Higgs Physics at the LHC

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Outline

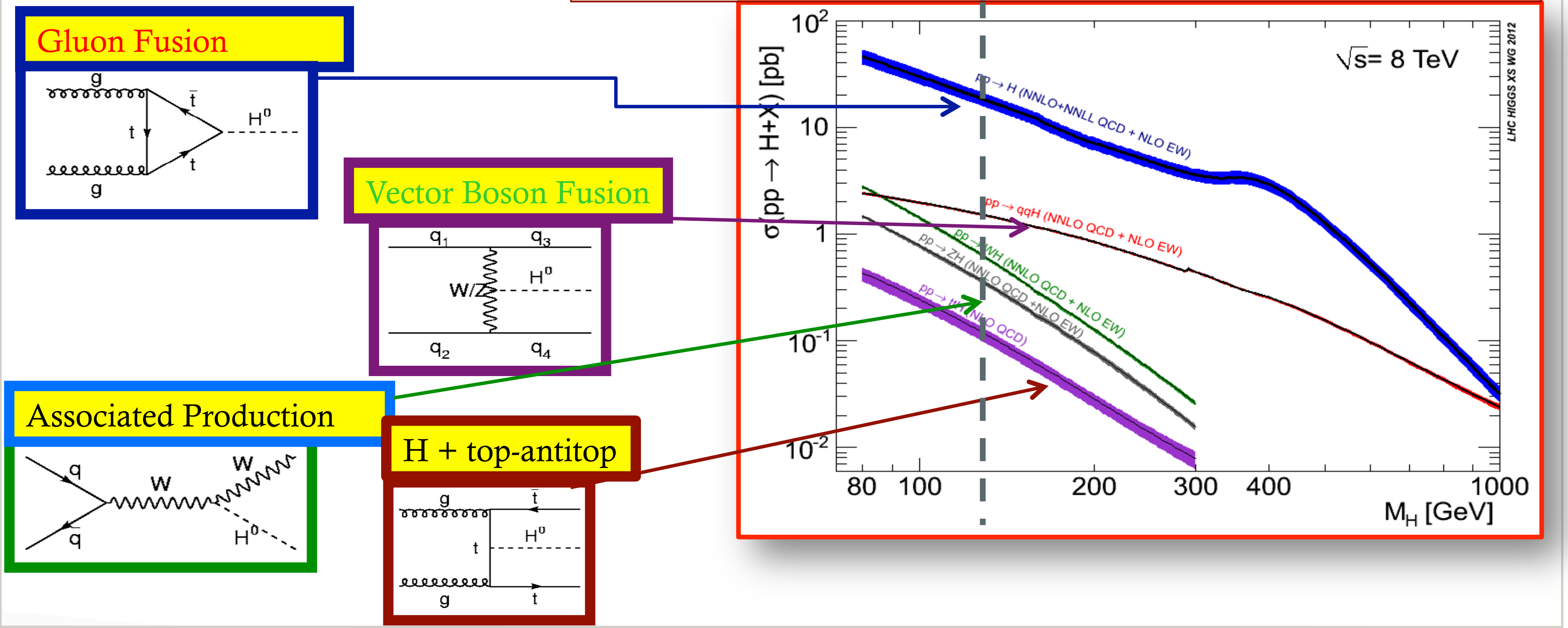
- Introduction: Higgs phenomenology at the LHC
- Introduction: LHC: 2012-2013 Run1 dataset
- Higgs signals observed in Run1
- Higgs properties from Run1
  - Mass
  - Width
  - Spin/CP
  - Couplings
- BSM Higgs: a short summary of the searches done
- Run2 and prospects in future LHC runs

ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults
CMS: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG

Higgs phenomenology at the LHC – production

The Higgs boson phenomenology at LHC is completely fixed if m_H is known
Theory uncertainties up to O(10%) (mostly QCD scale and PDFs knowledge)

Cross Section (pp→ H+X) vs. m_H (according to SM)



Gluon Fusion

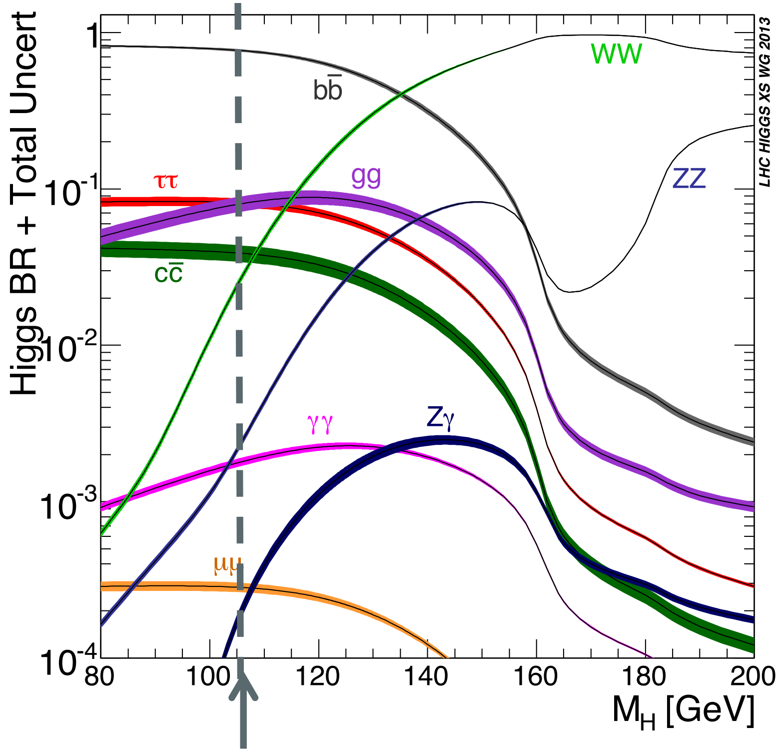
Vector Boson Fusion

Associated Production

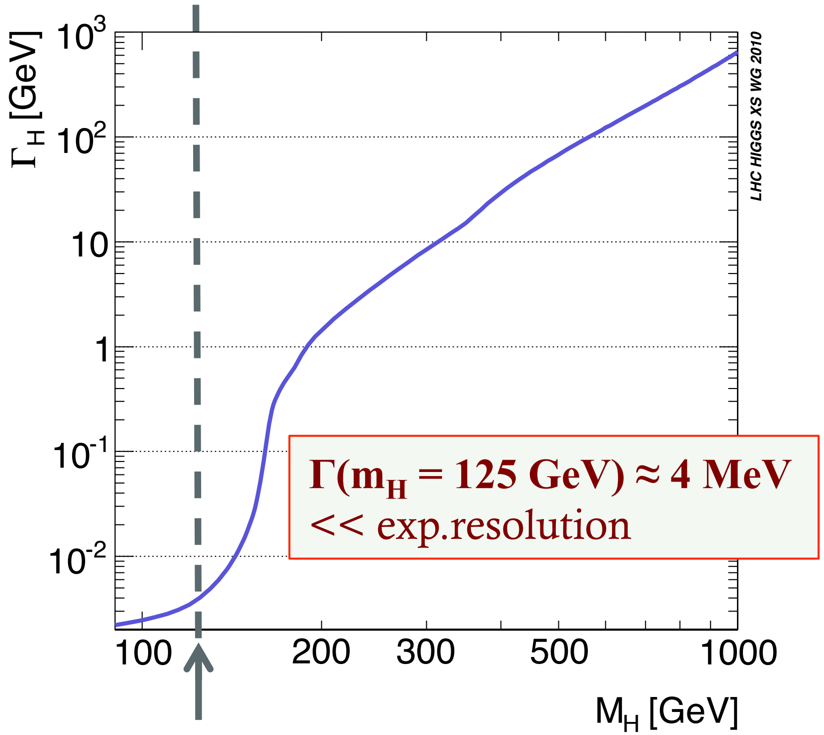
H + top-antitop

Higgs phenomenology at the LHC – decay

Higgs decays: branching ratios and decay width (according to SM)
Lower theoretical uncertainties (2 ÷ 5) % for most relevant decays



m_H = 125 GeV



Γ(m_H = 125 GeV) ≈ 4 MeV
<< exp.resolution

m_H = 125 GeV

Higgs physics at LHC – general strategy of the experiments

- General strategy:
  - *Di-boson channels* ($\gamma\gamma$, ZZ→4l, WW→ $l\nu l\nu$)➔ first observation, mass measurement, signal strength, spin/CP, width assessment;
  - *Di-fermion channels* ($\tau\tau$, bb) ➔ observation, signal strength;
  - *Overall fit* to check compatibility with SM coupling pattern;
  - *ATLAS + CMS combinations* (mass first then couplings).

- NB: All results are based on the full Run1 dataset after a careful re-analysis including the best understanding of the detectors.

- Some "Terminology":
  - μ is the signal strength $\mu = \sigma/\sigma_{SM}$: $\mu = 1$ SM ok, $\mu \neq 1$ → BSM!
  - κ is a coupling modifier $\kappa = g/g_{SM}$; …
  - Results on μ are given as central values and/or upper limits or significance
  - limits [obs. (exp.)] are given at 95% CL using the CL_s prescription.

LHC: 2011-2012 run1 dataset

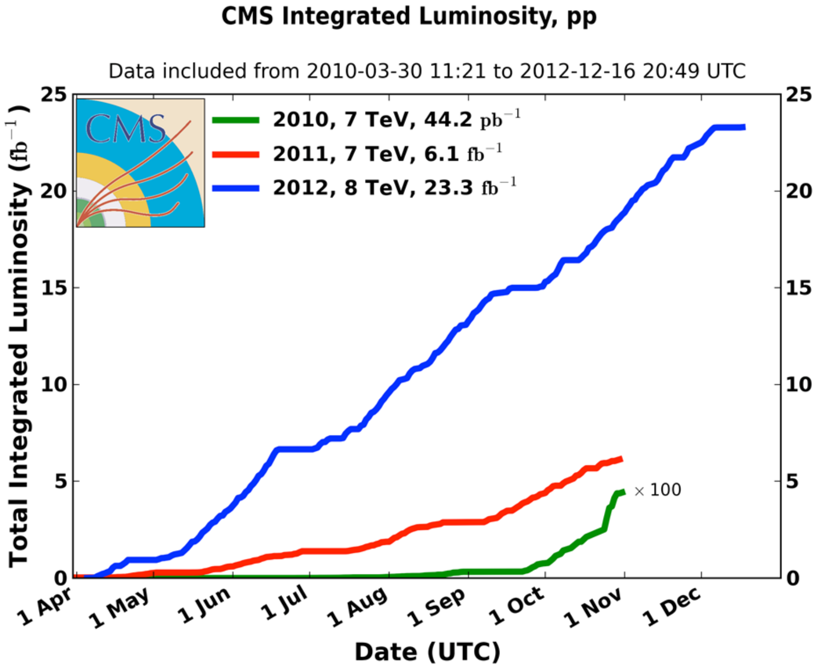
2011-2012 dataset: pp collisions

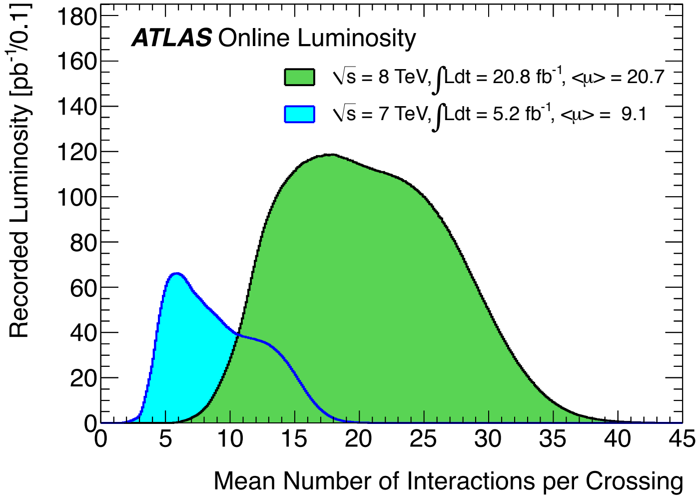
→ C.o.M. energy = 7 TeV (2011), 8 TeV (2012)

→ Max luminosity = 7 × 10^{33} $cm^{-2}s^{-1}$

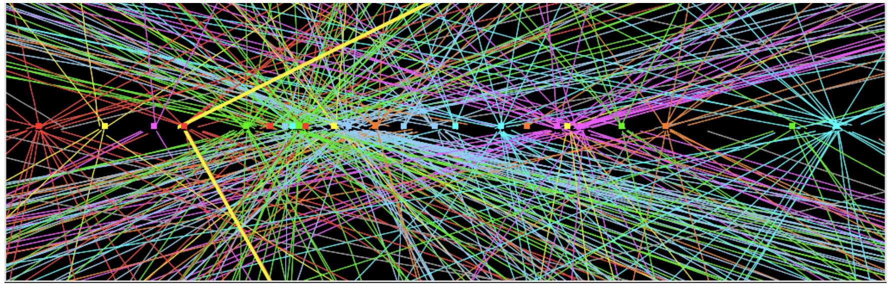
→ Int. Luminosity ≈ 5 fb^{-1} (2011), ≈ 20 fb^{-1} (2012)

→ Interbunch distance = 50 ns ➔ $<n_{int}>$= 9÷21





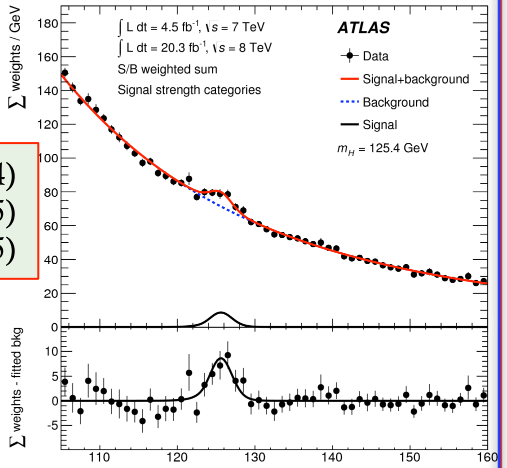
Event with 20 interactions: well reconstructed

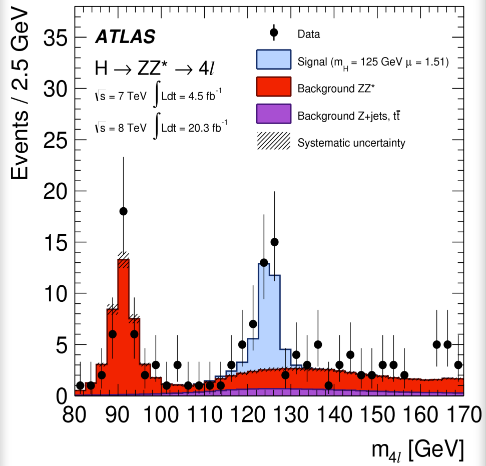


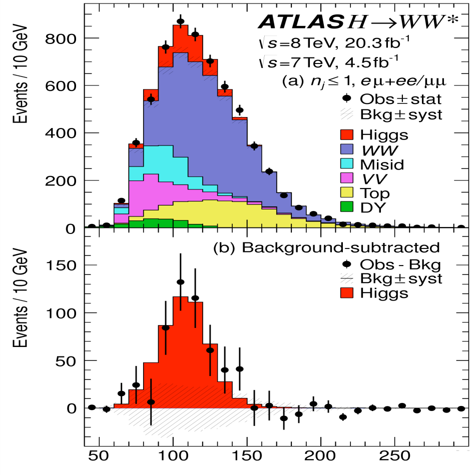
Higgs signals
the di-bosons discovery channels

ATLAS

PRD90,112015(2014)
PRD91,012006(2015)
PRD92,012006(2015)

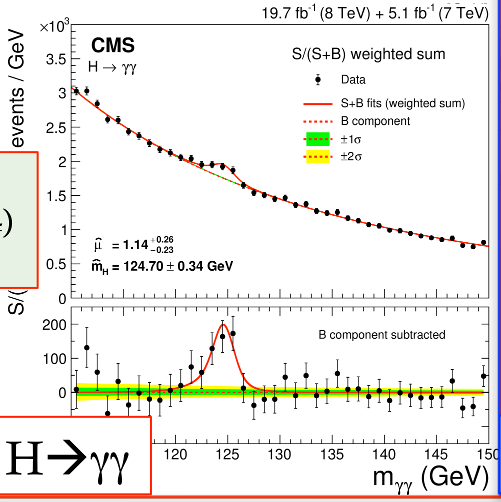


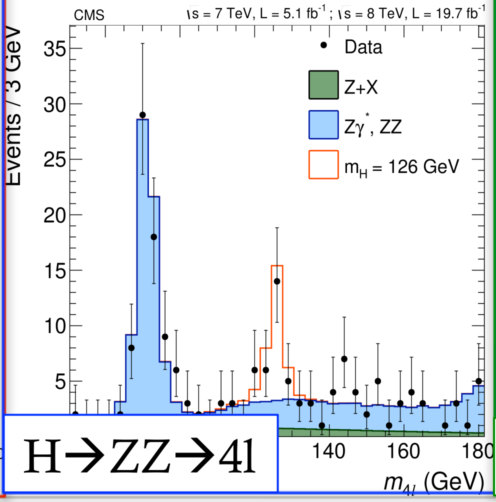


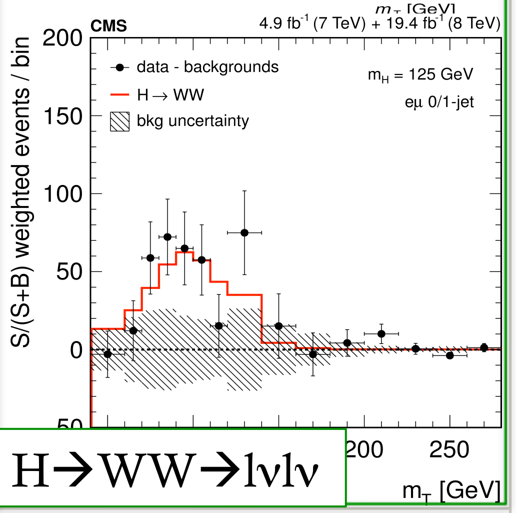


CMS

EPJC74,3076(2014)
PRD89,092007(2014)
JHEP01,096(2014)







