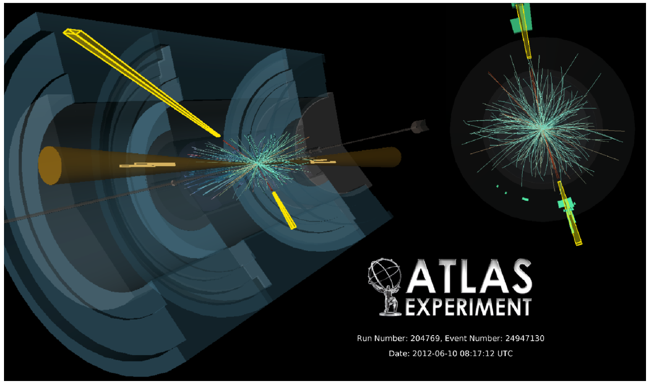
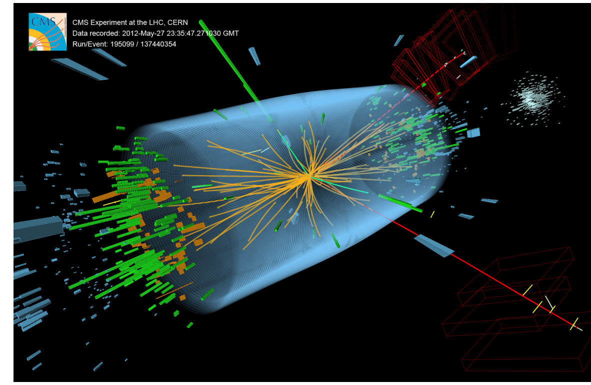


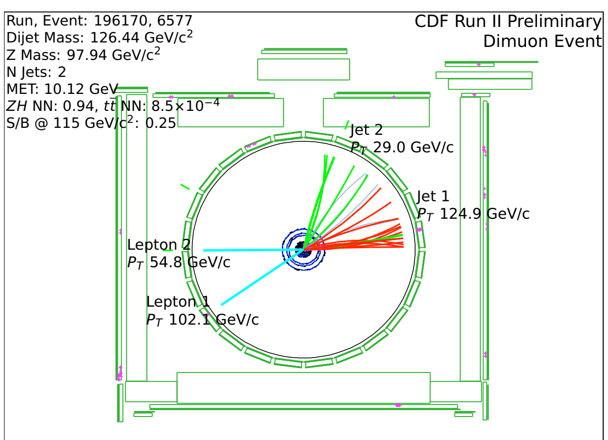


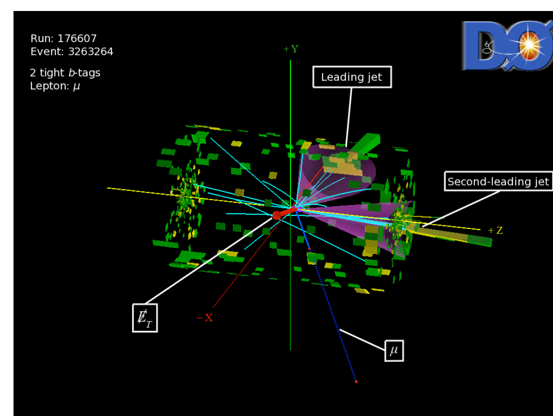
Properties of the New Boson

HEP 2013
Stockholm
18-24 July 2013

F. Cerutti – LBNL

On behalf of ATLAS, CMS, CDF and D0 Collaborations





Outline

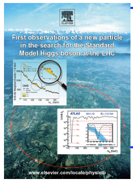
Thanks to Greg for nice experimental overview on Higgs results which are input to properties determination

- Introduction
- Properties:
  - Mass measurements
  - Spin-Parity determination
  - Couplings from signal strengths $\mu=[\sigma\times BR]/[\sigma\times BR]_{SM}$
  - Differential cross-sections in $\gamma\gamma$ final state
- Conclusions

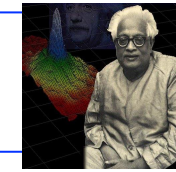
Bibliography used in this talk

- ATLAS:
  http://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-CONF-2013-072 (H→$\gamma\gamma$ diff. σ)
  - ATLAS-PHYS-PUB 2012-001/002 (HL-LHC)
- CDF + D0:
  http://tevnphwg.fnal.gov/
  - arXiv:1207.6436 – Phys. Rev. Lett 109 (Evidence H→bb)
  - arXiv:1303.6346 – Subm. Phys. Rev. D (Combination – Couplings)
  - D0 note 6387-CONF (Spin 2+ studies)
- CMS:
  http://cms.web.cern.ch/org/cms-papers-and-results
  - Phys. Lett. B 716 (Discovery)
  - arXiv:1212.6639 – Phys. Rev. Lett. 110 (ZZ*, Spin)
  - CSM-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-LHC)
- LHC-XS Higgs wg:
  http://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections
  - arXiv:1307.1347 (Yellow Report 3: σ, BR and coupling and spin/CP-fit models)

material form excellent parallel session talks !



Introduction

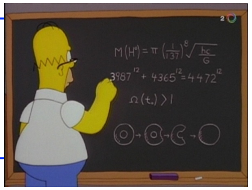


- 1 year ago ATLAS and CMS Collaborations announced the discovery of a NEW neutral Boson supported by D0 and CDF results

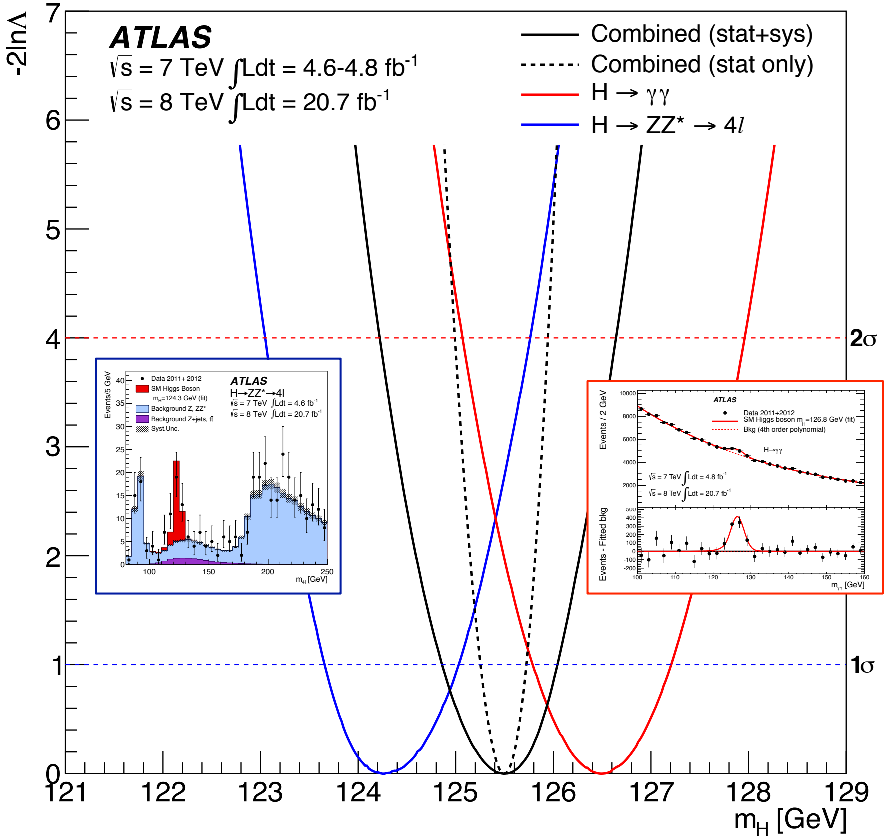
- Since then the ATLAS, CMS, CDF and D0 Collaborations focused on two questions:
  - Is this new boson responsible for the EW symmetry breaking - BEH mechanism - providing masses to Fermions and Bosons: “the SM Higgs boson” ?
  - Can we find signs of Physics Beyond the SM (BSM) studying its properties ?

