdot \text{BR}_{\text{SM}}(H \rightarrow \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

where κ_g and κ_g are effective scale factors:

$$\begin{aligned}\kappa_\gamma^2 &\sim 1.59 \cdot \kappa_W^2 - 0.66 \cdot \kappa_W \kappa_t + 0.07 \cdot \kappa_t^2 \\ \kappa_g^2 &\sim 1.06 \cdot \kappa_t^2 - 0.07 \cdot \kappa_t \kappa_b + 0.01 \cdot \kappa_b^2\end{aligned}$$



- Similarly:

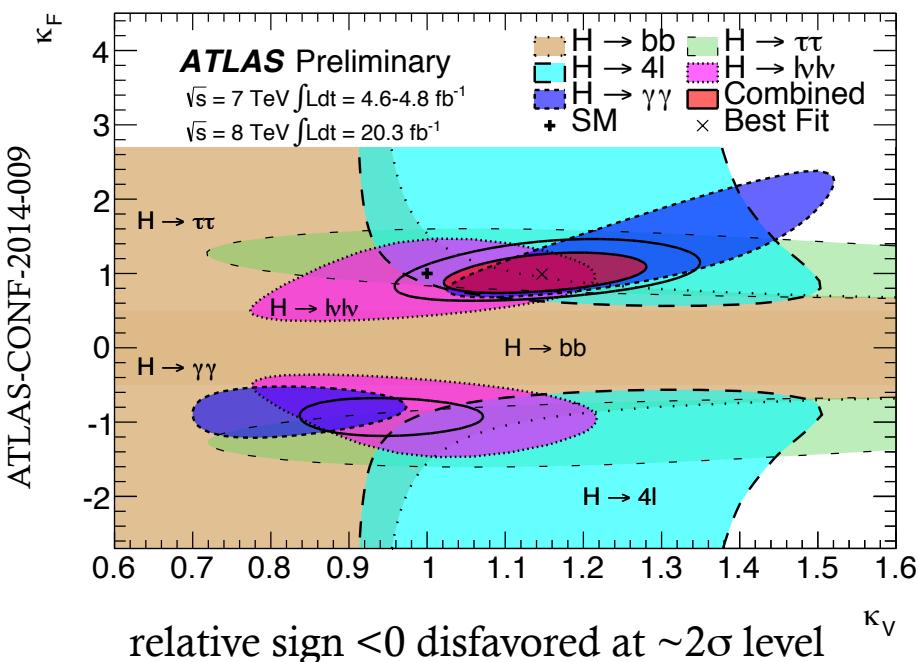
$$\kappa_{\text{VBF}}^2 \sim 0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$$

$$\kappa_H^2 \sim 0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 + 0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2$$

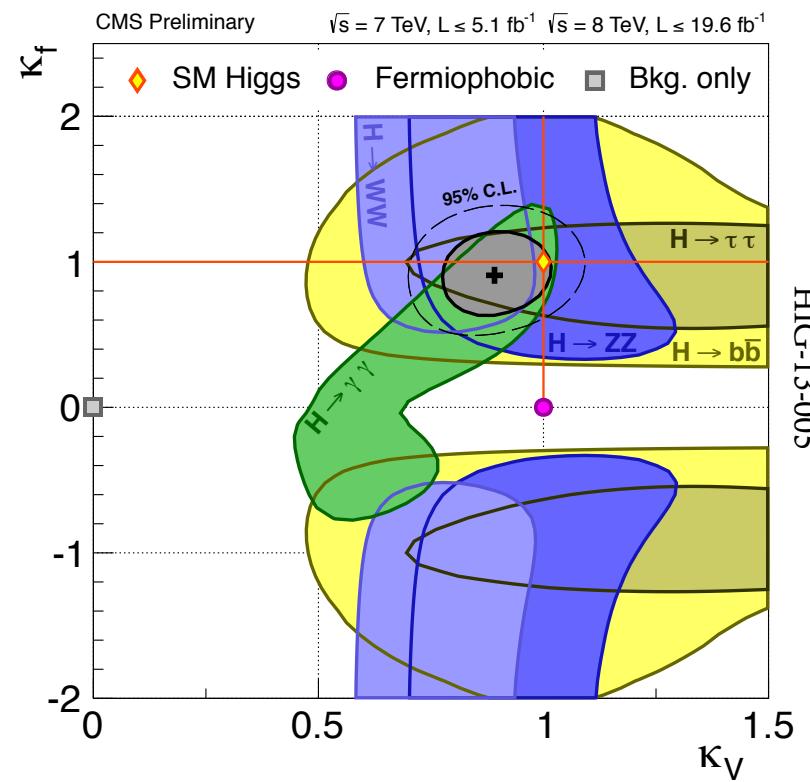
Vector vs fermion couplings

Assumptions:

- one scale factor for fermions: $\kappa_F = \kappa_b = \kappa_t = \kappa_\tau$
- one scale factor for vector bosons: $\kappa_V = \kappa_W = \kappa_Z$
- no new particles in loops or in decays ($\Gamma_H = \Gamma_H^{\text{SM}}$)

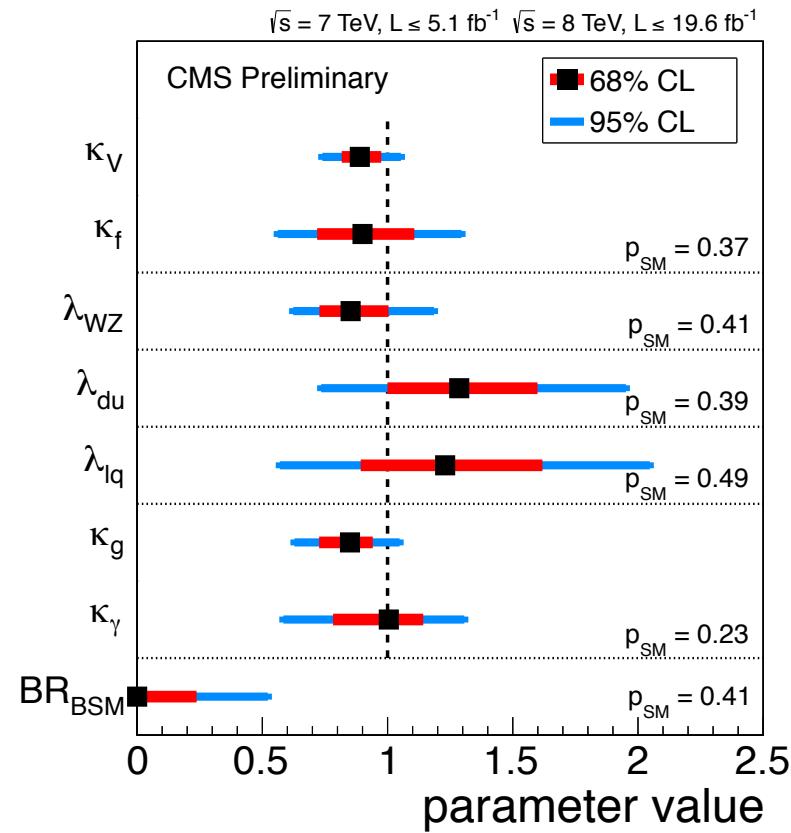
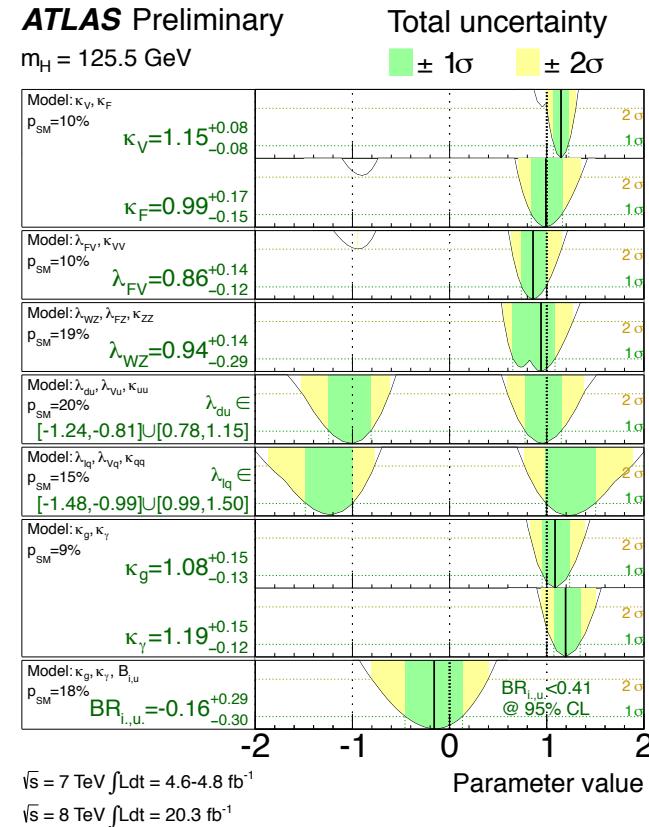


$\kappa_V: [1.07, 1.23]; \kappa_F: [0.84, 1.16] @ 68\% \text{ CL}$

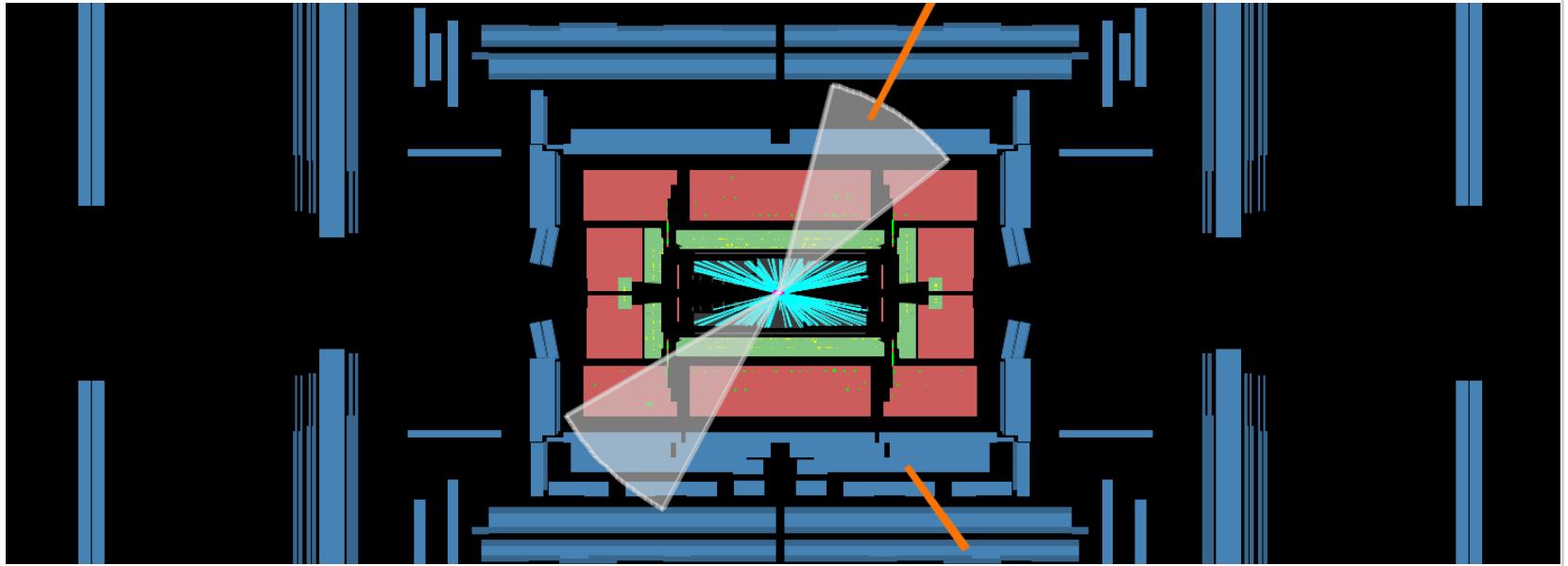


$\kappa_V: [0.74, 1.06]; \kappa_F: [0.61, 1.33] @ 68\% \text{ CL}$

Summary of coupling scale factor measurements



Couplings measured within benchmark models defined by the LHC WG
 No significant deviation from the Standard Model is observed



Beyond the Standard Model Searches

Higgs portal to Dark Matter

New particles coupling very weakly to SM particles except Higgs \rightarrow dark matter (e.g. WIMPs).