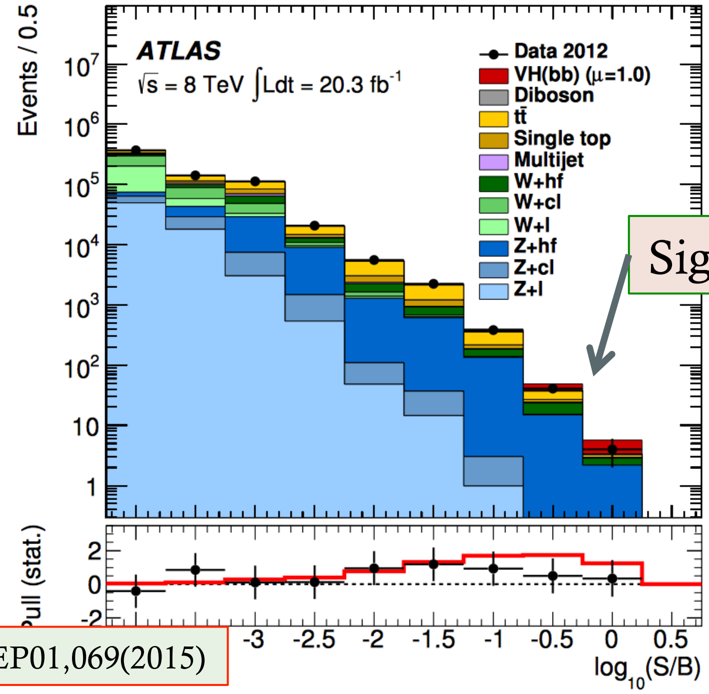
H→γγ

H→ZZ→4l

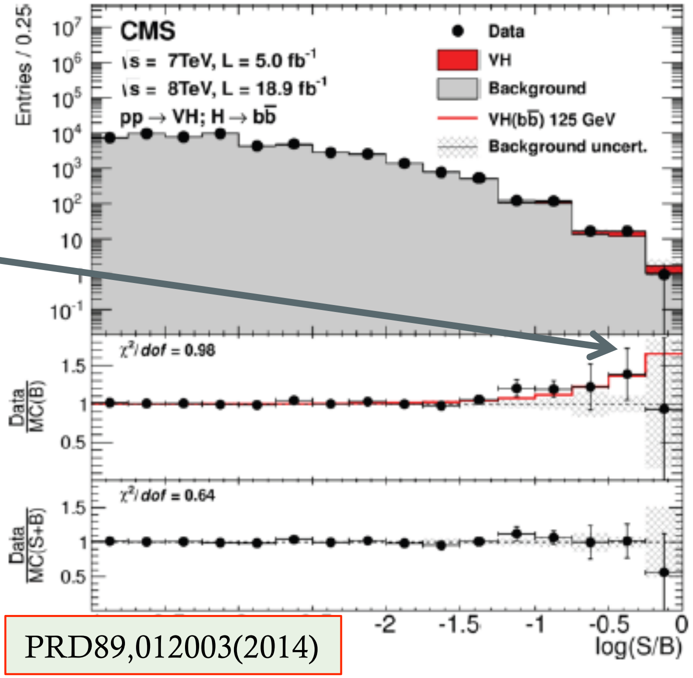
H→WW→lνlν

Higgs signals
the fermionic channels: the b-bbar

H→ bb: searched in association with a vector boson (W or Z) to reduce the huge background from QCD



Signal



JHEP01,069(2015)

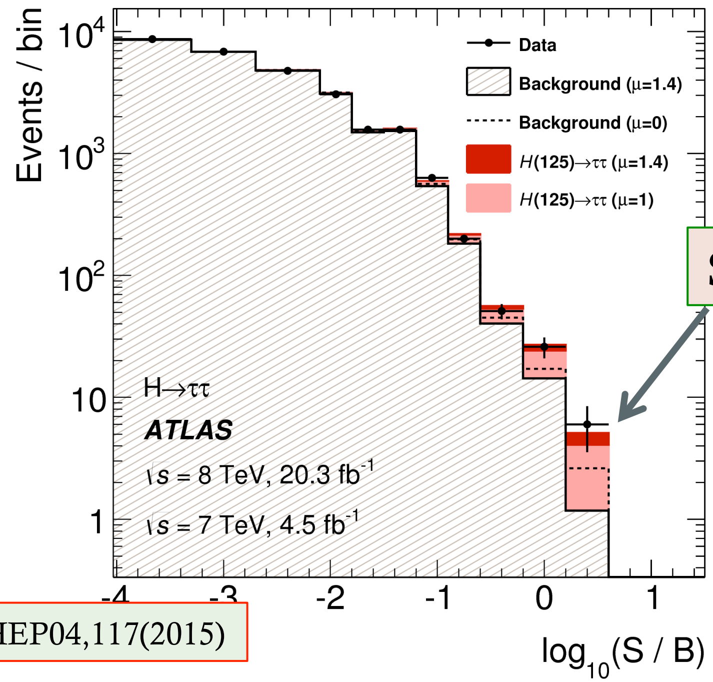
PRD89,012003(2014)

Very difficult analysis: ATLAS: μ = 0.52± 0.32±0.24 signif. =1.4σ (2.6σ)

CMS: μ = 1.0 ± 0.4 signif. = 2.6σ (2.7σ)

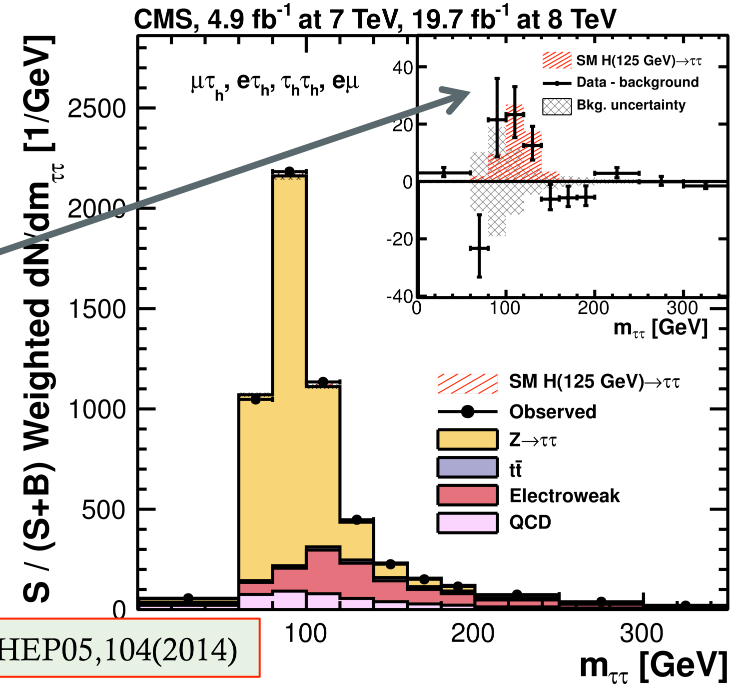
Higgs signals
the fermionic channels: the ττ

H→ ττ: to enhance sensitivity different categories are used: [VBF, VH, ggF enriched]



JHEP04,117(2015)

Signal



JHEP05,104(2014)

Results: ATLAS: $\mu = 1.43^{+0.43}_{-0.37}$ signif. = 4.5σ (3.4σ)

CMS: $\mu = 0.78 \pm 0.27$ signif. = 3.2σ (3.7σ)

Evidence of Higgs direct decay to fermions (CMS)

CMS published a combined **bb and ττ analysis** to evaluate the significance of the Higgs direct decay to fermion pairs signal.

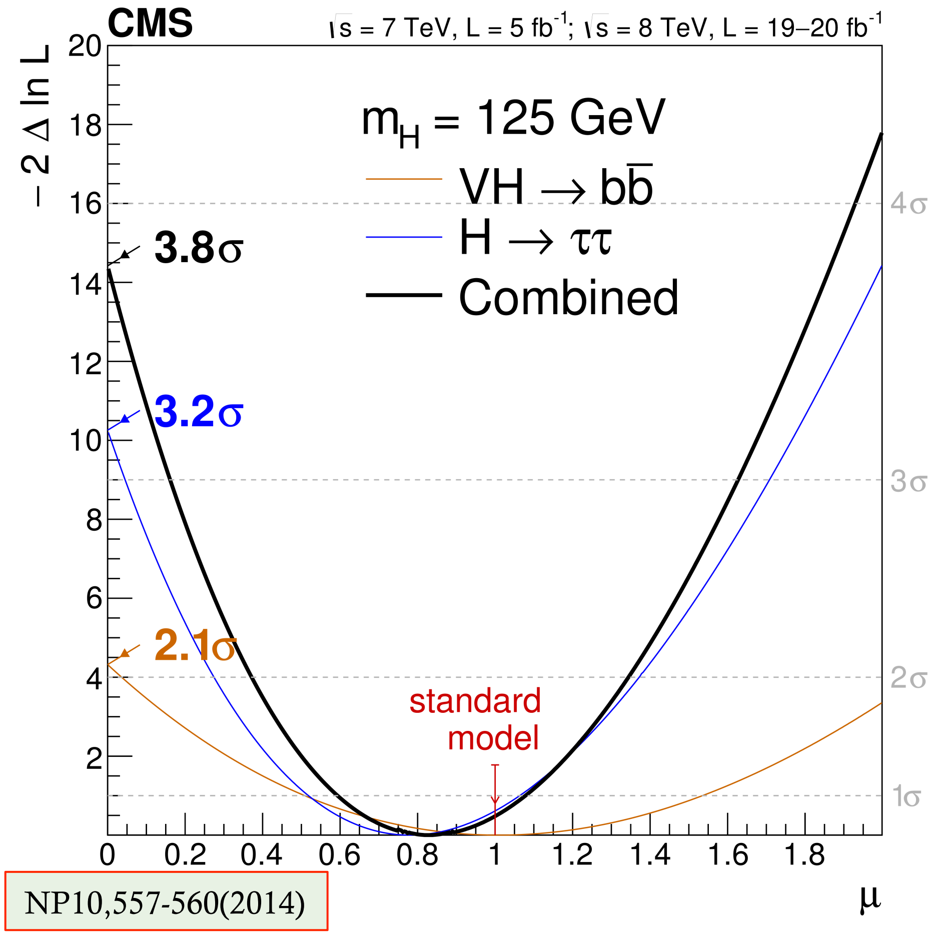
Signal significativity:

observed = 3.8 st.dev.

expected = 4.4 st.dev.

Central value:

$\mu = 0.83 \pm 0.24$

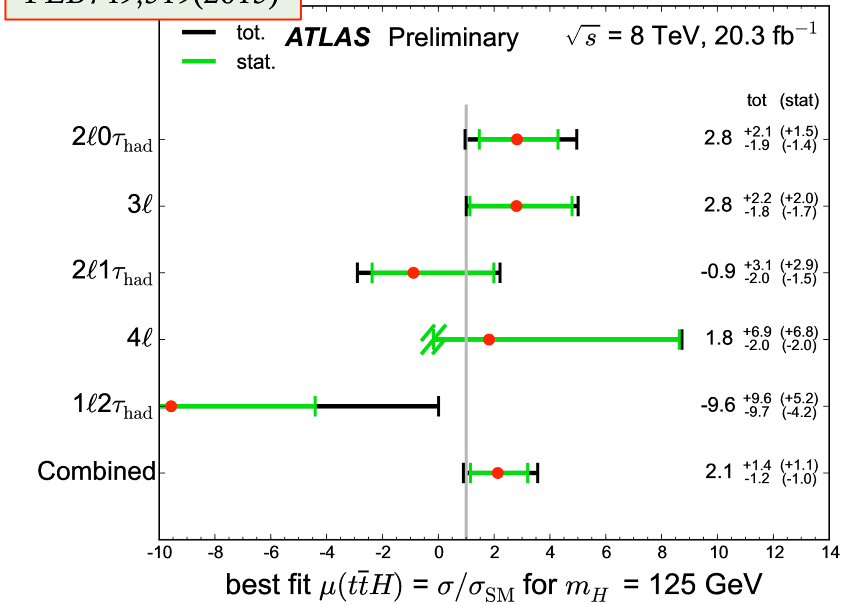


NP10,557-560(2014)

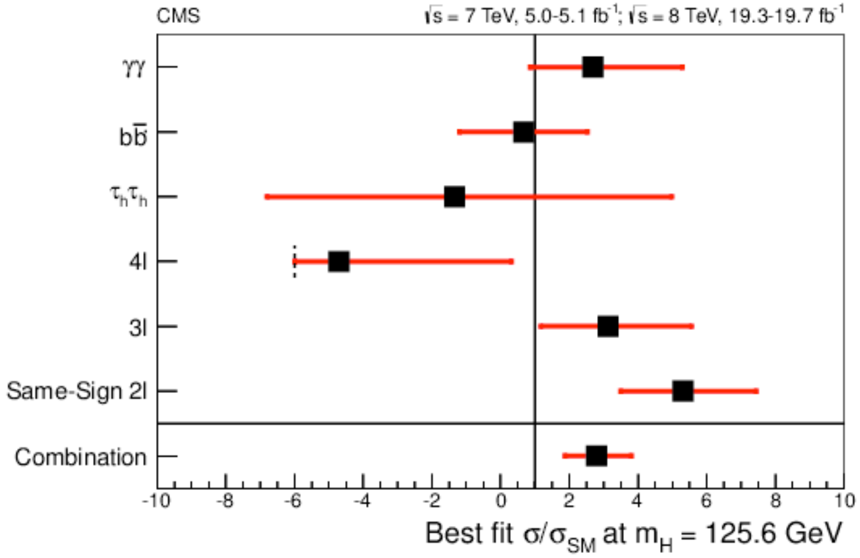
Higgs signals - ttH

Probe of the largest Higgs coupling using the ttH production mechanism.

PLB749,519(2015)



JHEP09,087(2014)



ATLAS: multilepton events (ττ, WW, ZZ) → $\mu = 2.1^{+1.4}_{-1.2}$ $\mu < 4.7$ (2.4)

CMS: hadrons, photons, leptons → $\mu = 2.8^{+1.0}_{-0.9}$ $\mu < 4.5$ (2.7)

Compatible with SM, BUT both experiments see μ>1

Higgs signals – limits on rare decays

Final state	**ATLAS**	**CMS**
μμ	7.0 (7.2)	7.4 (6.5)
ee		$\approx 3.7 \times 10^5$
Zγ	11 (9)	9.5 (10)
llγ (M_{ll}<20 GeV)		7.7 (6.4)
J/ψγ	≈500	≈500
Υ (nS) γ	$BR<10^{-3}$	

Also limit on "invisible" decays, using VBF and VH as tags.

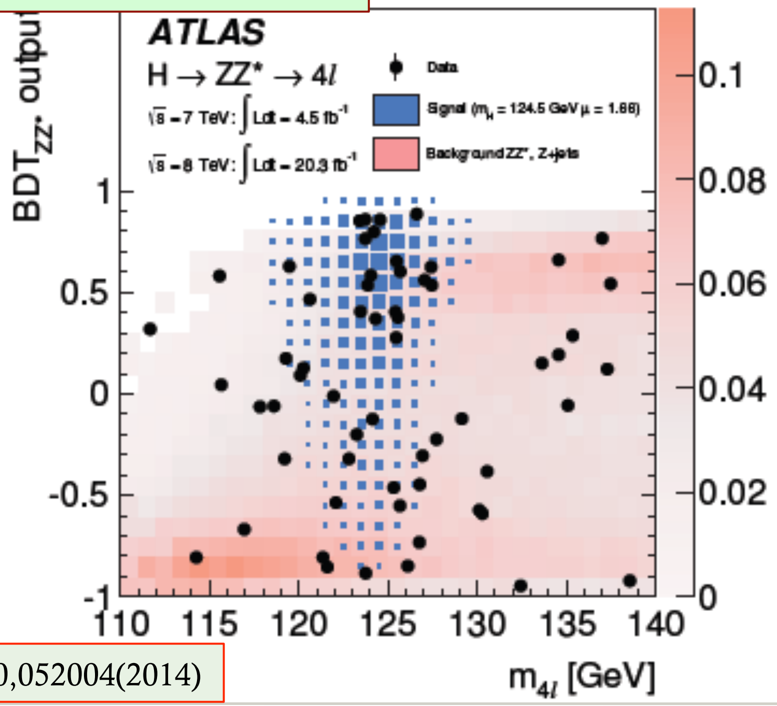
ATLAS BR_{inv} < 25% (27%) (VBF + VH)
CMS BR_{inv} < 58% (44%) (only VBF)

Higgs boson mass - I

Mass precision measurement in H → γγ and H → ZZ → 4l

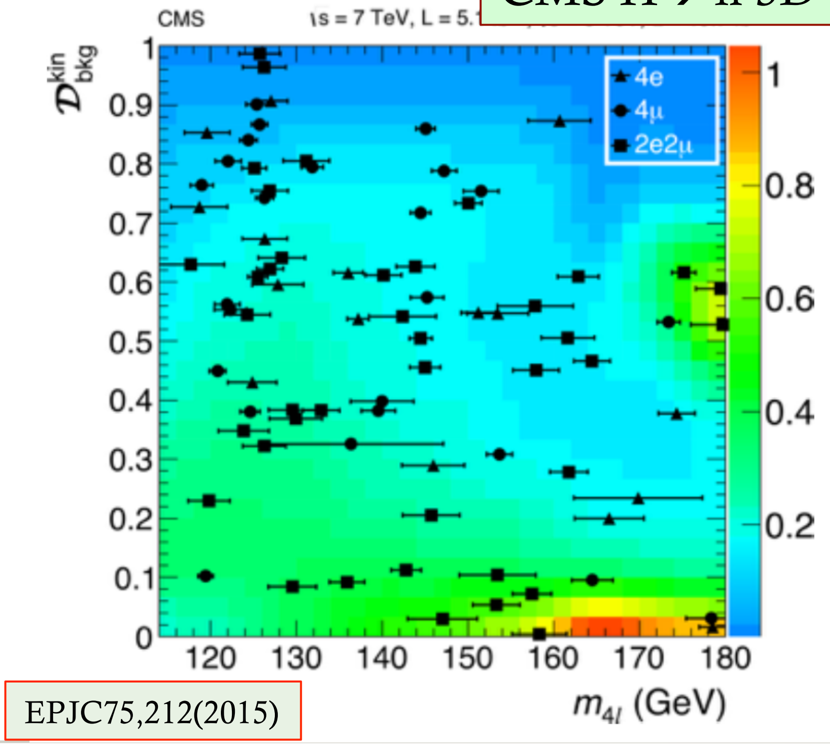
- Fully reconstructed channels, mass scales down to permill level.
- Discriminant variables added to invariant masses

ATLAS H→4l 2D fit



PRD90,052004(2014)

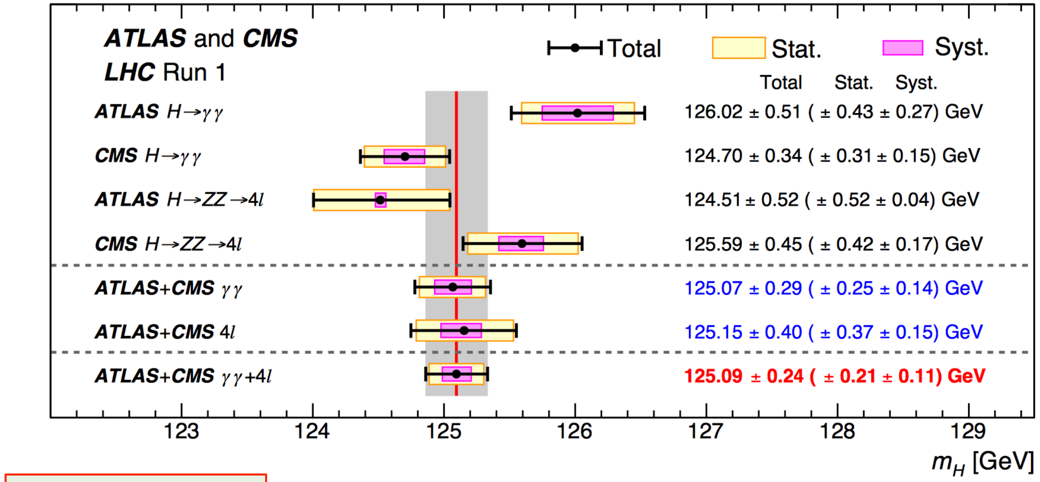
CMS H→4l 3D fit

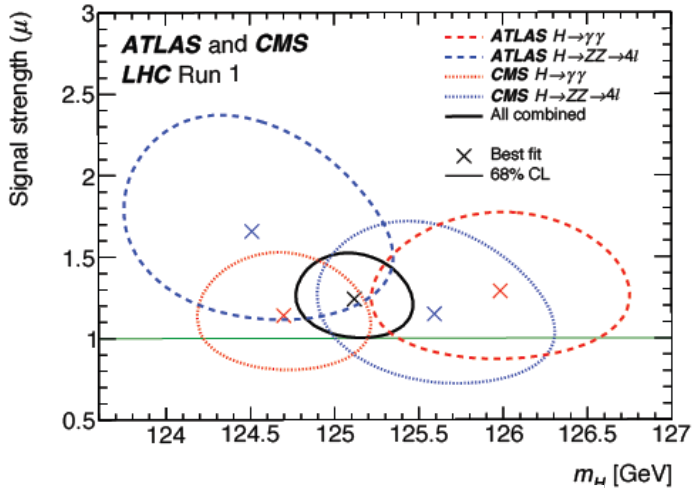


EPJC75,212(2015)