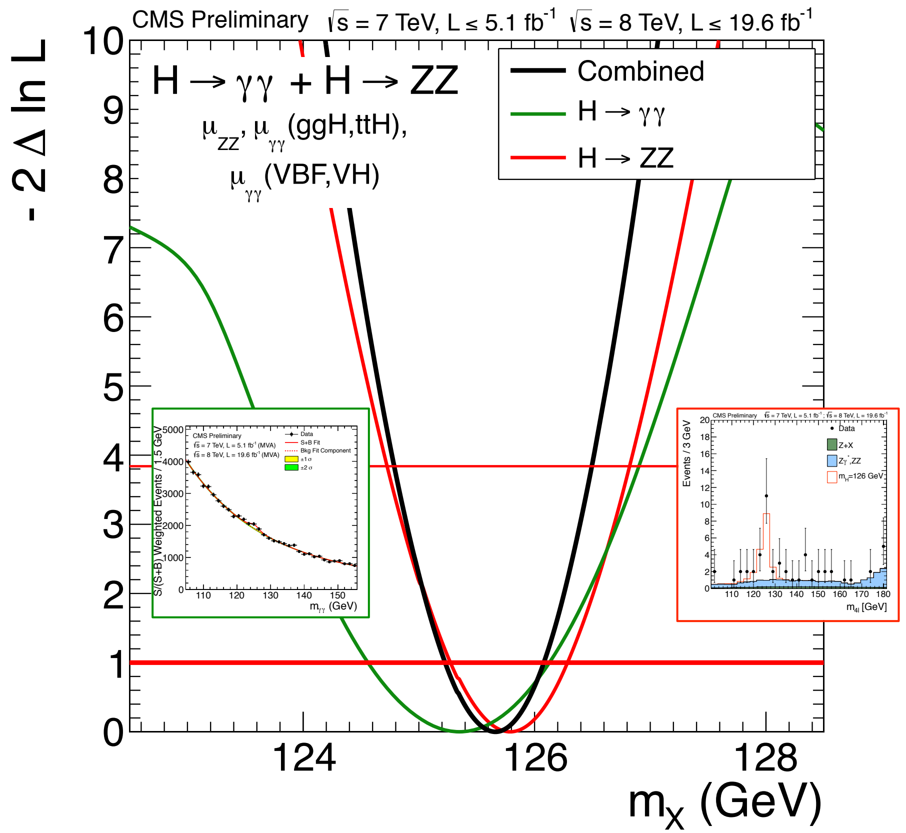
- Addressed experimentally by *properties measurement* in next slides ...

Mass Measurement



Measured from $\gamma\gamma$ and $ZZ^*(4\ell)$ mass spectra: needed to predict $\sigma \times BR$





ATLAS: $M_H = 125.5 \pm 0.2_{stat} \pm 0.6_{sys}$ GeV

CMS: $M_H = 125.7 \pm 0.3_{stat} \pm 0.3_{sys}$ GeV

New From $\gamma\gamma$: $\Gamma_H < 6.9$ GeV at 95% CL (direct)

**Independent of signal strengths: used by ATLAS and CMS coupling/spin analyses*

Spin-Parity Determination:

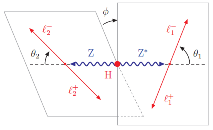
Experimental approach:

- Use observables that are sensitive to Spin and Parity of the New Boson independent of the *coupling strengths*

- Several alternative specific models: 0^-, 1^+, 1^-, 2^+ tested against the SM Higgs 0^+ hypothesis

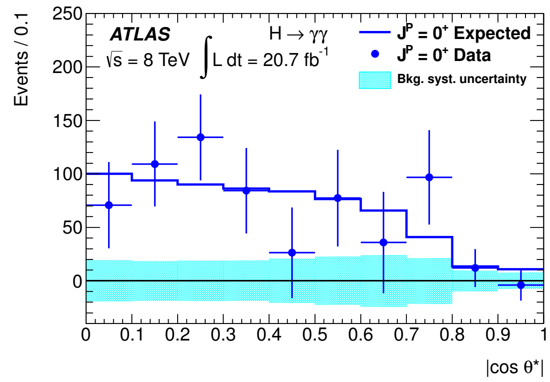
- On-shell X(J=1) $\not\to$ $\gamma\gamma$ by Landau-Yang theorem

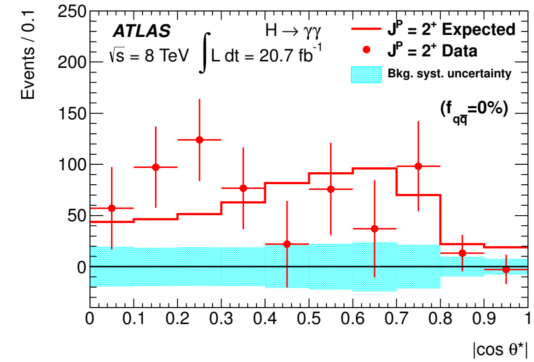
Spin-Parity Determination

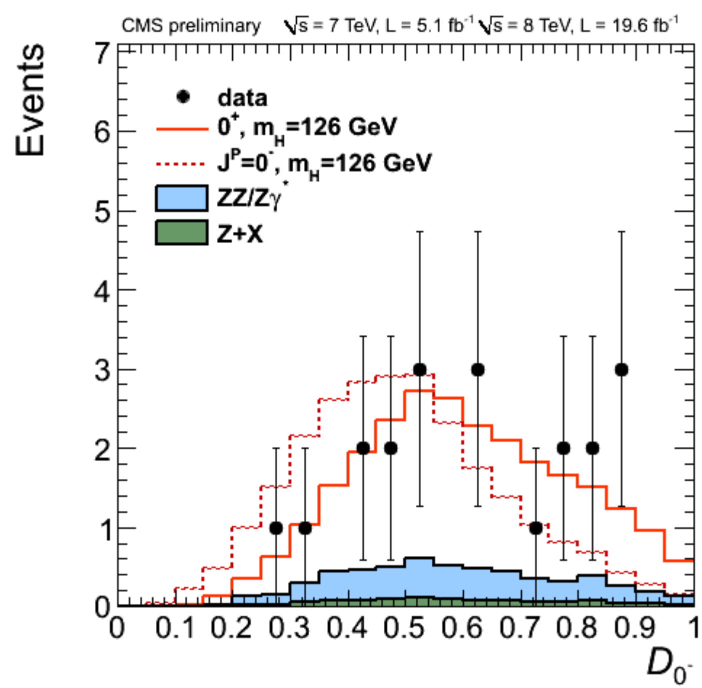


Analyzed channels:

- H→ γγ decay angle cos(θ*) in Collins-Sopper frame sensitive to J
- H → WW* → ℓνℓν Several variables sensitive to J^P
  - $\Delta\phi_{\ell\ell}$, $M_{\ell\ell}$, ..
  - Combined with Boosted-Decision-Tree (BDT)
- H → ZZ* →4ℓ: Full final state reconstruction sensitive to J^P
  - 2 masses (M_{Z1},M_{Z2}) and 5 angles
  - Combined with BDT or Matrix-Element-based discriminant D_{JP}



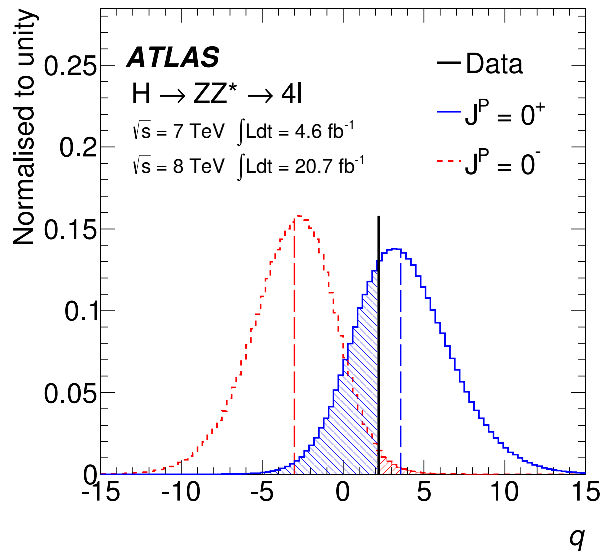




Test of 0^+ vs 0^-

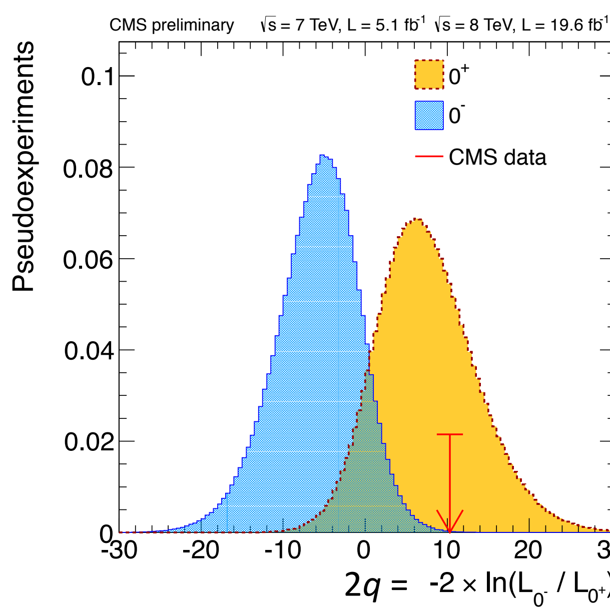
$ZZ^* \rightarrow 4\ell$ channel used by CMS and ATLAS:

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



ATLAS:

- **0^- Excluded @ 97.8% CL (exp. 99.6%)**



CMS:

- **0^- Excluded @ 99.8% CL (exp. 99.5%)**

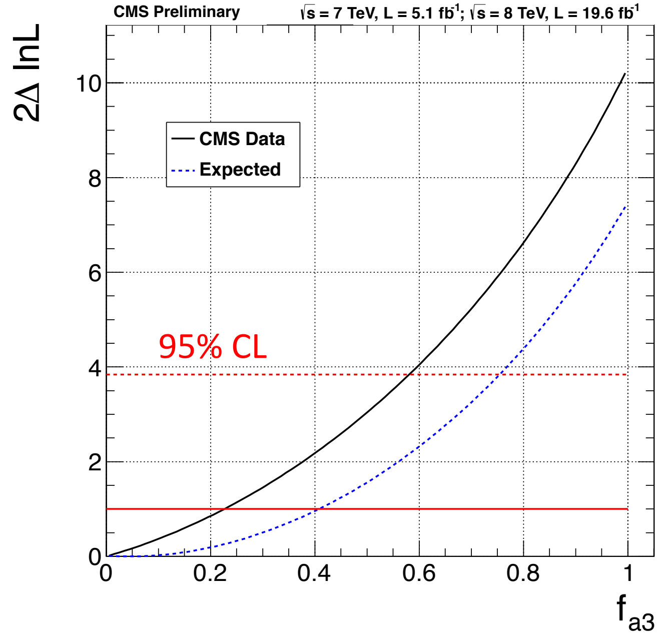
Compatible with SM 0^+

Beyond *2 hypotheses* Test: 0^+ vs 0^-

CMS investigated sensitivity to different CP Amplitudes in ZZ* channel

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

- SM Higgs at LO corresponds to **a_1=1** and **a_2=a_3=0**
- **A_3**= CP odd Amplitude
- Fit for $f_{a3} = |A_3|^2 / (|A_1|^2 + |A_3|^2)$: check the presence of a 0^- component (assuming a_2=0) - impact of interference very small on used observables



- CMS: $f_{a3} = 0.00^{+0.23}_{-0.00}$

f_{a3} < 0.56 at 95% CL (exp. 0.76)

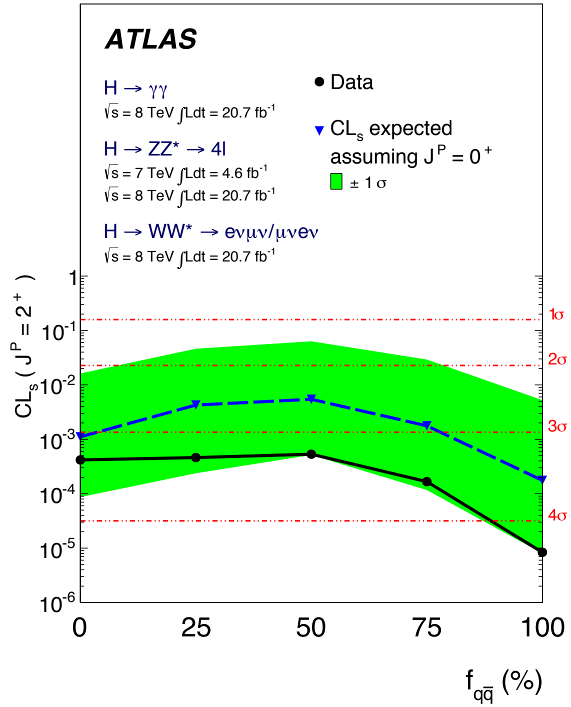
Test of 0^+ vs 2^+

Graviton inspired model with minimal couplings to SM particles

It can be produced via gg or qq annihilation:

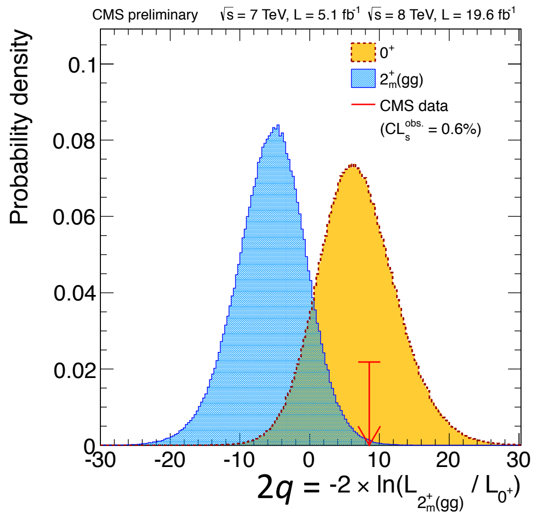
f_{qq} = faction of qq/gg produced signals

(In minimal model 2^+_m at LO in QCD expected f_{qq}=4%)



ATLAS: **Combined:** $\gamma\gamma$ + ZZ*→ 4ℓ + WW*→$\nu\ell\,\nu\ell$

- **2^+ (100% qq) Excluded at >99.9% CL (exp. >99.9%)**
- **2^+ (100% gg) Excluded at >99.9% CL (exp. 99.9%)**



CMS: **Combined** ZZ*→ 4ℓ + WW*→$\nu\ell\,\nu\ell$

- **2^+ (100% gg) Excluded at 99.4% CL (exp. 98.8%)**

Both experiments: Compatible with SM 0^+

Spin-Parity ATLAS - CMS Overview

CMS ZZ*(4ℓ)

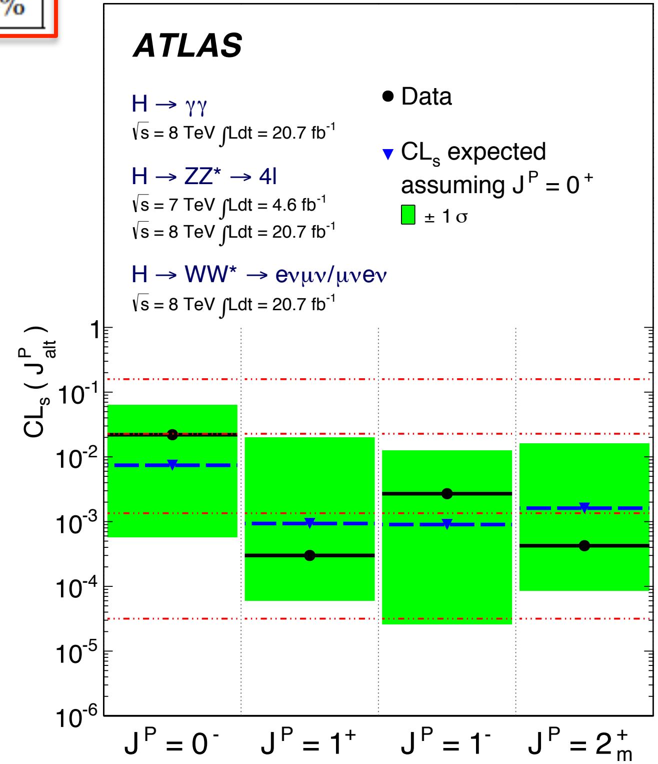
J^P	production	comment	expect (μ=1)	obs. 0^+	obs. J^P	CL_s
0^-	$gg \to X$	pseudoscalar	2.6σ (2.8σ)	0.5σ	3.3σ	0.16%
0_h^+	$gg \to X$	higher dim operators	1.7σ (1.8σ)	0.0σ	1.7σ	8.1%
2_{mgg}^+	$gg \to X$	minimal couplings	1.8σ (1.9σ)	0.8σ	2.7σ	1.5%
$2_{mq\bar{q}}^+$	$q\bar{q} \to X$	minimal couplings	1.7σ (1.9σ)	1.8σ	4.0σ	$<0.1\%$
1^-	$q\bar{q} \to X$	exotic vector	2.8σ (3.1σ)	1.4σ	$>4.0\sigma$	$<0.1\%$
1^+	$q\bar{q} \to X$	exotic pseudovector	2.3σ (2.6σ)	1.7σ	$>4.0\sigma$	$<0.1\%$

ATLAS and CMS: *"bosonic"* decay modes

Strongly favor $J^P = 0^+$ SM quantum numbers

All alternative J^P models tested:

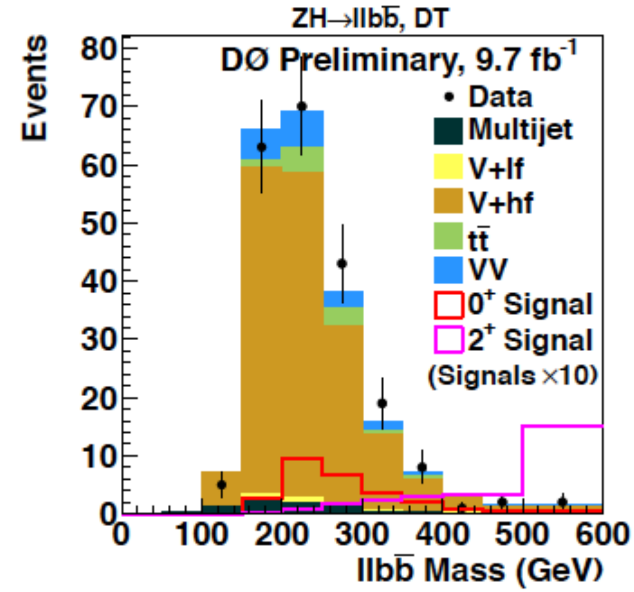
Excluded @ >95% CL



D0: Test of 0^+ vs 2^+

Graviton-inspired model with minimal couplings to SM

- $X=2^+ \sim\beta^5$ threshold behavior ($0^+ \sim\beta$) for VX→Vbb production: Sensitive observable *Mass (Transverse)* of the VX system

