Higgs quantum numbers and couplings

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On behalf of the ATLAS and CMS collaborations

Bibliography

ATLAS:

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults

Phys.Lett. B 716 (Discovery)

arXiv:1307.1432 Sub. Phys. Lett. B (Spin)

arXiv:1307.1427 Sub. Phys. Lett. B (Couplings)

ATLAS-CONF-2013-040 (Spin)

ATLAS-CONF-2013-029 ($\gamma\gamma$)

ATLAS-CONF-2013-031 (WW*)

ATLAS-CONF-2013-013 (ZZ*)

ATLAS-CONF-2013-079 (VH → bb)

ATLAS-PHYS_PUB 2012-001/002 (HL-LHC)

CMS:

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG

Phys.Lett. B 716 (Discovery)

arXiv:1212.6639 Phys. Rev. Lett. 110 (ZZ*, Spin)

CMS-PAS-HIG-13-016 (Properties $\gamma\gamma$)

CMS-PAS-HIG-13-018 (ZH →Z-invisible)

CMS-PAS-HIG-13-005 (Couplings)

CMS-PAS-HIG-13-012 (H → bb)

CMS-PAS-HIG-13-001 ($\gamma\gamma$)

CMS-PAS-HIG-13-002 (ZZ*, spin)

CMS-PAS-HIG-13-003 (WW*)

CMS-PAS-HIG-13-004 ($\tau\tau$)

CMS-NOTE-2012-006 (HL-HLC)

LHC Higgs Cross Section WG:

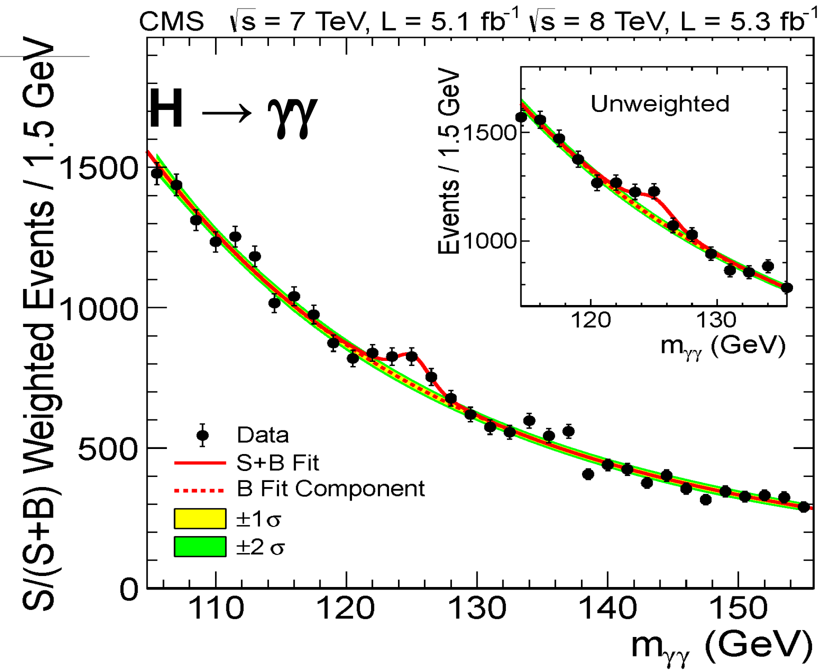
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections

arXiv: 1307.1347 (Yellow Report III: σ, BR, coupling and spin/CP model)

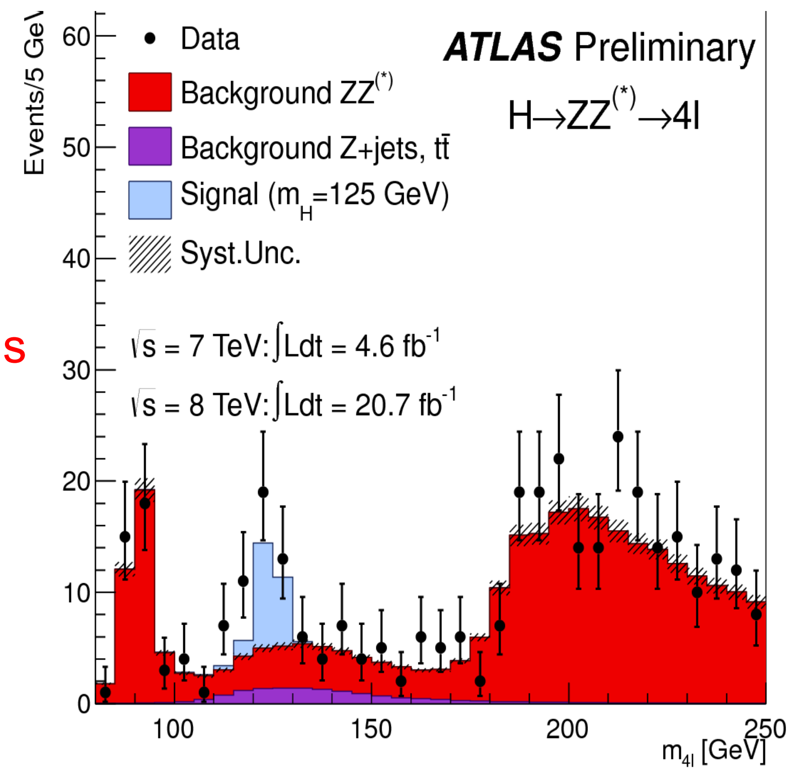
Introduction

The ATLAS and CMS experiments have unequivocally discovered a new neutral boson of mass ~ 125 GeV

Measuring its properties is a fundamental step to determine its nature



- Signal strengths
- Couplings (to fermions and bosons)
- Quantum numbers (Spin and Parity)



Events are categorized:
- by decay mode
- by additional tags to isolate specific production mechanisms (although purities of the tagged samples varies)

→ help with determination of properties and test of SM

Will not discuss details of the input analysis: see talks by J. Branson and R. Madar

Higgs Signal Strength

The procedure

- Construct a likelihood of Poisson probabilities, with expected numbers of events:

$$N^k = n^k_{\text{signal}} + n^k_{\text{background}}$$

- For the analysis *k*, signal scaling factors per production *i* and decay *f*

$$n^k_{\text{signal}} = \left(\sum_i \mu_i \sigma_{i,\text{SM}} \times A^k_{if} \times \varepsilon^k_{if}\right) \times \mu_f \times B_{f,\text{SM}} \times \mathcal{L}^k$$

Cross section modifier $\mu_i = \sigma_i / \sigma_{i,\text{SM}}$

Branching ratio modifier $\mu_f = BR_f / Br_{f,\text{SM}}$

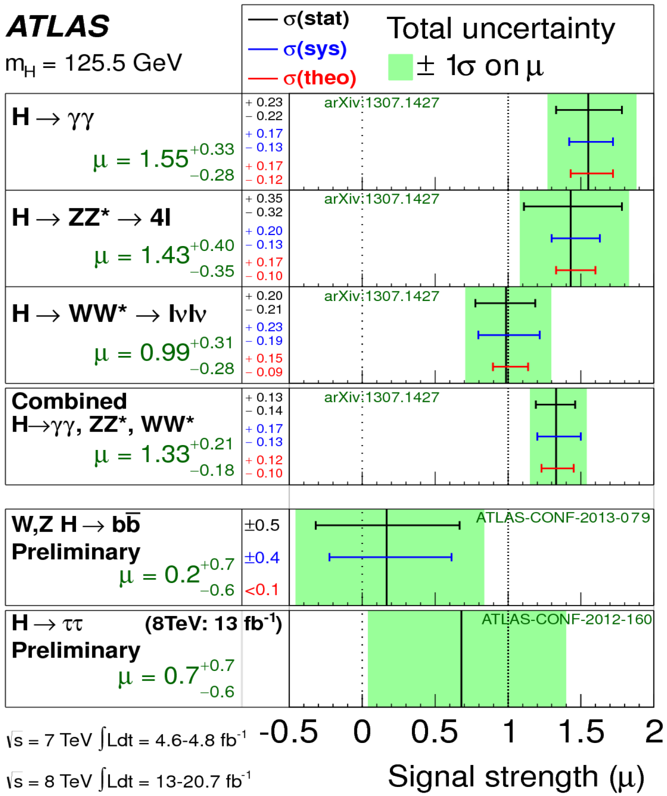
- Test hypothesized values of parameter of interest μ with profiled likelihood ratio:

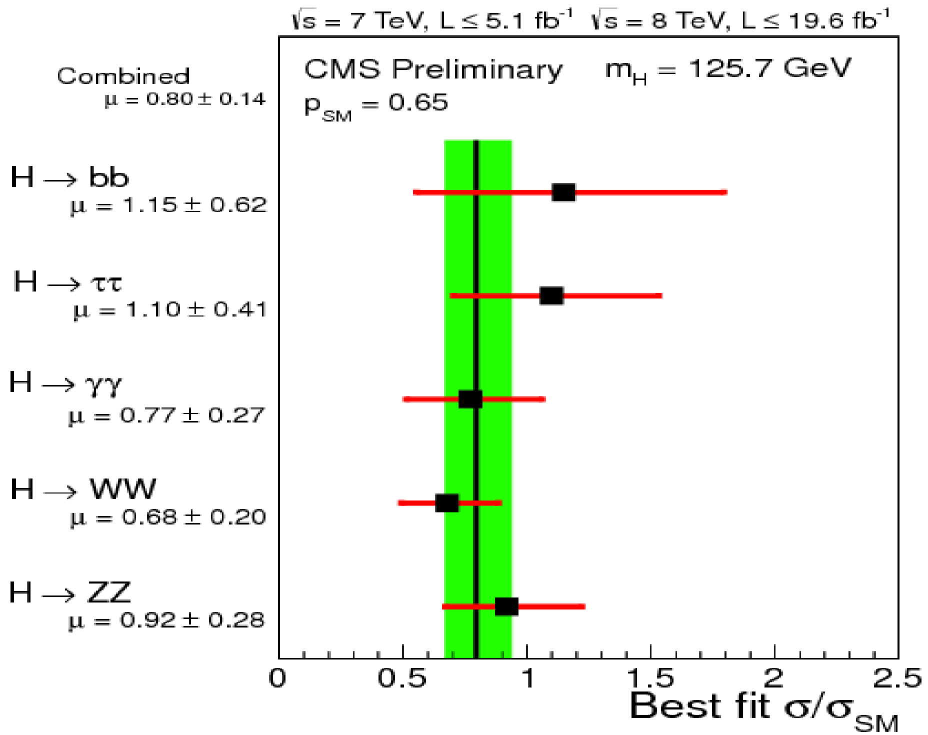
Maximized likelihood for a fixed μ

$$q_\mu = -2\,\Delta \ln \mathcal{L} = -2 \ln \frac{\mathcal{L}(\text{data} \mid \mu, \hat{\theta}_\mu)}{\mathcal{L}(\text{data} \mid \hat{\mu}, \hat{\theta})}$$

μ and θ that maximize likelihood

The Signal Strength modifier μ





Signal strength μ to test compatibility with bkg-only ($\mu = 0$) and SM ($\mu = 1$) hypothesis

Combined μ → best accuracy, test global compatibility with the SM

- **ATLAS** (γγ, WW* and ZZ*) $\mu = 1.33^{+0.21}_{-0.18}$ ($\mu = 1.23^{+0.18}_{-0.18}$ including bb and ττ)
- **CMS** (γγ,bb, ττ, WW* and ZZ*) $\mu = 0.80^{+0.14}_{-0.14}$

Compatible with the SM Higgs boson expectation at 15% level

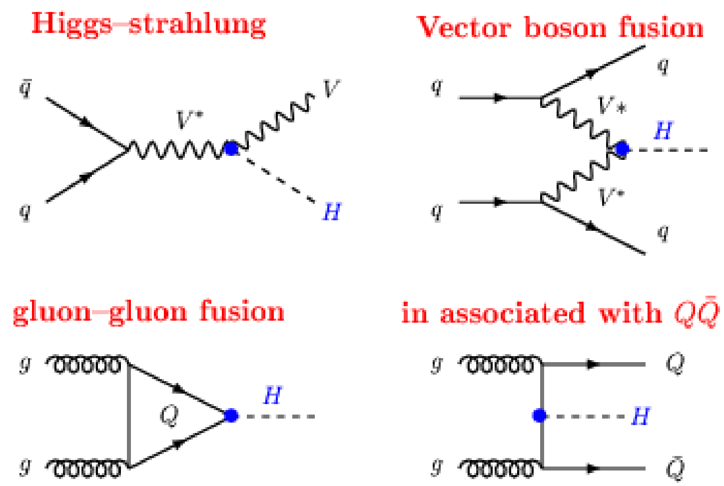
Production mechanism and decay modes

σ (qq → VH) = 1.1 pb (5%)

Depending on the V decay mode, extra leptons or jets present in the event

σ (gg → H) = 19.2 pb (88%)

No extra jets at tree level, can be present at higher order



σ (VBF) = 1.57 pb (6.6%)

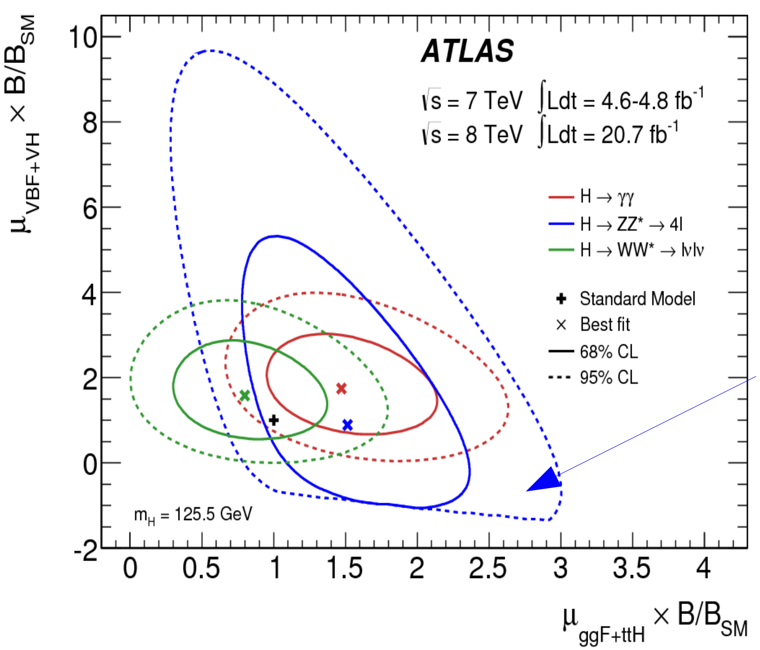
At least two high pt jets with large |Δη|

σ (gg → ttH) = 0.13 pb (0.4%)