Higgs boson mass - II

Combination: Profile Likelihood Ratio, μ additional “nuisance” parameter





PRL114,191803

	ATLAS	CMS
H→4l	124.51 ± 0.52 ± 0.06	125.6 ± 0.4 ± 0.2
H→γγ	125.98 ± 0.42 ± 0.28	124.70 ± 0.31 ± 0.15
Combination	**125.36 ± 0.37 ± 0.18**	**125.02 $^{+0.26}_{-0.27}$ $^{+0.14}_{-0.15}$**
ATLAS + CMS	**125.09** ± 0.21 (stat) ± 0.11(scale) ± 0.02 (other) ± 0.01(theory)	

Higgs boson width

Expected SM width: $\Gamma(H^0) = 4.1$ MeV

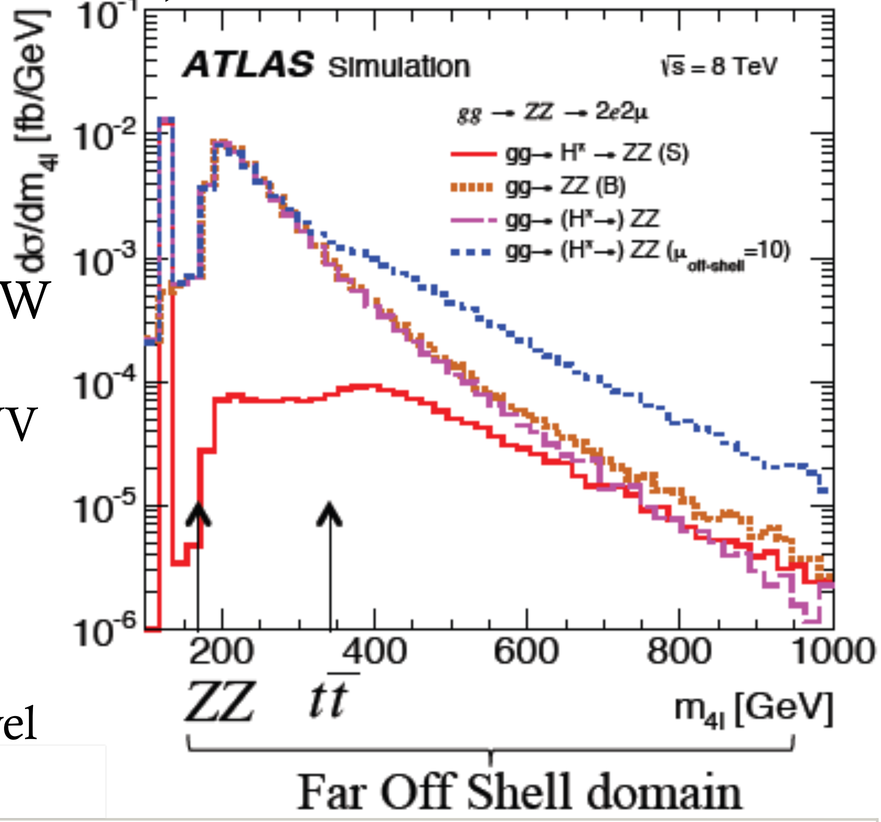
ATLAS: EPJC75,335(2015)
CMS: PLB736, 64(2014)

Direct limits (driven by experimental resolutions)

ATLAS: 2.6 (6.2) GeV (ZZ)
5.0 (6.2) GeV (γγ)
CMS: 1.7 (2.3) GeV (γγ and ZZ)

Indirect limits based on ZZ (4l and llνν), WW for $m_{VV} > 2m_V$ ➔ off-shell couplings

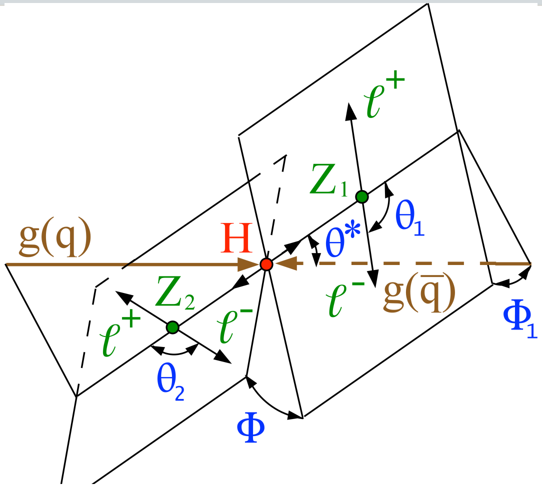
Interference btw gg→H→VV and gg→VV
BUT large bkg from qq→VV
Assume off-shell coupling = on-shell
ATLAS: 23 (33) MeV
CMS: 22 (33) MeV
HL-LHC will bring sensitivity at SM-level
(BUT theory effort needed !)



Higgs boson Spin/CP - I

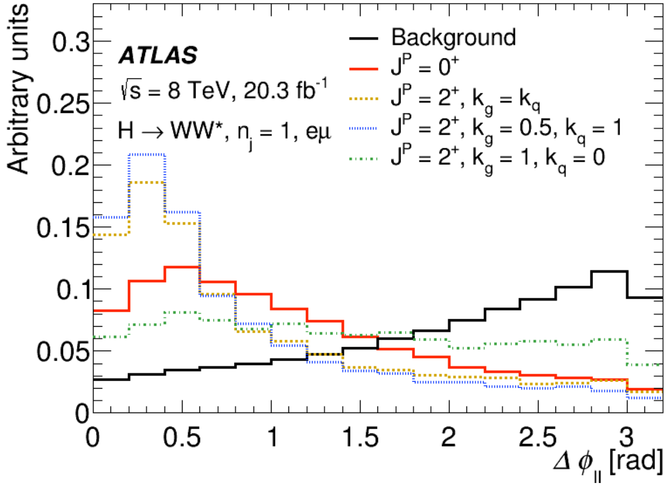
Spin and Parity *hypothesis tests* in the di-boson channels using *discriminant variables* based on kinematics

- **ZZ → 4l**
  Matrix element dependent on 5 angles and 3 masses: sensitivity to J^P and bck



- **γγ**
  Only 2 variables used: $p_T(\gamma\gamma)$ and cos θ* (Collins-Soper frame)

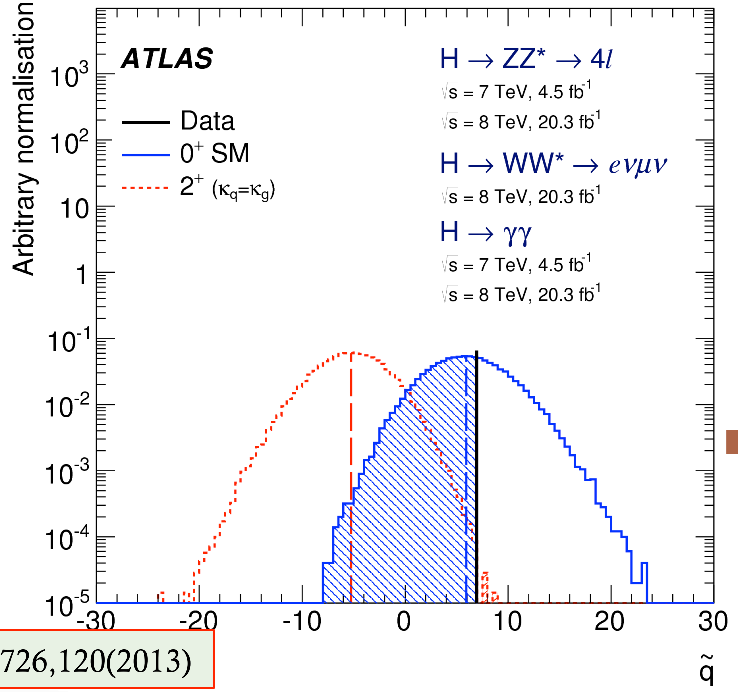
- **WW→eνμν:**
  ATLAS: BDT with $\Delta\phi(ll)$, $p_t(ll)$, $m(ll)$
  CMS: 2D fit to m(ll) and m_T



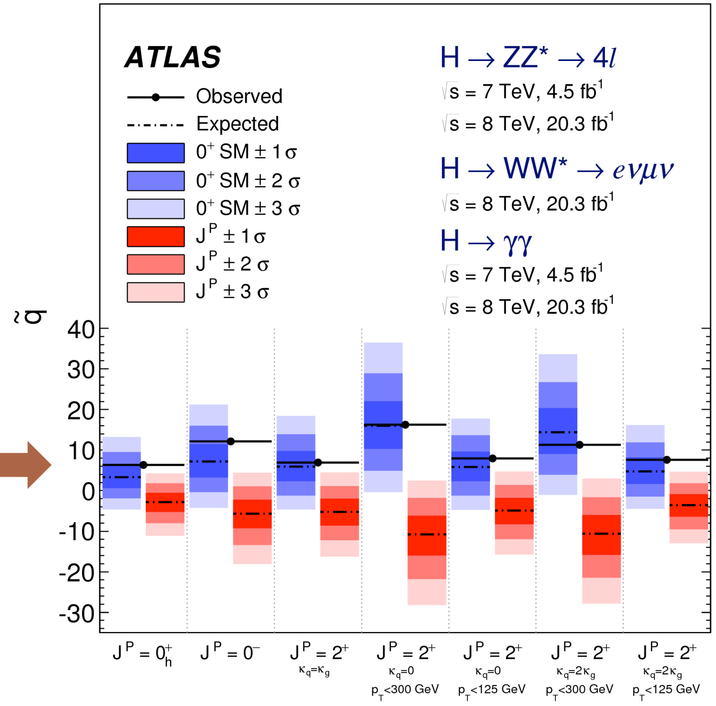
Higgs boson Spin/CP - II

Hyp. test: SM vs. alternative hypothesis.
A discriminant variable is built for each possible alternative hyp.:

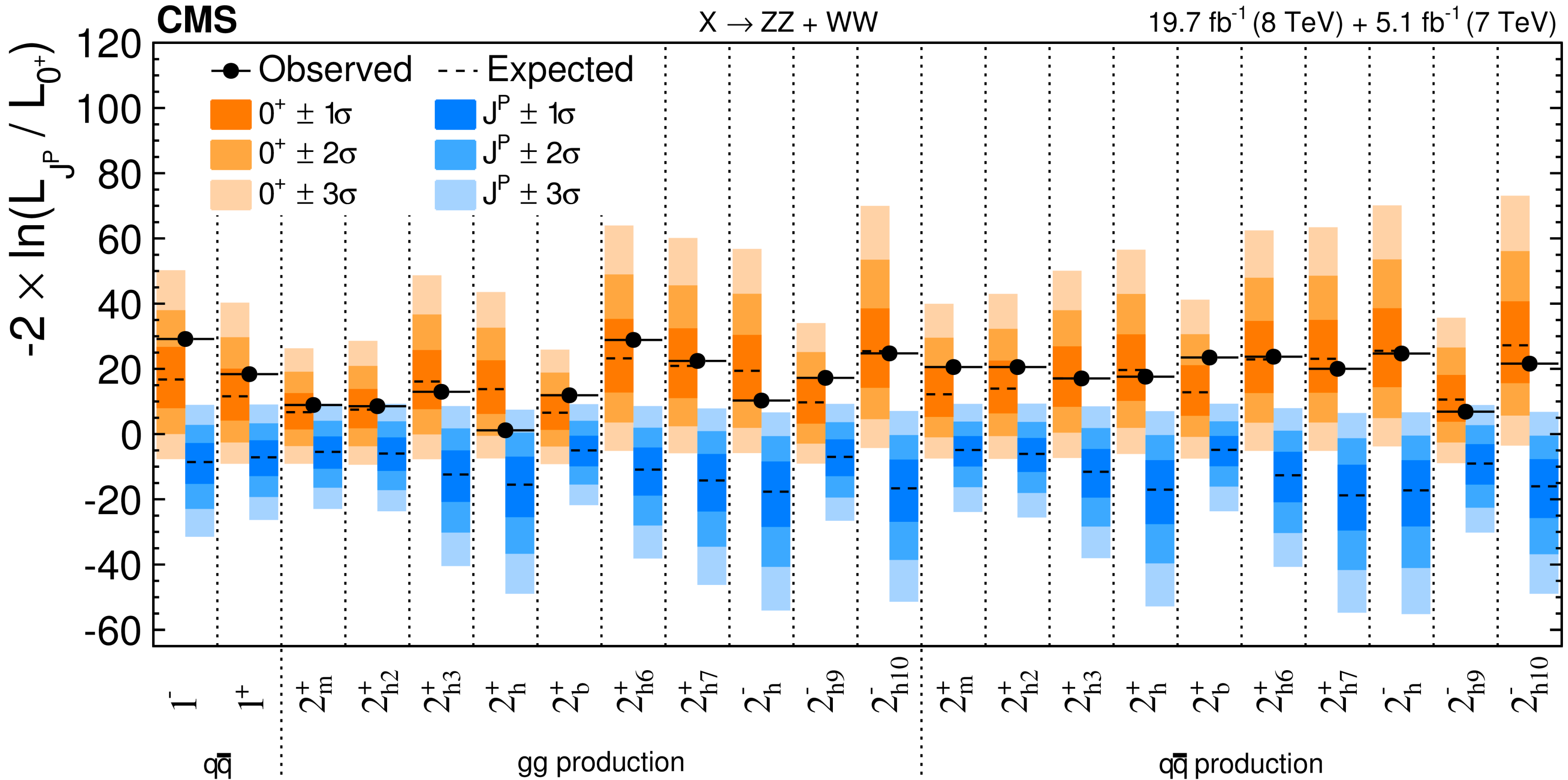
$$\tilde{q} = \log \frac{\mathcal{L}(J^P_{\mathrm{SM}}, \hat{\hat{\mu}}_{J^P_{\mathrm{SM}}}, \hat{\hat{\theta}}_{J^P_{\mathrm{SM}}})}{\mathcal{L}(J^P_{\mathrm{alt}}, \hat{\hat{\mu}}_{J^P_{\mathrm{alt}}}, \hat{\hat{\theta}}_{J^P_{\mathrm{alt}}})}$$



PLB726,120(2013)



Higgs boson Spin/CP - III

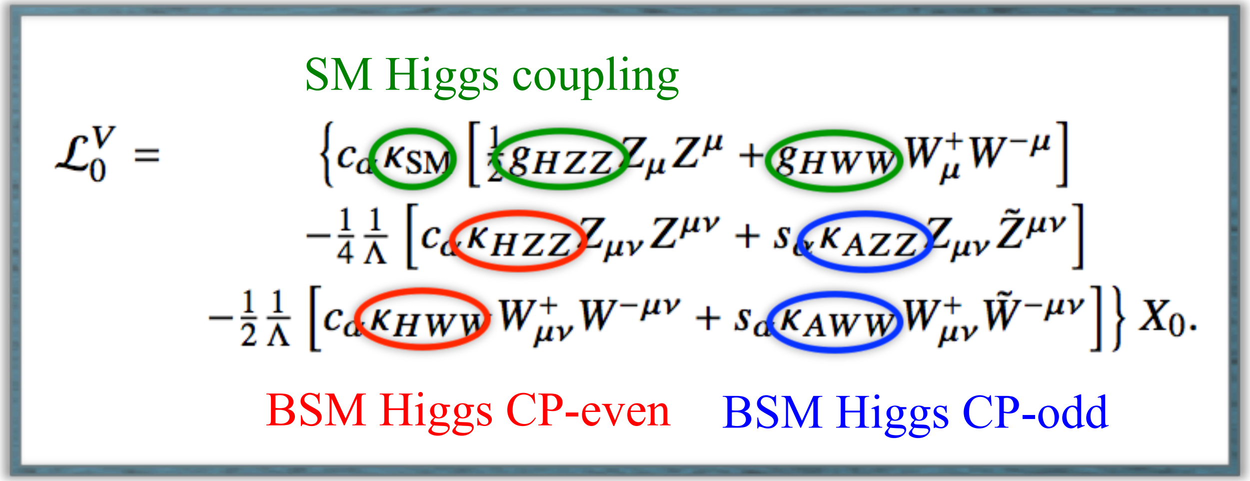


PRD92,012004(2015)

Alternative Spin/Parity scenarios can be all excluded with CL>99.9%

Higgs boson Spin/CP
Alternative tensor structure

Higgs couplings to *VV* could have additional tensor terms either CP-even or CP-odd (negligible in the SM)



SM Higgs coupling

$$\mathcal{L}_0^V = \Big\{ c_\alpha \kappa_{\rm SM} \left[\tfrac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W^+_\mu W^{-\mu} \right] - \tfrac{1}{4}\tfrac{1}{\Lambda}\left[c_\alpha \kappa_{HZZ} Z_{\mu\nu} Z^{\mu\nu} + s_\alpha \kappa_{AZZ} Z_{\mu\nu}\tilde{Z}^{\mu\nu}\right] - \tfrac{1}{2}\tfrac{1}{\Lambda}\left[c_\alpha \kappa_{HWW} W^+_{\mu\nu}W^{-\mu\nu} + s_\alpha \kappa_{AWW} W^+_{\mu\nu}\tilde{W}^{-\mu\nu}\right]\Big\} X_0.$$

BSM Higgs CP-even BSM Higgs CP-odd

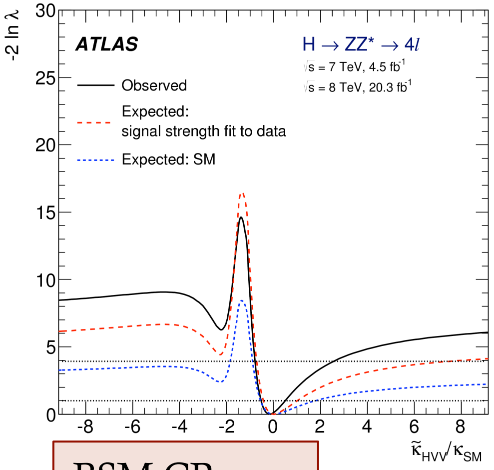
FIT *VV* data introducing the additional terms and estimate the BSM parameters (Λ=1 TeV in ATLAS analysis):

$\kappa_{\rm HZZ}/\kappa_{\rm SM}$ and $\kappa_{\rm AZZ}/\kappa_{\rm SM}\ \tan\alpha$ (ATLAS formulation)

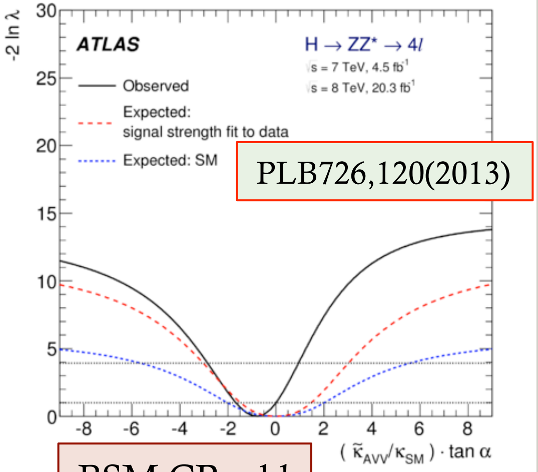
Λ and a_1, a_2 (CMS formulation)

Higgs boson Spin/CP
Search for CP violation terms

- Test coupling and mixing angle in CP even and odd hypotheses
- No evidence of CP violation observed

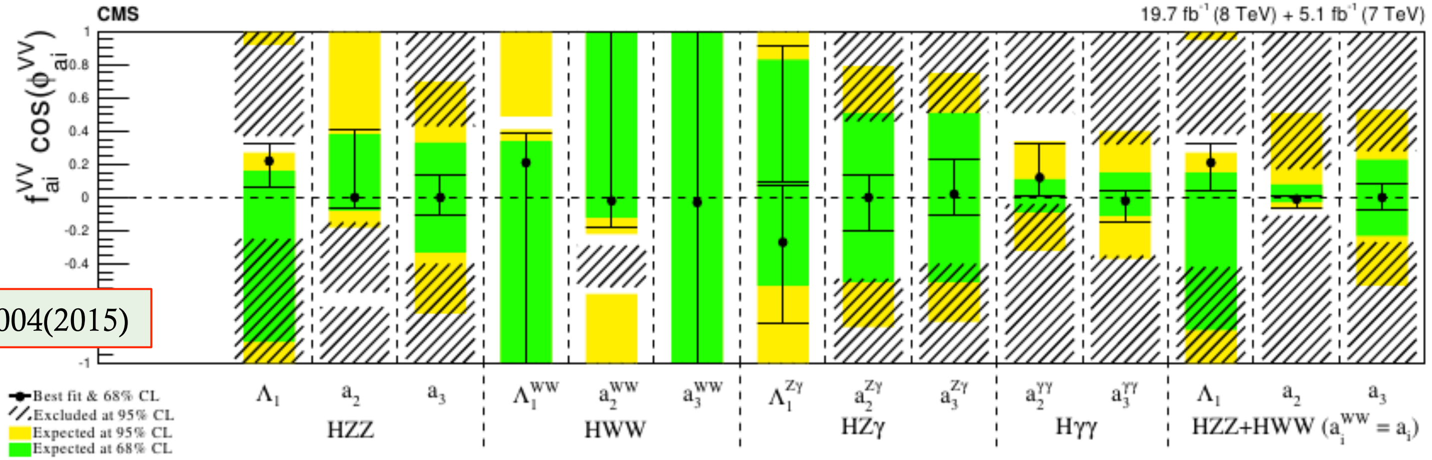


BSM CP-even



PLB726,120(2013)

BSM CP-odd



PRD92,012004(2015)

Higgs boson couplings
Introduction

Combine channels to extract informations on the way the Higgs couples with particles to be compared to SM expectations.