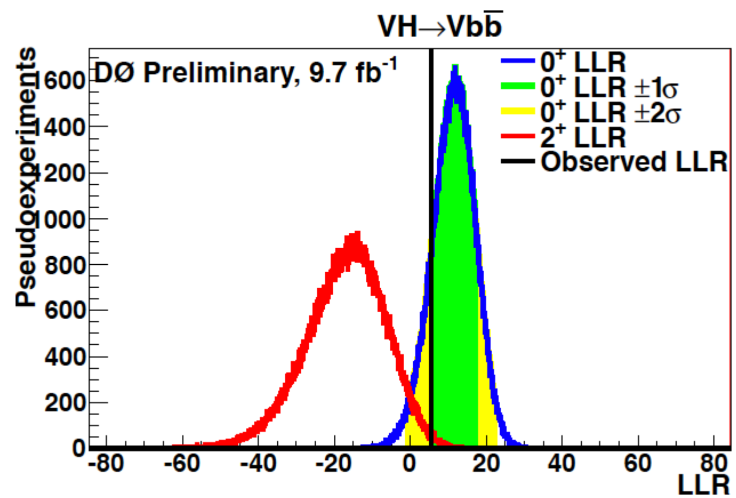


assuming μ=1.23 (as measured in the Data for the SM Higgs search) - Combining ℓℓbb, ℓνbb and ννbb

- **2^+ Excluded at 99.9% CL – 3.1σ (μ =1 exp. 99.9%)**

Compatible with SM 0^+

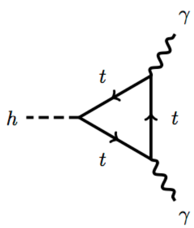
*Studies for 0^- hypothesis in the pipeline ...

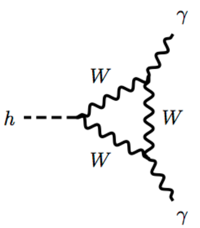


NEW Boson Couplings

Crucial TEST of SM BEH mechanism → $\mathbf{g_F \propto m_F}$ and $\mathbf{g_{W,Z,H} \propto M^2_{W,Z,H}}$

- SM couplings tested introducing *coupling scale factors* κ → $g_i = g_i^{SM} \times \kappa_i$
  - SM Tree-Level Amplitudes:
    - $\Gamma_{ff} \propto (\kappa_f \times m_f / v)^2 \propto \kappa_f^2 \times \Gamma_{ff}^{SM}$ (v= 246 GeV from G_F)
    - $\Gamma_{WW} \propto (\kappa_W \times M_W^2 / v)^2 \propto \kappa_W^2 \times \Gamma_{WW}^{SM}$
    - $\Gamma_{ZZ} \propto (\kappa_Z \times M_Z^2 / v)^2 \propto \kappa_Z^2 \times \Gamma_{ZZ}^{SM}$
  - SM Loop-level: best place to look for physics Beyond the Standard Mode
    - $\Gamma_{\gamma\gamma} \propto |1.28\, \kappa_W - 0.28\, \kappa_t|^2 \times \Gamma^{SM}_{\gamma\gamma}$ → **Wt interference**
    - $\Gamma_{gg}, \Gamma_{\gamma Z}, \ldots$





- Theory errors for SM Higgs boson:
  - σ_H ~ (11-5)% larger in ggH and ttH - BR_H ~ (3-6%)

**Mass dependency small: Max ~ 4%/0.5 GeV for* Γ_{ZZ}

The Couplings Test

- Follow recommendations from LHC Higgs xs-wg: arXiv1307.1347 (YR3) *assuming*:
  - 1 resonance + Zero-Width Approx. + SM Lagrangian Tensor Structure ($J^P=0^+$)

$$\sigma \times BR(ii \to \mathrm{H} \to ff) = \frac{\sigma_{ii} \cdot \Gamma_{ff}}{\Gamma_{\mathrm{H}}}$$

- *Approach suitable to **test SM predictions** exploiting correlations between production (gg, VBF, VH, ttH) and decay modes with current precision*

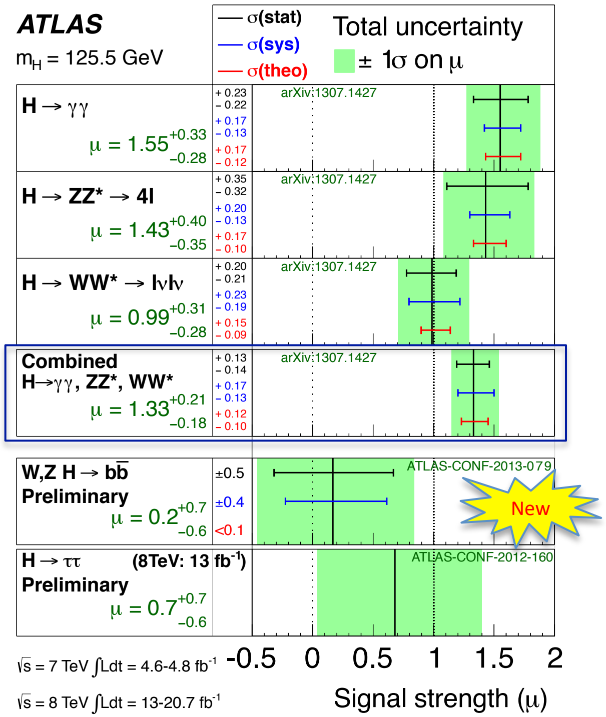
- e.g., measured yield ZH→Zbb parameterized as:

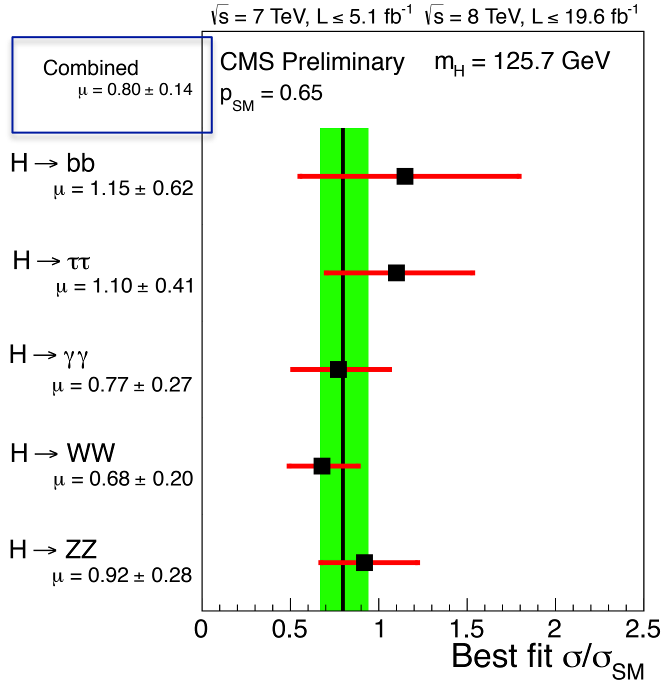
$$\mu(ZH \to Zbb) = [\sigma_{ZH} xBR(H \to bb)]/[\sigma_{ZH} xBR(H \to bb)]_{SM} = (\kappa_Z^2 \times \kappa_b^2)/\kappa_H^2$$