- Indirect search: contribution from new particles in loops can modify effective couplings to gluons (κ_g), photons (κ_γ), with or without altering Γ_H (branching ratio to « invisible » $BR_i = 0$ or $\neq 0$).
- Direct search for $H \rightarrow$ invisible (E_T^{miss}):
 - in ZH production, with $Z \rightarrow l^+l^-$ or bb
 - in vector boson fusion (two forward/backward jets with large rapidity gap)

No signal is observed. No deviation from SM for the effective couplings:

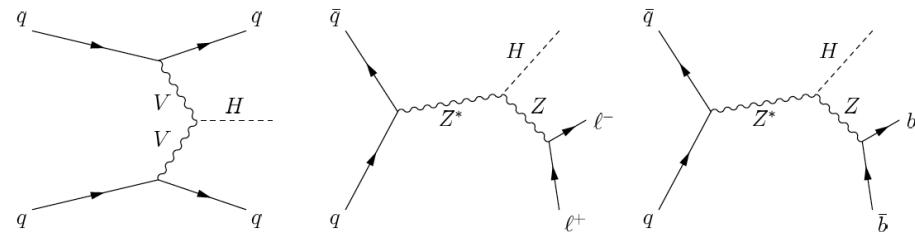
ATLAS:

$$\kappa_g = 1.08^{+0.15}_{-0.13}, \kappa_\gamma = 1.19^{+0.15}_{-0.12} \quad (BR_i=0)$$

$$\kappa_g = 1.00^{+0.23}_{-0.16}, \kappa_\gamma = 1.17^{+0.16}_{-0.13} \quad (BR_i \neq 0)$$

CMS:

$$\kappa_g \text{ in } [0.59, 1.30], \kappa_\gamma \text{ in } [0.63, 1.05]_2 \quad (BR_i=0)$$

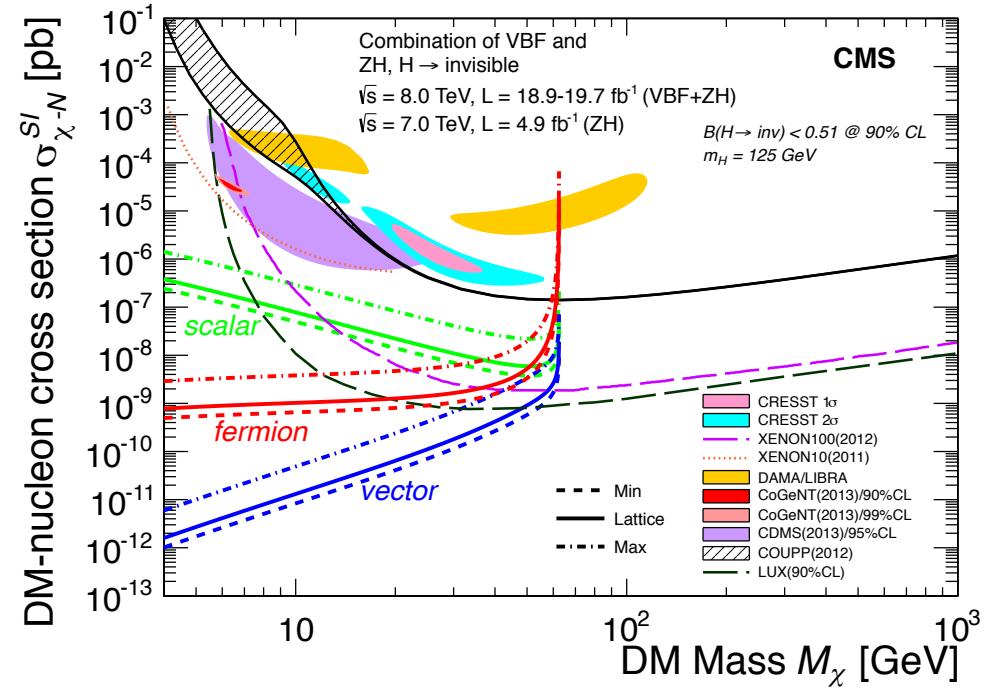
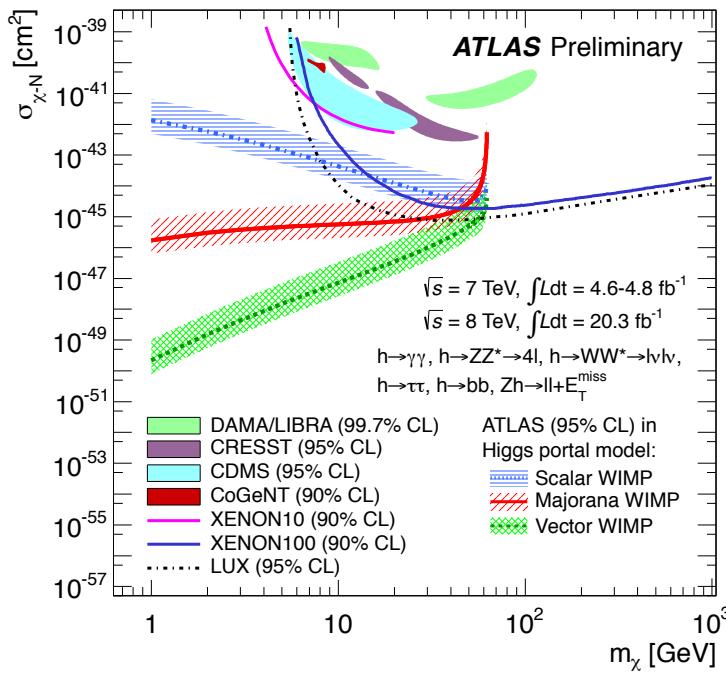


limits on BR_i @ 95%	ATLAS $m_H=125.5$ GeV	CMS $m_H=125$ GeV
ZH	0.75 (0.62)	0.81 (0.83)
VBF		0.65 (0.49)
ZH+VBF		0.58 (0.44)
indirect	0.41 (0.55)	0.52
direct+indirect	0.37 (0.39)	

ATLAS-CONF-2014-009, 010, arXiv:1402.3244, HIG-13-005, arXiv:1404.1344

Limits on DM-neucleon scattering cross sections

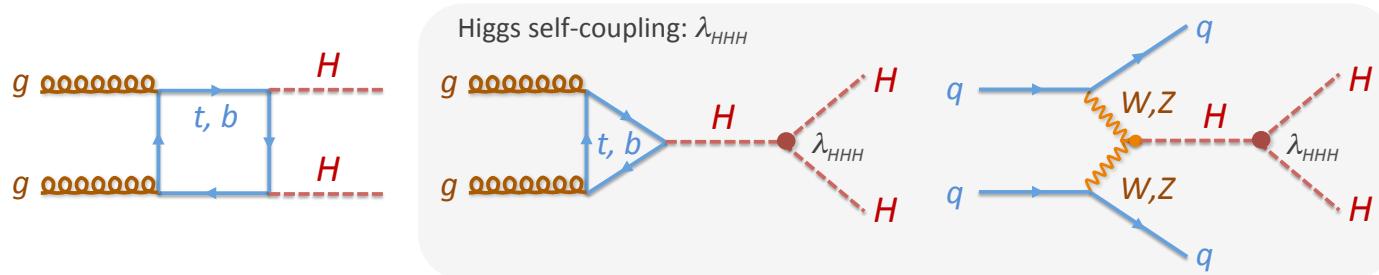
Comparison with direct WIMP detection experiments: interpretation of the results in terms of WIMP-nucleon scattering via Higgs exchange. Assume $\text{BR}_i = \text{BR}(H \rightarrow \chi\chi)$, $m_\chi < m_H/2$.



Very stringent limits from both ATLAS and CMS up to $m_\chi < m_H/2$

Search for di-Higgs production in $\gamma\gamma bb$ final state

SM di-Higgs production as a probe of Higgs self-coupling



Too rare to be observed with Run-1 data (SM prediction ~ 10 fb) but can be enhanced in some BSM models:

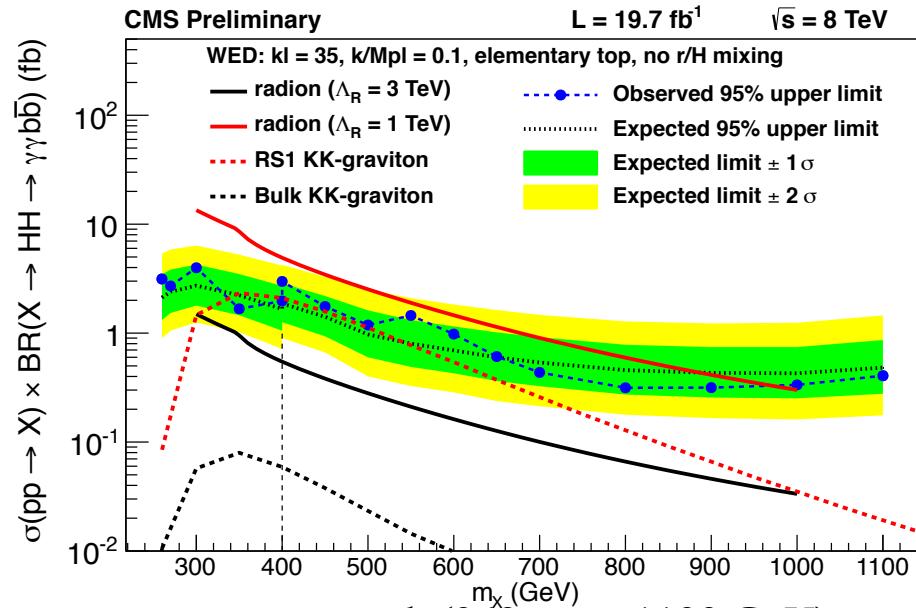
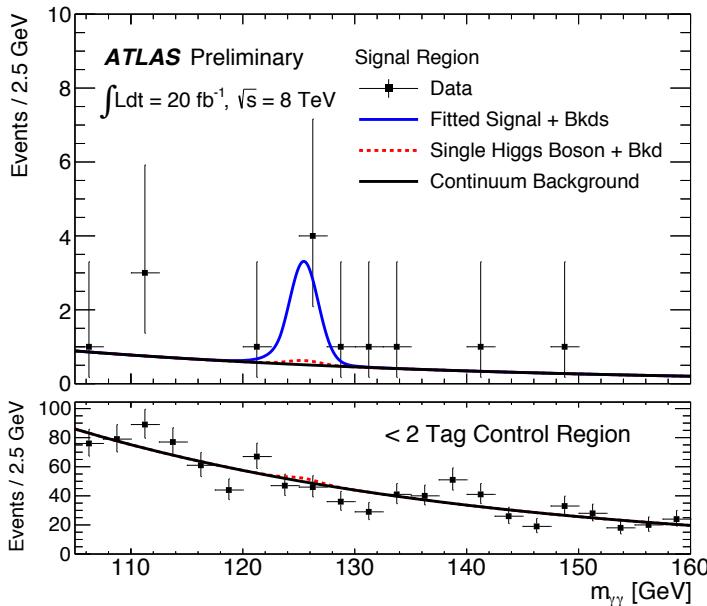
- Resonant production:
 - 2HDM $H \rightarrow hh$ (up to $\sim pb$)
 - Warped Extra Dimensions: radion (spin-0), KK graviton (spin-2) decays
- Non-resonant production: direct $ttHH$ vertex in composite models, light colored scalars