- Signal strengths μ_i and μ_f related to channels for data category c

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

- Coupling modifiers κ according to different scenarios related to "couplings to particles" (based on LO diagrams)

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

Reminder: μ and κ are "normalized" to SM ➔ any significant deviation from 1 means BSM…

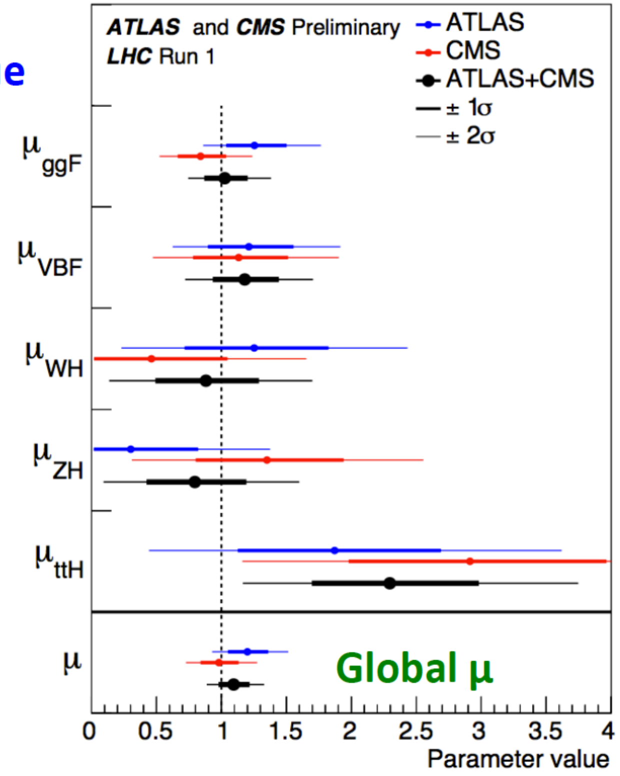
Higgs boson signal strengths ATLAS+CMS combination

Overall μ

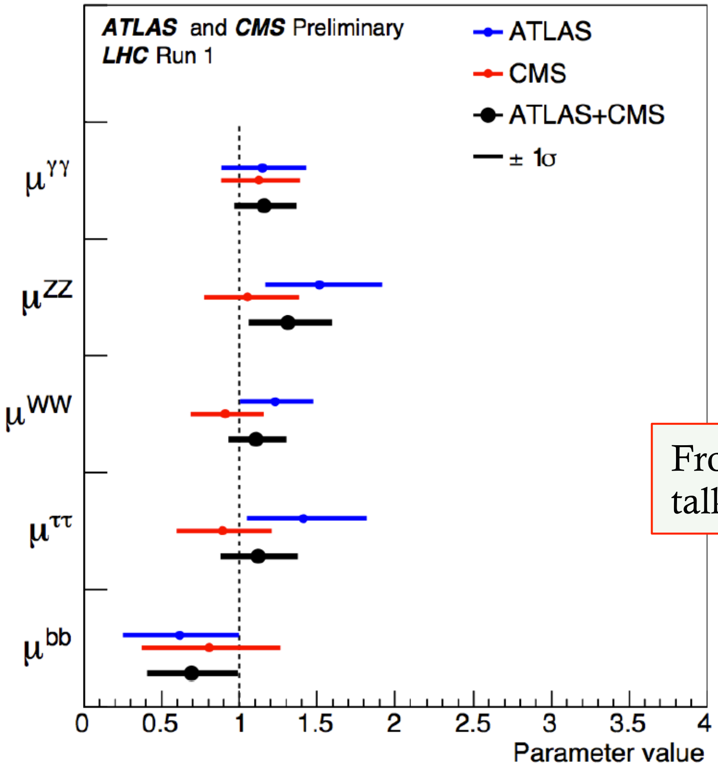
$$\mu = 1.09^{+0.11}_{-0.10} \quad = 1.09^{+0.07}_{-0.07}\,(\text{stat})\,{}^{+0.04}_{-0.04}\,(\text{expt})\,{}^{+0.03}_{-0.03}\,(\text{thbgd})^{+0.07}_{-0.06}\,(\text{thsig})$$

SM p-value 25%

SM BRs assumed



SM production σ assumed



SM p-value 60%

From M.Pieri talk at LHCP

Higgs boson signal strengths
Significativities

Production process	Observed Significance(σ)	Expected Significance (σ)
VBF	**5.4**	**4.7**
WH	2.4	2.7
ZH	2.3	2.9
VH	3.5	4.2
ttH	4.4	2.0
Decay channel		
H→ττ	**5.5**	**5.0**
H→bb	2.6	3.7

After combination:

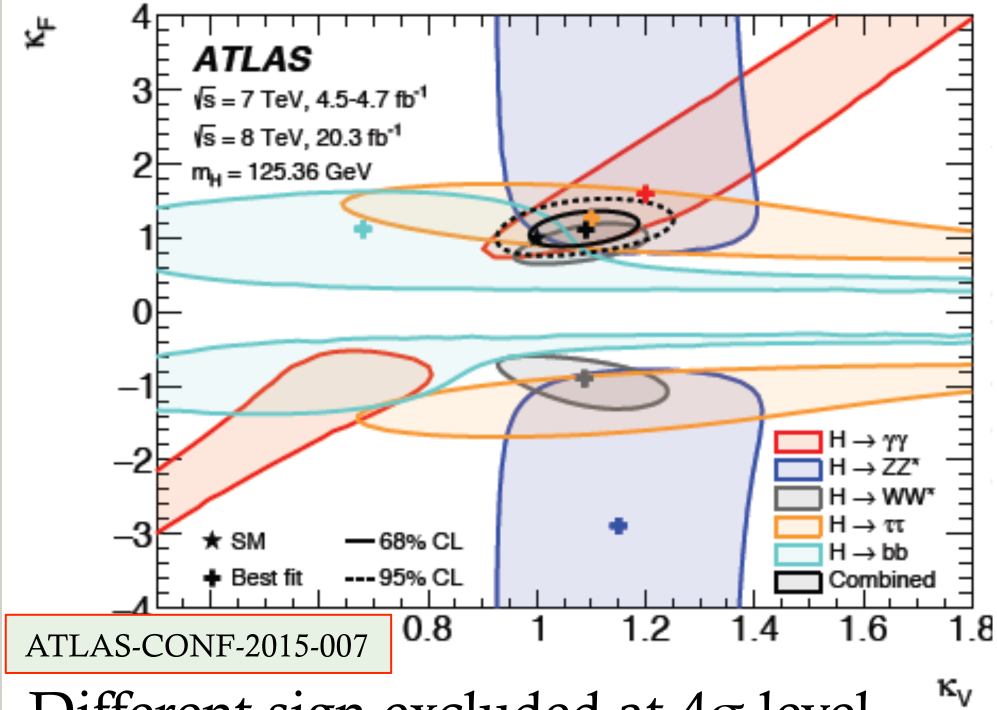
➔ *Observation* of **VBF**, of **H→ττ**
➔ *Evidence* of **VH**
➔ *"Evidence"* of **ttH** *"Non-Evidence"* of **bb**

Higgs boson couplings
Fermion vs. Vector boson couplings

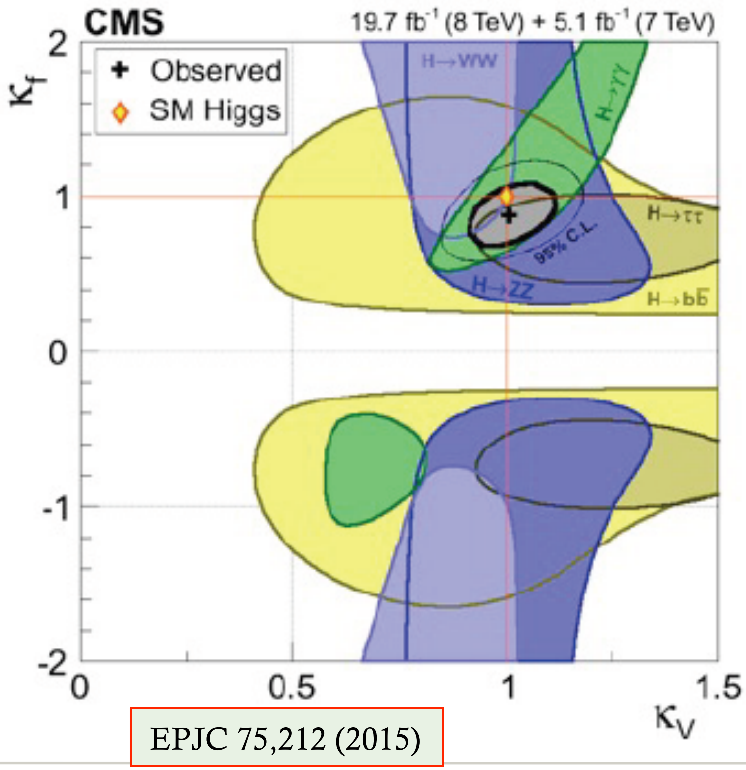
The first coupling fit is the “Fermion vs Boson” model. Assume:

All fermions scale the same (κ_F) and all bosons scale the same (κ_V)

No BSM interactions in width or loops. Sensitivity to the relative sign.



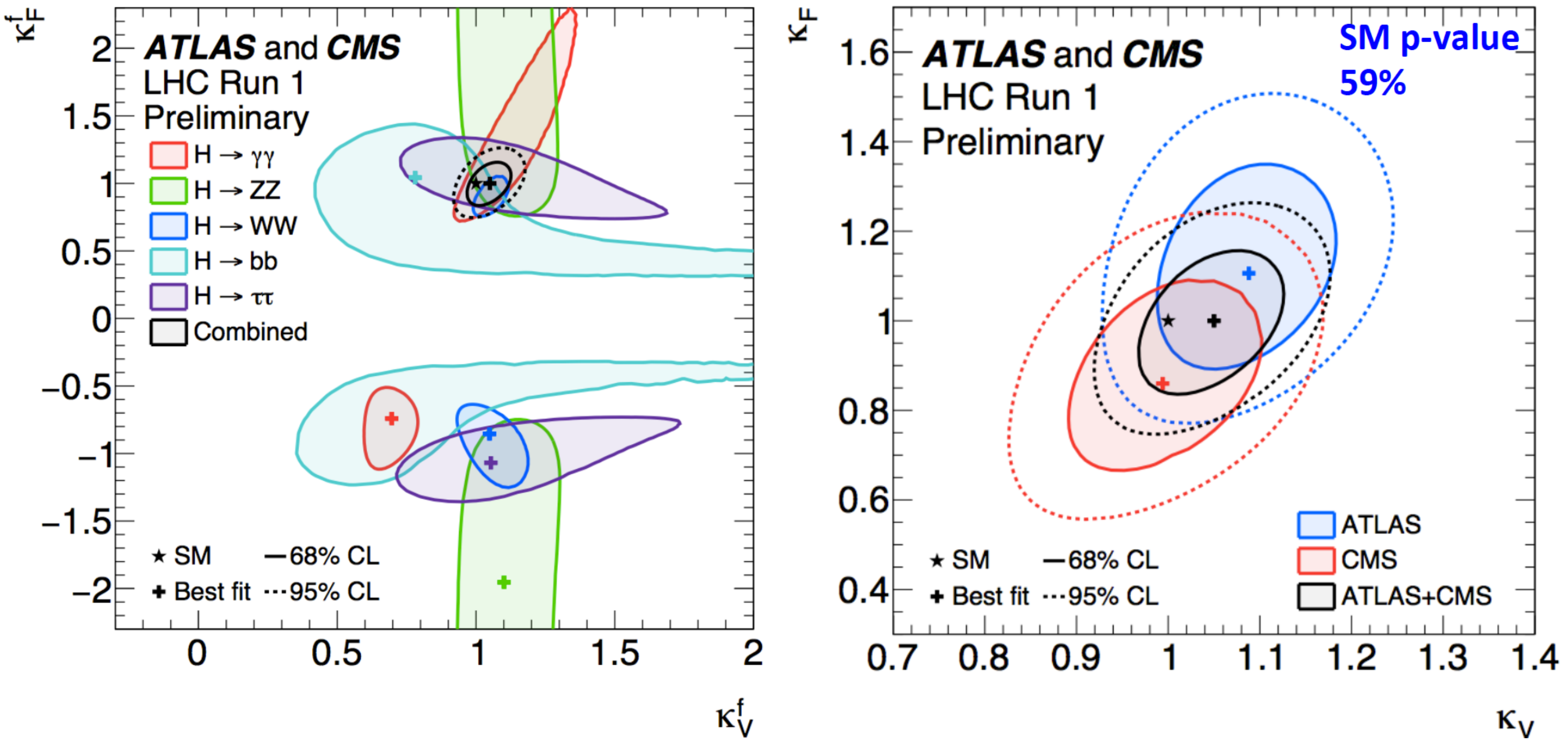
ATLAS-CONF-2015-007



EPJC 75,212 (2015)

Different sign excluded at 4σ level

Higgs boson F vs. V couplings ATLAS+CMS combination



All results in agreeement with the SM within 1σ

$\kappa_F<0$ excluded at ≈5σ level

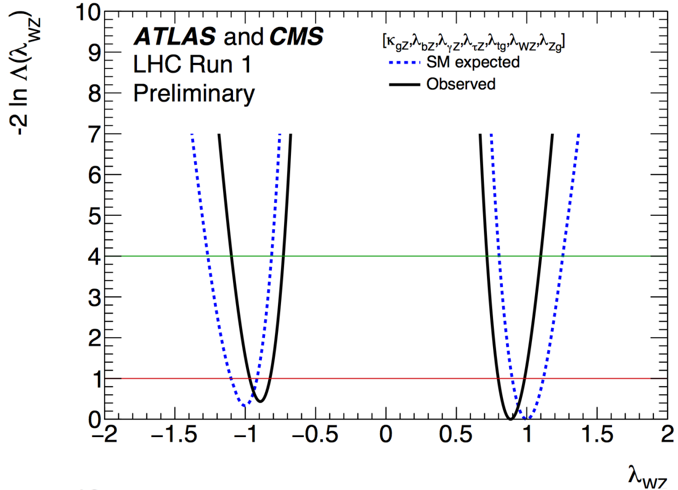
Higgs boson coupling ratios ATLAS+CMS combination

Additional fits based on the ratios of different channels (some syst. cancel)

-- WZ (custodial symmetry)