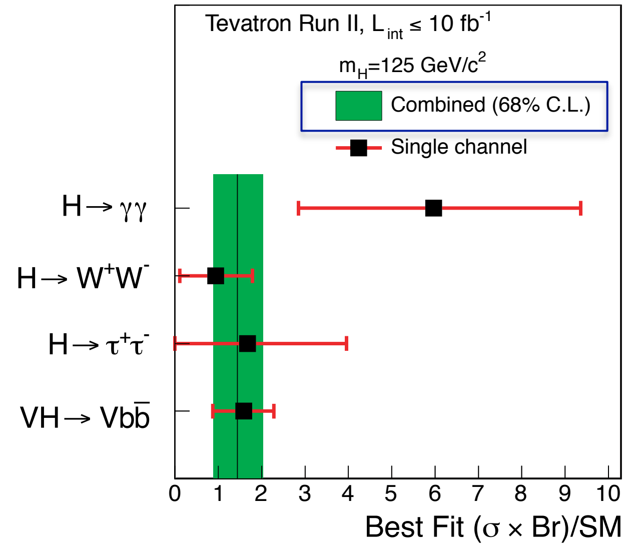
SM Higgs boson → All μ and κ compatible with 1

- Loop *scaling factors* κ_γ , κ_g can be :
  - Expressed as a function of SM couplings scale factors: $\kappa_\gamma(\kappa_W,\kappa_t)$
  - Treated as free parameter to test BSM contributions
- Γ_H need assumptions: ratios, relationships $\kappa_H=\kappa_H(\kappa_b, \kappa_W,...)$, ...

The signal Strength μ



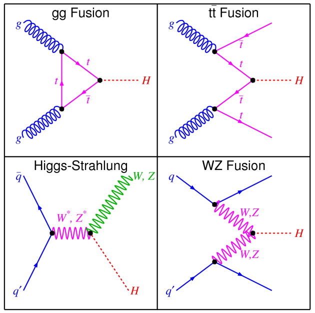




- Combined μ → Best accuracy but no strong physics motivation:
  - **ATLAS (γγ, WW* and ZZ*)** μ = (**1.33 ± 0.20**) (1.23±0.18 including bb and ττ)
  - **CMS (γγ, ττ, bb, WW* and ZZ*)** μ = (**0.80 ± 0.14**)
  - **TEVATRON (bb, γγ, ττ, WW*)** μ = (**1.44 ± 0.60**)

Compatible with SM Higgs boson expectation: Accuracy ~ 15%

Evidence for V-mediated Production

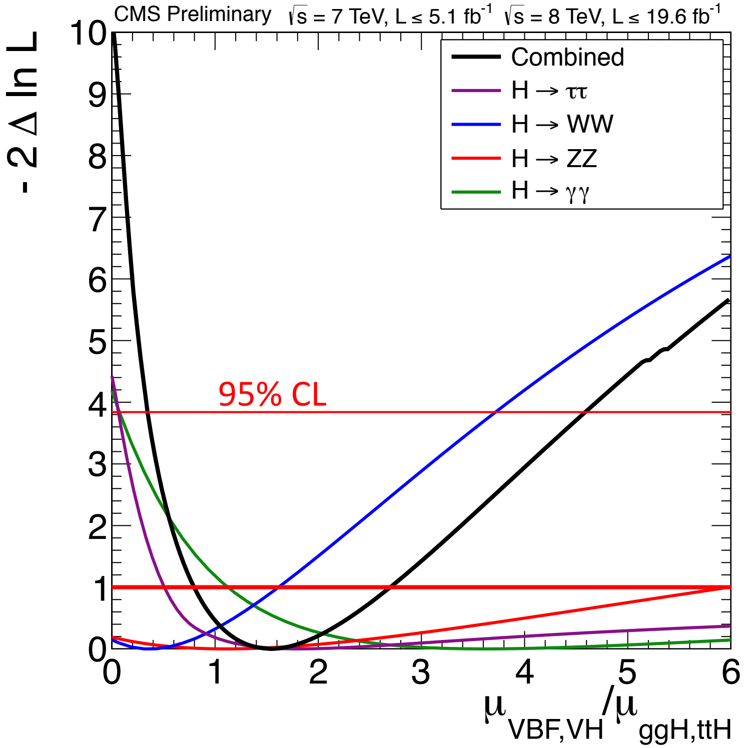


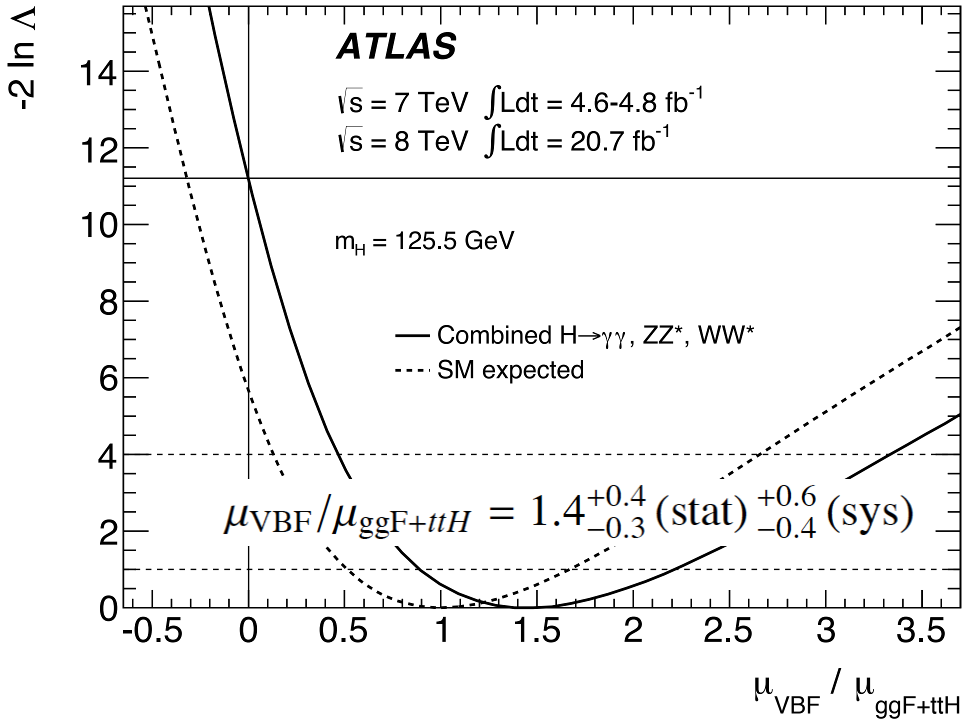
Disentangle production modes: V-mediated vs F-mediated

Fit to $\mu_{VBF+VH}/\mu_{gg+ttH}$ in different channels (BR's cancels out):

- CMS: **Evidence for V-boson mediated production 3.2σ**
- ATLAS: **Evidence for VBF production (VH "profiled") 3.3σ**