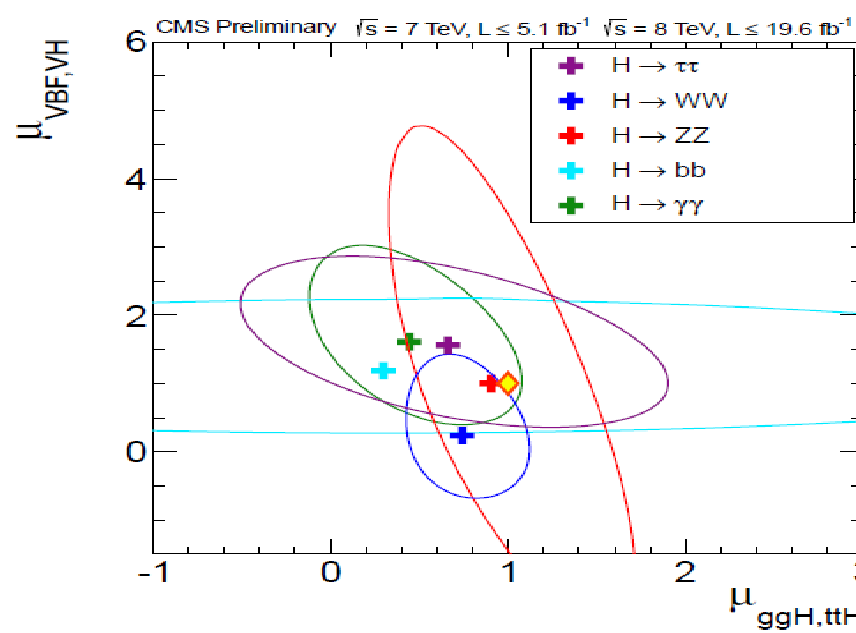
High jet multiplicity, presence of b-tagged jets

Events categorization enhance sensitivity to signal strength of individual production mechanism

- Common ggF and ttH scale factor $\mu_{ggH+ttH}$ /Common μ_{VBF+VH} as VBF and VH scale with WH/ZH gauge coupling



Sharp lower edge: due to the small number of events in H → ZZ → 4l and the requirement of a positive pdf*



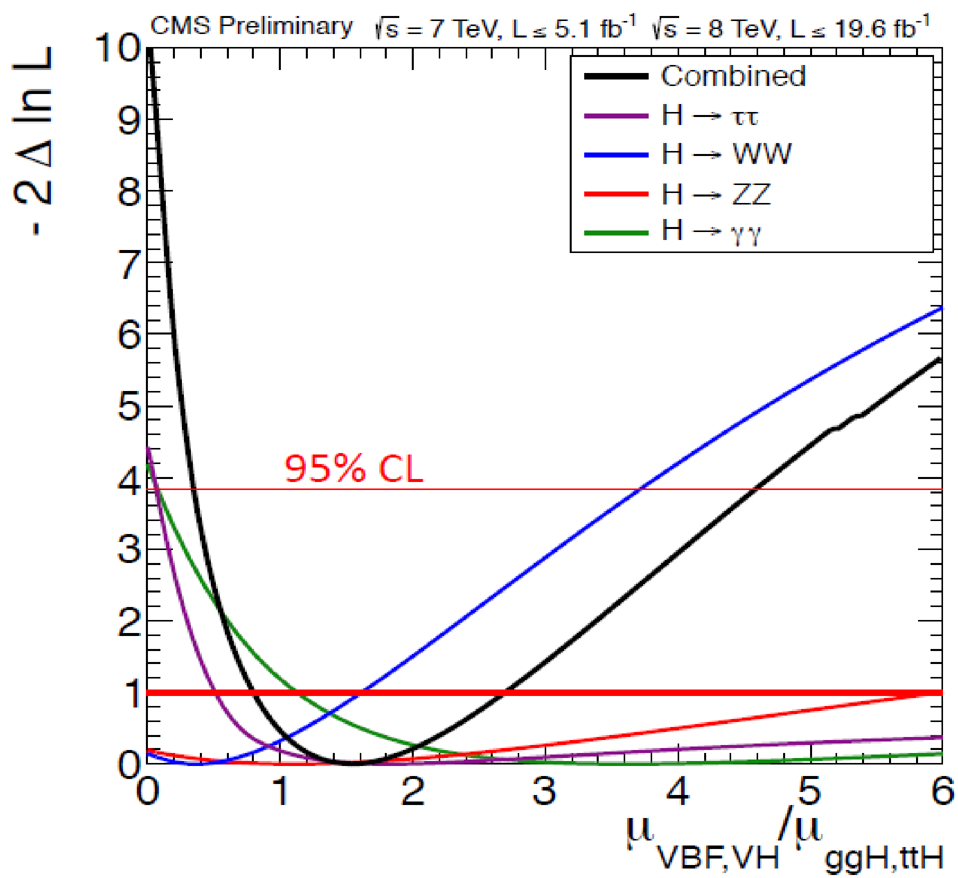
ATLAS: Consistent with SM inside 95% contours **CMS:** Consistent with SM inside 65% contours

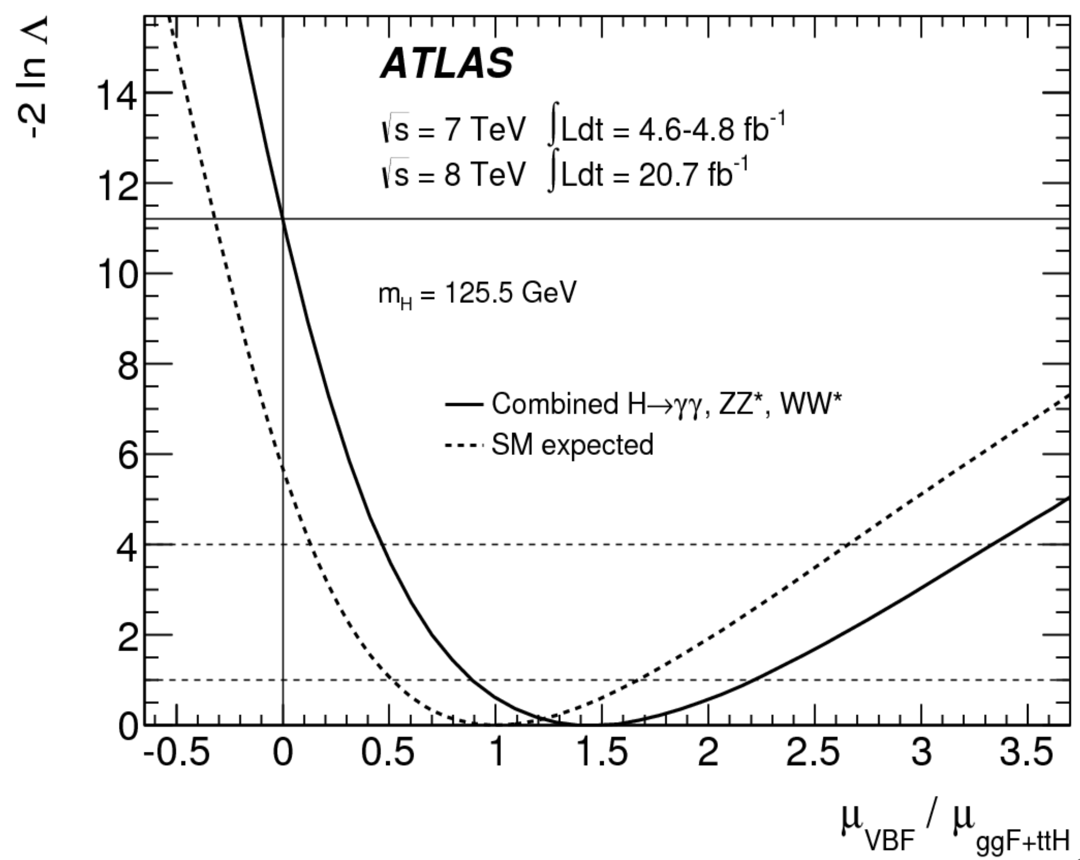
Evidence for VBF and VH production

Combine results from separate decay mode to disentangle production modes:
Fit to $\mu_{VBF+VH}/\mu_{ggH+ttH}$ in different channels (independent on Branching Ratios)

- **CMS** : Evidence for VBF+VH production **3.2σ**
- **ATLAS**: Evidence for VBF production (VH 'profiled') **3.3σ**

VBF and VH production compatible with SM prediction





Couplings

A coherent framework for couplings determination

Crucial test of SM Higgs model : **$g_{W,Z,H} \propto M^2_{W,Z,H}$ and $g_F \propto m_F$**

arXiv1307.1347 (YR3)

Both ATLAS and CMS follow recommendation from LHC Higgs cross section working group:
- to either confirm or establish deviation from SM behavior
- model suitable to test SM predictions using correlation among production and decay modes

Assume:
- One single resonance at m_H = 125 GeV
- Narrow width approximation.
- Consider only modification to coupling strength. Assume Tensor structure of CP even scalar (SM)

$$(\sigma \cdot BR)(ii \to H \to ff) = \frac{(\sigma_i \cdot \Gamma_f)}{\Gamma_H}$$

SM modifiers

production

$$\kappa_i^2 = \frac{\sigma_i}{\sigma_i^{SM}}$$

decay

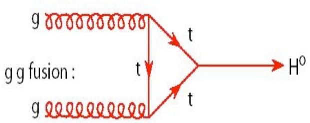
$$\kappa_i^2 = \frac{\Gamma_i}{\Gamma_i^{SM}}$$

Total width

$$\kappa_H^2 = \frac{\Gamma_H}{\Gamma_H^{SM}}$$

- Not observable (SM: ~4 MeV)
- Impose external constraints. Two options:
  - No invisible decays: $\kappa_H^2 \sim 0.75\ \kappa_F^2 + 0.25\ \kappa_V^2$
  - Measure ratios of couplings λ

SM modifiers



Production modes

$$\frac{\sigma_{ggH}}{\sigma_{ggH}^{SM}} = \begin{cases} \kappa_g^2(\kappa_b, \kappa_t, m_H) \\ \kappa_g^2 \end{cases}$$

$$\frac{\sigma_{VBF}}{\sigma_{VBF}^{SM}} = \kappa_{VBF}^2(\kappa_W, \kappa_Z, m_H)$$

$$\frac{\sigma_{WH}}{\sigma_{WH}^{SM}} = \kappa_W^2$$

$$\frac{\sigma_{ZH}}{\sigma_{ZH}^{SM}} = \kappa_Z^2$$

$$\frac{\sigma_{t\bar{t}H}}{\sigma_{t\bar{t}H}^{SM}} = \kappa_t^2$$

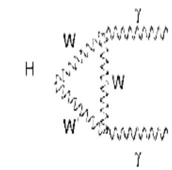
Detectable decay modes

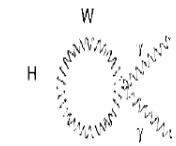
$$\frac{\Gamma_{WW^{(*)}}}{\Gamma_{WW^{(*)}}^{SM}} = \kappa_W^2$$

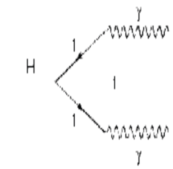
$$\frac{\Gamma_{ZZ^{(*)}}}{\Gamma_{ZZ^{(*)}}^{SM}} = \kappa_Z^2$$

$$\frac{\Gamma_{b\bar{b}}}{\Gamma_{b\bar{b}}^{SM}} = \kappa_b^2$$

$$\frac{\Gamma_{\tau^-\tau^+}}{\Gamma_{\tau^-\tau^+}^{SM}} = \kappa_\tau^2$$







$$\frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{SM}} = \begin{cases} \kappa_\gamma^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_\gamma^2 \end{cases}$$

$$\frac{\Gamma_{Z\gamma}}{\Gamma_{Z\gamma}^{SM}} = \begin{cases} \kappa_{(Z\gamma)}^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_{(Z\gamma)}^2 \end{cases}$$

Total width

$$\frac{\Gamma_H}{\Gamma_H^{SM}} = \begin{cases} \kappa_H^2(\kappa_i, m_H) \\ \kappa_H^2 \end{cases}$$

- κ_W, κ_Z and κ_t present in production and decay mode
- for the undetectable decay mode, assume:
  $\kappa_{ss} = \kappa_{bb}$, $\kappa_{cc} = \kappa_{tt}$, $\kappa_{\mu\mu} = \kappa_{\tau\tau}$
- Loop induced couplings
  $\kappa_{\gamma\gamma}$, $\kappa_{Z\gamma}$ and can κ_g can be:
  - Left unresolved: model independent
  - κ_i (κ_b, κ_t, κ_W ...): SM driven (NLO QCD)

Example: $(\sigma \cdot BR)(gg \to H \to \gamma\gamma) = \sigma_{SM}(gg \to H) \cdot BR_{SM}(H \to \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$

SM Higgs boson: when κ compatible with 1

Custodial Symmetry

Custodial Symmetry: W and Z have identical couplings to the Higgs

Ratio of couplings is independent of assumption on the total width.

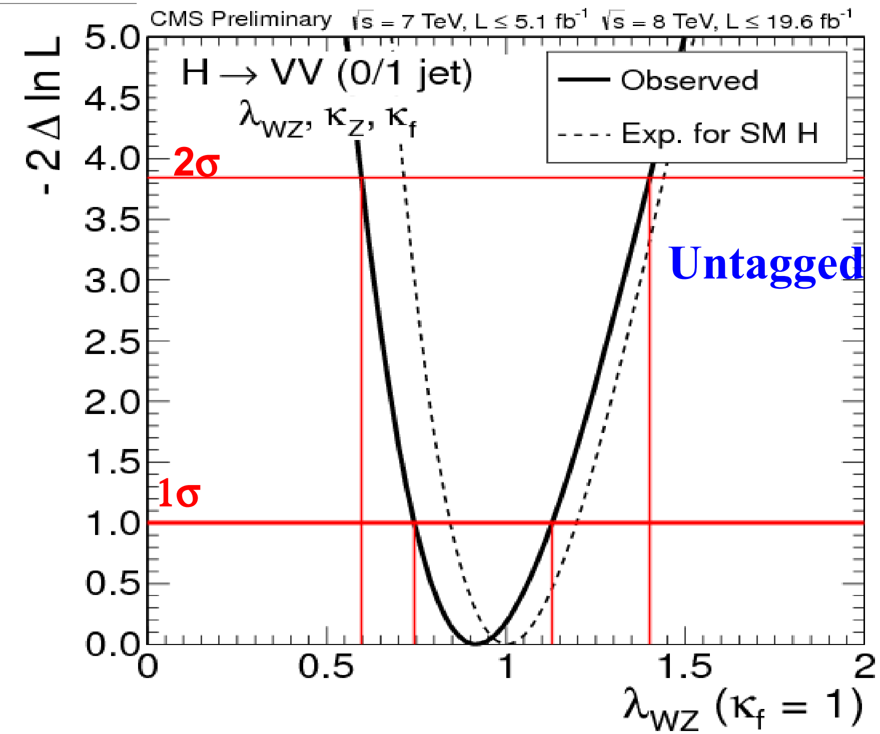
Test value of $\lambda_{WZ} = \kappa_W / \kappa_Z$

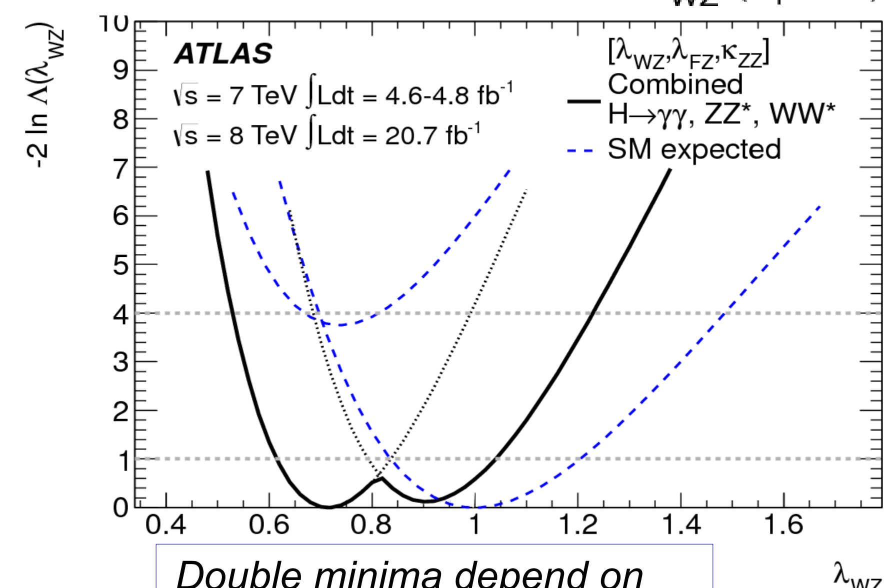
- More model independent: using only "untagged" WW* and ZZ* channels