Very recent results in the $\gamma\gamma bb$ final state from both ATLAS (arXiv:1406.5053) and CMS (HIG-13-032).

very good mass resolution
to reject background

large branching fraction

Search for di-Higgs production in $\gamma\gamma bb$ final state



resonance search ($260 < m_X < 500 \text{ GeV}$):

- signal model: spin-0
- counting experiment: measure bkg ϵ in side-bands
- max deviation from bkg $2.1\sigma \rightarrow \sigma \times Br(HH) < 0.3\text{-}3.5 \text{ pb}$

non-resonance search

- fit $m_{\gamma\gamma}$ in signal (≥ 2 b-jets) and bkg (< 2 b-jets) regions
- $N_{\text{exp}} = 1.5$; $N_{\text{obs}} = 5$ (2.4σ) $\rightarrow \sigma < 2.2 \text{ pb} @ 95\% \text{ CL}$

resonance search ($260 < m_X < 1100 \text{ GeV}$):

- analysis benchmark model: spin-0 (radion)
- intermediate mass ($m_X \geq 400 \text{ GeV}$): fit $m_{\gamma\gamma bb}$ with $m_{bb} = 125 \text{ GeV}$
- low mass ($m_X < 400 \text{ GeV}$): fit $m_{\gamma\gamma}$

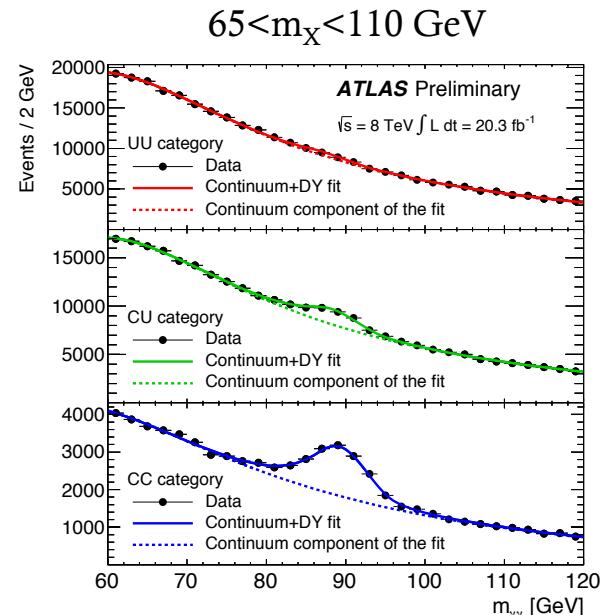
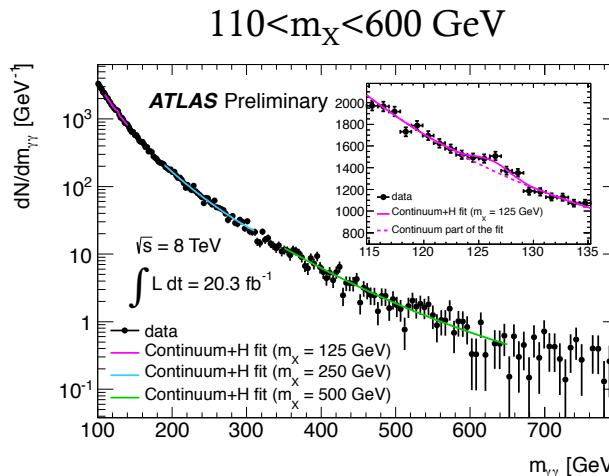
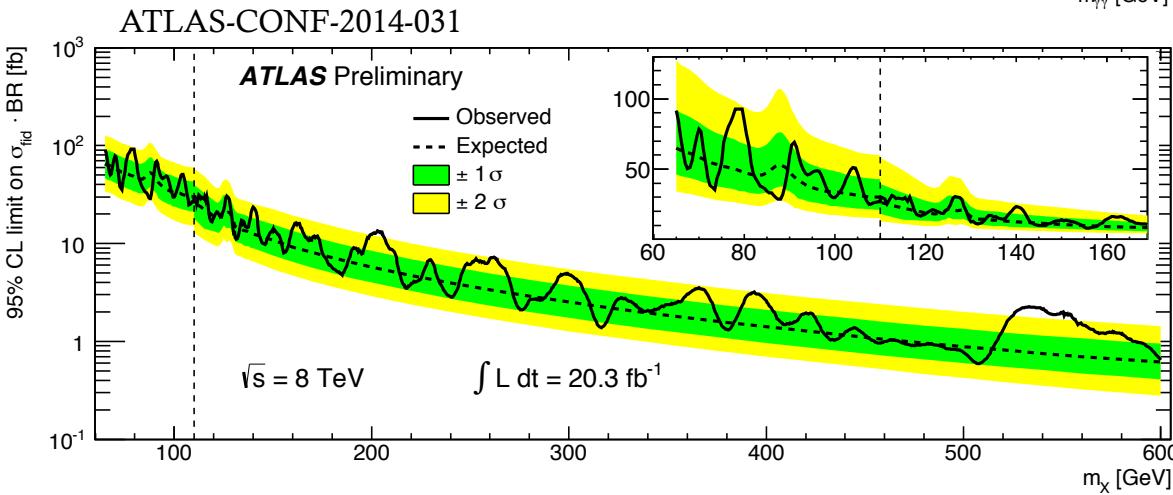
Observed (expected) exclusion for radion:

$M_R < 0.97 \text{ (0.88)} \text{ TeV} @ 95\% \text{ CL}$ ($\Lambda_R = 1 \text{ TeV}$)

Search for scalar diphoton resonances

New ATLAS search for extra Higgs-like state X in an extended mass range:
 $65 < m_X < 600 \text{ GeV}$

Possible signal in 2HDM (H or A), also additional Higgs singlet models.



No significant excess

- Limits on fiducial cross-section
- $E_T^{\gamma 1}, E_T^{\gamma 2} > 22 \text{ GeV}$ (low mass)
 - $E_T^{\gamma 1(\gamma 2)}/m_{\gamma\gamma} > 0.4 (0,3)$ (high mass)
 - $|\eta| < 2.37$
 - isolation < 12 GeV in $\Delta R < 0.4$

Summary

- ATLAS and CMS have established the existence of a Higgs boson. Clear observation of Higgs decays to di-bosons. Evidence for $H \rightarrow$ fermions at the $3.7\text{-}3.8\sigma$ level.

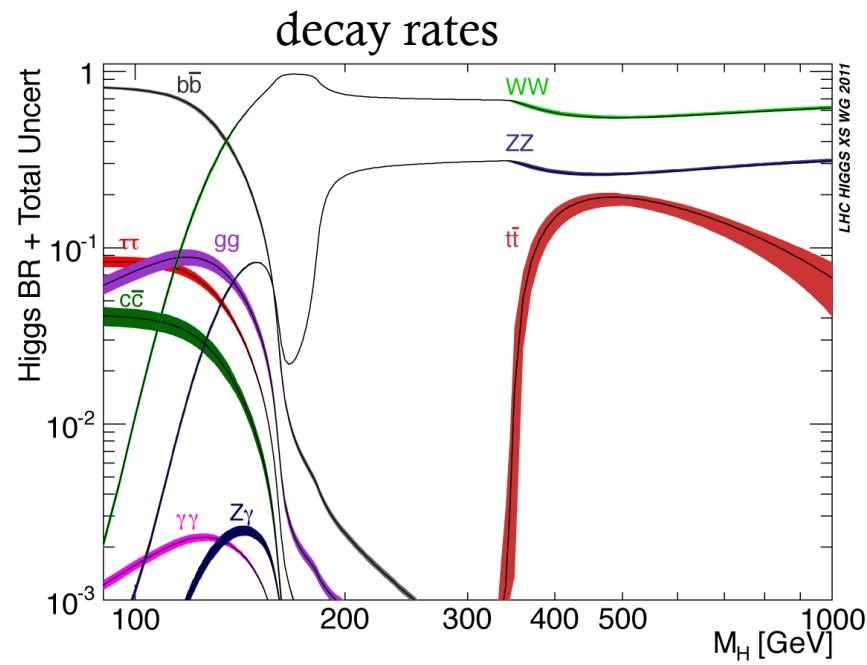
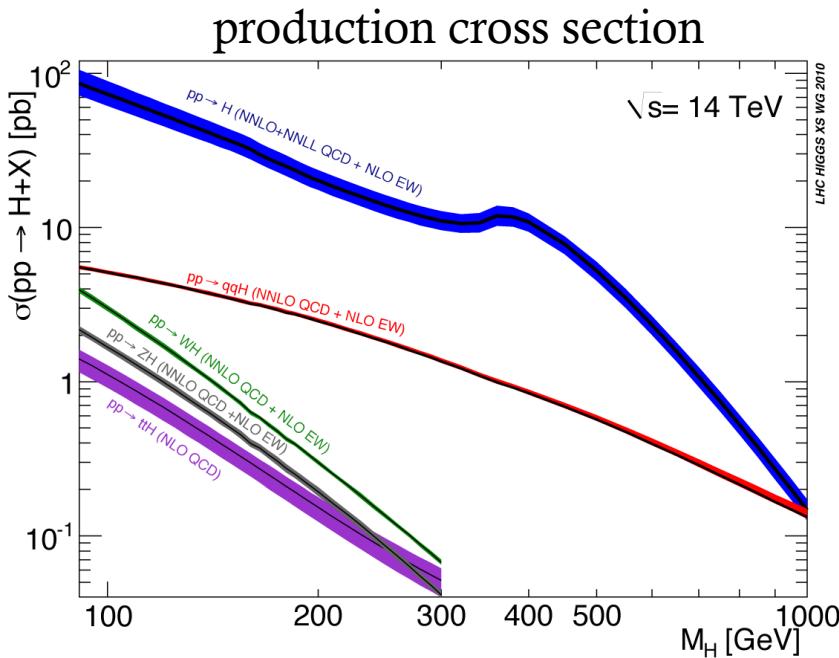
ATLAS: $m_H = 125.36 \pm 0.37 \pm 0.18$ GeV
CMS : $m_H = 125.7 \pm 0.3 \pm 0.3$ GeV

CMS (off-shell analysis): $\Gamma_H \leq 22$ MeV
JCP=0⁺⁺ hypothesis strongly favoured

- Coupling analysis: no significant deviation from SM is observed.
- Many searches for deviation from SM or for extra states in the Higgs sector. Only a few analyses shown here. No evidence for BSM physics yet.