-- Up/Down fermions

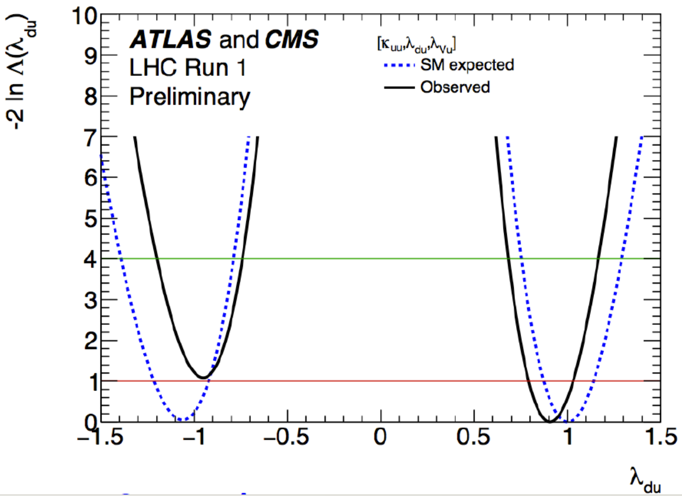
-- Leptons/Quarks

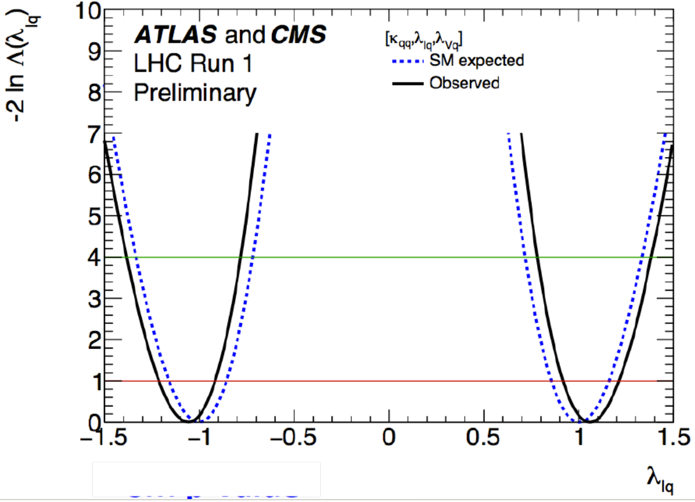


$\lambda_{WZ}=\kappa_W/\kappa_Z$

$\lambda_{du} = \kappa_d/\kappa_u$

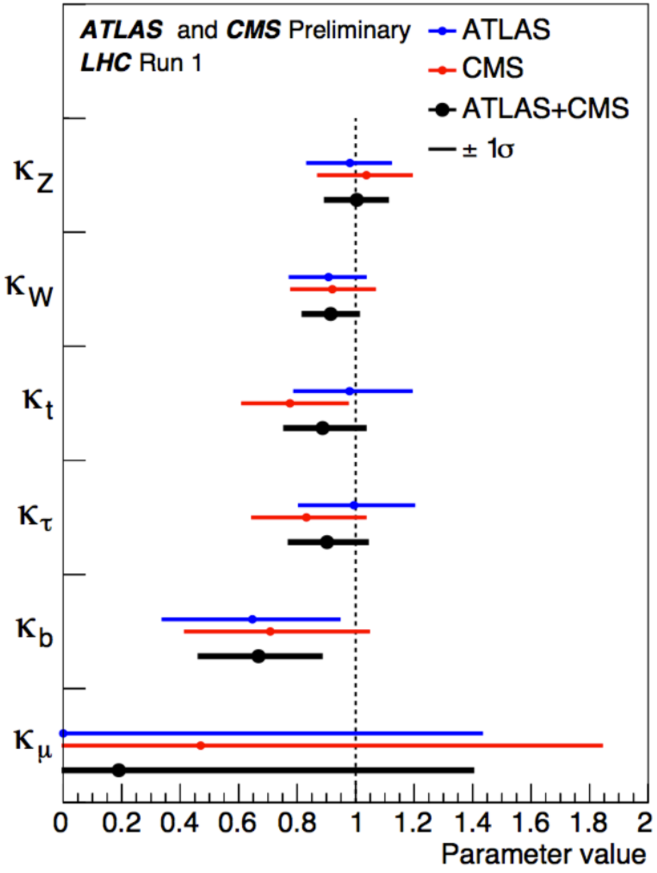
$\lambda_{lq} = \kappa_l/\kappa_q$

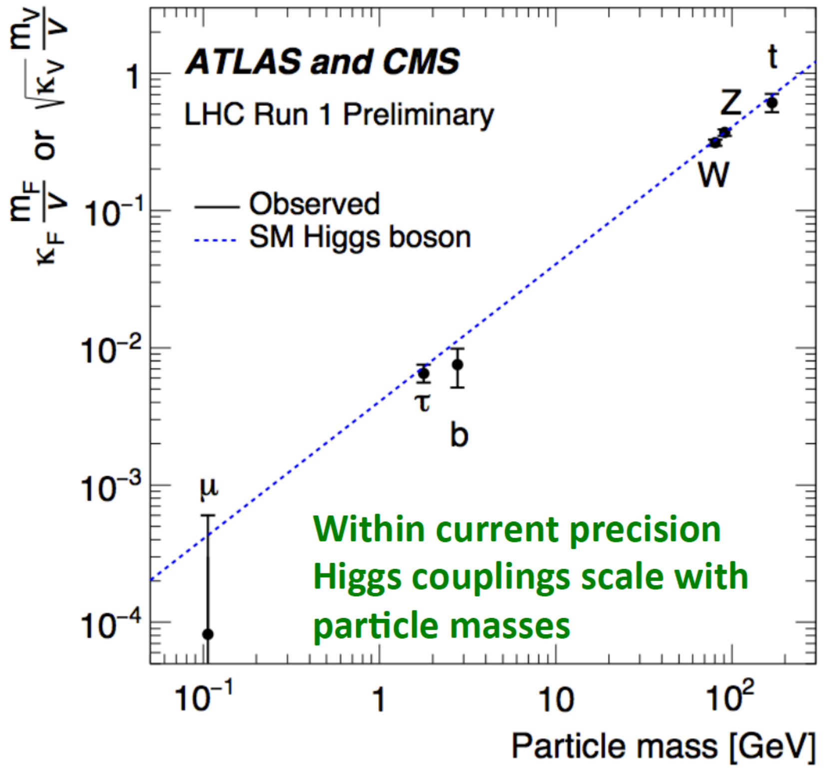




Higgs boson couplings
5(+1)-parameter fit

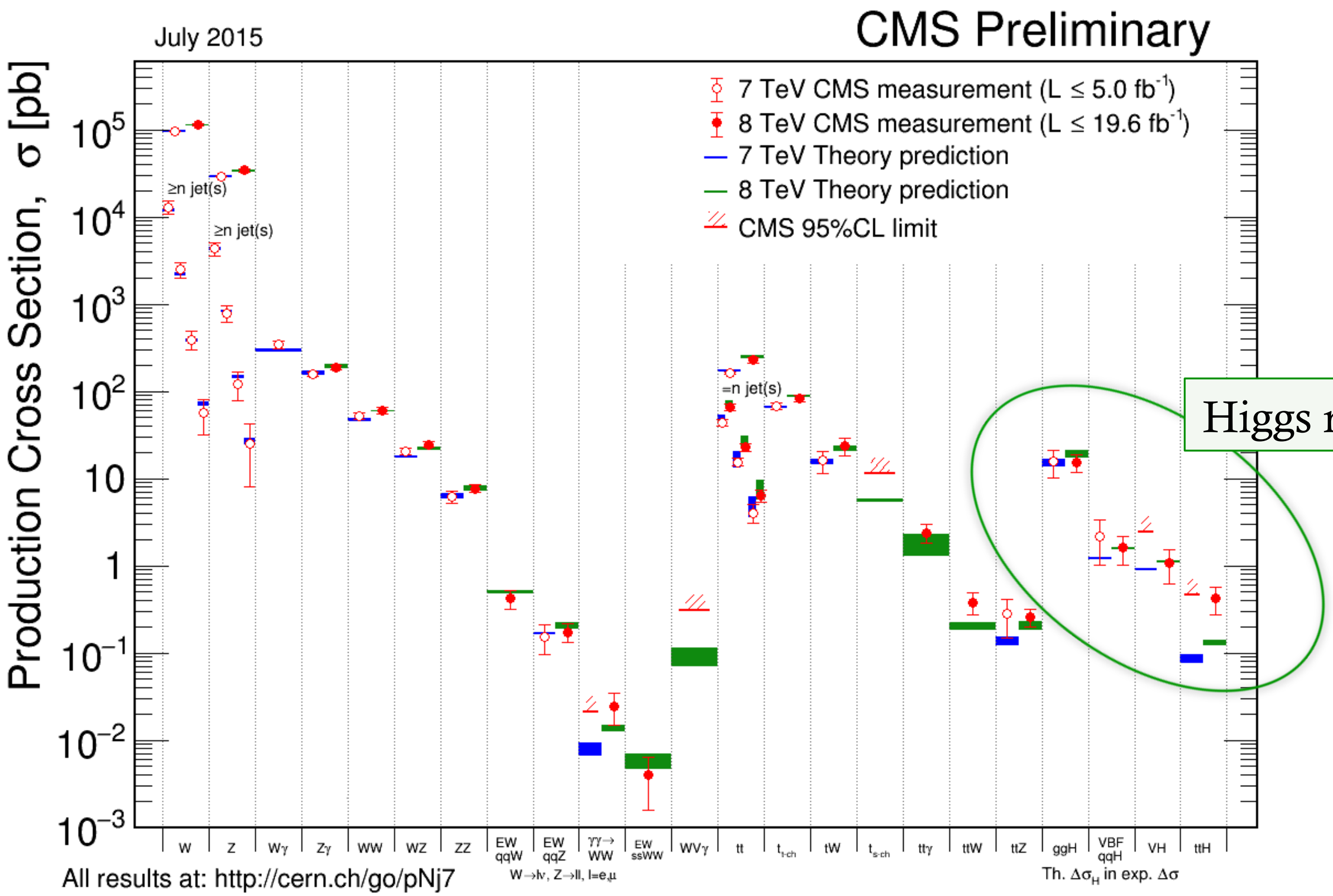
Fit including 5 most relevant coupling modifiers: **κ_W κ_Z κ_t κ_τ κ_b+ κ_μ**





Within current precision Higgs couplings scale with particle masses

LHC: 2011-2012 run1 dataset
A complete SM "radiography"



All results at: http://cern.ch/go/pNj7

Higgs results

BSM Higgs searches
A summary

- Anomalies in H^0 properties:
  μ, $\kappa \neq 1$, $\text{spin}^P \neq 0^+$,…(see above)
- SM forbidden H^0 decays
  - Lepton Flavour Violations ($H \rightarrow \mu\tau$)
  - Invisible decays (tagged by VBF and/or VH)
- Extra Higgs
  - $X \rightarrow WW/ZZ$ to $m_X = 1 \div 1.5$ TeV
  - $X \rightarrow$ invisible / quasi-invisible
  - $A \rightarrow Zh$
  - $H/A \rightarrow Z + A/H$
- Charged Higgses
  - $H^\pm \rightarrow \tau^\pm \nu$,
  - $H^\pm \rightarrow cs$
  - $H^\pm \rightarrow W^\pm Z$, Higgs cascade
- Supersymmetric ϕ Higgs boson
  - $\phi \rightarrow bb$,
  - $\phi \rightarrow \mu\mu$,
  - $\phi \rightarrow \tau\tau$

Many analyses ongoing,
“open eyes”
as soon as new data come

LHC: status of run2

Ongoing **run2** at 13 TeV

→50 → 25 ns interbunch (pileup reduced)

→Relevant experiment upgrades

→Aiming 1×10^{34} $cm^{-2}s^{-1}$ luminosity

→Program:

10÷15 fb^{-1} within 2015
100 fb^{-1} within 2018

→At the end of run2 about × (8 ÷18) Higgses produced

Cross-sections at 125 GeV

	8 TeV	13 TeV
ggF	19 pb	44 pb
VBF	1.6 pb	3.7 pb
VH	1.1 pb	2.2 pb
ttH	0.13 pb	0.51 pb
tH	~20 fb	~90 fb

"Today" 0.2 fb^{-1}/expt.: first results (not yet Higgs) already there

Prospects of Higgs physics in future LHC runs

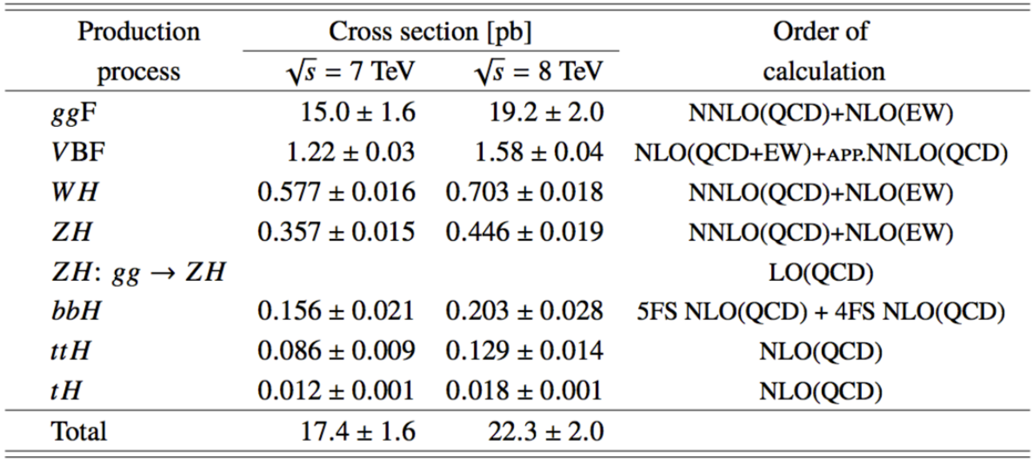
- **LHC Run2**: 13 TeV - 100 fb^{-1} expected 2018
  - Observation of $H \rightarrow \tau\tau$, bb by ATLAS and CMS independently;
  - Observation of VBF and VH by ATLAS and CMS independently;
  - Clarification of evidence for ttH

- **LHC Run3**: 14 TeV - 300 fb^{-1} expected 2022
  - Probable observation of ttH
  - Evidence $H \rightarrow \mu\mu$
  - Precision measurement of Higgs couplings at the level of ≈10 %

- **HL-LHC**: 14 TeV - 3000 fb^{-1}: expected >2030…
  - Observation ttH
  - Observation of $H \rightarrow \mu\mu$ and $H \rightarrow Z\gamma$
  - Precision measurement of Higgs couplings at the level of few %
  - Evidence for HH production
  - Sensitivity to SM Γ_H through indirect "off-shell" method

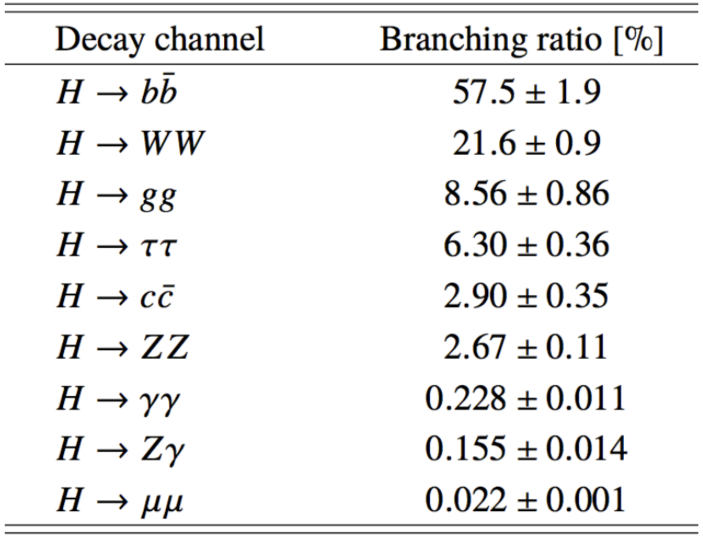
Backup Slides

Theoretical uncertainties



Production process	Cross section [pb]		Order of calculation
	$\sqrt{s}$ = 7 TeV	$\sqrt{s}$ = 8 TeV	
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)+APP.NNLO(QCD)
WH	0.577 ± 0.016	0.703 ± 0.018	NNLO(QCD)+NLO(EW)
ZH	0.357 ± 0.015	0.446 ± 0.019	NNLO(QCD)+NLO(EW)
ZH: $gg \to ZH$			LO(QCD)
bbH	0.156 ± 0.021	0.203 ± 0.028	5FS NLO(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	

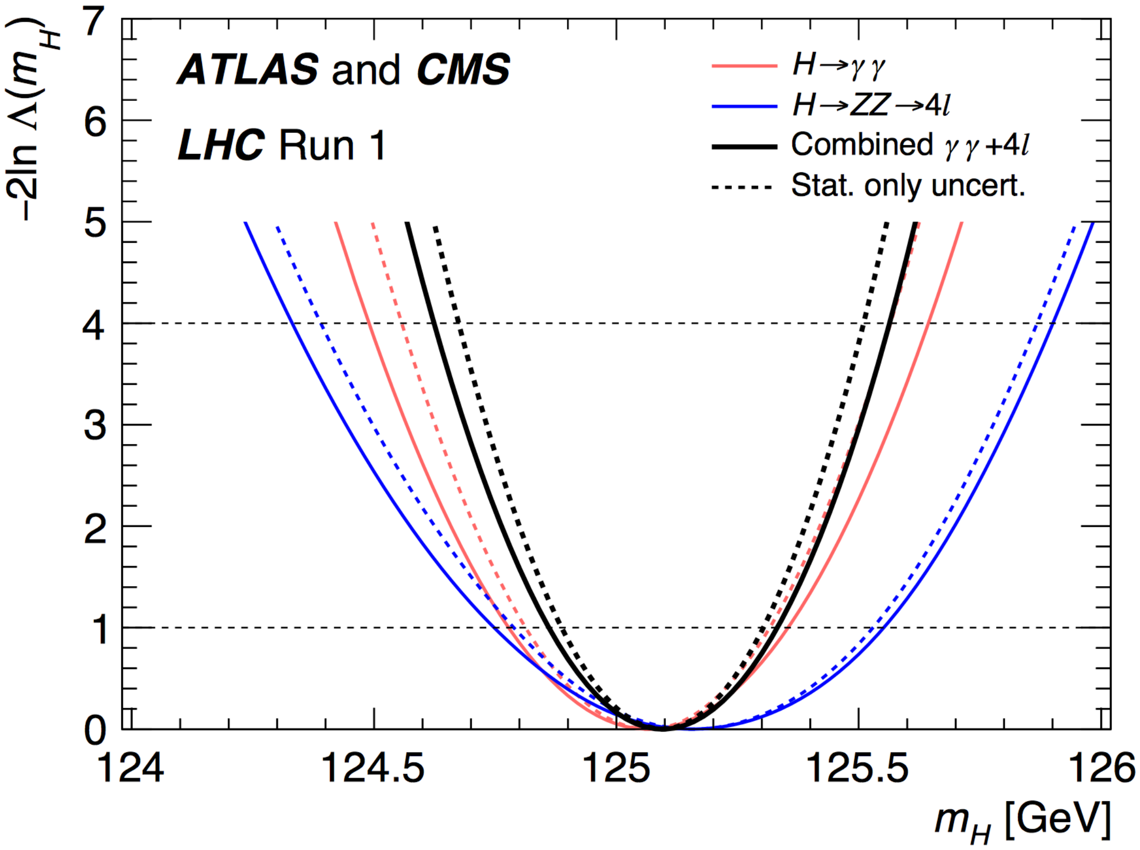
SM ggF, ttH, bbH theory uncertainty: ~10%
VBF, VH, ZH: 2-3%



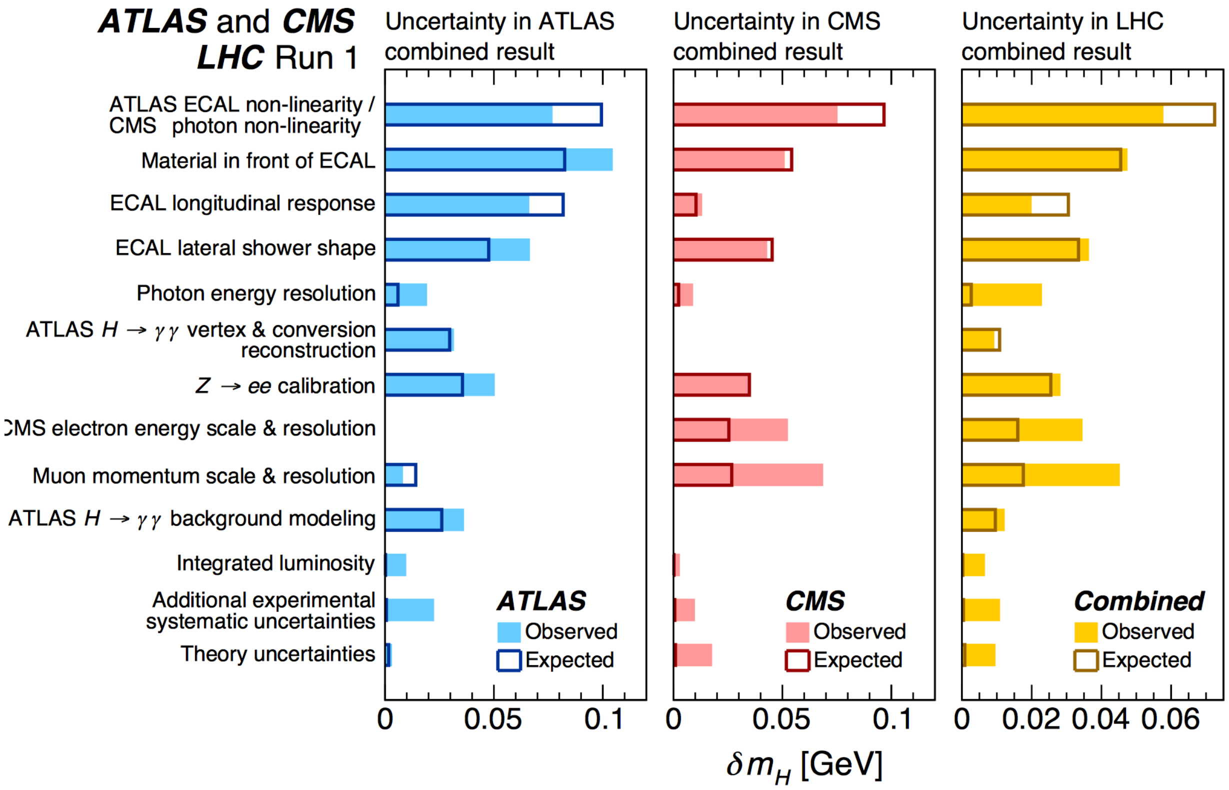
Decay channel	Branching ratio [%]
$H \to b\bar{b}$	57.5 ± 1.9
$H \to WW$	21.6 ± 0.9
$H \to gg$	8.56 ± 0.86
$H \to \tau\tau$	6.30 ± 0.36
$H \to c\bar{c}$	2.90 ± 0.35
$H \to ZZ$	2.67 ± 0.11
$H \to \gamma\gamma$	0.228 ± 0.011
$H \to Z\gamma$	0.155 ± 0.014
$H \to \mu\mu$	0.022 ± 0.001

SM BR theory uncertainties
2-5% for most important ones

γγ vs. 4l mass compatibility



Mass measurement systematics



Higgs boson width - II

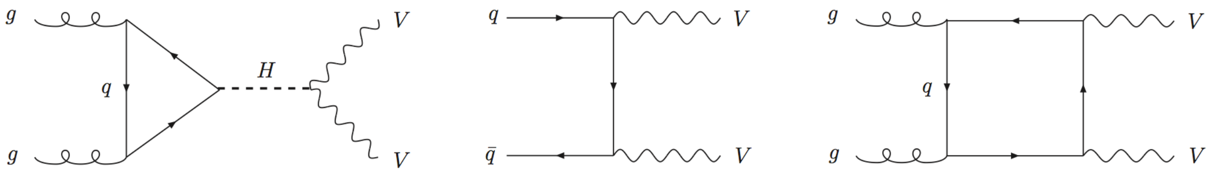
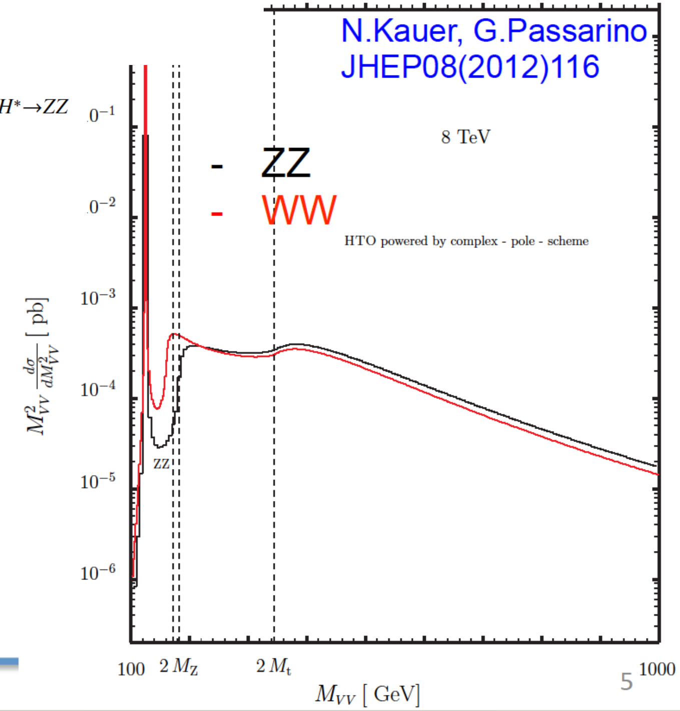


Figure 1. Representative Feynman graphs for the Higgs signal process (left) and the $q\bar{q}$- (center) and gg-initiated (right) continuum background processes at LO.