- **CMS** : λ_{WZ} [0.60,1.40] at 95% CL
- **ATLAS**: λ_{WZ} =(0.81 ± 0.16) at 68% CL

-Assuming SM content in the $\gamma\gamma$ loop and using VBF+VH production

- **CMS** : λ_{WZ} [0.62,1.19] at 95% CL
- **ATLAS** : λ_{WZ} [0.61,1.04] at 68% CL

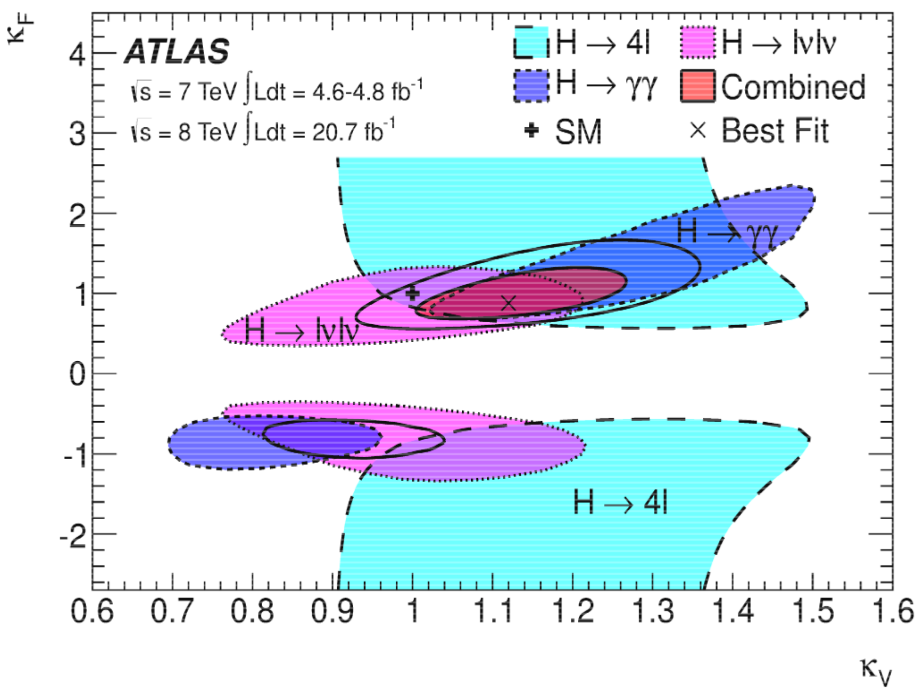


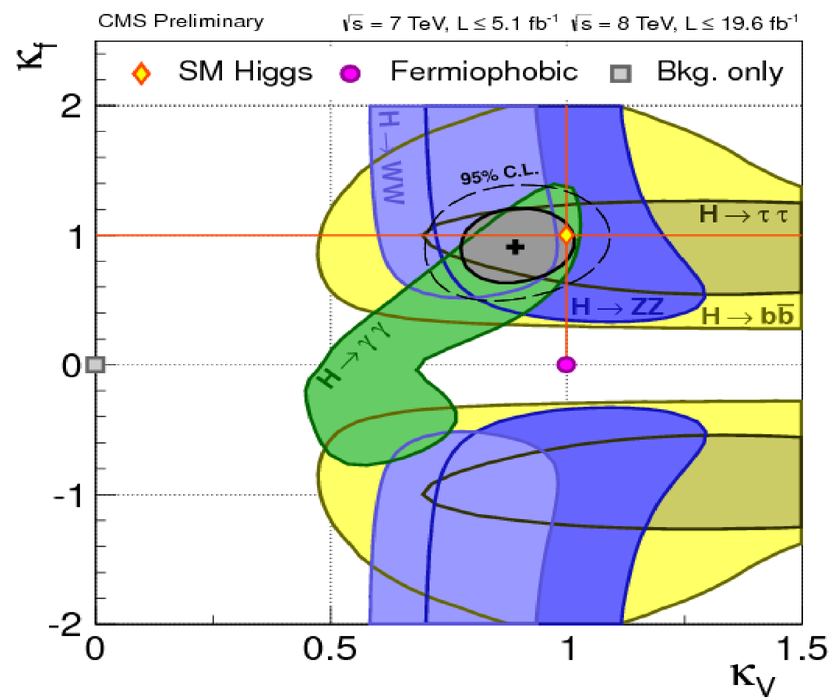


Double minima depend on ambiguity on the sign of λ_{FZ}

Vector versus Fermion Couplings

- All fermion couplings scale as $\kappa_F = \kappa_g = \kappa_\tau = \kappa_b = \kappa_t$
- All Vector Boson couplings scale as $\kappa_V = \kappa_W = \kappa_Z$
- No BSM contributions : $\kappa_H^2 \sim 0.75\,\kappa_F^2 + 0.25\,\kappa_V^2$





All experiments compatible with SM predictions at ~10-20%

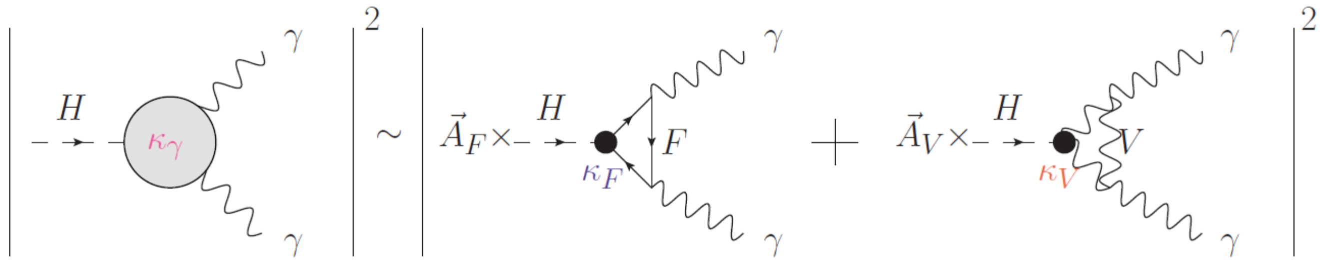
- **ATLAS**: κ_V [1.05,1.22] at 68% CL - κ_F [0.76,1.18] at 68% CL
- **CMS** : κ_V [0.74,1.06] at 95% CL - κ_F [0.61,1.33] at 95% CL

→ **κ_F = 0 excluded at > 5σ** (mainly indirectly via gg loop)

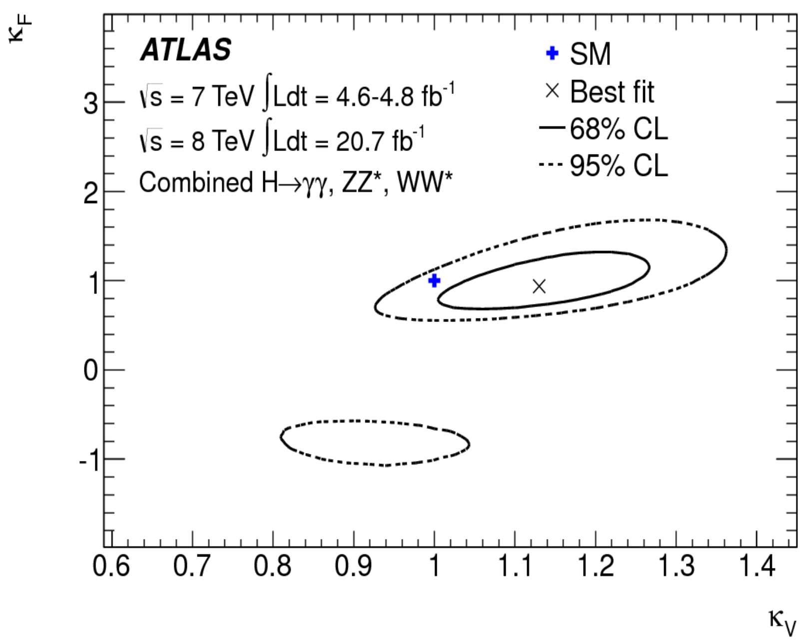
V/F interference in loops

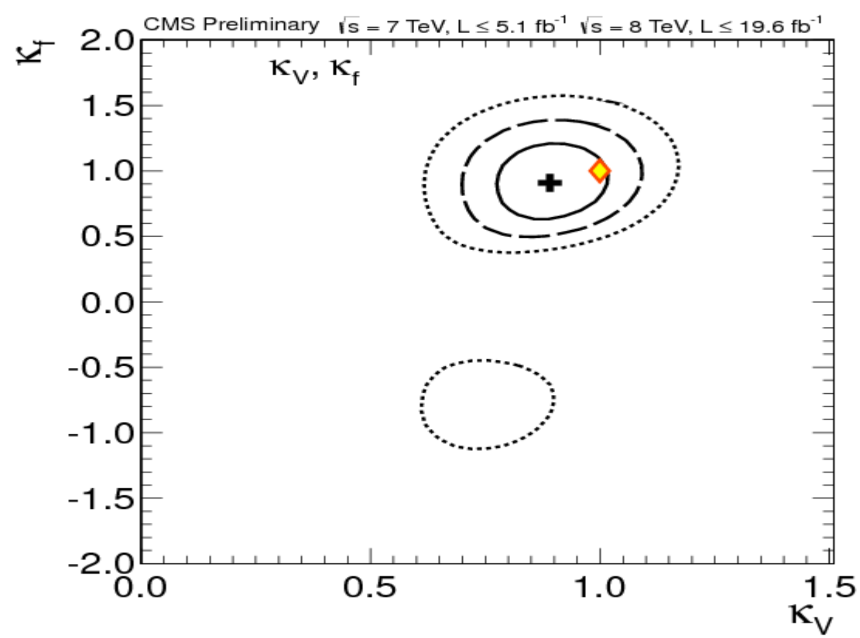
V/F interference in the γγ decay loop sensitive to relative sign of the κ_V - κ_F couplings

- assume κ_V positive, without loss of generality



$$\kappa_\gamma^2 \sim 0.07\,\kappa_F^2 - 0.66\,\kappa_F\kappa_V + 1.59\,\kappa_V^2$$



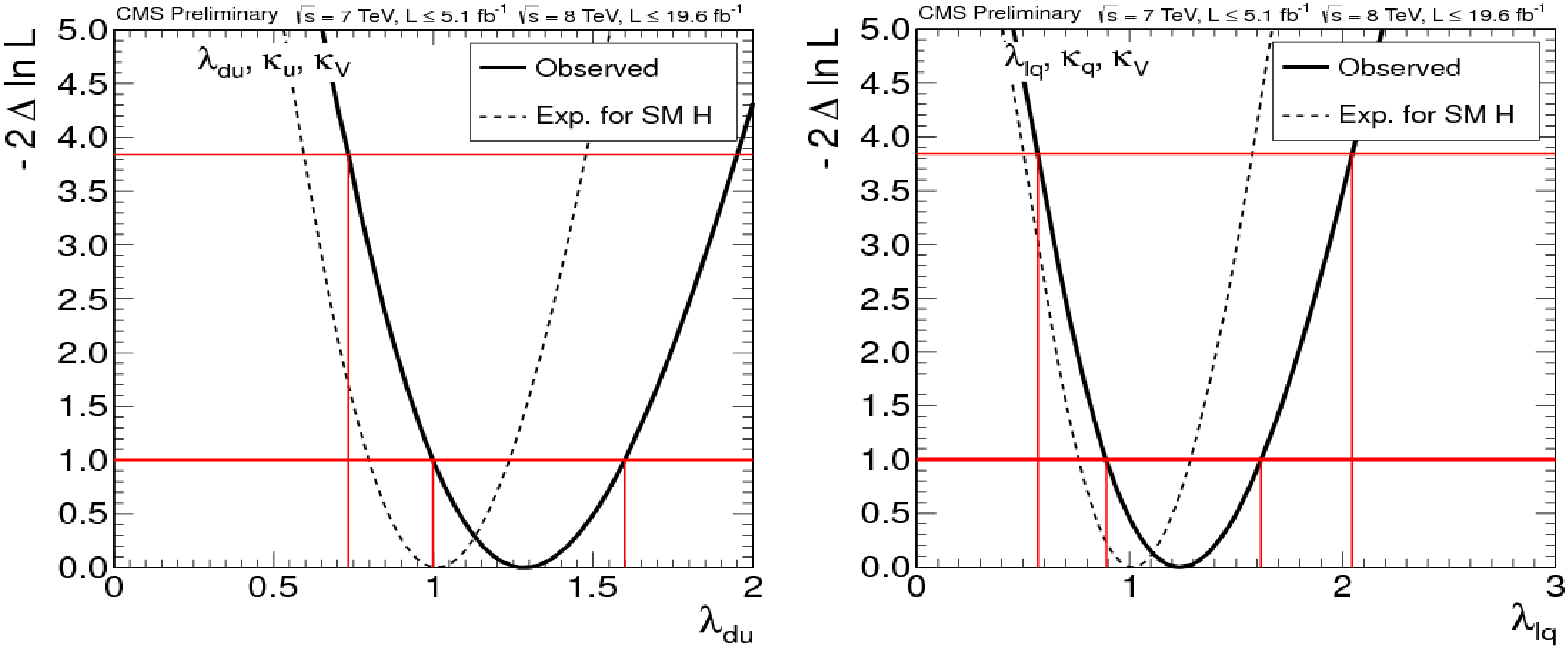


Data prefer a positive sign of (κ_V, κ_F), but negative sign is still compatible a ~2(3)σ level (ATLAS/CMS)

Probing fermionic couplings

CMS

- In extensions on SM, the Higgs couples differently to different types of fermions.
- Test:
  - ratio of couplings to down/up fermions: $\lambda_{du} = \kappa_d / \kappa_u$
  - ratio of couplings to leptons and quarks: $\lambda_{lq} = \kappa_l / \kappa_q$
- Assume Γ_{BSM} =0



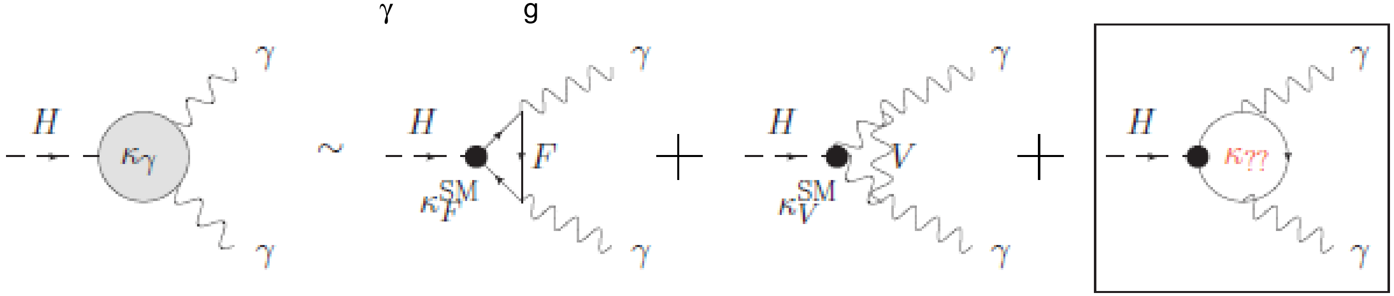
Both are constrained to be positive.