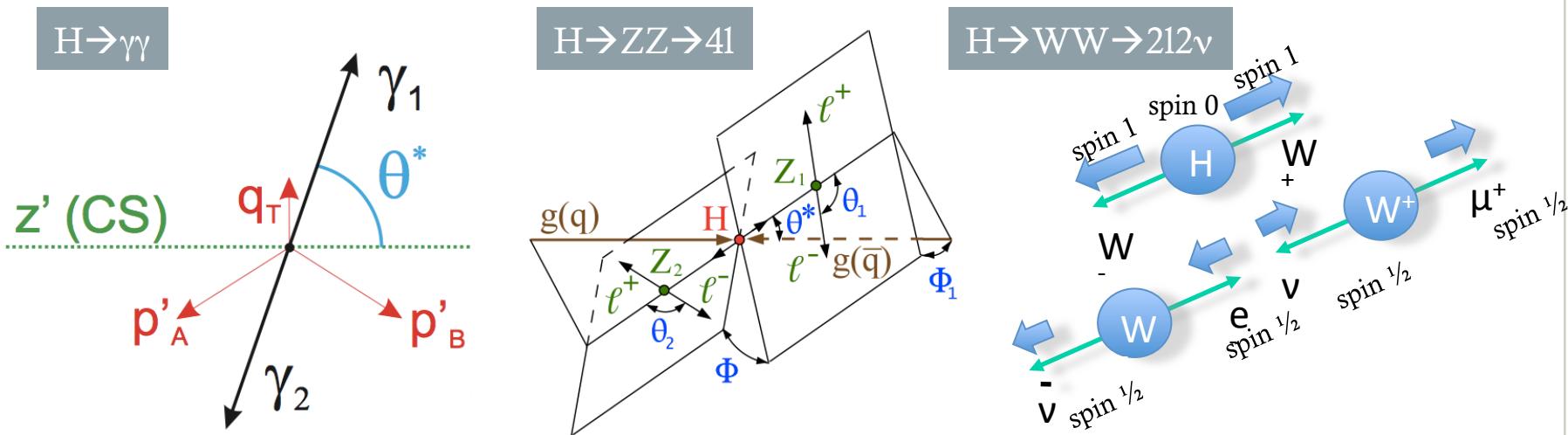
Backup Slides

Production cross sections and decay rates



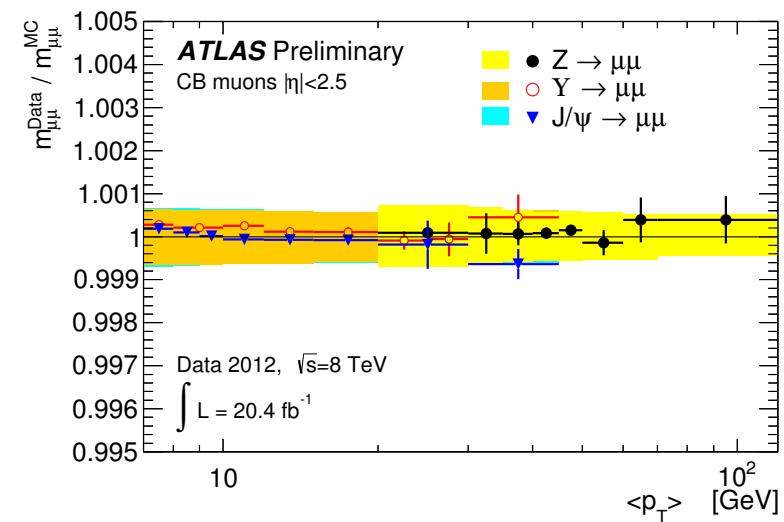
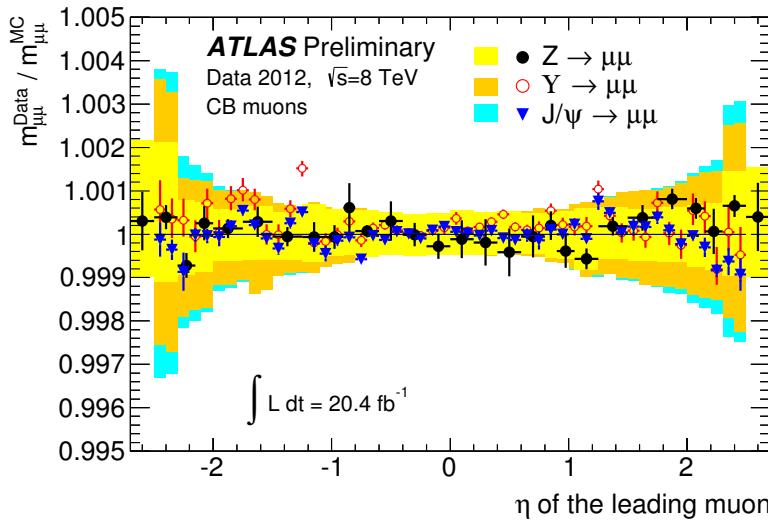
Spin and CP Analysis

- The SM Higgs boson is scalar and CP-even: $J^{CP}=0^{++}$
- Observation of the $H \rightarrow \gamma\gamma$ decay excludes spin-1 state through the Landau-Yang theorem:
Massive particle with spin J, mass M, momentum p decaying to 2γ (helicities λ_i with $|\lambda_1 - \lambda_2| \leq J$):
 $|\Phi\rangle = |p, J, M, \lambda_1, \lambda_2\rangle + (-1)^J |p, J, M, \lambda_1, \lambda_2\rangle$. For $J=1$, $\lambda_1=\lambda_2$ so $|\Phi\rangle=0$
- Measure angular distributions to discriminate between different spin and CP hypotheses and check the compatibility with SM expectation.



New ATLAS mass measurement

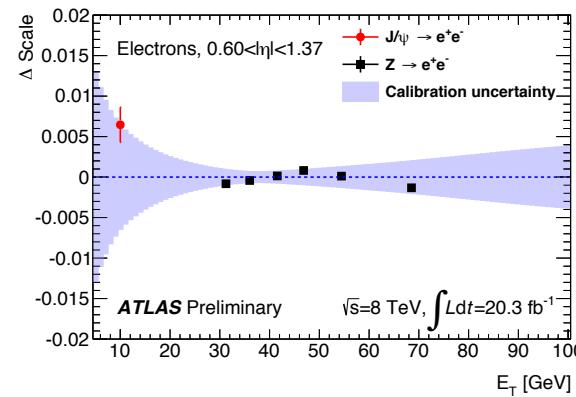
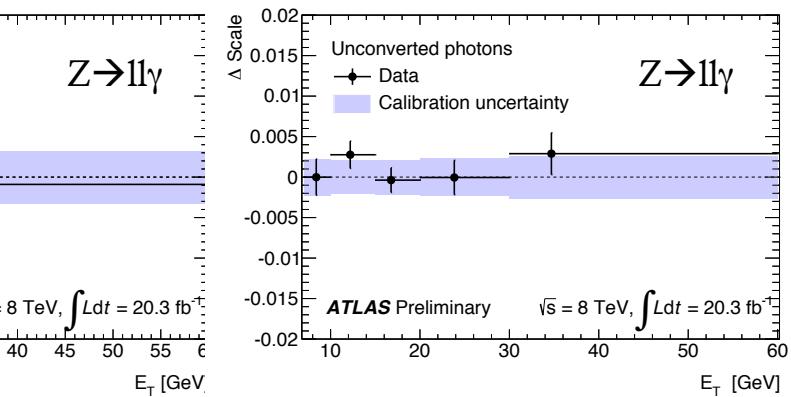
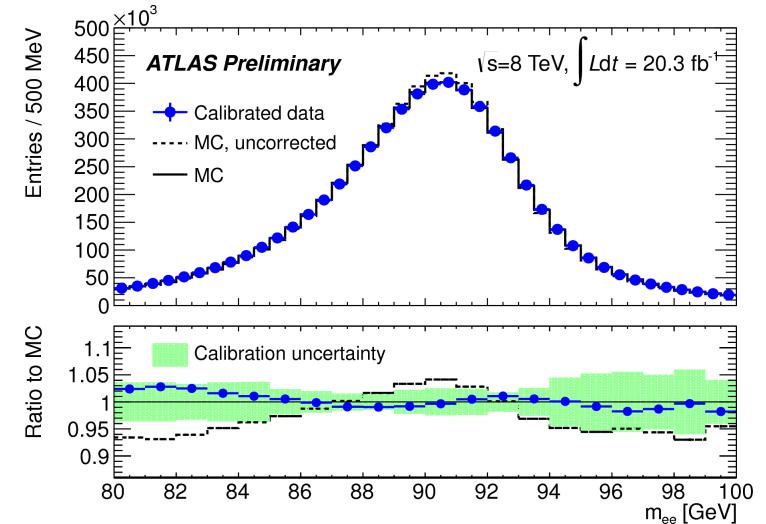
- Performed on 2011 (7TeV) and 2012 (8 TeV) data using $H \rightarrow ZZ \rightarrow 4\mu, 2e2\mu, 4e$ and $H \rightarrow \gamma\gamma$ (arXiv:1406.3827)
- **muon energy scale and resolution** extracted from $Z \rightarrow \mu\mu$ (9M) and $J/\psi \rightarrow \mu\mu$ (6M, **new!**) with p_T in \sim 6-100 GeV. Checked with Z (9M), J/ψ (17M), and Y (5M)



- systematic uncertainties vary from 0.04% @ $|\eta| \sim 0$ to 0.2% @ $|\eta| > 2.0$