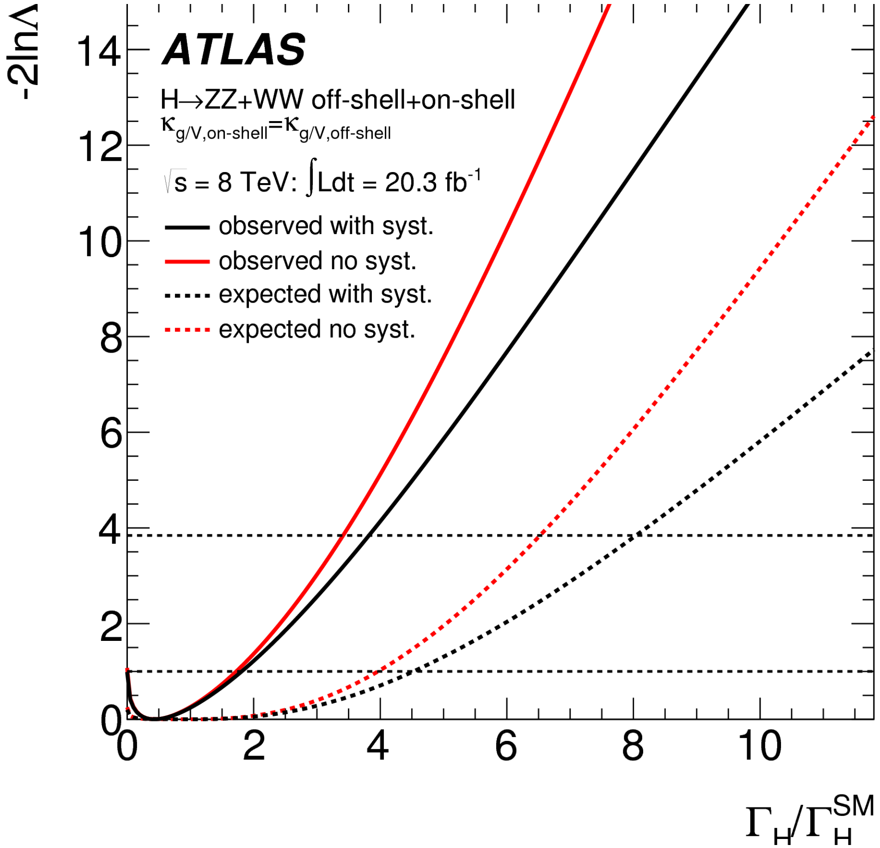
$$\begin{aligned} MC_{gg\to(H^*\to)ZZ}(\mu_{\text{off-shell}}) = {} & \left(\boxed{K^{H^*}(m_{ZZ})}\cdot\mu_{\text{off-shell}} - \boxed{K^{H^*}_{gg}(m_{ZZ})}\cdot\sqrt{\boxed{R^{B}_{H^*}}\cdot\mu_{\text{off-shell}}}\right)\cdot MC^{\text{SM}}_{gg\to H^*\to ZZ} \\ & + \boxed{K^{H^*}_{gg}(m_{ZZ})}\cdot\sqrt{\boxed{R^{B}_{H^*}}\cdot\mu_{\text{off-shell}}}\cdot MC^{\text{SM}}_{gg\to(H^*\to)ZZ} \\ & + \boxed{K^{H^*}_{gg}(m_{ZZ})}\cdot\left(\boxed{R^{B}_{H^*}} - \sqrt{\boxed{R^{B}_{H^*}}\cdot\mu_{\text{off-shell}}}\right)\cdot MC^{\text{cont}}_{gg\to ZZ}, \end{aligned}$$

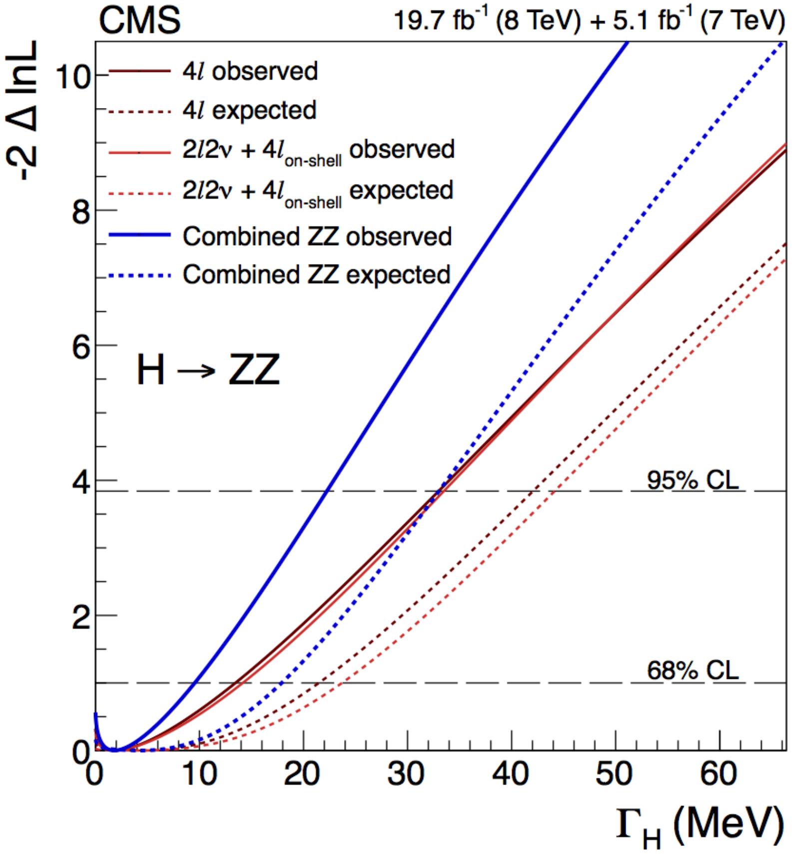
Systematic uncertainty ***ATLAS***	95% CL lim. (CL_s) on $\mu_{\text{off-shell}}$
Interference $gg \to (H^* \to)VV$	7.2
QCD scale $K^{H^*}(m_{VV})$ (correlated component)	7.1
PDF $q\bar{q} \to VV$ and $gg \to (H^* \to)VV$	6.7
QCD scale $q\bar{q} \to VV$	6.7
Luminosity	6.6
Drell–Yan background	6.6
QCD scale $K^{H^*}_{gg}(m_{VV})$ (uncorrelated component)	6.5
Remaining systematic uncertainties	6.5
All systematic uncertainties	8.1
No systematic uncertainties	6.5



N.Kauer, G.Passarino JHEP08(2012)116

Higgs boson width - III



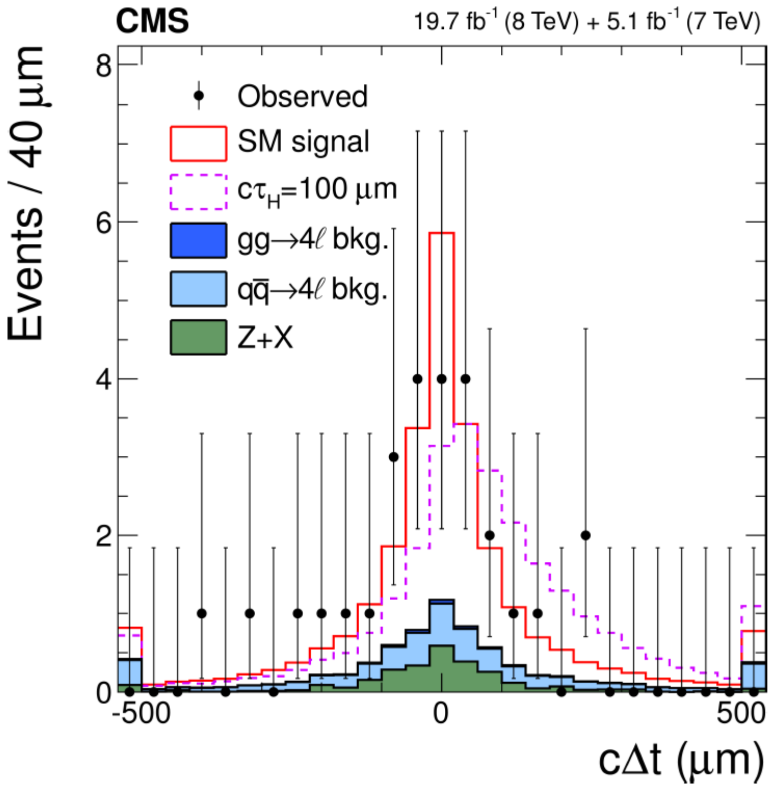


Γ_H/Γ_H^{SM} < 4.5 - 7.5 (6.5 - 11.2)

Γ_H/Γ_H^{SM} < 5.4 (8.0)

Higgs boson lifetime

CMS has presented an analysis of the Higgs lifetime based on the measurement of the flight distance in H→ZZ→4l events



- Lifetime from flight distance in H→ZZ*→4l events

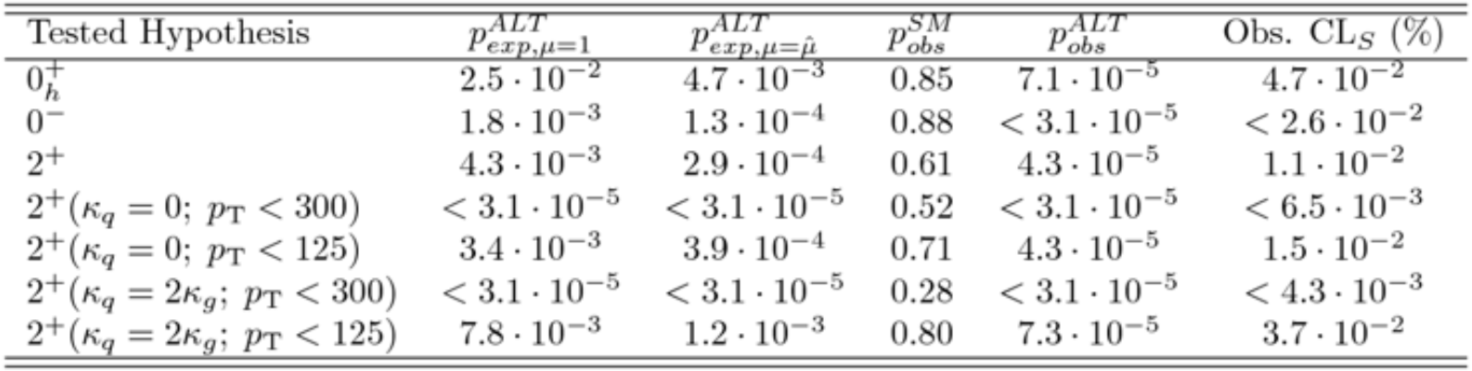
$$\Delta t = \frac{m_{4\ell}}{p_T}\left(\Delta\vec{r}_T . \hat{p}_T\right)$$

Displacement vertex between H production and decay

$c\tau_H < 57\mu m$ at the 95% CL

$\Gamma_H > 3.5\times10^{-3}$ eV at 95% CL

Higgs Spin/CP – ATLAS exclusions



Tested Hypothesis	$p^{ALT}_{exp,\mu=1}$	$p^{ALT}_{exp,\mu=\hat{\mu}}$	p^{SM}_{obs}	p^{ALT}_{obs}	Obs. CL_S (%)
0^+_h	$2.5 \cdot 10^{-2}$	$4.7 \cdot 10^{-3}$	0.85	$7.1 \cdot 10^{-5}$	$4.7 \cdot 10^{-2}$
0^-	$1.8 \cdot 10^{-3}$	$1.3 \cdot 10^{-4}$	0.88	$< 3.1 \cdot 10^{-5}$	$< 2.6 \cdot 10^{-2}$
2^+	$4.3 \cdot 10^{-3}$	$2.9 \cdot 10^{-4}$	0.61	$4.3 \cdot 10^{-5}$	$1.1 \cdot 10^{-2}$
$2^+(\kappa_q = 0;\ p_{\mathrm{T}} < 300)$	$< 3.1 \cdot 10^{-5}$	$< 3.1 \cdot 10^{-5}$	0.52	$< 3.1 \cdot 10^{-5}$	$< 6.5 \cdot 10^{-3}$
$2^+(\kappa_q = 0;\ p_{\mathrm{T}} < 125)$	$3.4 \cdot 10^{-3}$	$3.9 \cdot 10^{-4}$	0.71	$4.3 \cdot 10^{-5}$	$1.5 \cdot 10^{-2}$
$2^+(\kappa_q = 2\kappa_g;\ p_{\mathrm{T}} < 300)$	$< 3.1 \cdot 10^{-5}$	$< 3.1 \cdot 10^{-5}$	0.28	$< 3.1 \cdot 10^{-5}$	$< 4.3 \cdot 10^{-3}$
$2^+(\kappa_q = 2\kappa_g;\ p_{\mathrm{T}} < 125)$	$7.8 \cdot 10^{-3}$	$1.2 \cdot 10^{-3}$	0.80	$7.3 \cdot 10^{-5}$	$3.7 \cdot 10^{-2}$

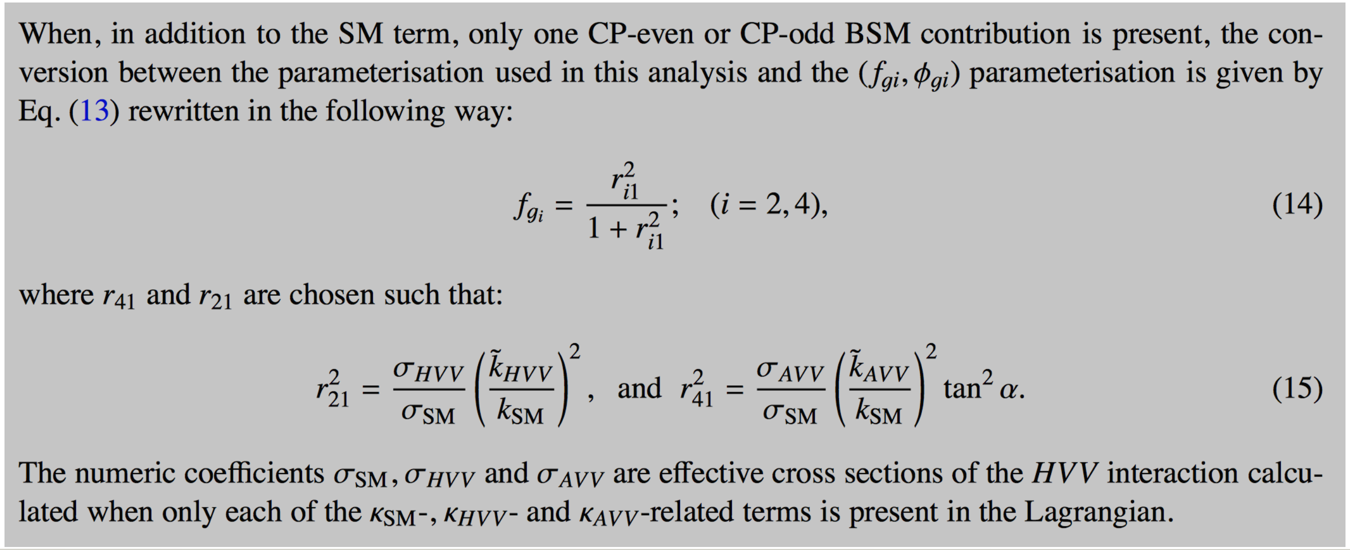
Alternative tensor structure: different formulations

ATLAS

$$\mathcal{L}_0^V = \Big\{c_\alpha \kappa_{\rm SM}\left[\tfrac{1}{2}g_{HZZ}Z_\mu Z^\mu + g_{HWW}W^+_\mu W^{-\mu}\right] -\tfrac{1}{4}\tfrac{1}{\Lambda}\left[c_\alpha \kappa_{HZZ}Z_{\mu\nu}Z^{\mu\nu} + s_\alpha \kappa_{AZZ}Z_{\mu\nu}\tilde{Z}^{\mu\nu}\right] -\tfrac{1}{2}\tfrac{1}{\Lambda}\left[c_\alpha \kappa_{HWW}W^+_{\mu\nu}W^{-\mu\nu} + s_\alpha \kappa_{AWW}W^+_{\mu\nu}\tilde{W}^{-\mu\nu}\right]\Big\} X_0.$$

CMS

$$A(\mathrm{HVV}) \sim \left[\underbrace{a_1^{\mathrm{VV}}}_{\text{SM}} + \frac{\kappa_1^{\mathrm{VV}} q_{\mathrm{V}1}^2 + \kappa_2^{\mathrm{VV}} q_{\mathrm{V}2}^2}{(\Lambda_1^{\mathrm{VV}})^2}\right] m_{\mathrm{V}1}^2 \epsilon^*_{\mathrm{V}1}\epsilon^*_{\mathrm{V}2} + a_2^{\mathrm{VV}} \underbrace{f^{*(1)}_{\mu\nu} f^{*(2),\mu\nu}}_{\text{BSM CP-even}} + a_3^{\mathrm{VV}} \underbrace{f^{*(1)}_{\mu\nu} \tilde{f}^{*(2),\mu\nu}}_{\text{BSM CP-odd}}$$



When, in addition to the SM term, only one CP-even or CP-odd BSM contribution is present, the conversion between the parameterisation used in this analysis and the (f_{gi}, ϕ_{gi}) parameterisation is given by Eq. (13) rewritten in the following way:

$$f_{g_i} = \frac{r_{i1}^2}{1 + r_{i1}^2}; \quad (i = 2, 4), \tag{14}$$

where r_{41} and r_{21} are chosen such that:

$$r_{21}^2 = \frac{\sigma_{HVV}}{\sigma_{\rm SM}}\left(\frac{\tilde{k}_{HVV}}{k_{\rm SM}}\right)^2, \quad \text{and} \quad r_{41}^2 = \frac{\sigma_{AVV}}{\sigma_{\rm SM}}\left(\frac{\tilde{k}_{AVV}}{k_{\rm SM}}\right)^2 \tan^2\alpha. \tag{15}$$

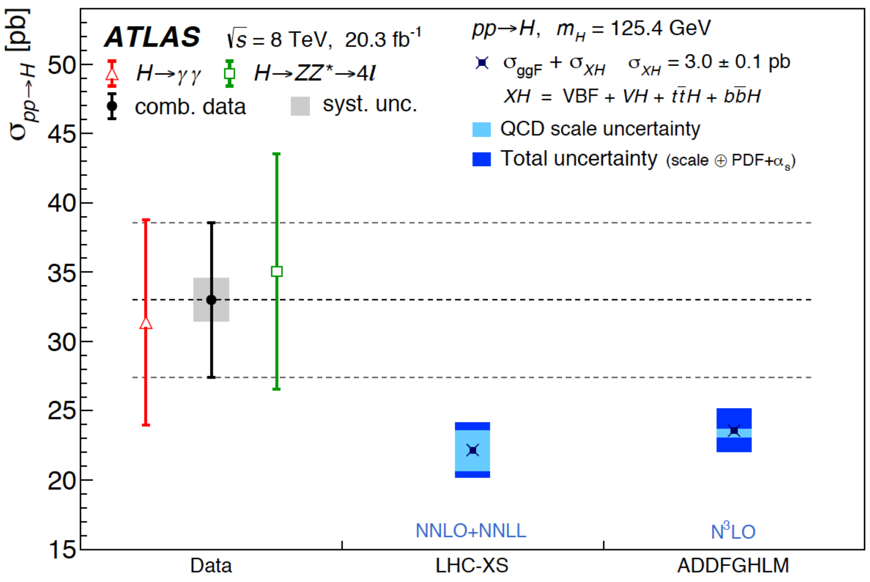
The numeric coefficients $\sigma_{\rm SM}, \sigma_{HVV}$ and σ_{AVV} are effective cross sections of the HVV interaction calculated when only each of the $\kappa_{\rm SM}$-, κ_{HVV}- and κ_{AVV}-related terms is present in the Lagrangian.