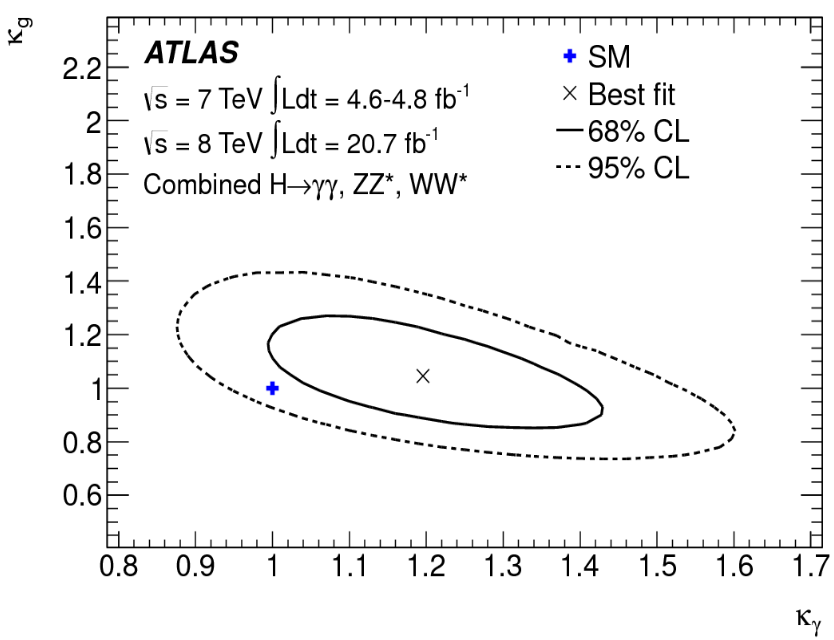
λ_{du} [0.74,1.95] at 95% CL

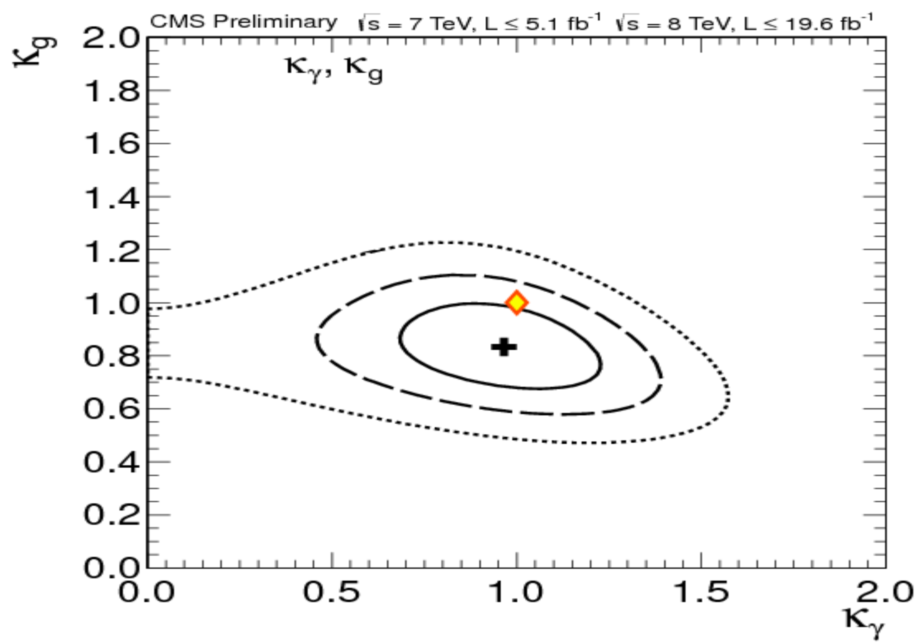
λ_{lq} [0.57,2.05] at 95% CL

New particles in the loops

- Fix all non-loop κ_i to SM value: $\kappa_V = \kappa_F = 1$
- Assume new particles do not contribute to Γ_H
- Directly measure effective κ_γ and κ_g – test non SM contributions







- Both experiments: compatible with SM predictions at ~10-15%
  - **ATLAS**: κ_g = (1.04 ± 0.14) at 68% CL - κ_γ = (1.20 ± 0.15) at 68% CL
  - **CMS** : κ_g [0.63,1.05] at 95% CL - κ_γ [0.59,1.30] at 95% CL

Contribution to the width from BSM

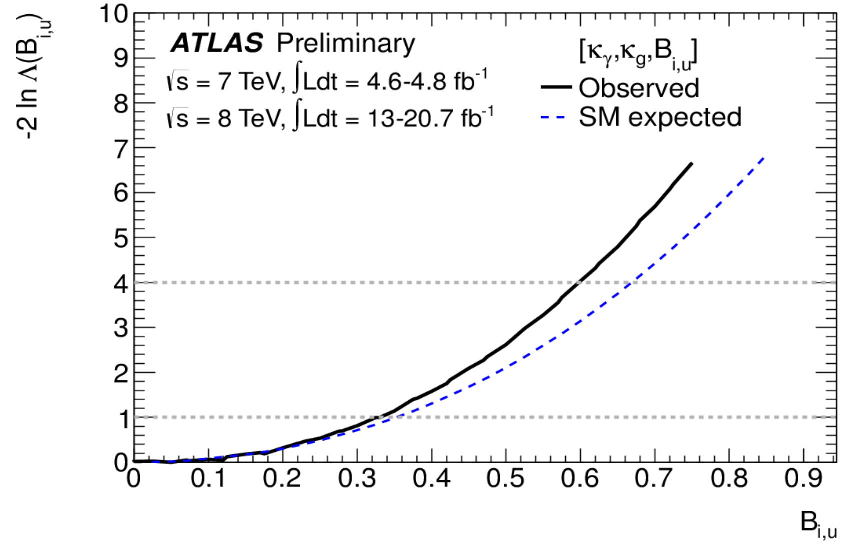
- Limits from direct searches (ZH → ll – invisible)
  ATLAS: BR_{inv} < 0.65 @ 95% CL
  CMS : BR_{inv} < 0.75 @ 95% CL

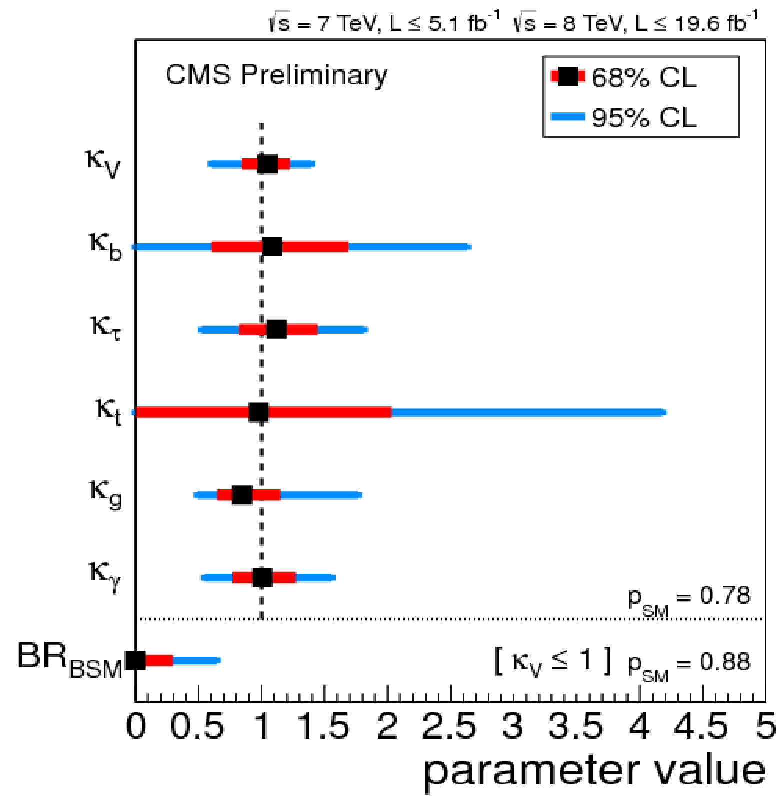
- $\Gamma_H = \Gamma_{SM} + \Gamma_{BSM} \rightarrow BR_{BSM} = \Gamma_{BSM} / \Gamma_H$

- BR_{BSM} is sensitive to invisible and undetectable decay modes (H → light hadrons)

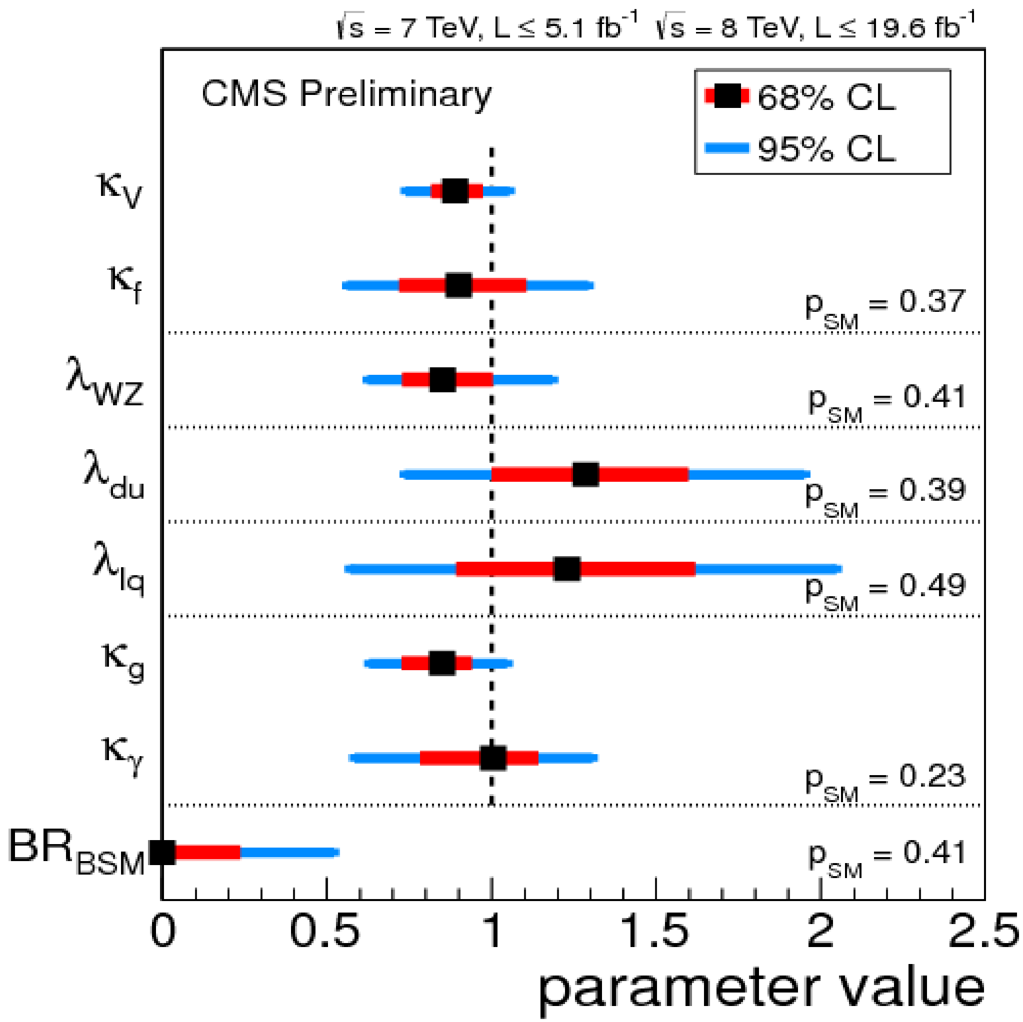
- **ATLAS**
  Assume tree level couplings: $\kappa_b = \kappa_W ... = 1$
  $\Gamma_{SM} \sim 0.9 + 0.1\ \kappa_g$
  3 fitted parameters: κ_γ , κ_g and BR_{BSM}
  - BR_{BSM} < 0.6 @ 95% C.L.

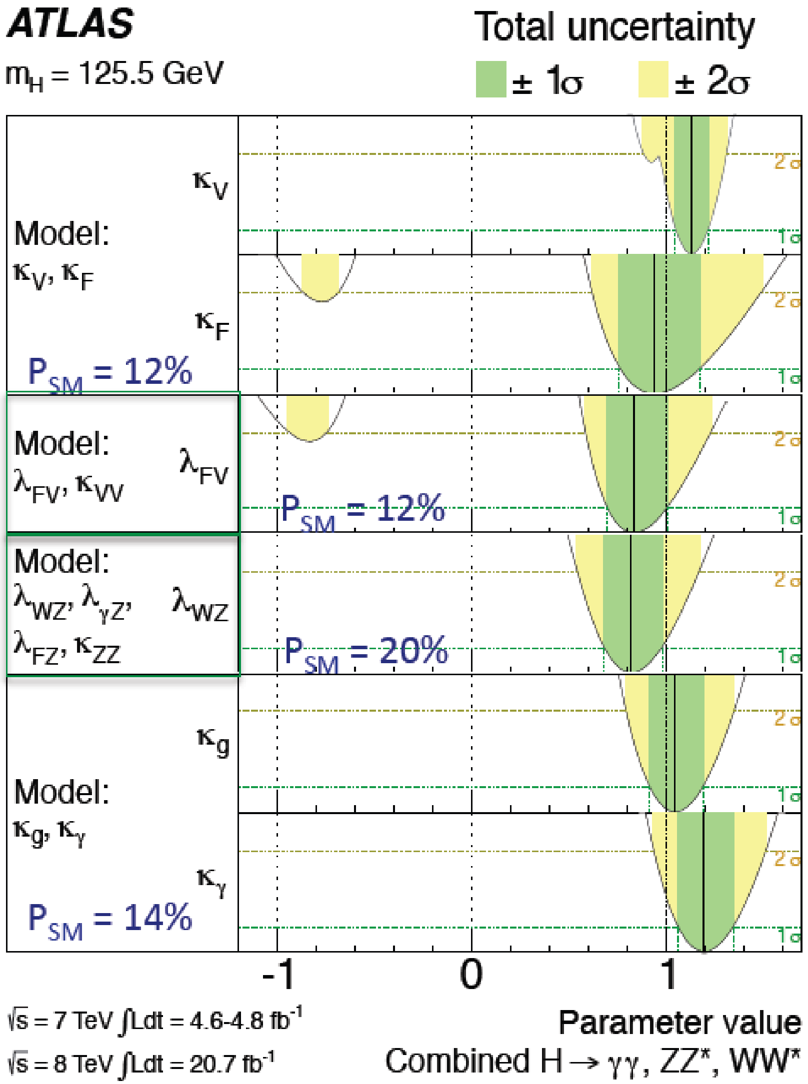
- **CMS**
  Assume $\kappa_V \leq 1$ (motivated by EWSB)
  7 fitted parameters: $\kappa_V, \kappa_t, \kappa_b, \kappa_\tau, \kappa_\gamma, \kappa_g$ and BR_{BSM}
  - BR_{BSM} < 0.64 @ 95% C.L.