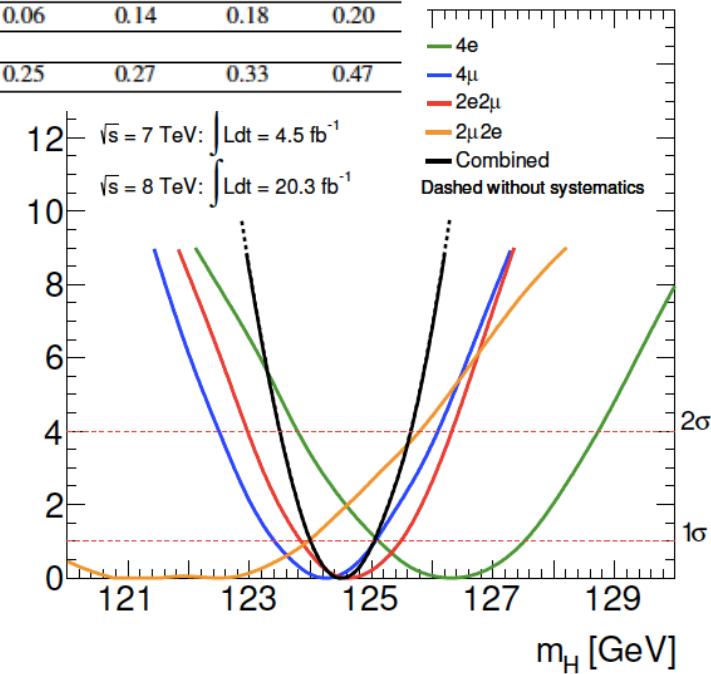
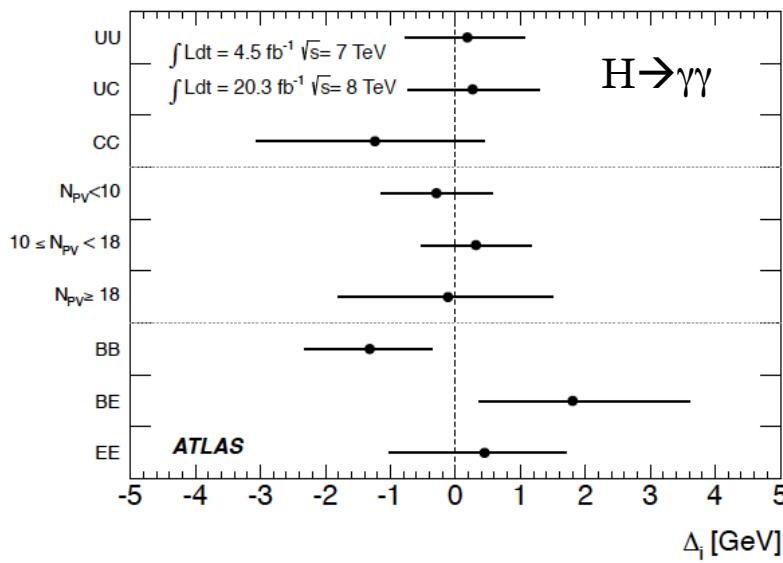
New ATLAS mass measurement: e/γ calibration

- Calibrate EM cluster energy on MC
- Electron energy scale derived from data/MC comparison of 7M $Z \rightarrow ee$ events.
- Check energy scales on $J/\psi \rightarrow ee$ and $Z \rightarrow ll\gamma$
- Improved performance thanks to:
 - new MVA-based calibration
→ 10% improvement on $\sigma(m_{H \rightarrow \gamma\gamma})$
 - better material description
 - better simulation
 - larger $Z \rightarrow ee$ sample



New ATLAS mass measurement

Class	$H \rightarrow \gamma\gamma$	Unconverted								Converted							
		Central				Rest		Trans.	Central				Rest		Trans.		
		low p_T	high p_T	low p_T	high p_T	low p_T	high p_T	low p_T	high p_T	low p_T	high p_T	low p_T	high p_T	low p_T	high p_T		
$Z \rightarrow e^+e^-$ calibration		0.02	0.03	0.04	0.04	0.11	0.02	0.02	0.05	0.05	0.05	0.11					
LAr cell non-linearity		0.12	0.19	0.09	0.16	0.39	0.09	0.19	0.06	0.14	0.29						
Layer calibration		0.13	0.16	0.11	0.13	0.13	0.07	0.10	0.05	0.07	0.07	0.07					
ID material		0.06	0.06	0.08	0.08	0.10	0.05	0.05	0.06	0.06	0.06	0.06					
Other material		0.07	0.08	0.14	0.15	0.35	0.04	0.04	0.07	0.08	0.08	0.20					
Conversion reconstruction		0.02	0.02	0.03	0.03	0.05	0.03	0.02	0.05	0.04	0.04	0.06					
Lateral shower shape		0.04	0.04	0.07	0.07	0.06	0.09	0.09	0.18	0.19	0.19	0.16					
Background modeling		0.10	0.06	0.05	0.11	0.16	0.13	0.06	0.14	0.18	0.18	0.20					
Vertex measurement						0.03											
Total		0.23	0.28	0.24	0.30	0.59	0.21	0.25	0.27	0.33	0.47						



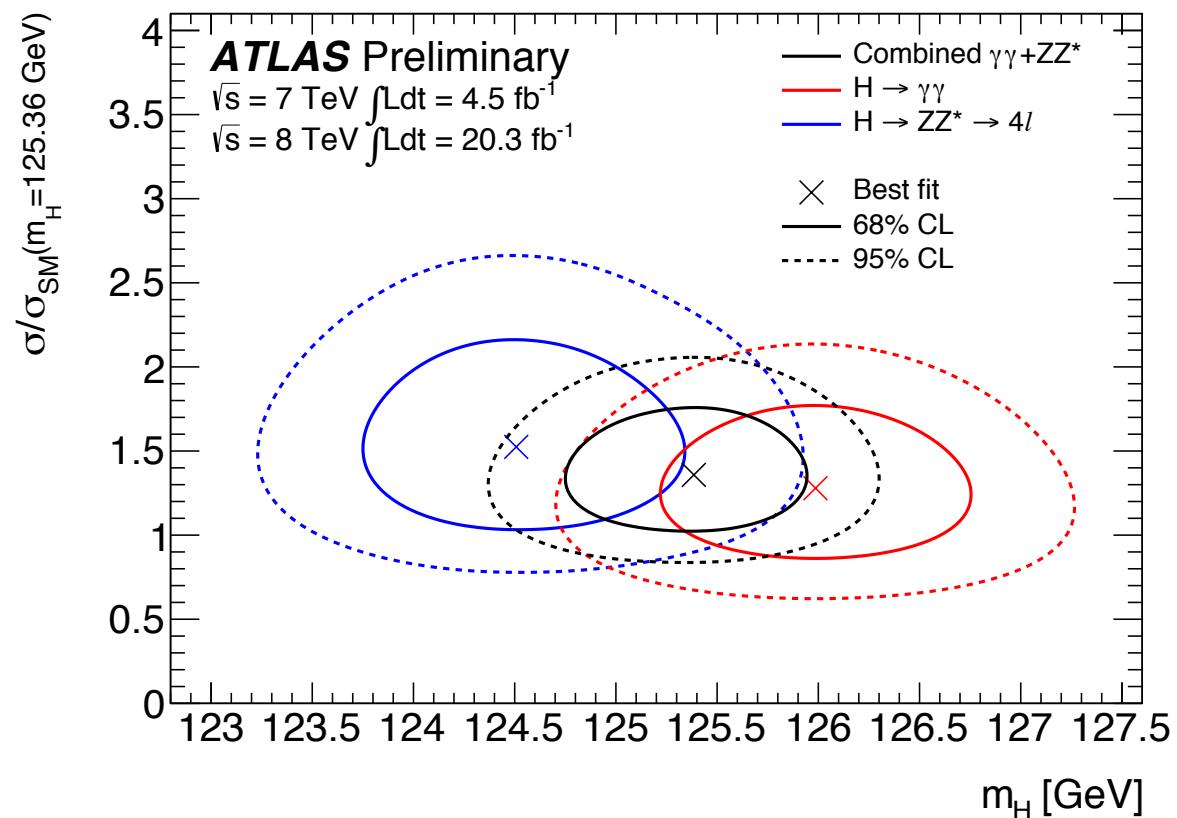
New ATLAS mass measurement

Table 4: Principal systematic uncertainties on the combined mass. Each uncertainty is determined from the change in the 68% CL range for m_H when the corresponding nuisance parameter is removed (fixed to its best fit value), and is calculated by subtracting this reduced uncertainty from the original uncertainty in quadrature.

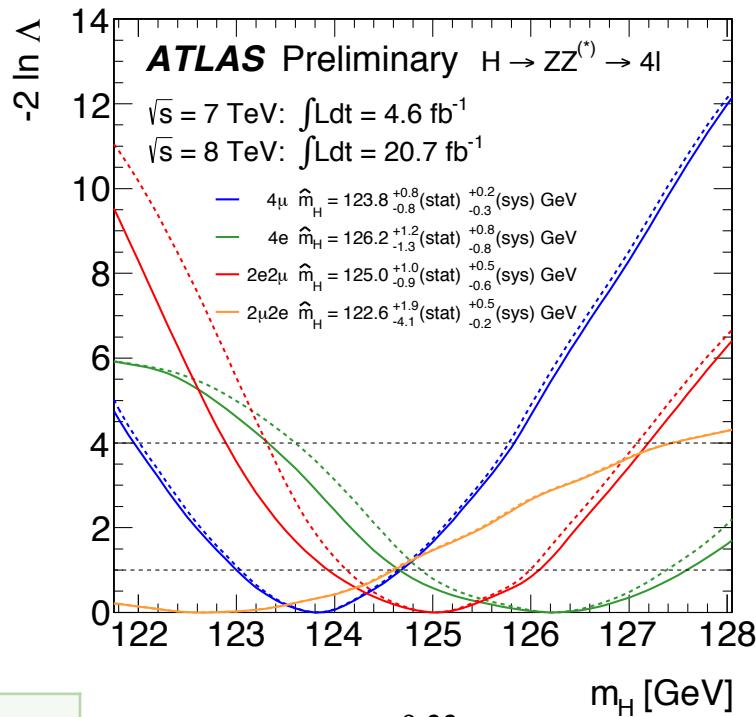
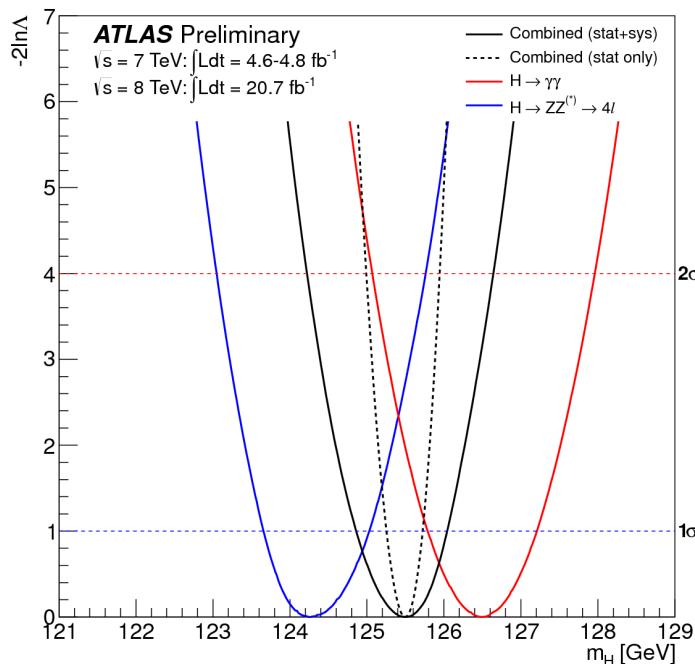
Systematic	Uncertainty on m_H [MeV]
LAr syst on material before presampler (barrel)	70
LAr syst on material after presampler (barrel)	20
LAr cell non-linearity (layer 2)	60
LAr cell non-linearity (layer 1)	30
LAr layer calibration (barrel)	50
Lateral shower shape (conv)	50
Lateral shower shape (unconv)	40
Presampler energy scale (barrel)	20
ID material model ($ \eta < 1.1$)	50
$H \rightarrow \gamma\gamma$ background model (unconv rest low p_{Tt})	40
$Z \rightarrow ee$ calibration	50
Primary vertex effect on mass scale	20
Muon momentum scale	10
Remaining systematic uncertainties	70
Total	180