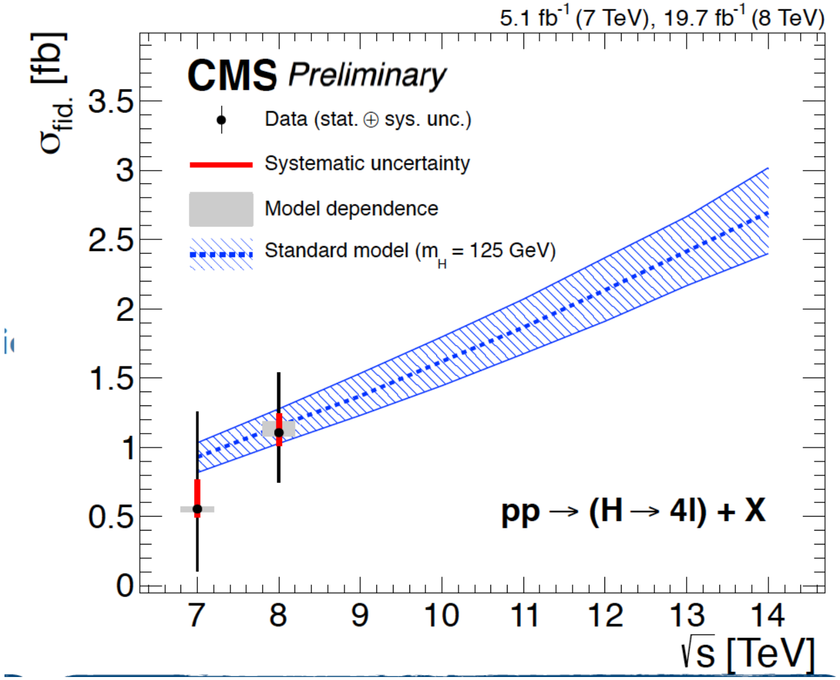
Higgs boson cross-sections - I

Measurement of total and fiducial cross-sections

ATLAS → combination of γγ and 4l to get σ(pp→H) total c-s

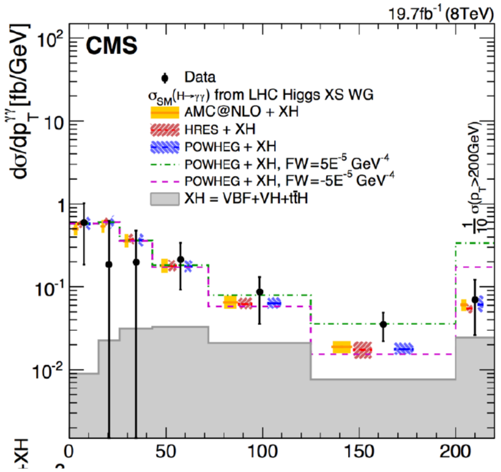
CMS → fiducial σ(pp→H→4l) compared to SM

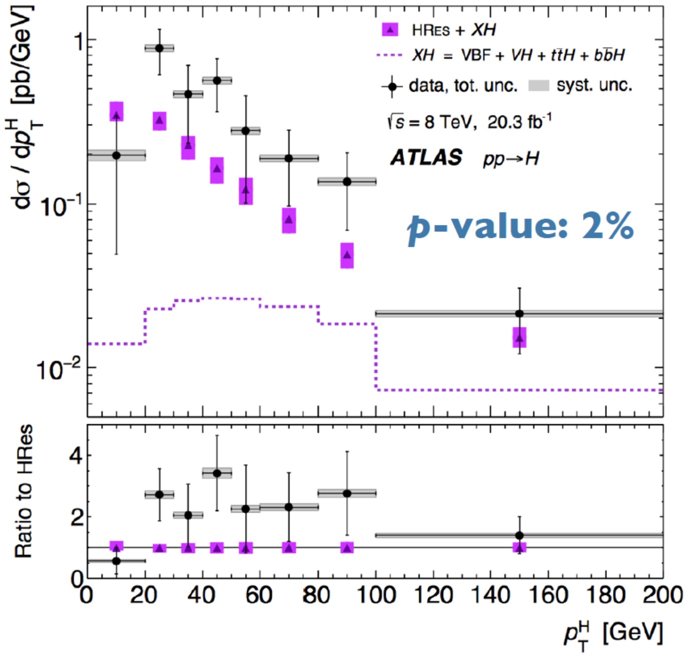




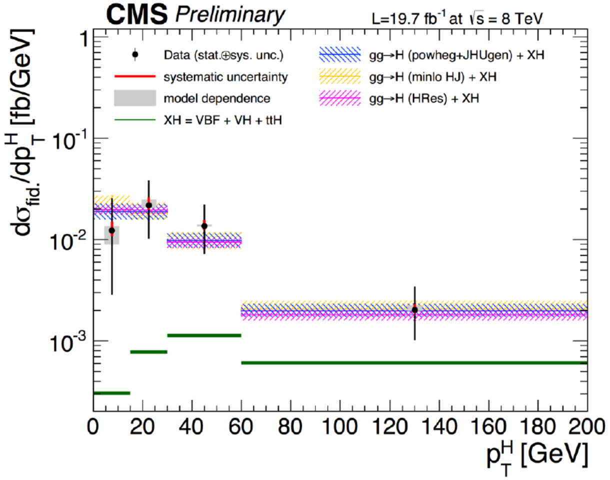
Higgs boson cross-sections - II

Differential cross-sections
(vs. $\mathbf{p_T^H}$, $\mathbf{y^H}$, $\mathbf{p_T^{j1}}$, $\mathbf{N_{jets}}$) sensitive to QCD, PDFs,…
Still statistic-limited.



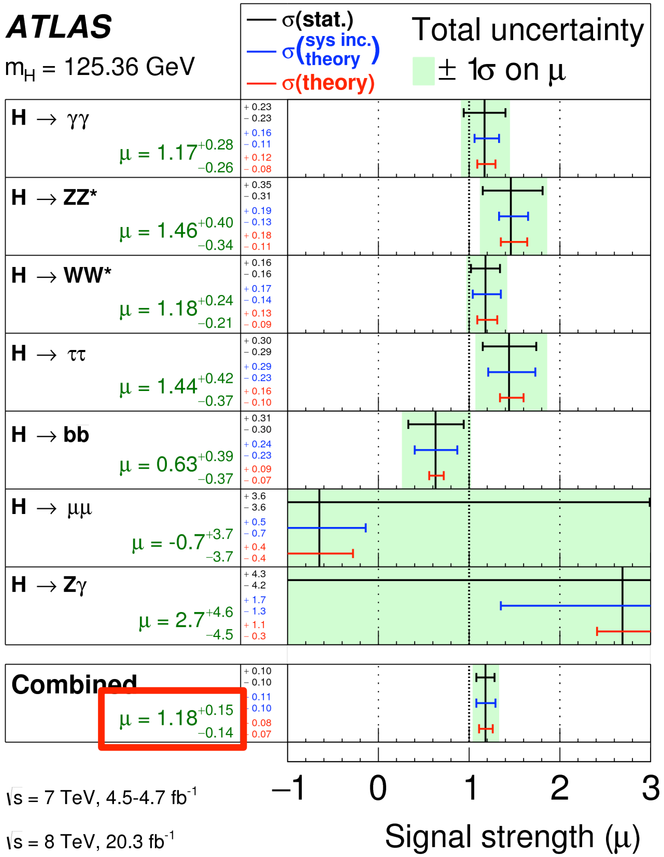


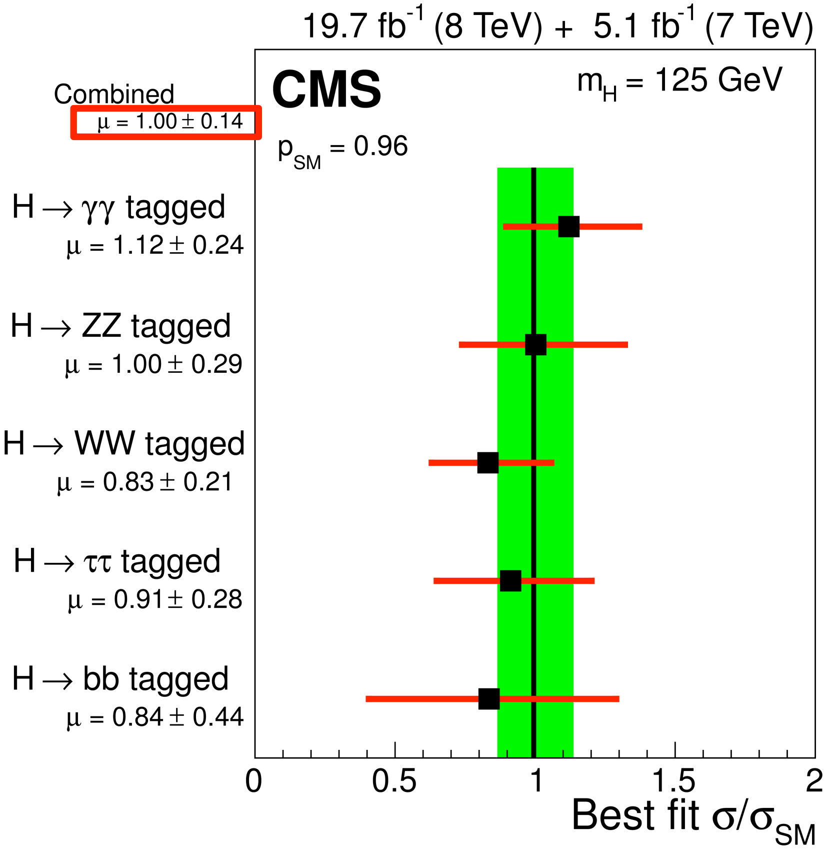
p-value: 2%



Higgs boson couplings
Decay signal strengths

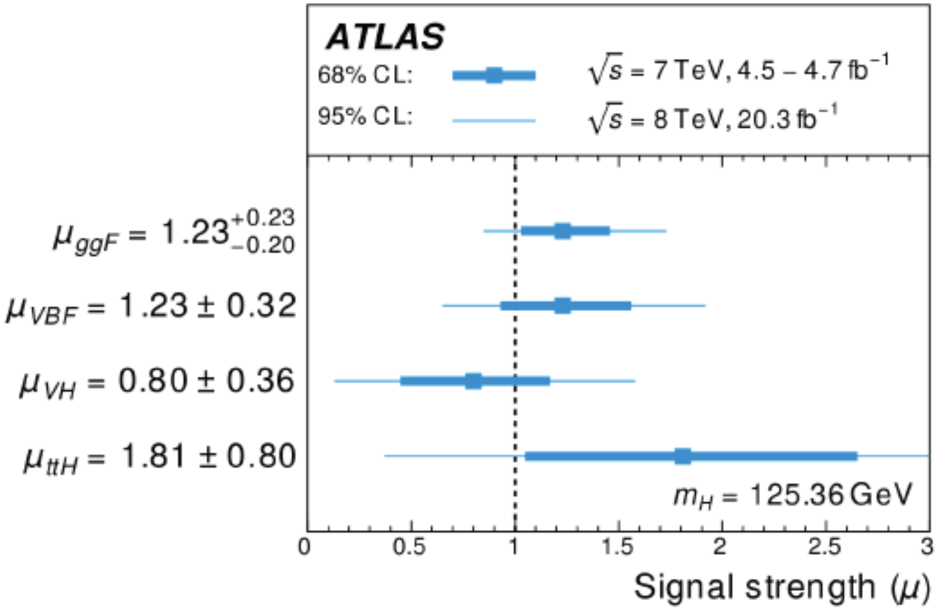
Global fits of the decay signal strengths μ_f (assuming μ_i=1)

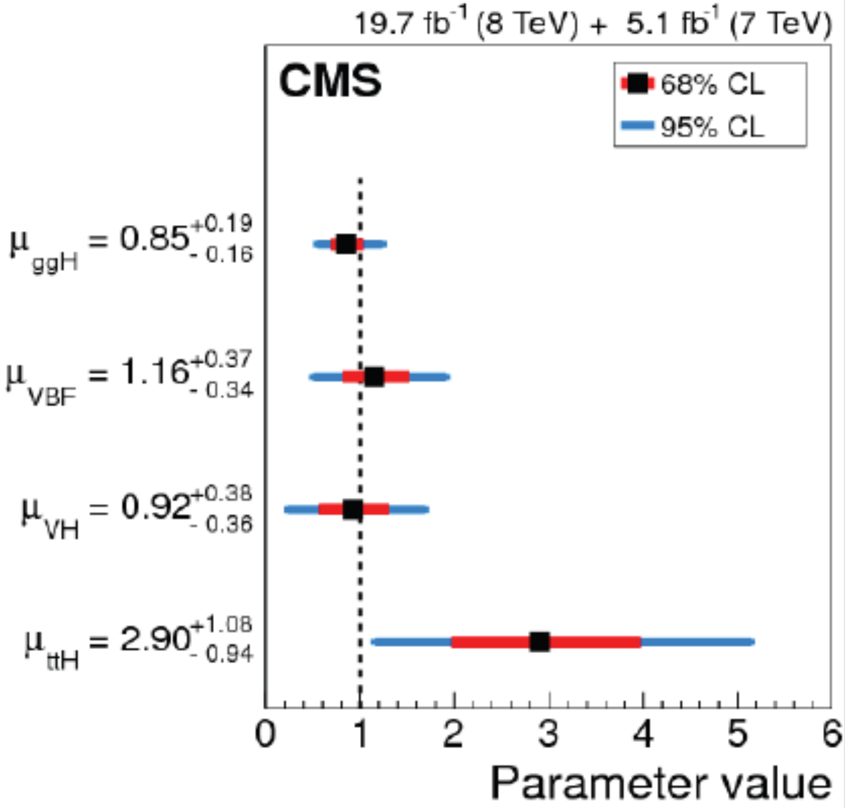




Higgs boson couplings
Production signal strengths

Global fits of the production signal strengths μ_i (assuming μ_f=1)

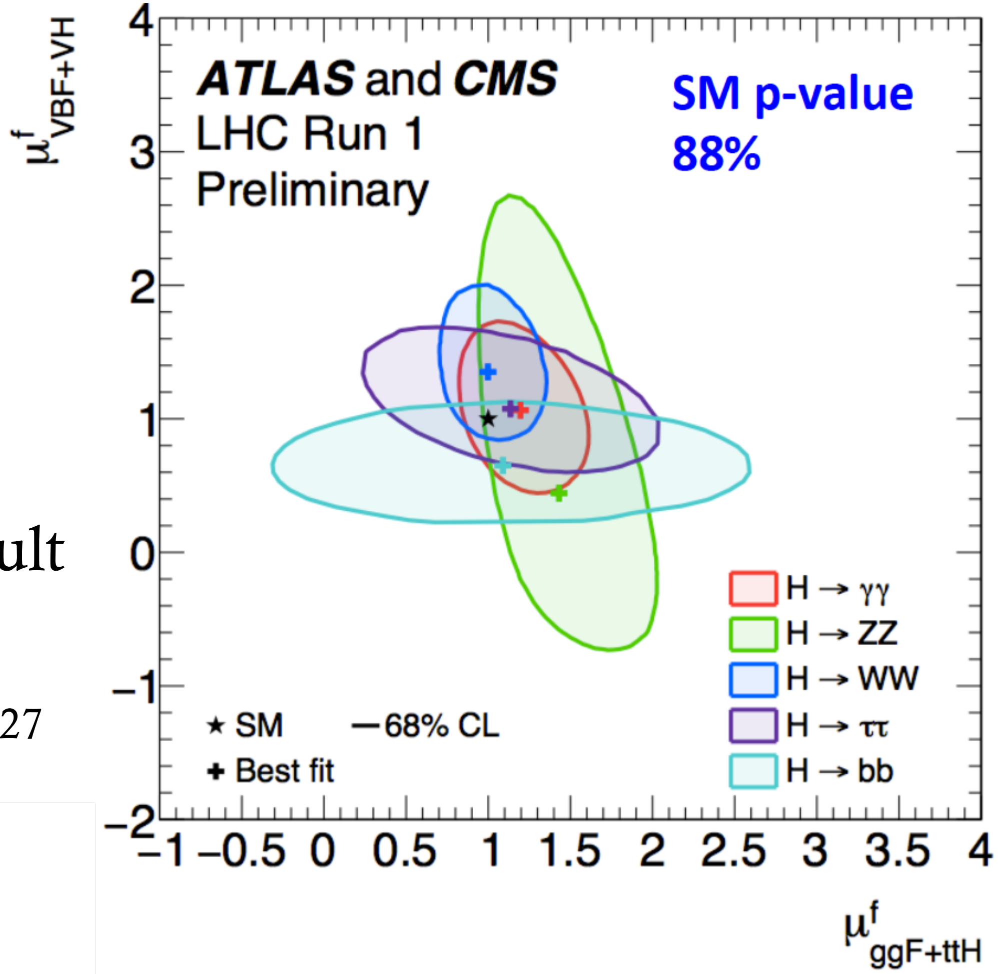




Higgs boson signal strengths: Vector vs. Fermions

ATLAS+CMS result

$\mu_V/\mu_F=1.06^{+0.35}_{-0.27}$



Coupling parameterization

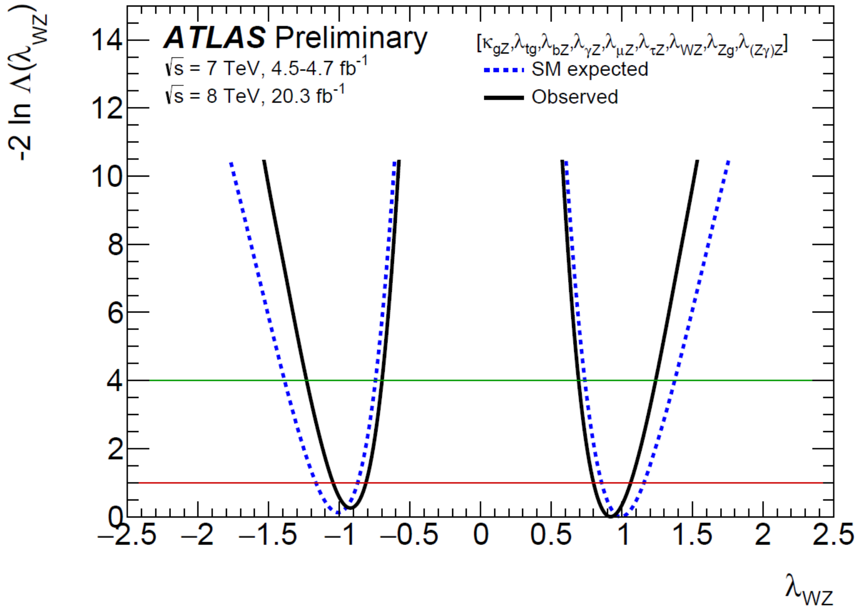
Production	Loops	Interference	Expression in fundamental coupling-strength scale factors
$\sigma(\text{ggF})$	✓	b–t	$\kappa_g^2 \sim 1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$
$\sigma(\text{VBF})$	-	-	$\sim 0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	-	-	$\sim \kappa_W^2$
$\sigma(q\bar{q} \to ZH)$	-	-	$\sim \kappa_Z^2$
$\sigma(gg \to ZH)$	✓	Z–t	$\kappa_{ggZH}^2 \sim 2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t$
$\sigma(bbH)$	-	-	$\sim \kappa_b^2$
$\sigma(ttH)$	-	-	$\sim \kappa_t^2$
$\sigma(gb \to WtH)$	-	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			
$\Gamma_{b\bar{b}}$	-	-	$\sim \kappa_b^2$
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	✓	$W - t$ $b - t$	$\kappa_H^2 \sim$ $0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 +$ $0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 +$ $0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{Z\gamma}^2 + 0.00022 \cdot \kappa_\mu^2$