Couplings Overview





Different sectors of the new boson couplings tested,
all measurements are consistent with the SM

Higgs Quantum Numbers

Spin-parity determination

Kinematics of production and decay of new bosons are sensitive to its spin and parity
→ test agreement with data for SM hypothesis and one alternative model at the time

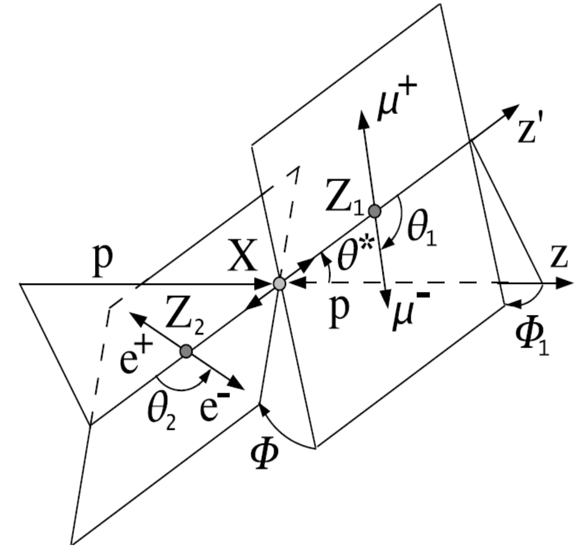
Couplings for alternative models are not known a priori → number of signal events in each channel and for each tested hypothesis are treated as independent nuisance parameters

J^P	production	description
0^+	$gg \to X$	SM Higgs boson
0^-	$gg \to X$	pseudoscalar
0^+_h	$gg \to X$	BSM scalar with higher dim operators in decay amplitude
2^+_{mgg}	$gg \to X$	KK Graviton-like with minimal couplings
$2^+_{mq\bar{q}}$	$q\bar{q} \to X$	KK Graviton-like with minimal couplings
1^-	$q\bar{q} \to X$	exotic vector
1^+	$q\bar{q} \to X$	exotic pseudovector

On-shell X(J=1) $\not\to$ γγ by Landau-Yang theorem
→ still worth testing with other decay modes

J =2: KK graviton as a consistent effective description of a spin-2 particle
At LO in mininal model, produced via gluon fusion, but 4% contribution of qq annihilation
Higher-order QCD corrections could largely change this ratio
→ consider models with different production modes admixture (scan $f_{q\bar{q}}$ between 0 and 100%)

$H \rightarrow ZZ^* \rightarrow 4l$ ($l=e/\mu$)



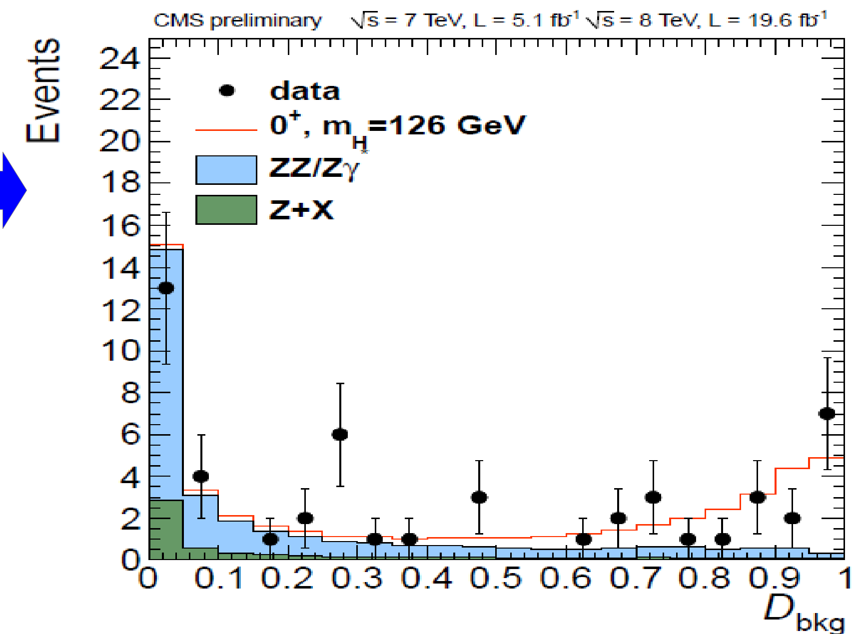
- Kinematic variables sensitive to J^P:
  - 2 masses (M_{Z1}, M_{Z2})
  - production angle cos(θ^*) in X rest frame
  - decay angles Φ, Φ_1, θ_1, θ_1, in X rest frame
- Fully reconstructed final state → test all alternative hypothesis

CMS:

Use the ratio of LO matrix elements to build kinematic discriminants. 2D analysis of $(\mathcal{D}_{\mathrm{bkg}}, \mathcal{D}_{J^P})$

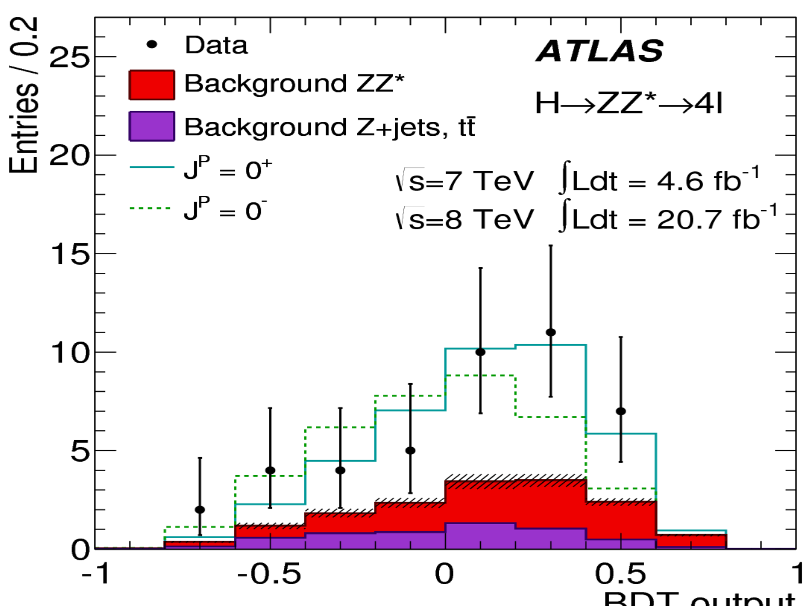
$\mathcal{D}_{\mathrm{bkg}}$:separate SM Higgs from bkg

$\mathcal{D}_{J^P}$: separate SM from other JP hypothesis



ATLAS:

combine kinematics variable using a BDT



$H \rightarrow \gamma\gamma$

- Photons production angle cos(θ*) in Collins-Soper frame sensitive to J

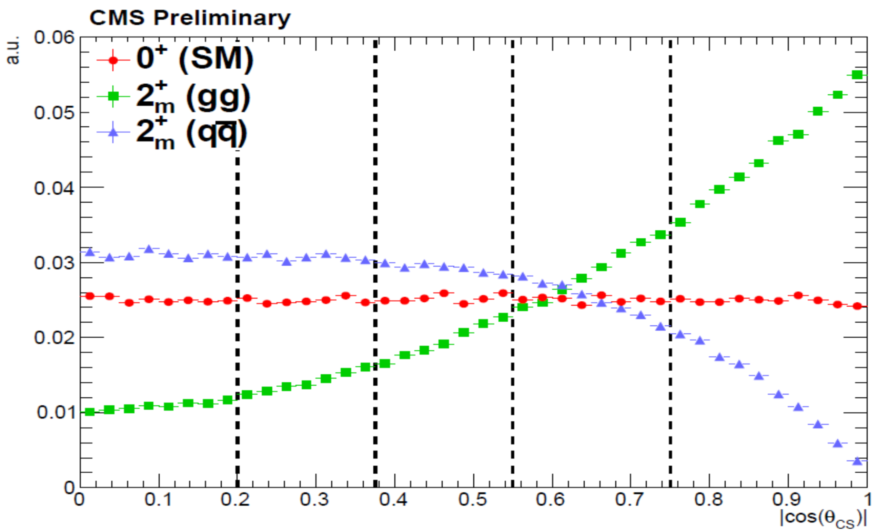
Before selection

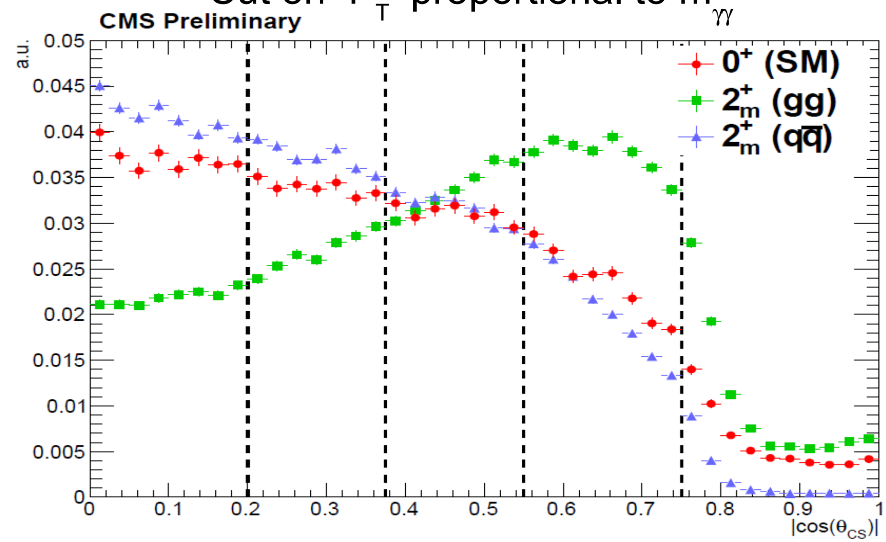
J = 0 → flat distribution

After selection

Modified by acceptance cuts

Cut on P_T^{γ} proportional to $m_{\gamma\gamma}$



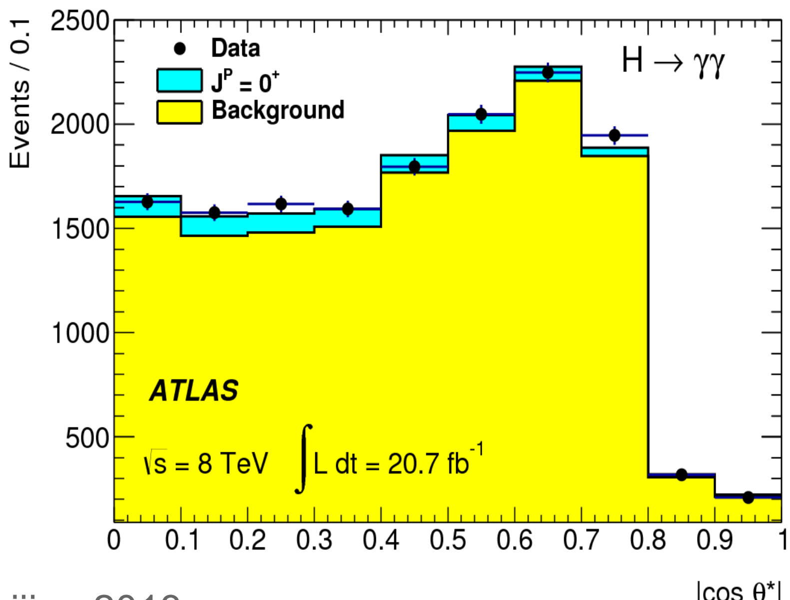


ATLAS: background from fit of $m_{\gamma\gamma}$ in side-bands

Assume $m_{\gamma\gamma}$ and |cos (θ*)| uncorrelated -checked in data

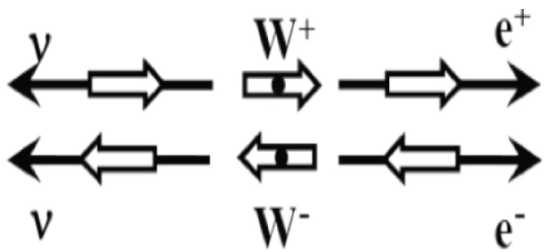
Likelihood: function of both $m_{\gamma\gamma}$ and |cos (θ*)|

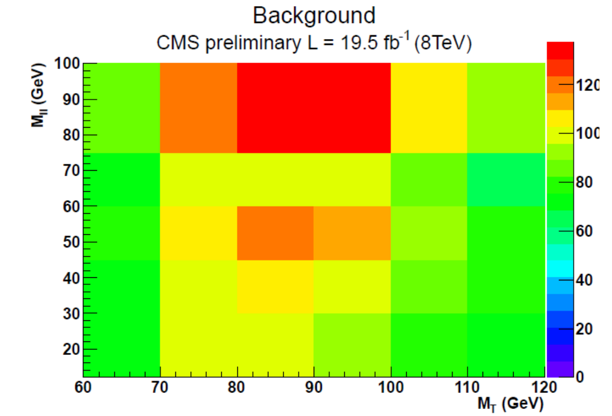
CMS: classify events depending on photon resolution

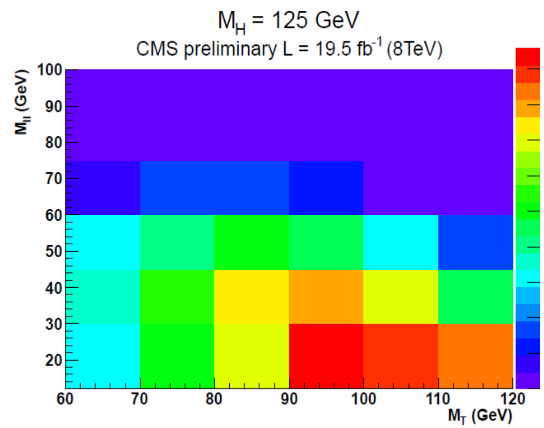


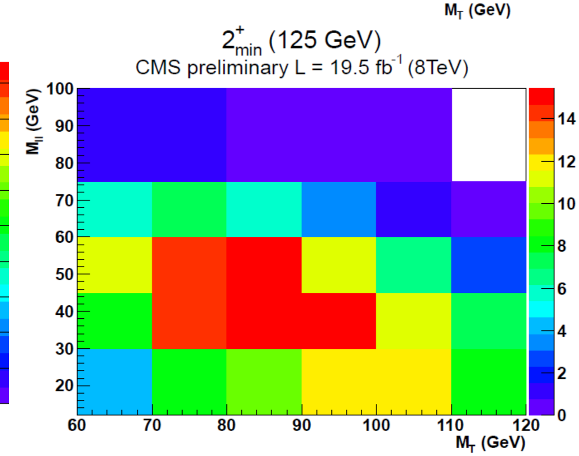
$H \to WW^* \to e\nu\, \mu\nu$

Neutrinos in the final state → it cannot be fully reconstructed
Analysis based on kinematical observables sensitive to JP