New ATLAS mass measurement

$$\begin{aligned}\mu_{\gamma\gamma} &= 1.29 \pm 0.30 \\ \mu_{ZZ} &= 1.66^{+0.45}_{-0.38}\end{aligned}$$



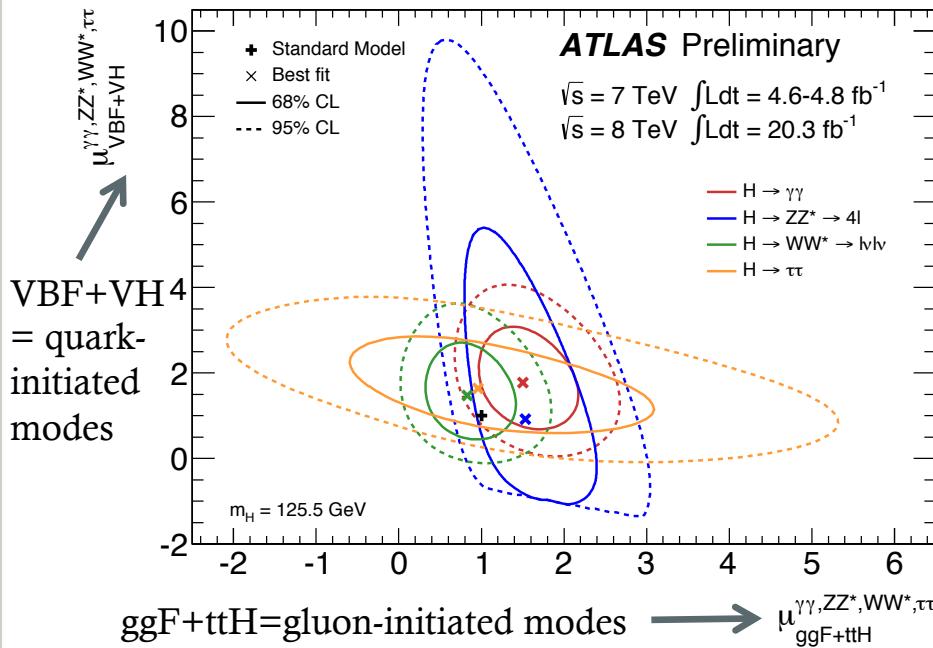
Previous ATLAS mass measurement



$H \rightarrow \gamma\gamma$	$126.8 \pm 0.2 \pm 0.7 \text{ GeV}$
$H \rightarrow 4l$	$124.3^{+0.6}_{-0.5} {}^{+0.5}_{-0.3} \text{ GeV}$
combined	$125.5 \pm 0.2 {}^{+0.5}_{-0.6} \text{ GeV}$

$$\begin{aligned}\mu_{\gamma\gamma} &= 1.57^{+0.33}_{-0.28} \\ \mu_{ZZ} &= 1.66^{+0.40}_{-0.35}\end{aligned}$$

Probing the Higgs production modes



Production via Vector Boson Fusion:

- $\mu_{VBF}/\mu_{ggF+ttH} = 1.4^{+0.5}_{-0.4}(\text{stat})^{+0.4}_{-0.3}(\text{syst})$
- 4.1σ evidence

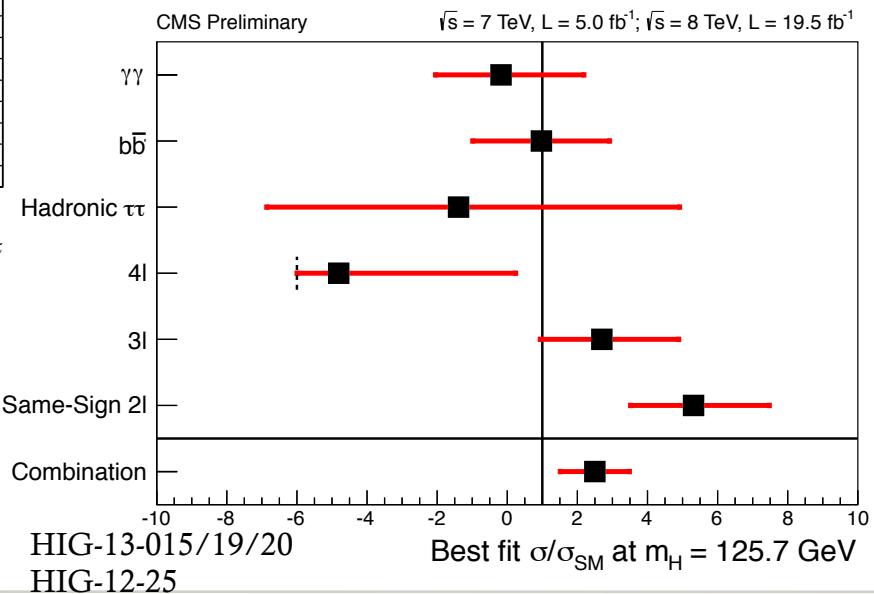
ATLAS-CONF-2014-009

Probe ttH production by exploring all accessible H decay modes

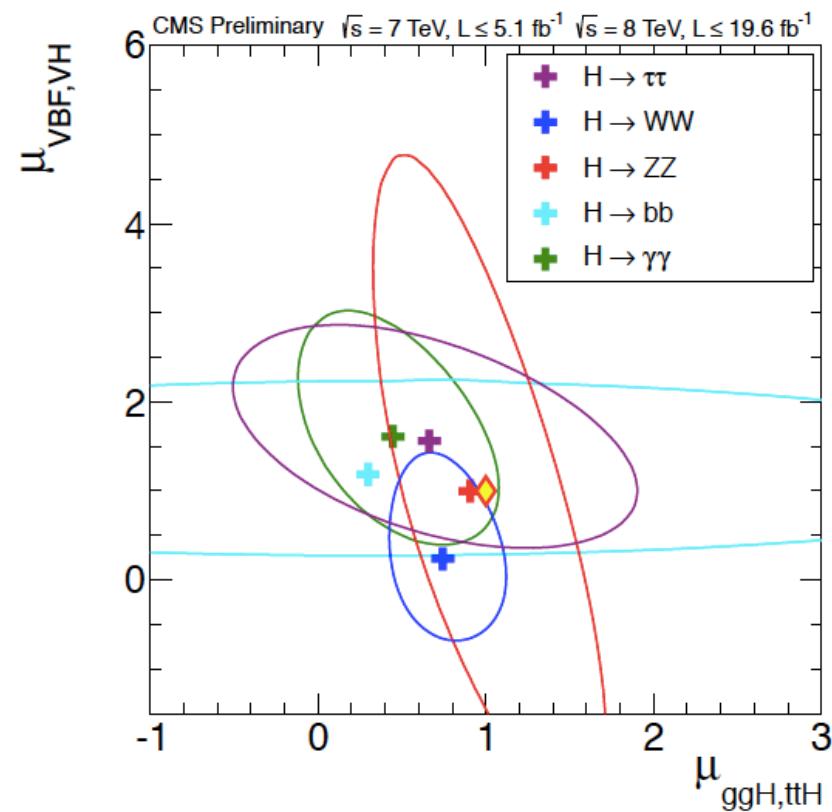
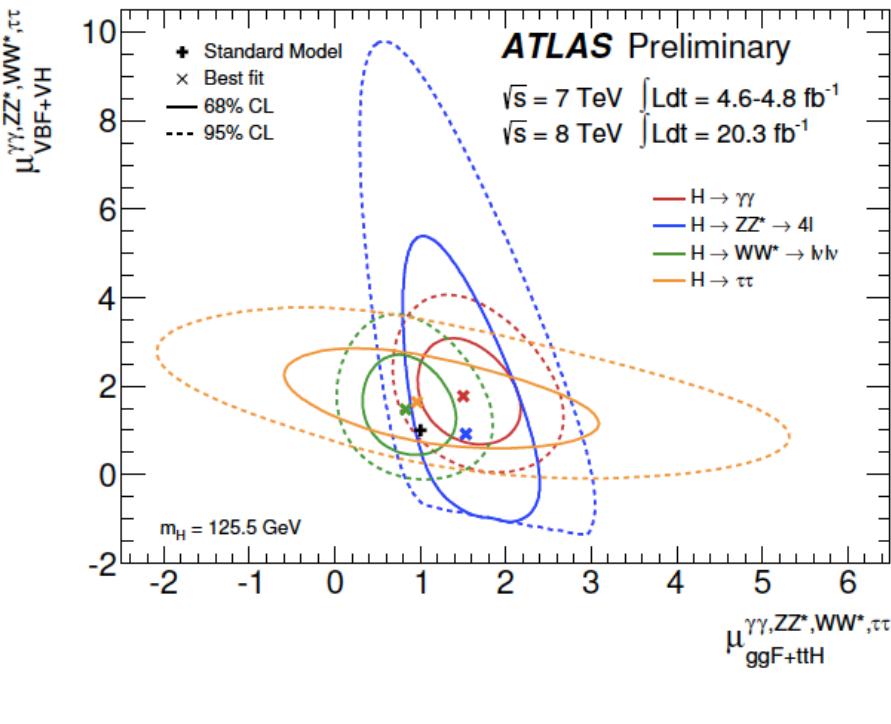
Combined result:

$$\mu = 1.4^{+1.1}_{-1.0}$$

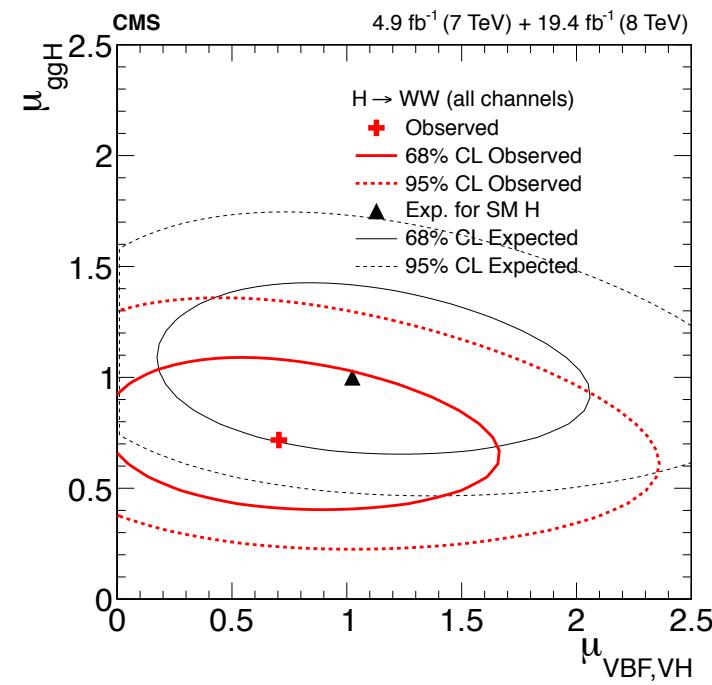
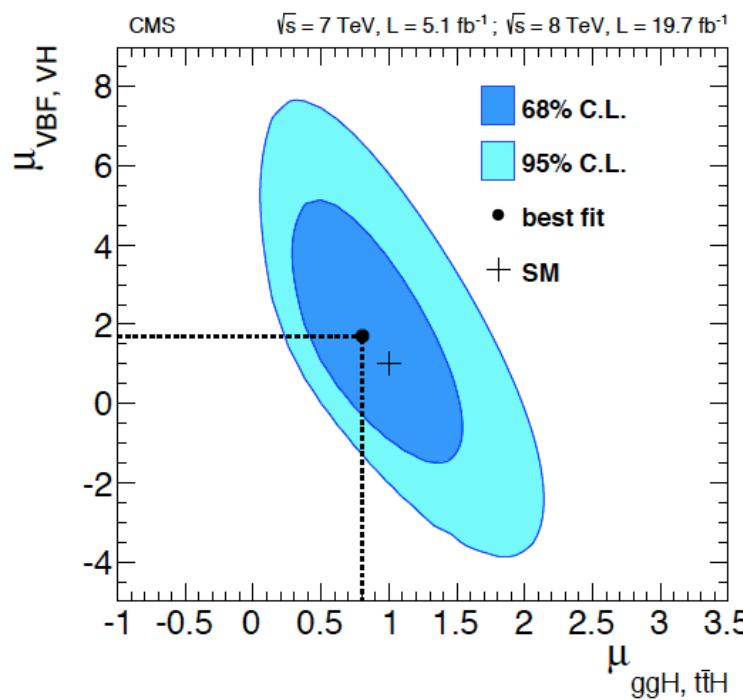
$\sim 5 \times$ more ttH events at run-2
for the same lumi (according to SM)



Production rates



Production rates



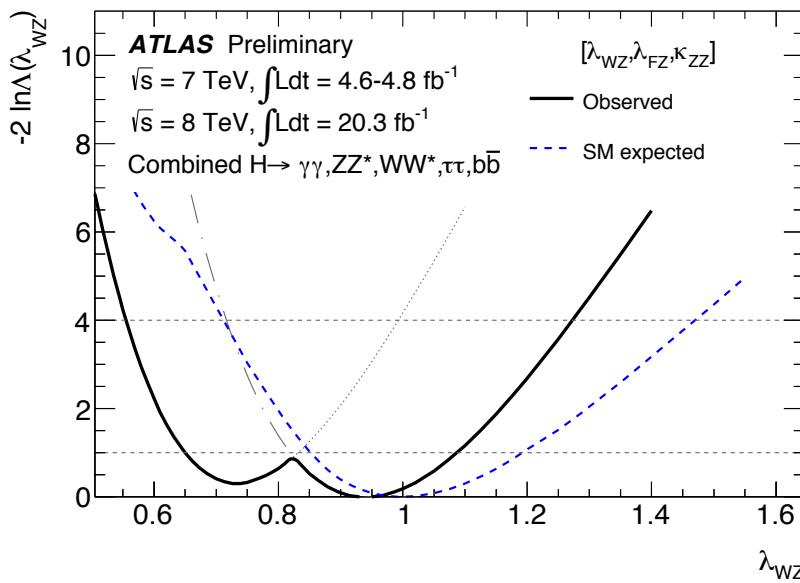
Test of custodial symmetry

Couplings to W and Z are protected against large radiative corrections in the SM by SU(2) custodial symmetry: $\lambda_{WZ} = \kappa_W / \kappa_Z \sim 1$

Assumptions:

- $\kappa_F = \kappa_b = \kappa_t = \kappa_\tau$
- total width is unchanged.

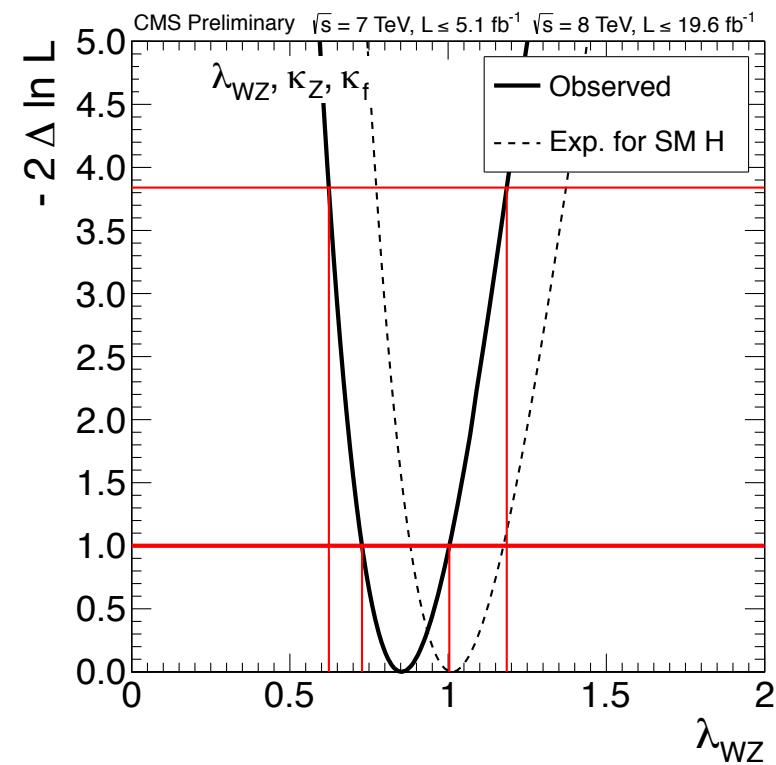
ATLAS-CONF-2014-009



$$\lambda_{WZ} = 0.94^{+0.14}_{-0.29}$$

23/06/14

37



$$\lambda_{WZ}: [0.62, 1.19] @ 68\% \text{ CL}$$

Lydia Roos (LPNHE - Paris) T2HEP, Russia

HIG-13-005

Two Higgs Doublet Models

2HDM: two Higgs doublets ϕ_1, ϕ_2 with vacuum expectation values $v_1^2 + v_2^2 = (246 \text{ GeV})^2$
 → 5 Higgs (3 neutral, 2 charged): h, H (CP-even, mixing angle α),
 A (CP-even), H^\pm

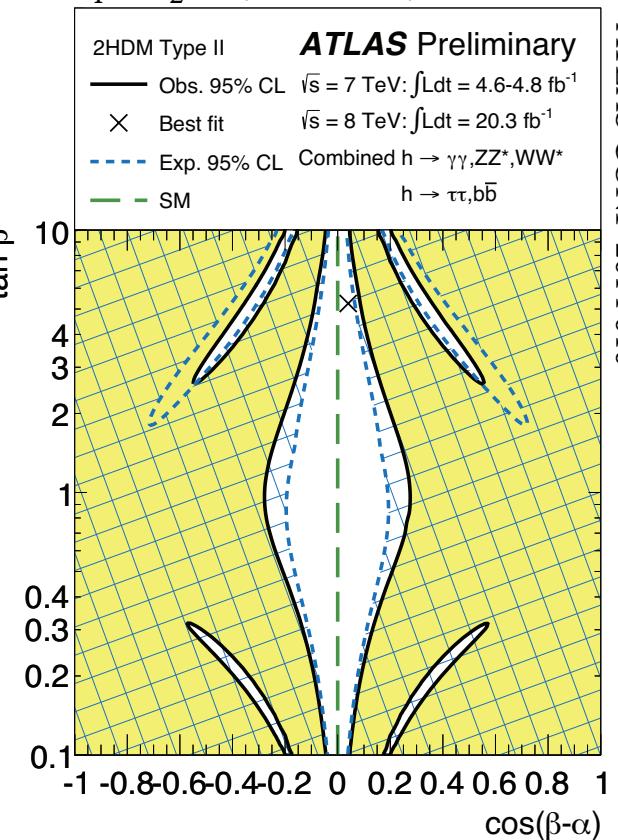
Coupling scale factors expressed in terms of α and β
 $(\tan\beta = v_1/v_2)$

Example from Type-II models in which down-type fermions couple to ϕ_1 and up-type to ϕ_2 . Assume h decay modes identical to those of SM Higgs.

scale factor	h
κ_v	$\sin(\beta - \alpha)$
κ_u	$\cos(\alpha)/\sin(\beta)$
κ_d	$-\sin(\alpha)/\cos(\beta)$
κ_l	$-\sin(\alpha)/\cos(\beta)$

Use the measured production and decay rates of the observed Higgs to constrain the parameters (type I-IV)

Data consistent with SM



Similar analyses on composite Higgs, additional electroweak singlet, Higgs portal to dark matter, ...

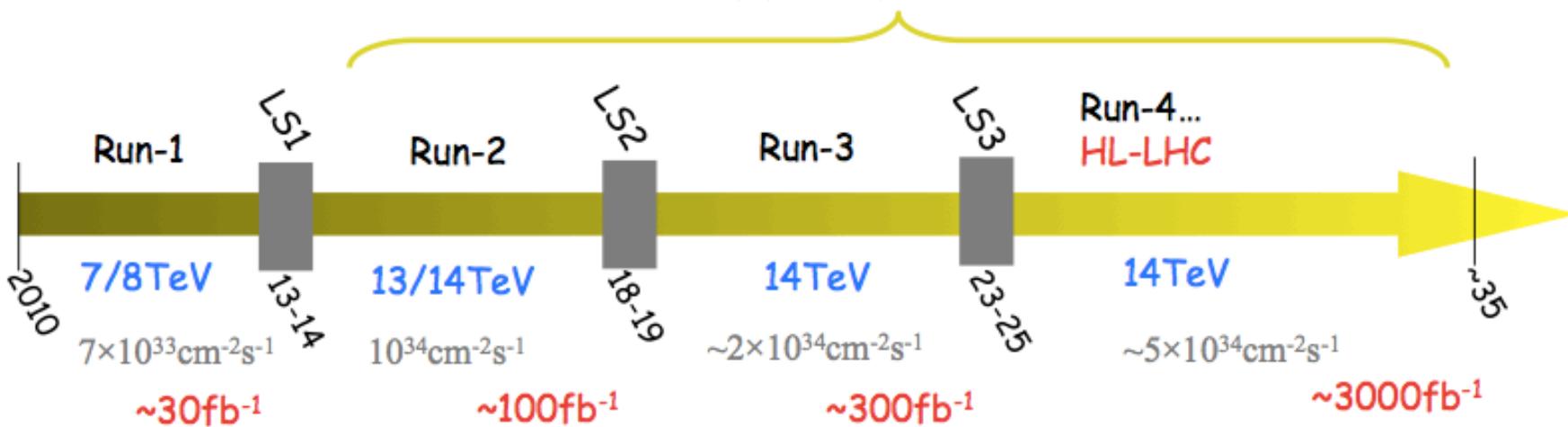
Direct search: H \rightarrow hh, A \rightarrow Zh