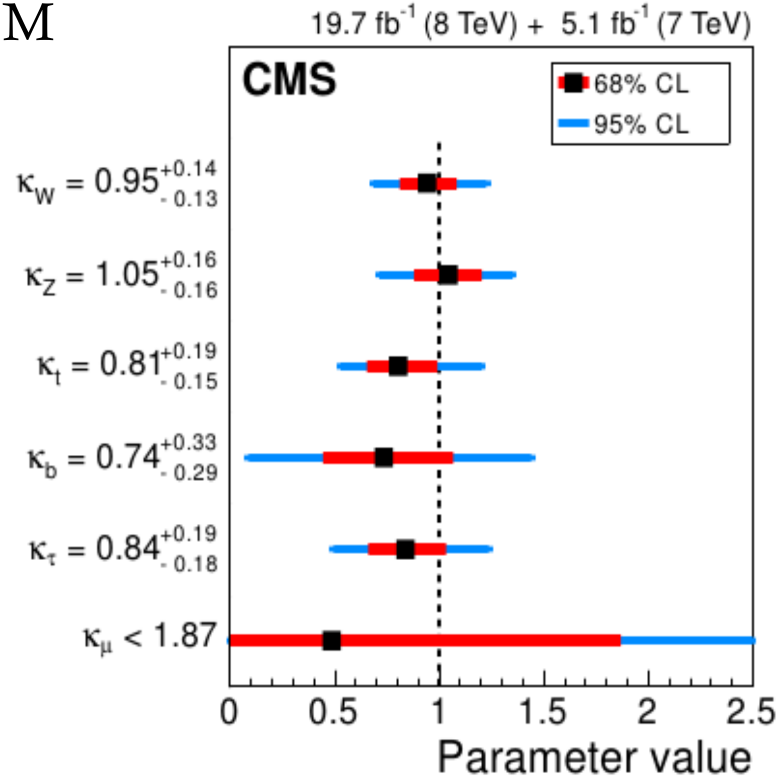
Higgs boson couplings
Additional fits

Other approaches:

“Custodial symmetry fit” $\lambda_{WZ} = \kappa_W/\kappa_Z$

“Fit *almost* without assumptions”: all SM particles move in the loops..



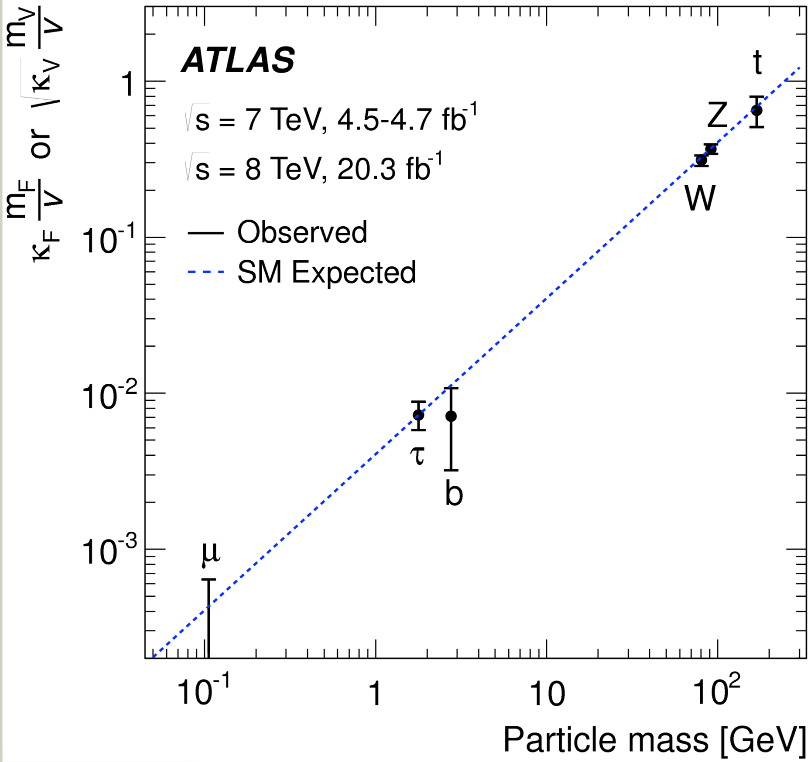


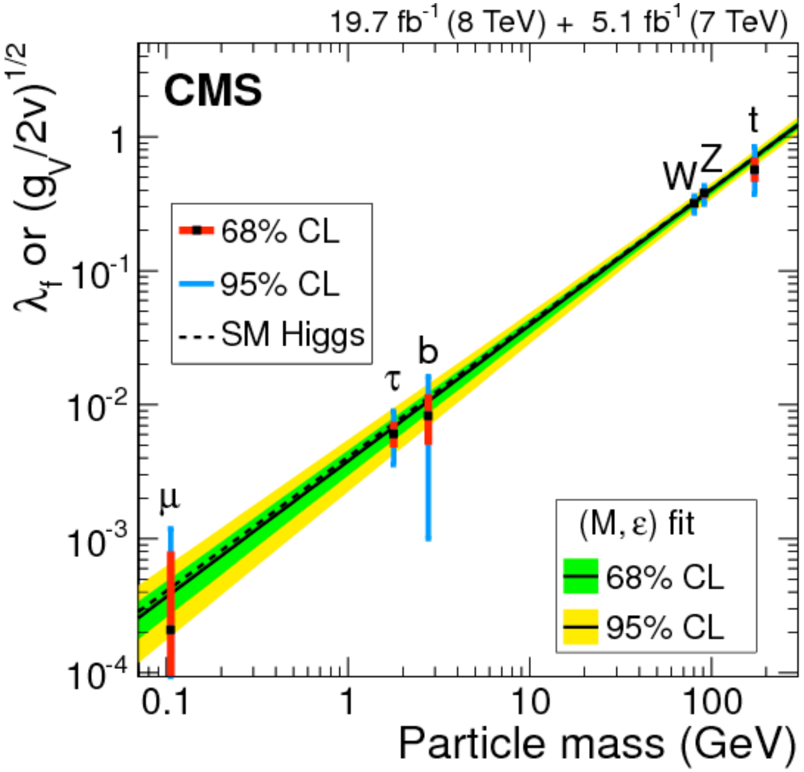
Higgs boson couplings
Couplings vs. Mass

Higgs coupling scaling with mass: vector bosons V
fermions F

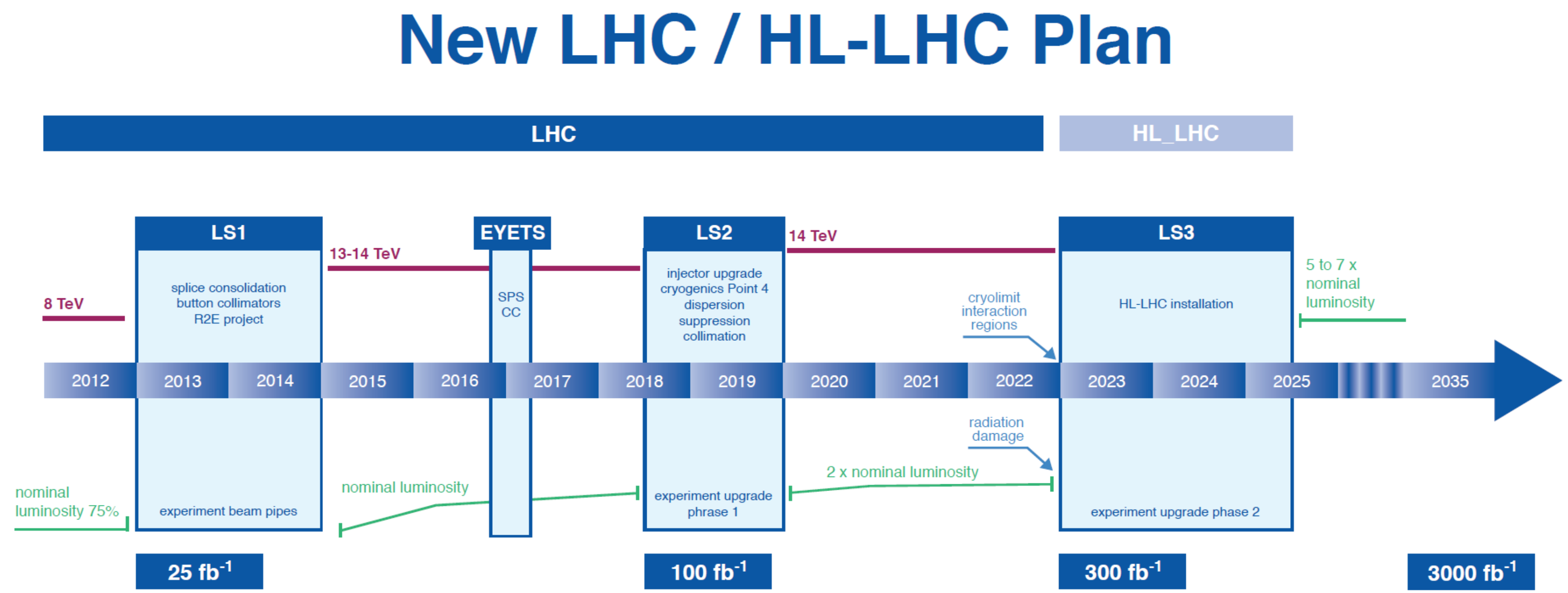
$$y_{V,i} = \sqrt{\kappa_{V,i}\frac{g_{V,i}}{2v}} = \sqrt{\kappa_{V,i}}\frac{m_{V,i}}{v}$$

$$y_{F,i} = \kappa_{F,i}\frac{g_{F,i}}{\sqrt{2}} = \kappa_{F,i}\frac{m_{F,i}}{v}$$





LHC and HL-LHC timeline



- 2015 $\sqrt{s}$ = 13 TeV – 10 fb^{-1}
- 2015-2018 $\sqrt{s}$ = 13-14 TeV – 100 fb^{-1}
- 2020-2022 $\sqrt{s}$ = 14 TeV – 300 fb^{-1}
- 2025-2033 $\sqrt{s}$ = 14 TeV – 3000 fb^{-1}

- Discussion on the update of this schedule is ongoing
- A new version has not officially announced yet

Expected precision on signal strength

channel	Prec. (%) 100 fb^{-1}	Prec. (%) 300 fb^{-1}		Prec. (%) 3000 fb^{-1}	
ttH H→γγ	~65	38	36	17	12
ttH H→ZZ*→4l	~85	49	48	20	16
VBF H→γγ	~80	47	43	22	15
VBF H→ZZ*→4l	~60	36	33	21	16
H→μμ	~70	39	38	16	12
H→ττ	~18	14	8	8	5
H→bb	~20	14	11	7	5
H→γγ	~15	12	6	8	4
H→4l	~15	11	7	9	4
H→4l	~15	11	7	7	4

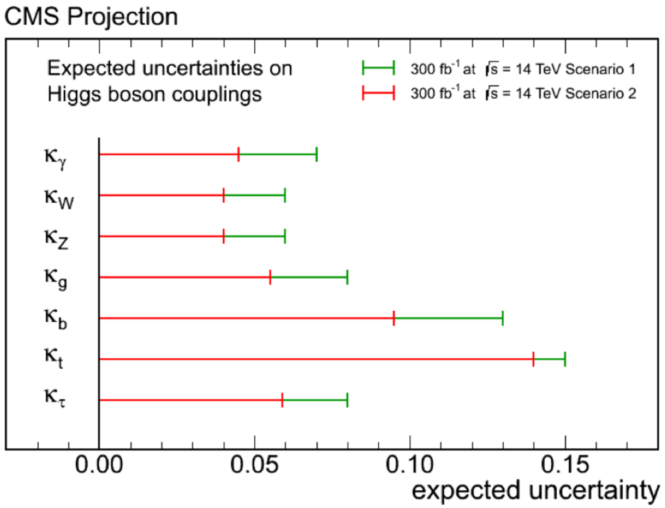
ATLAS: experimental & theory uncertianties; only exp. uncertainty

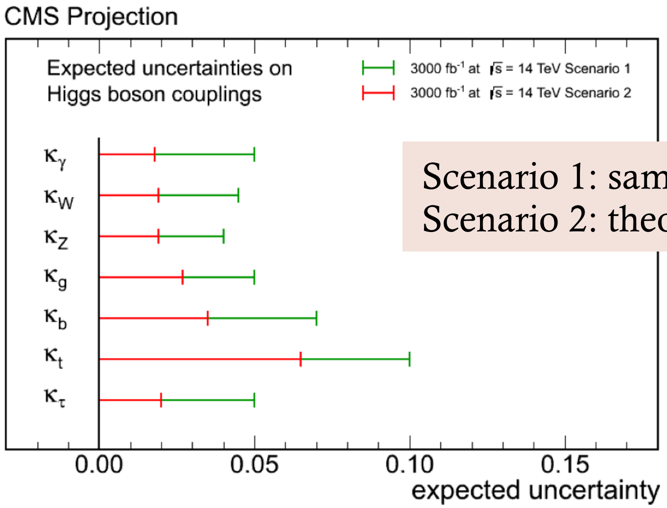
CMS: current exp.l & theory uncertianties; exp. unc. ∝ 1/√L and ½ theory unc.

Expected precision on coupling modifiers with L=300 and 3000 fb^{-1}

Coupling modifier	300 fb^{-1}	3000 fb^{-1}	
$k_{W,Z}$, $k_{\gamma,}$	6%	3%	
k_b	12%	5%	down-quark type
k_t	15%	7%	Top Yukawa coup.
k_τ	10%	5%	lepton coupling
k_μ	22%	8%	2nd generation

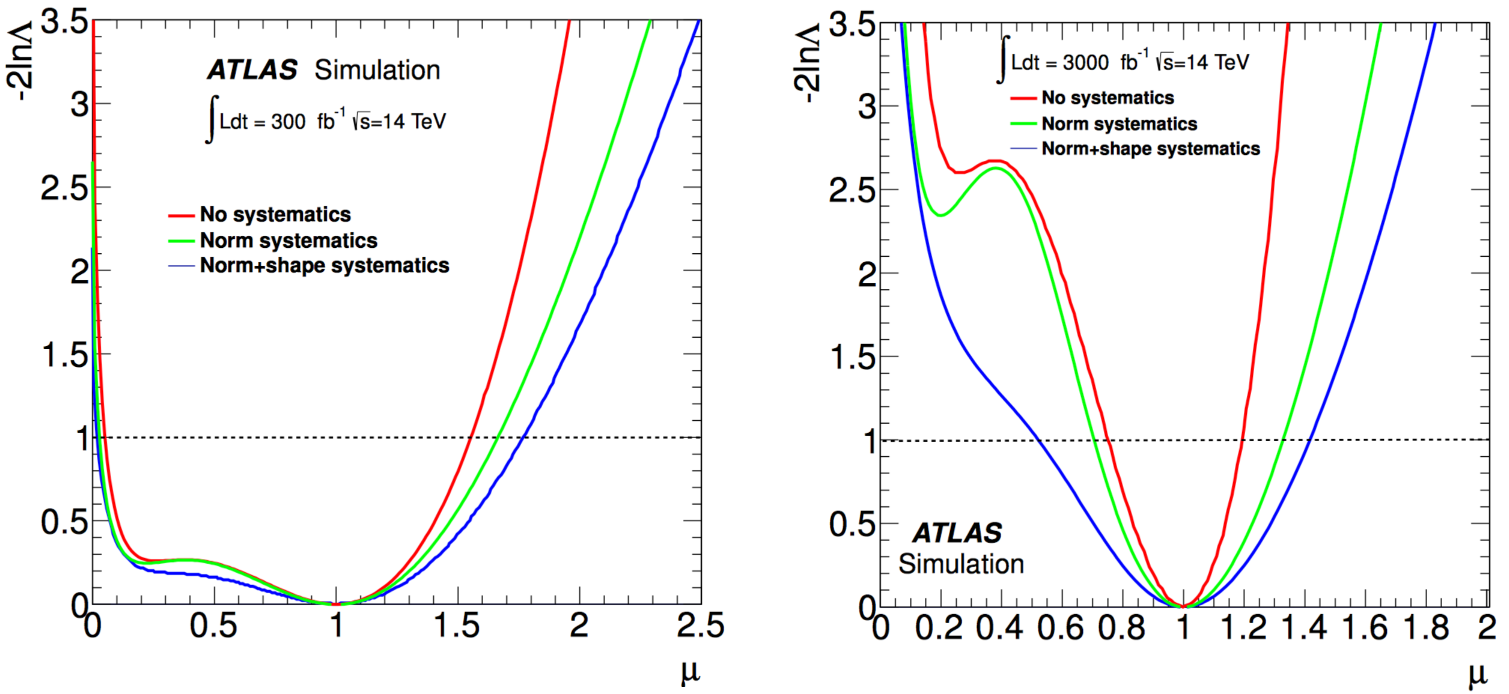
Per experiment





Scenario 1: same theo erro
Scenario 2: theo error/2

Higgs width at HL-LHC



$$\Gamma_H^{(L2)} = 4.2^{+1.5}_{-2.1}\ \text{MeV (stat+sys).}$$