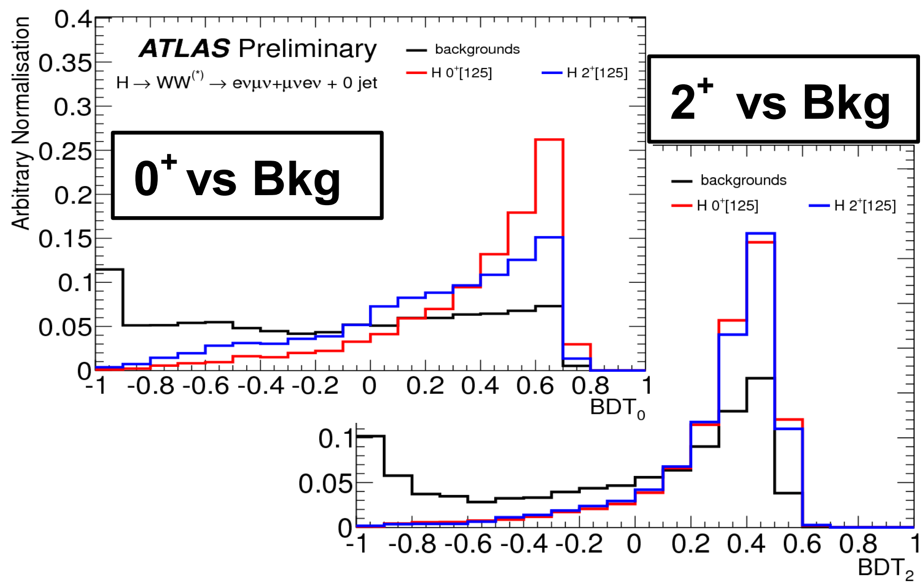


CMS:

- compare 2^+(gg) versus 0^+ hypothesis only
- 2D analysis of (M_T^H, M^{ll})

ATLAS:

- M_T^H
- P_T^{ll}
- M^{ll}
- $\Delta\Phi^{ll}$



2D analysis of (BDT_0 , BDT_2)

Compare 2^+ ($f_{q\bar{q}}$) and 0^+ hypothesis

Spin-parity two hypothesis testing

Used as a test statistic the likelihood ratio q:

$$q = \log \frac{\mathcal{L}(J^P = 0^+, \hat{\hat{\mu}}_{0^+}, \hat{\hat{\theta}}_{0^+})}{\mathcal{L}(J^P_{\text{alt}}, \hat{\hat{\mu}}_{J^P_{\text{alt}}}, \hat{\hat{\theta}}_{J^P_{\text{alt}}})}$$

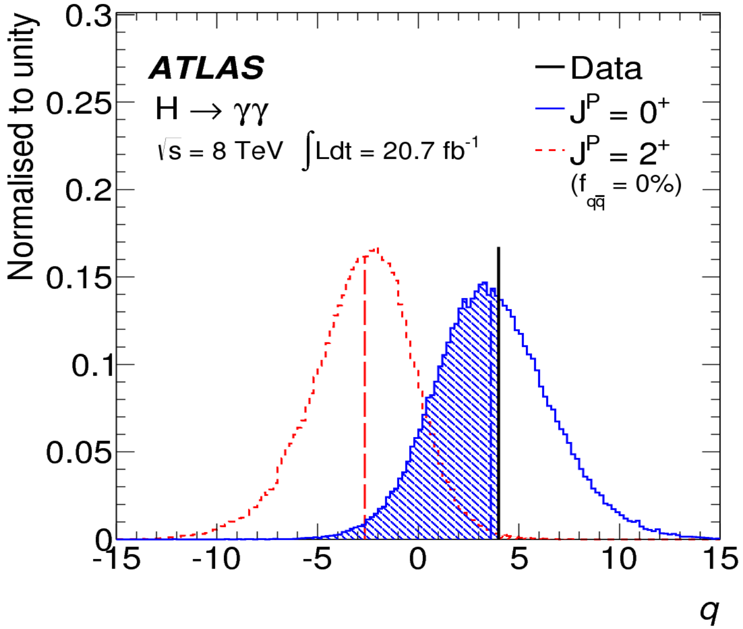
μ and θ fitted to data under one J^P hypothesis

Signal strengths μ_{JP} treated as independent nuisance-parameter for each channel and each spin hypothesis

Probability distribution function for q for different J_P hypothesis derived via pseudo-experiments

When deriving exclusion use CL_s :

$$\text{CL}_\text{s}(J^P_{\text{alt}}) = \frac{p_0(J^P_{\text{alt}})}{1 - p_0(0^+)}$$



Test 0^+ versus 2^+

2^+ graviton inspired model with minimal couplings

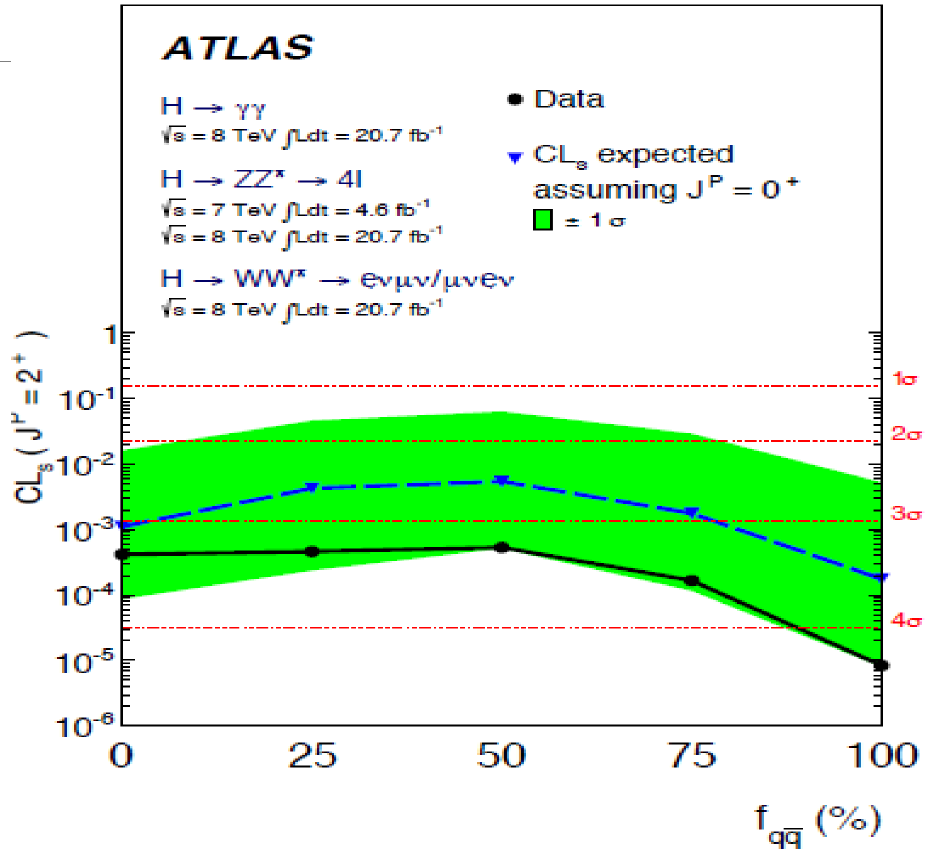
ATLAS: Combined $\gamma\gamma$ + ZZ* + WW*
2^+ (100% gg) Excluded > 99.9% CL
2^+ (100% qq) Excluded > 99.9% CL

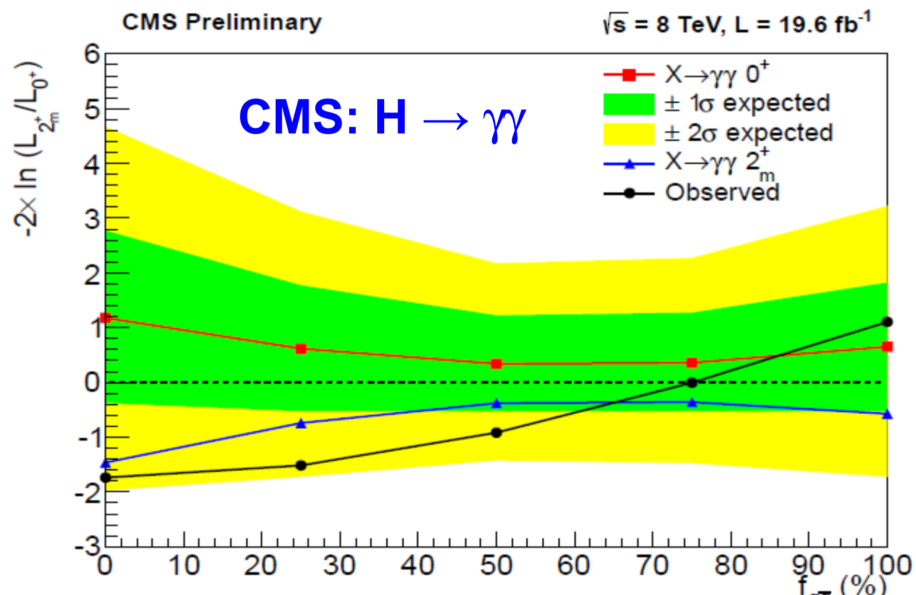
CMS: Combined ZZ* + WW*
2^+ (100% gg) Excluded at 99.4% CL
2^+ (100% qq) Excluded at 99.9% CL

Both experiments: compatible with SM 0^+

CMS: $\gamma\gamma$

Not included in the combination
No good 2^+ exclusions





Beyond hypothesis testing: 0^+ versus 0^-

CMS estimates contribution of CP-violating amplitude to $H \to ZZ^*$ decay

Most general spin 0 $H \to VV$ amplitude

$$A = v^{-1}\epsilon_1^{*\mu}\epsilon_2^{*\nu}\left(\underline{a_1 g_{\mu\nu} m_H^2} + a_2\, q_\mu q_\nu + \underline{a_3 \epsilon_{\mu\nu\alpha\beta}\, q_1^\alpha q_2^\beta}\right) = \underline{A_1} + A_2 + \underline{A_3}$$

CP odd amplitude

0^+ decays dominated by A_1 amplitude, 0^- decays dominated by A_3 amplitude

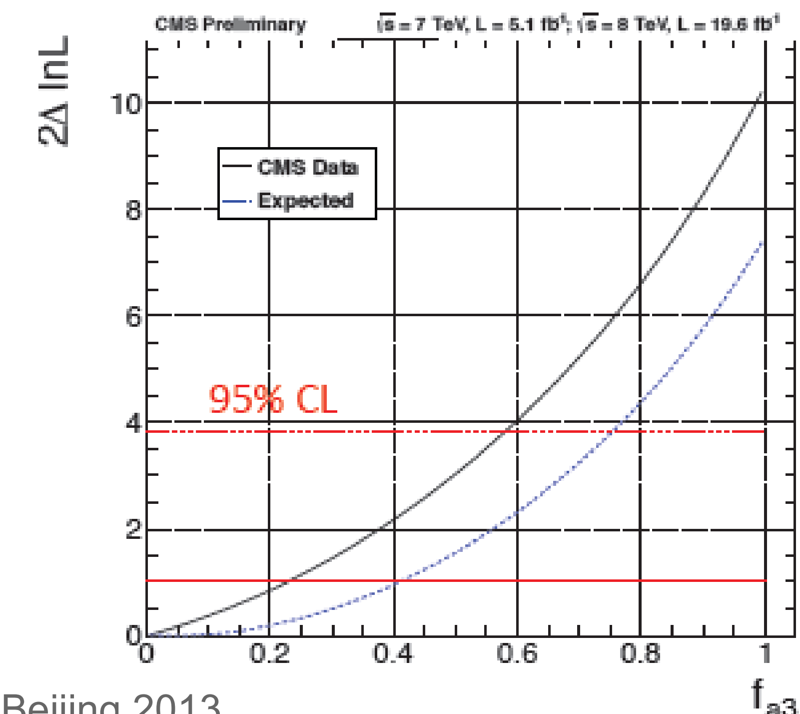
Take separate 2D template for 0^+ and 0^- and fit to data for their relative presence

$$f_{a3} = |A_3|^2 / |A_1|^2 + |A_3|^2$$

- check presence of CP violation (a_2: assume zero)
- interference term has negligible effect on observable or yields

CMS: $H \to ZZ^* \to 4l$

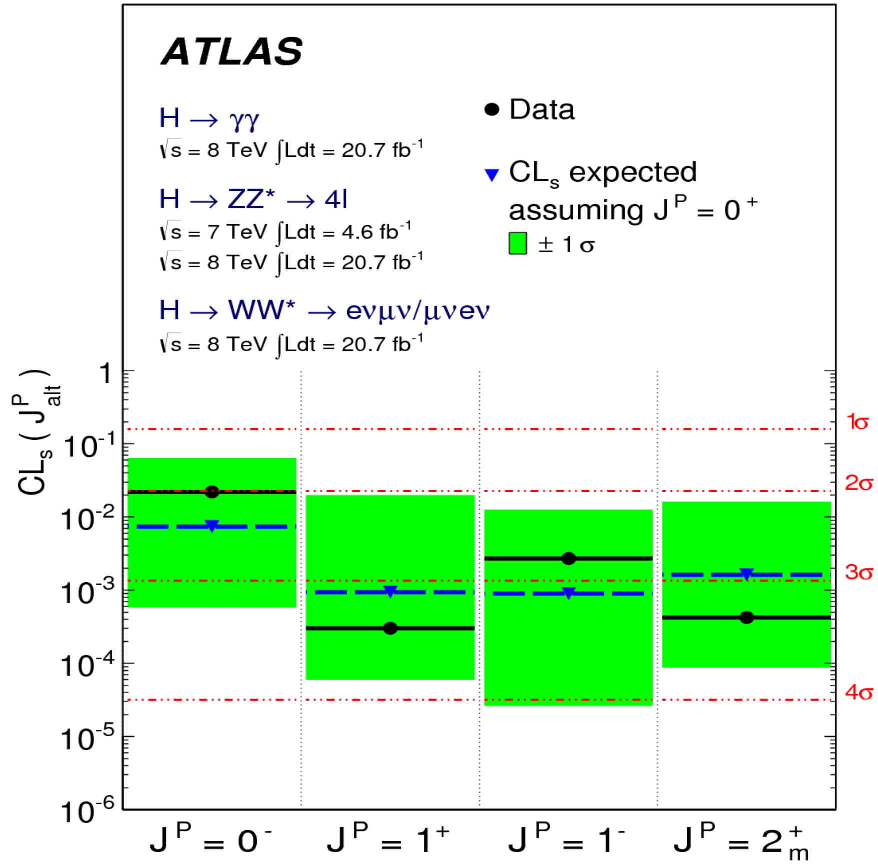
$f_{a3} = 0.00^{+0.23}_{-0.00}$ $\quad$ $f_{a3} < 0.58$ @ 95% CL



Spin-Parity Summary

CMS

CL_s	$ZZ \rightarrow 4l$	$WW \rightarrow 2l2\nu$	Comb ZZ-WW	$\gamma\gamma$
0^-	0.16 %	-	-	-
1^-	< 0.1%			
1^+	< 0.1%			
$2_m^+(gg)$	1.5%	14%	0.6%	60.9%
$2_m^+(q\bar{q})$	0.1%	-	-	16.9%



Spin-parity tested in bosonic modes

Strongly favored SM 0^+ hypothesis

Many alternative models tested:
Excluded at > 95% CL

Conclusion

1 year has passed since a new boson was discovered. Thanks to the outstanding performance of the LHC and the people operating it, over 25 fb^{-1} of good collision data could be collected and analyzed by each of the experiments.

- evidence for scalar nature 0^{+} (but CP mixing not excluded)
- evidence for couplings with fermions: direct > 3 σ and indirect > 5 σ
- evidence for VBF production
- coupling test compatibles with SM predictions
- no sign yet for BSM contributions

→ all measured properties are compatible with the SM Higgs boson, but more data will lead to better precision and the last word is not yet spoken!