Final states from hh decays	Search Channels h decays populate
WW^*WW^* $WW^*\tau\tau$ $\tau\tau\tau\tau$ WW^*ZZ^* $ZZ^*\tau\tau$ ZZ^*bb	Three or four leptons (upto one τ_h), OSSF pair off-Z or no OSSF pair in bins of E_T^{miss} and b-tag
$\gamma\gamma WW^*$ $\gamma\gamma ZZ^*$ $\gamma\gamma\tau\tau$	2photons ($M_{\gamma\gamma}$ within higgs bin) + 1 or more leptons(upto 2 τ_h),in bins of E_T^{miss}

h & Z boson decays	Search Channels h & Z boson decays populate
$Z(\rightarrow ll)WW^*$ $Z(\rightarrow ll)ZZ^*$ $Z(\rightarrow ll)\tau\tau$ $qqZ(\rightarrow ll)Z^*$ $\nu\nu Z(\rightarrow ll)Z^*$	1 on-shell Z($\rightarrow ee, \mu\mu$)+ 1 or more lepton(up to 1 τ_h) in bins of E_T^{miss} & b-tag
$\gamma\gamma ll$	2 photons($M_{\gamma\gamma}$ within higgs bin)+1 or more leptons (up to 2 τ_h), in bins of E_T^{miss}

LHC Runs & Current Schedule

Exploit full physics potential @ LHC
is the top priority (CERN Council 2013)



→ LHC will run for about 20 years!

LS1: Long Shutdown 1 ongoing for increasing \sqrt{s} up to 14 TeV

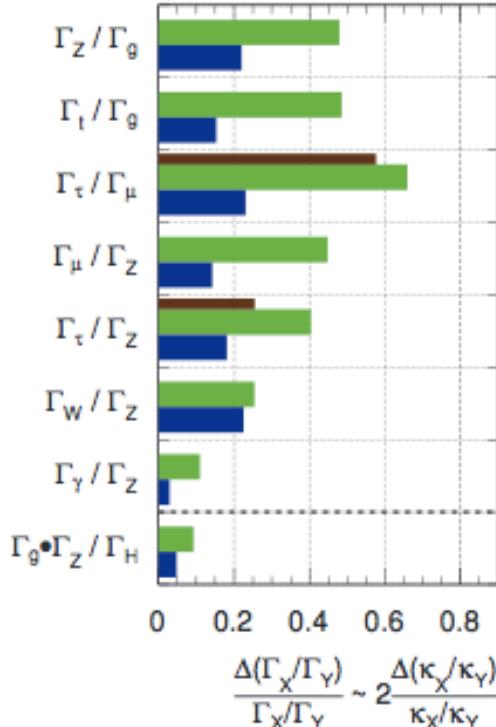
LS2: LHC injector upgrades; phase-1 detector upgrade

LS3: Major intervention on more than 1.2km for **HL-LHC** (High Luminosity LHC);
phase-2 detector upgrade

5. High Luminosity LHC (HL-LHC)

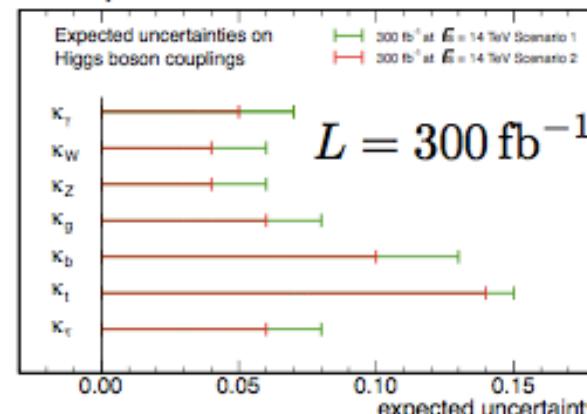
- ECFA HL-LHC with $L=300 \text{ fb}^{-1}$ (3 ab^{-1}) physics study.
- Higgs mass precision $\Delta M_H \sim 100$ (50) MeV.
- Access to top-Yukawa coupling via $t\bar{t}H$, and rare decay $H \rightarrow \mu\mu$.
- Coupling precision of 10 to 5% reachable (even few% in κ_y/κ_z).
- Detector performances (trigger, lepton-id, fake, τ/b -id) are crucial.
- Theory uncertainty dominates - challenge for theorists!

ATLAS-PHYS-PUB-2013-007

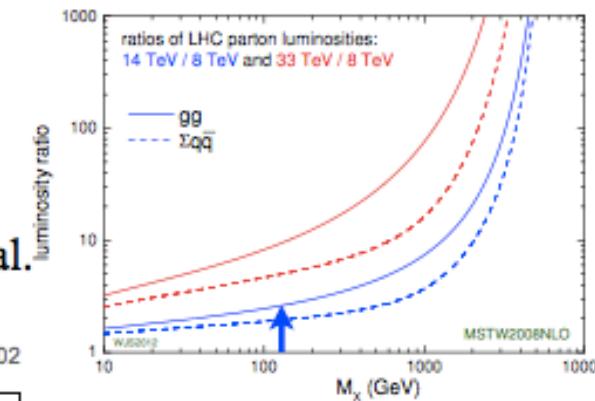
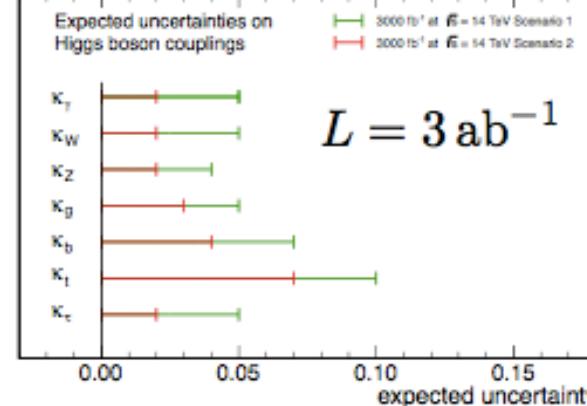
ATLAS Simulation $\sqrt{s} = 14 \text{ TeV}: \int L dt = 300 \text{ fb}^{-1}; \int L dt = 3000 \text{ fb}^{-1}$ $\int L dt = 300 \text{ fb}^{-1}$ extrapolated from 7+8 TeV

CMS Projection

CMS NOTE-13-002



CMS Projection



	$\sigma(14\text{TeV})/\sigma(8\text{TeV})$
$gg \rightarrow H$	2.6 ($M_x = M_H$)
$qq \rightarrow qqH$	2.6 (probes high M_x)
$qq \rightarrow VH$	2.1 ($M_x = M_V + M_H$)
$gg \rightarrow ttH$	4.7 (phase space+ M_x)

Scenario 1

current systematic uncert.

Scenario 2

theory uncert. $\searrow 1/2$ other systematics $\searrow 1/\sqrt{L}$

Future of Higgs coupling measurements at LHC

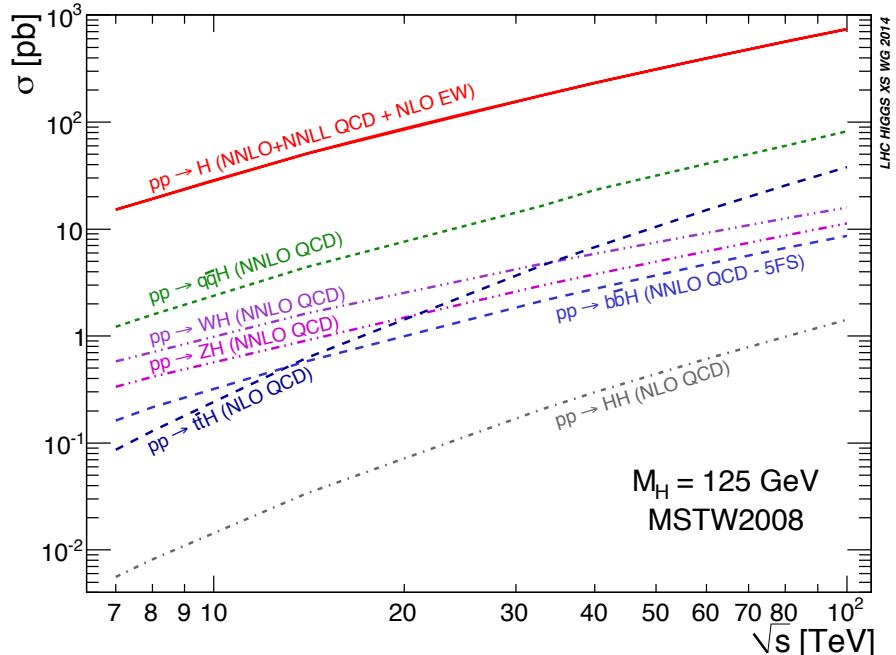
Expected deviations

Snowmass, Higgs, 1310.8361

Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3 - 9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

$$\frac{\delta g_{\text{HXX}}}{g_{\text{HXX}}^{\text{SM}}} \leq 5\% \times \left(\frac{1\text{TeV}}{\Lambda} \right)^2$$

up to 20% on HHH



First evidence for Higgs self-coupling
at HL-LHC?

Mass, width and couplings at future colliders

Snowmass, Higgs, 1310.8361

Facility	LHC	HL-LHC	ILC500	CLIC	TLEP (4 IPs)
\sqrt{s} (GeV)	14,000	14,000	250/500	350/1400/3000	240/350
$\int \mathcal{L} dt$ (fb $^{-1}$)	300/expt	3000/expt	250+500	500+1500+2000	10,000+2600
κ_γ	5 – 7%	2 – 5%	8.3%	–/5.5/<5.5%	1.45%
κ_g	6 – 8%	3 – 5%	2.0%	3.6/0.79/0.56%	0.79%
κ_W	4 – 6%	2 – 5%	0.39%	1.5/0.15/0.11%	0.10%
κ_Z	4 – 6%	2 – 4%	0.49%	0.49/0.33/0.24%	0.05%
κ_ℓ	6 – 8%	2 – 5%	1.9%	3.5/1.4/<1.3%	0.51%
$\kappa_d = \kappa_b$	10 – 13%	4 – 7%	0.93%	1.7/0.32/0.19%	0.39%
$\kappa_u = \kappa_t$	14 – 15%	7 – 10%	2.5%	3.1/1.0/0.7%	0.69%

Facility	LHC	HL-LHC	ILC500	CLIC	TLEP (4 IP)	μ C
\sqrt{s} (GeV)	14,000	14,000	250/500	350/1400/3000	240/350	126
$\int \mathcal{L} dt$ (fb $^{-1}$)	300	3000	250+500	500+1500+2000	10,000+2600	4.2
m_H (MeV)	100	50	32	33	7	0.06
Γ_H	–	–	5.0%	8.4%	1.0%	4.3%