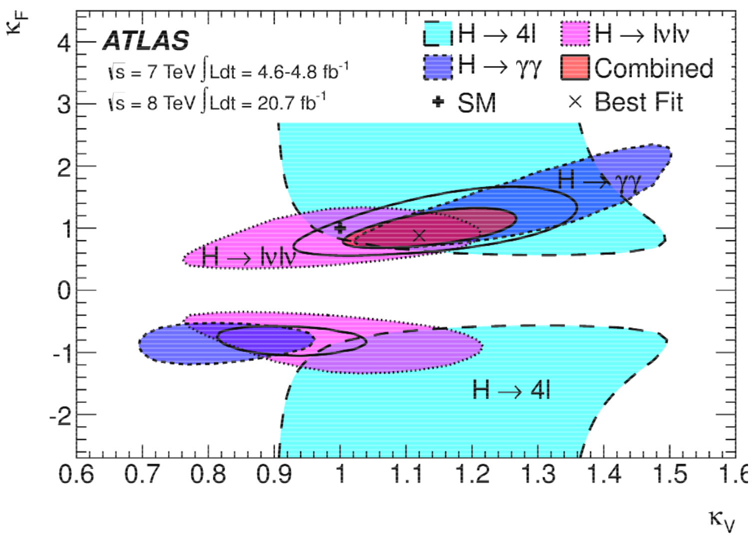
V-mediated production compatible with SM prediction

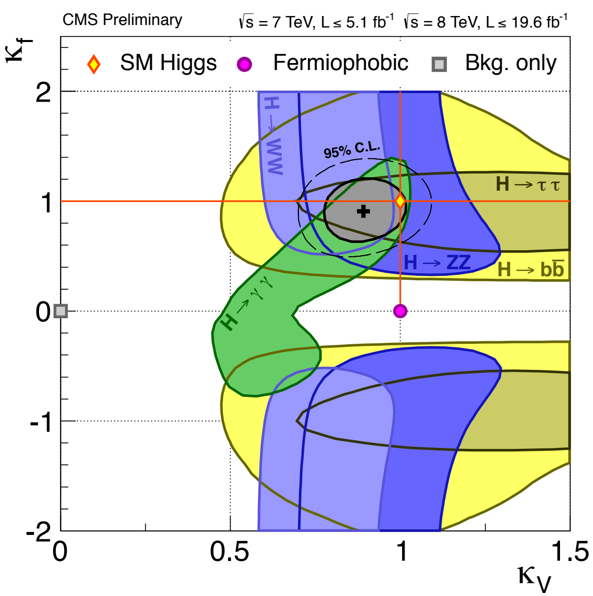


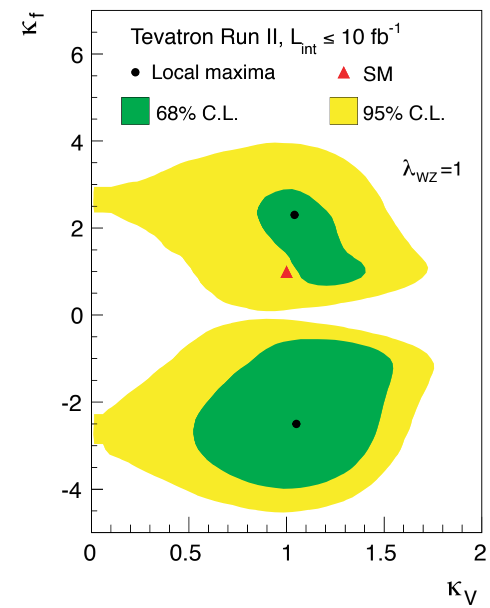


Test of Vector vs Fermion sectors κ_V-κ_F

- *Assumptions:*
  - All Fermion couplings scale as κ_F ($=\kappa_t=\kappa_b=\kappa_\tau=\ldots$)
  - All Vector Boson couplings scale as κ_V ($=\kappa_W=\kappa_Z$)
  - No BSM contributions to $\Gamma_H \rightarrow \kappa^2_H(\kappa_F\ \kappa_V) \sim 0.7\ \kappa^2_F + 0.3\ \kappa^2_V$ and $\kappa_g(\kappa_F\ \kappa_V)$ $\kappa_\gamma(\kappa_F\ \kappa_V)$



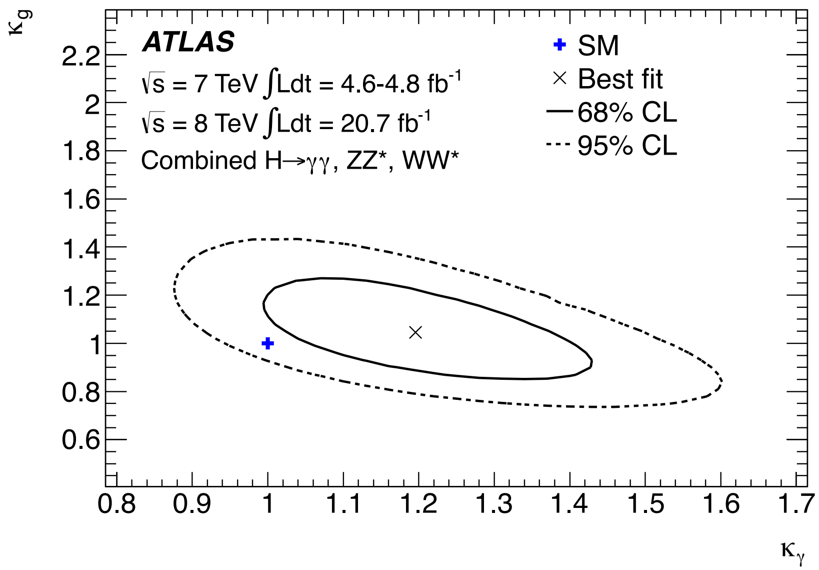


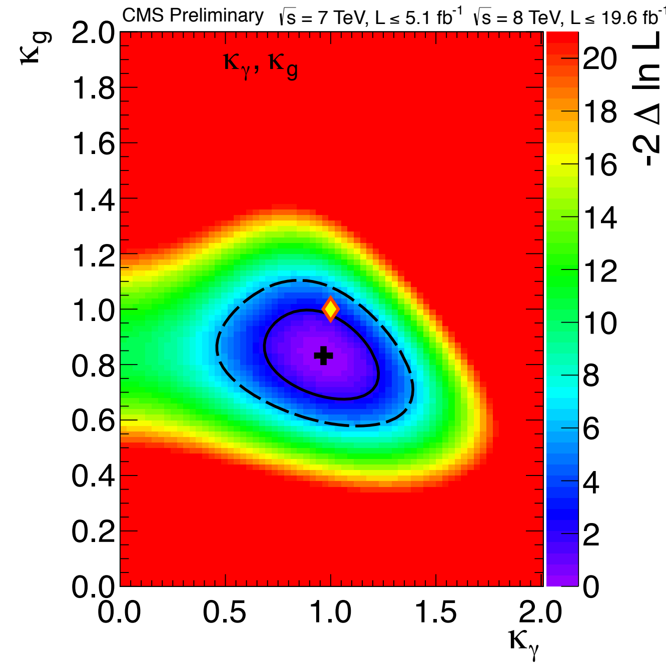


- **All experiments compatible with SM predictions: accuracy ~10-20%**
  - **ATLAS: κ_V [1.05,1.22] at 68% CL - κ_F [0.76,1.18] at 68% CL**
  - **CMS: κ_V [0.74,1.06] at 95% CL - κ_F [0.61,1.33] at 95% CL**
- κ_F=0 Excluded at $>5\sigma$ (mainly indirect via gg loop)