In 2015 LHC with higher energy/luminosity we can improve the precision of couplings and CP violation down to 1-10% at LHC → challenge SM predictions

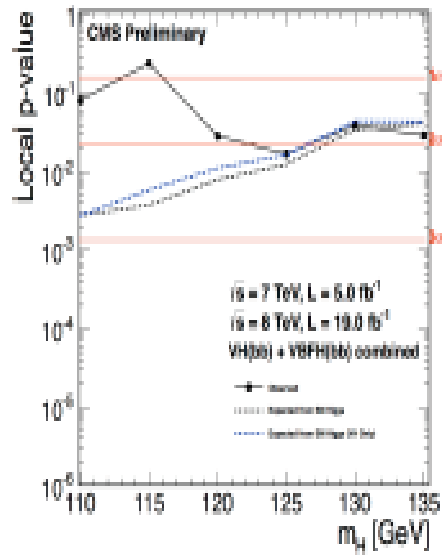
LHC is a discovery machine:
→ ultimate goal is 3000 fb^{-1}
→ direct searches may open the door to BSM much sooner

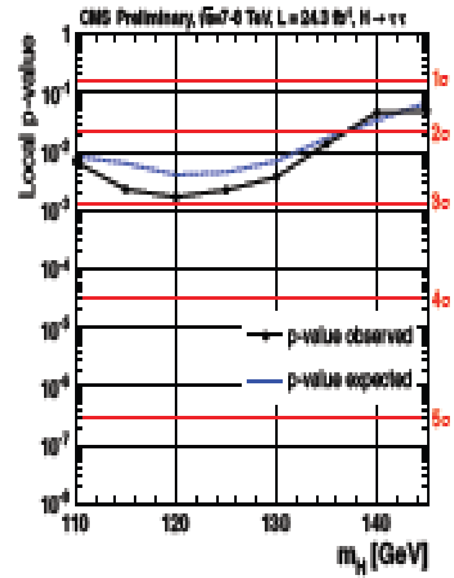
In the mean time, still expect final Run I publication from ATLAS and CMS

Back up

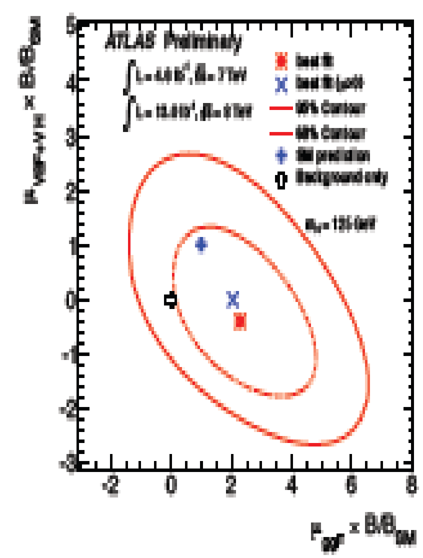
Evidence for direct fermionic decay

- CMS (for M_H=125 GeV):
  - (VBF+V)H → bb combination 2.1σ excess
  - H→ ττ 2.85σ excess
  - Combined H→ (ττ + bb) 3.4σ excess





- ATLAS (for M_H=125 GeV):
  - H → ττ μ= (0.7 ± 0.7) (compatible with SM, with or without Higgs boson)
  - VH→bb μ= (0.2 ± 0.7) (compatible with SM, with or without Higgs boson)



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Looser assumptions: allow BSM contributions

ATLAS

Assumption on Γ_{tH} ($\kappa_H^2 \sim 0.75\,\kappa_F^2 + 0.25\,\kappa_V^2$) → strong constraint on κ_F

Allow Higgs decaying to new particles

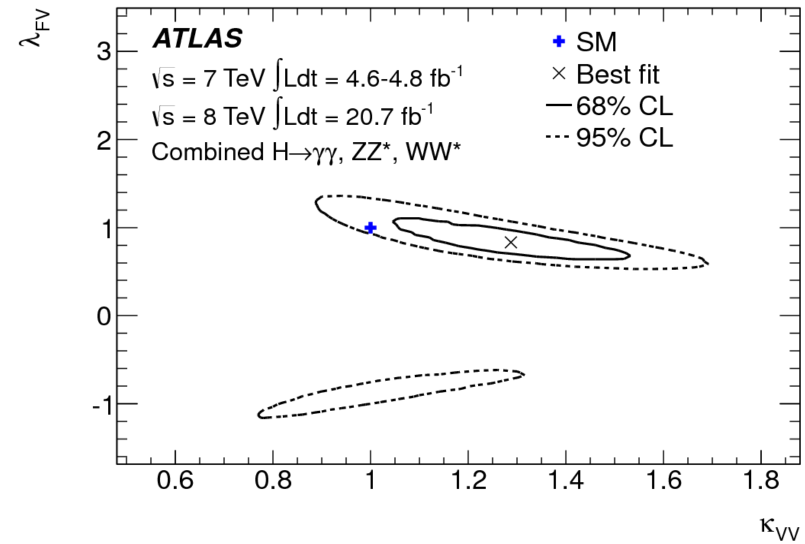
Free parameters

$$\lambda_{FV} = \frac{\kappa_F}{\kappa_V}$$

$$\kappa_{VV} = \frac{\kappa_V^2}{\kappa_H}$$

λ_{fV} [0.70,1.01] at 68% CL

κ_{VV} [1.13,1.45] at 68% CL



Compatible with SM, with accuracy of ~12%

Avoid a bias on the λ_{fV} measurement from potential beyond-the-SM contributions to H → γγ

Relax assumption on κ_γ

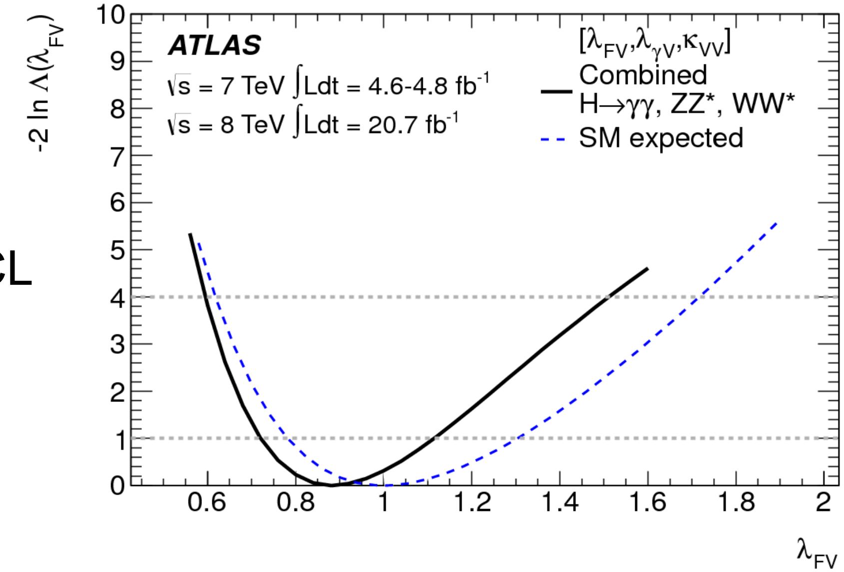
Free parameters

$$\lambda_{FV} = \frac{\kappa_F}{\kappa_V}$$

$$\kappa_{VV} = \frac{\kappa_V^2}{\kappa_H}$$

$$\kappa_{\gamma V} = \frac{\kappa_\gamma}{\kappa_V}$$

λ_{fV} [0.72, 1.11] at 68% CL



Test 0^+ versus 2^+

$H \to \gamma\gamma$

$f_{q\bar{q}}$	2^+ assumed Exp. $p_0(J^P = 0^+)$	0^+ assumed Exp. $p_0(J^P = 2^+)$	Obs. $p_0(J^P = 0^+)$	Obs. $p_0(J^P = 2^+)$	$CL_s(J^P = 2^+)$
100%	0.148	0.135	0.798	0.025	0.124
75%	0.319	0.305	0.902	0.033	0.337
50%	0.198	0.187	0.708	0.076	0.260
25%	0.052	0.039	0.609	0.021	0.054
0%	0.012	0.005	0.588	0.003	0.007

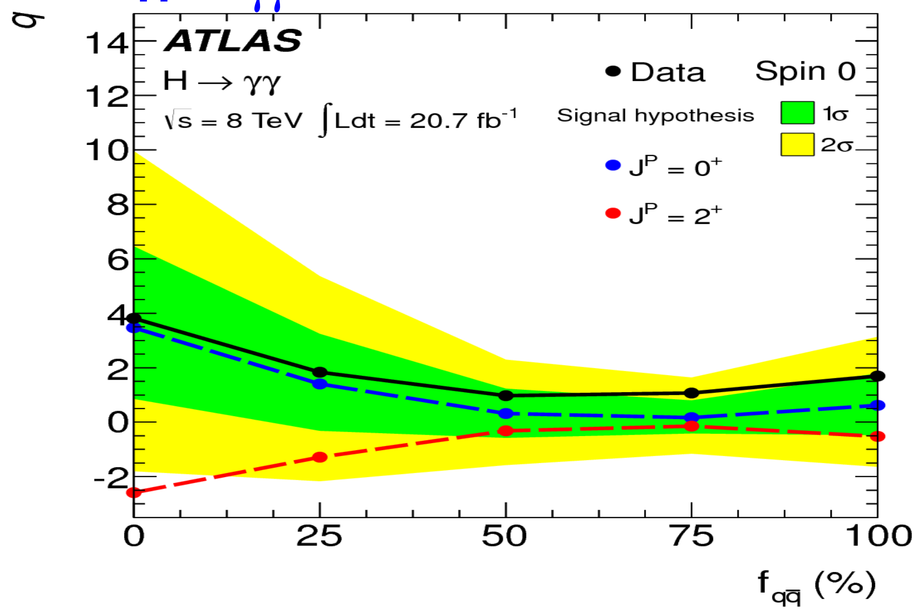
$H \to ZZ^*$

$f_{q\bar{q}}$	2^+ assumed assumed Exp. $p_0(J^P = 0^+)$	0^+ assumed Exp. $p_0(J^P = 2^+)$	Obs. $p_0(J^P = 0^+)$	Obs. $p_0(J^P = 2^+)$	$CL_s(J^P = 2^+)$
100%	0.102	0.082	0.962	0.001	0.026
75%	0.117	0.099	0.923	0.003	0.039
50%	0.129	0.113	0.943	0.002	0.035
25%	0.125	0.107	0.944	0.002	0.036
0%	0.099	0.092	0.532	0.079	0.169

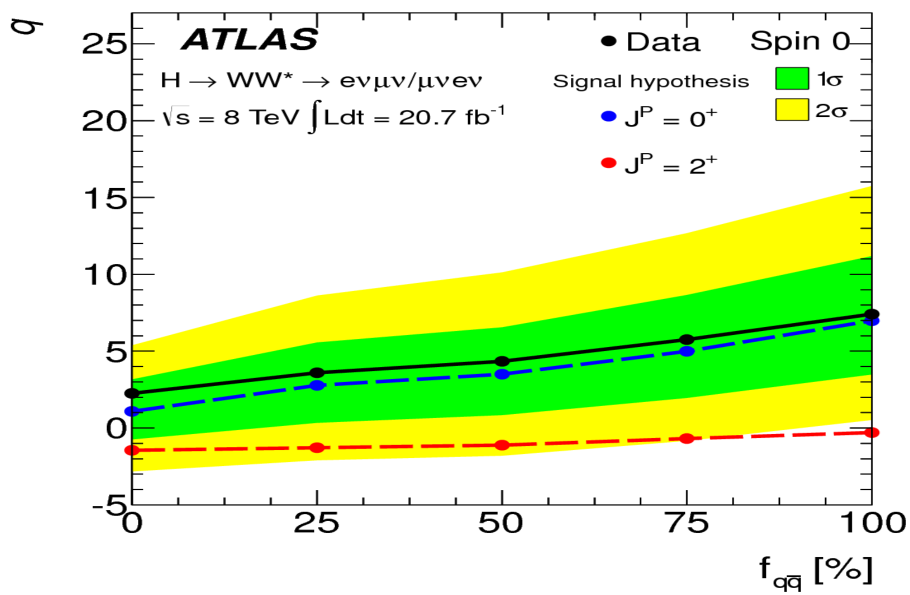
$H \to WW^*$

$f_{q\bar{q}}$	2^+ assumed Exp. $p_0(J^P = 0^+)$	0^+ assumed Exp. $p_0(J^P = 2^+)$	Obs. $p_0(J^P = 0^+)$	Obs. $p_0(J^P = 2^+)$	$CL_s(J^P = 2^+)$
100%	0.013	$3.6 \cdot 10^{-4}$	0.541	$1.7 \cdot 10^{-4}$	$3.6 \cdot 10^{-4}$
75%	0.028	0.003	0.586	0.001	0.003
50%	0.042	0.009	0.616	0.003	0.008
25%	0.048	0.019	0.622	0.008	0.020
0%	0.086	0.054	0.731	0.013	0.048

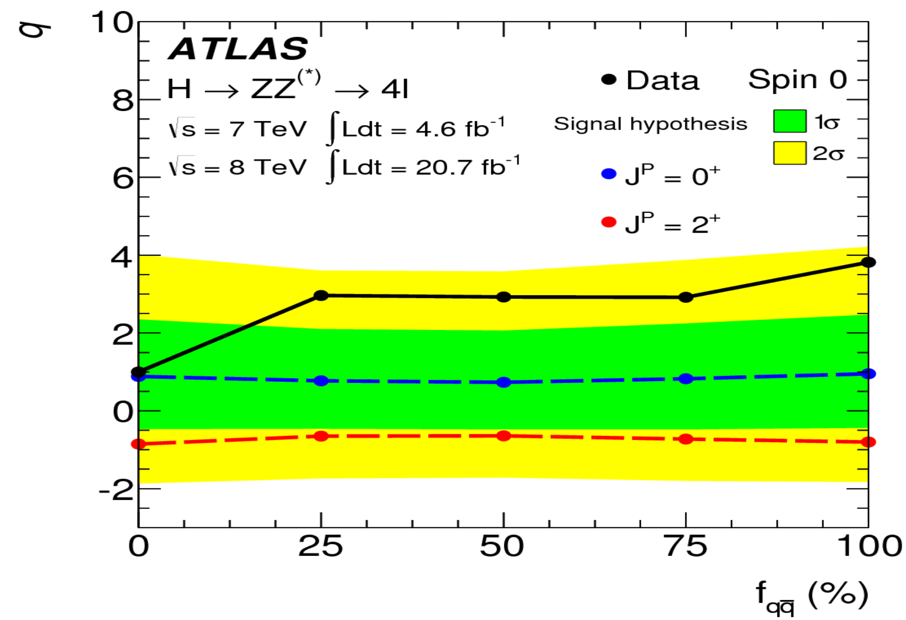
$H \to \gamma\gamma$



$H \to WW^*$



$H \to ZZ^*$



Channel/Categories used for coupling test

ATLAS: - arXiv:1307.1427 Sub. Phys Lett. B

Higgs Boson Decay	Subsequent Decay	Sub-Channels	$\int L\,dt$ [fb^{-1}]
		2011 $\sqrt{s}$ =7 TeV	
$H \to ZZ^{(*)}$	4ℓ	$\{4e, 2e2\mu, 2\mu 2e, 4\mu$, 2-jet VBF, ℓ-tag$\}$	4.6
$H \to \gamma\gamma$	–	10 categories $\{p_{Tt} \otimes \eta_\gamma \otimes$ conversion$\} \oplus \{$2-jet VBF$\}$	4.8
$H \to WW^{(*)}$	$\ell\nu\ell\nu$	$\{ee, e\mu, \mu e, \mu\mu\} \otimes \{$0-jet, 1-jet, 2-jet VBF$\}$	4.6
		2012 $\sqrt{s}$ =8 TeV	
$H \to ZZ^{(*)}$	4ℓ	$\{4e, 2e2\mu, 2\mu 2e, 4\mu$, 2-jet VBF, ℓ-tag$\}\}$	20.7
$H \to \gamma\gamma$	–	14 categories $\{p_{Tt} \otimes \eta_\gamma \otimes$ conversion$\} \oplus \{$2-jet VBF$\} \oplus \{\ell$-tag, E_T^{miss}-tag, 2-jet VH$\}$	20.7
$H \to WW^{(*)}$	$\ell\nu\ell\nu$	$\{ee, e\mu, \mu e, \mu\mu\} \otimes \{$0-jet, 1-jet, 2-jet VBF$\}$	20.7

CMS - CSM-PAS-HIG-13-005

H decay	Prod. tag	Analyses: Exclusive final states	No. of channels	m_H resolution	Lumi (fb^{-1}) 7 TeV	Lumi (fb^{-1}) 8 TeV	Ref.
$\gamma\gamma$	untagged	$\gamma\gamma$ (4 diphoton classes)	4 + 4	1-2%	5.1	19.6	[63]
	VBF-tag	$\gamma\gamma + (jj)_{VBF}$ (two dijet classes for 8 TeV)	1 + 2	<1.5%	5.1	19.6	
	VH-tag	$\gamma\gamma$ + (e, μ, MET)	3	<1.5%		19.6	
$ZZ \to 4\ell$	$N_{jet} < 2$	4e, 4μ, $2e2\mu$	3 + 3	1-2%	5.1	19.6	[64]
	$N_{jet} \geq 2$		3 + 3				
$WW \to \ell\nu\ell\nu$	0/1-jets	(DF or SF dileptons) × (0 or 1 jets)	4 + 4	20%	4.9	19.5	[65]
	VBF-tag	$\ell\nu\ell\nu + (jj)_{VBF}$ (DF or SF dileptons for 8 TeV)	1 + 2	20%	4.9	12.1	[66]
	WH-tag	$3\ell 3\nu$ (same-sign SF and otherwise)	2 + 2		4.9	19.5	[67]
$\tau\tau$	0/1-jet	$(e\tau_h, \mu\tau_h, e\mu, \mu\mu) \times$ (low or high p_T^τ)	16 + 16	15%	4.9	19.6	[68]
	1-jet	$\tau_h\tau_h$	1 + 1				
	VBF-tag	$(e\tau_h, \mu\tau_h, e\mu, \mu\mu, \tau_h\tau_h) + (jj)_{VBF}$	5 + 5				
	ZH-tag	$(ee, \mu\mu) \times (\tau_h\tau_h, e\tau_h, \mu\tau_h, e\mu)$	8 + 8		5.0	19.5	[69]
	WH-tag	$\tau_h\mu\mu, \tau_h e\mu, e\tau_h\tau_h, \mu\tau_h\tau_h$	4 + 4				
bb	VH-tag	$(\nu\nu$, ee, $\mu\mu$, $e\nu$, $\mu\nu$ with 2 b-jets) × (low or high $p_T(V)$ or loose b-tag)	10 + 13	10%	5.0	12.1	[70]
	ttH-tag	(ℓ with 4, 5 or $\geq$6 jets) × (3 or $\geq$4 b-tags); (ℓ with 6 jets with 2 b-tags); ($\ell\ell$ with 2 or $\geq$3 b-tagged jets)	6 + 6 3 + 3		5.0	5.1	[71]

The couplings roadmap

Test Higgs boson couplings depending on available L:

- Total signal yield μ: tested at 20% (κ tested at 10%)
- Couplings to Fermions and Vector Bosons 20-30%
- Loop couplings tested at 40%
- *Custodial symmetry W/Z Couplings tested at 30%
- Test Down vs Up fermion couplings
- Test Lepton vs Quark fermion couplings
- Top Yukawa direct measurement ttH: κ_t
- Test second generation fermion couplings: κ_μ
- Higgs self-couplings couplings HHH: κ_H

Today

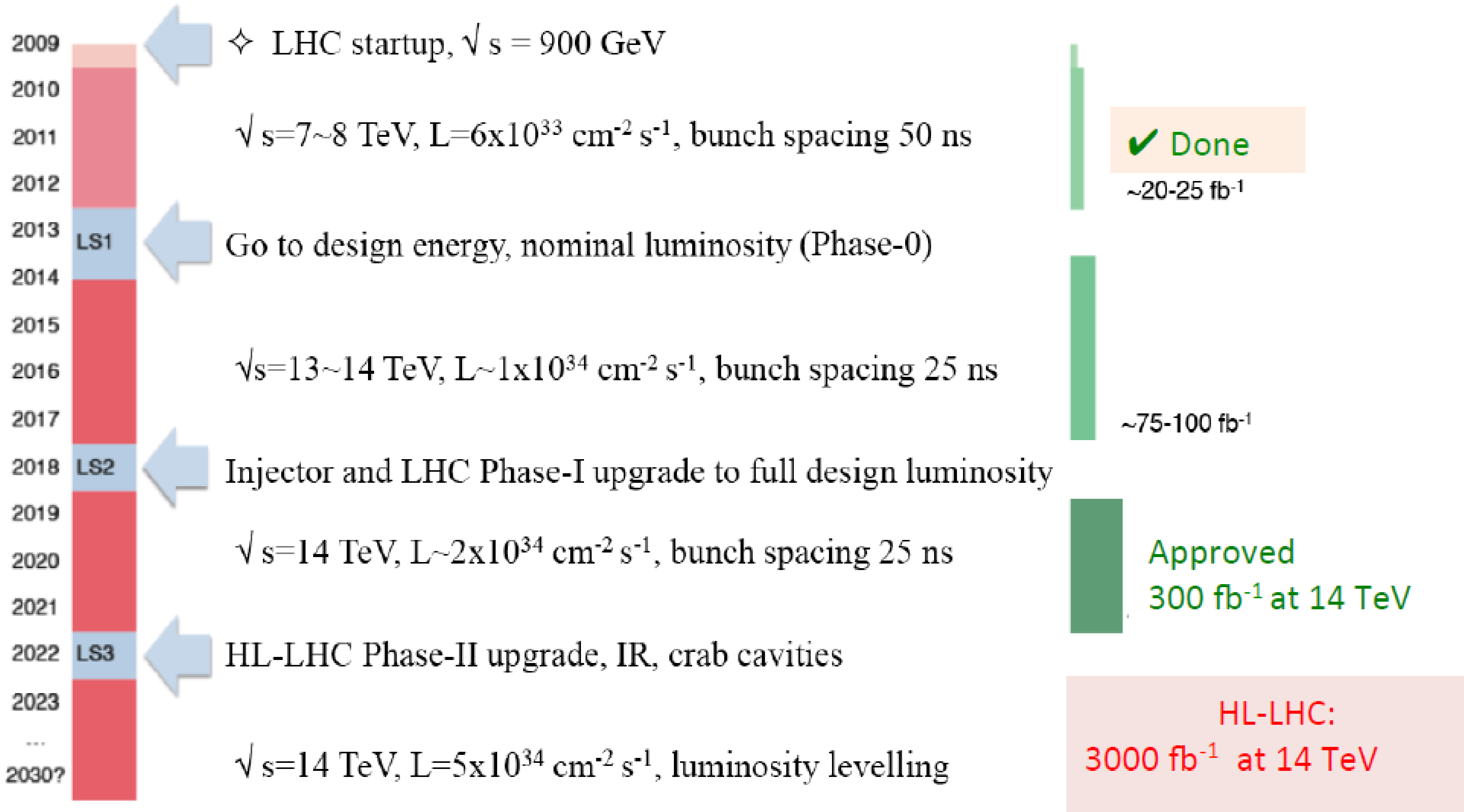
7+8 TeV
~ 30 fb^{-1}

LHC Upgrade

14 TeV
~ 3000 fb^{-1}

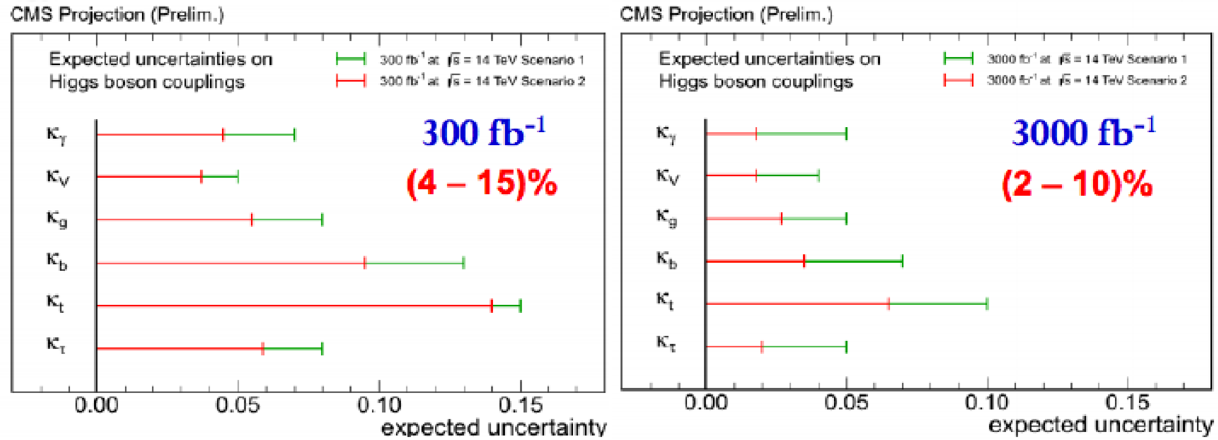
results in backup slides

Timeline of HL-HLC



CMS at HL-LHC

Higgs Projections: 300(0) fb^{-1}



Numbers in brackets are % uncertainties on coupling deviations for [scenario 2, scenario 1]

L (fb^{-1})	κ_γ	κ_V	κ_g	κ_b	κ_t	κ_τ
300	[5, 7]	[4, 5]	[6, 8]	[10, 13]	[14, 15]	[6, 8]
3000	[2, 5]	[2, 3]	[3, 5]	[4, 7]	[7, 10]	[2, 5]

Goal: ultimate precision of ~5% or better

CMS Projection

Assumption NO invisible/undetectable contribution to Γ_H:

- Scenario 1: system./Theory err. unchanged w.r.t. current analysis (also unchanged)
- Scenario 2: systematics scaled by 1/sqrt(L), theory errors scaled by ½

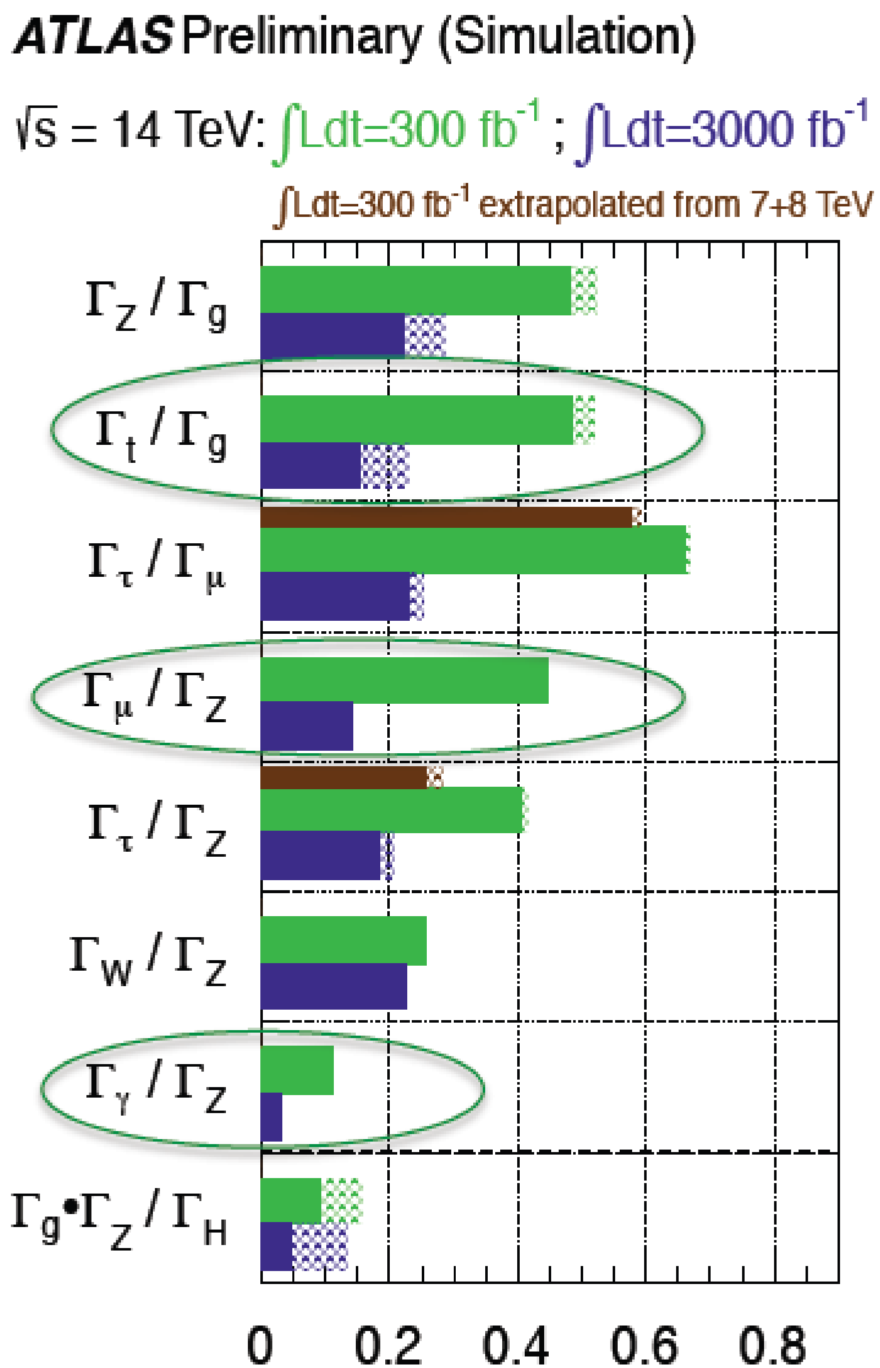
✓ γγ loop at 2-5% level

✓ down-type fermion couplings at 2-10% level

✓ direct top coupling at 7-10% level

✓ gg loop at 3-5% level

ATLAS at HL-LHC



- Fit to coupling ratios:
  - No assumption BSM contributions to Γ_H
  - Some theory systematics cancels in the ratios
- Loop-induced Couplings $\gamma\gamma$ and gg treated as independent parameter
  - κ_γ/κ_Z tested at 2%
  - gg loop (BSM) κ_t/κ_g at 7-12%
  - 2nd generation ferm. κ_μ/κ_Z at 8%

$$\frac{\Delta(\Gamma_X/\Gamma_Y)}{\Gamma_X/\Gamma_Y} \sim 2\frac{\Delta(\kappa_X/\kappa_Y)}{\kappa_X/\kappa_Y}$$