Test of loop induced couplings: κ_g vs κ_γ

- *Assumptions:*
  - Tree-level Coupling to SM particles as in SM: $\kappa_b = \kappa_W = \kappa_Z = \kappa_\tau = \kappa_t \ldots = 1$
  - No BSM contributions to $\Gamma_H \rightarrow \kappa_H \sim 0.9 + 0.1\,\kappa_g$





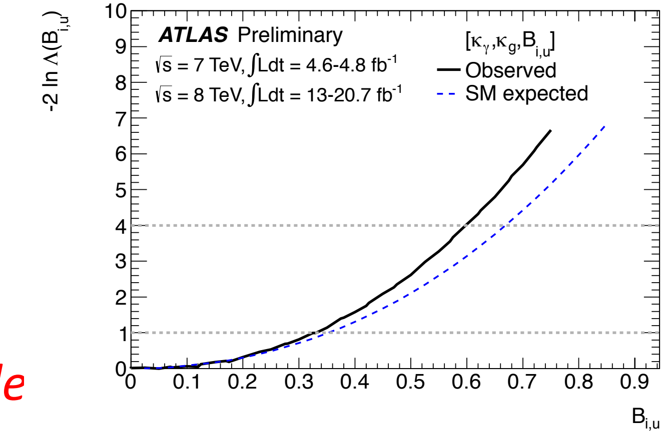
- Both experiments: **compatible with SM predictions - Accuracy ~10-15%**
  - **ATLAS: κ_g =(1.04 ± 0.14) at 68% CL - κ_γ = (1.20 ± 0.15) at 68% CL**
  - **CMS: κ_g [0.63,1.05] at 95% CL - κ_γ [0.59,1.30] at 95% CL**

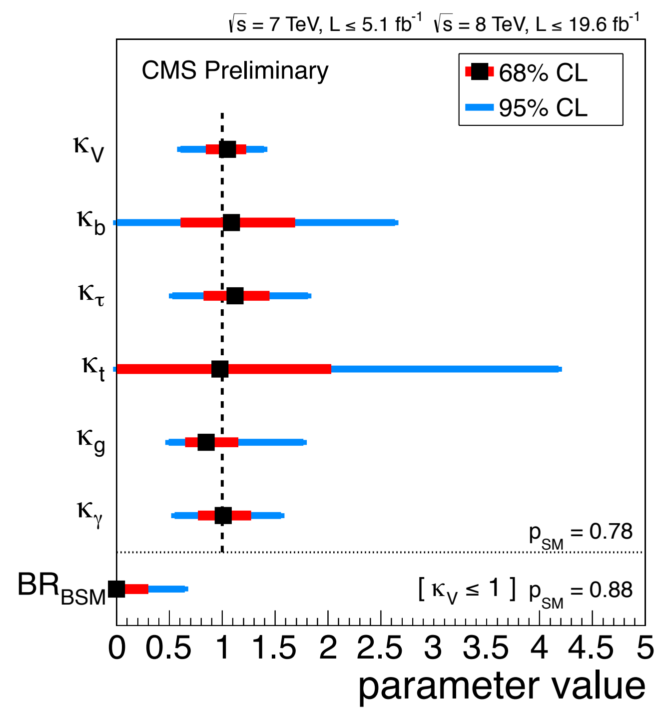
Constraints on BR_{BSM}

- Greg has shown direct search for: ZH→ℓℓ-**Invisible**
  - ATLAS: **BR_{inv} < 0.60** @ 95% CL (0.84 exp.)
  - CMS: **BR_{inv} < 0.75** @ 95% CL (0.91 exp.)

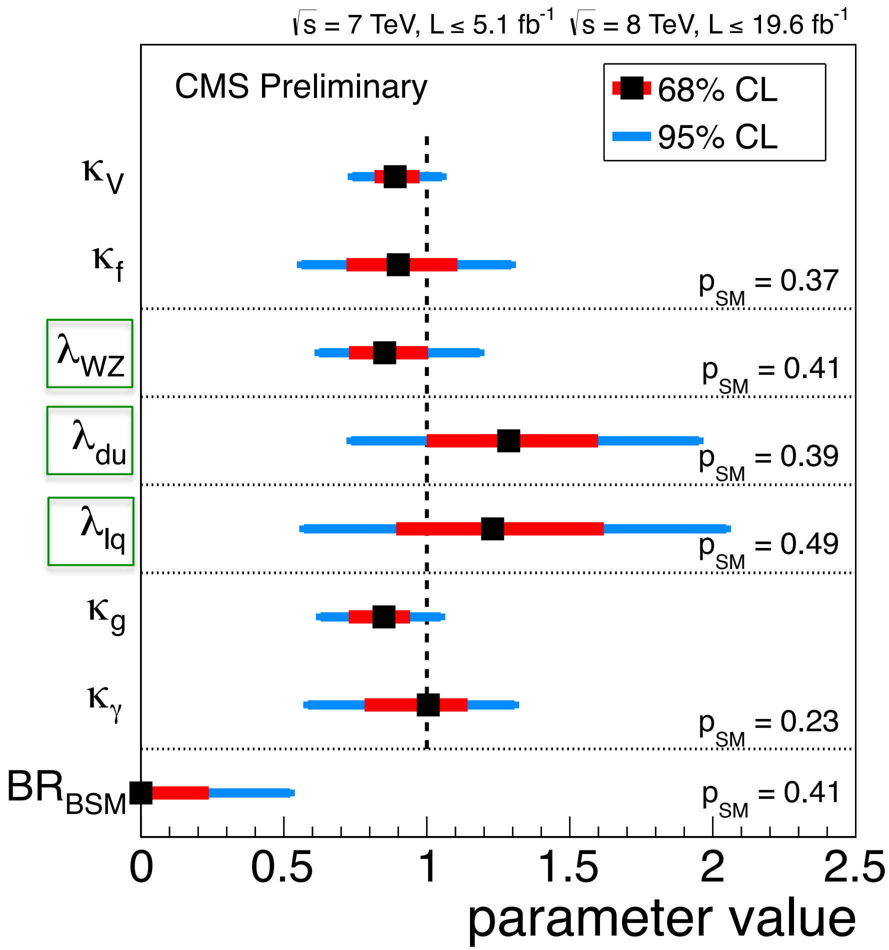
- We can parameterize: $\Gamma_H = \Gamma_{SM} + \Gamma_{BSM}$

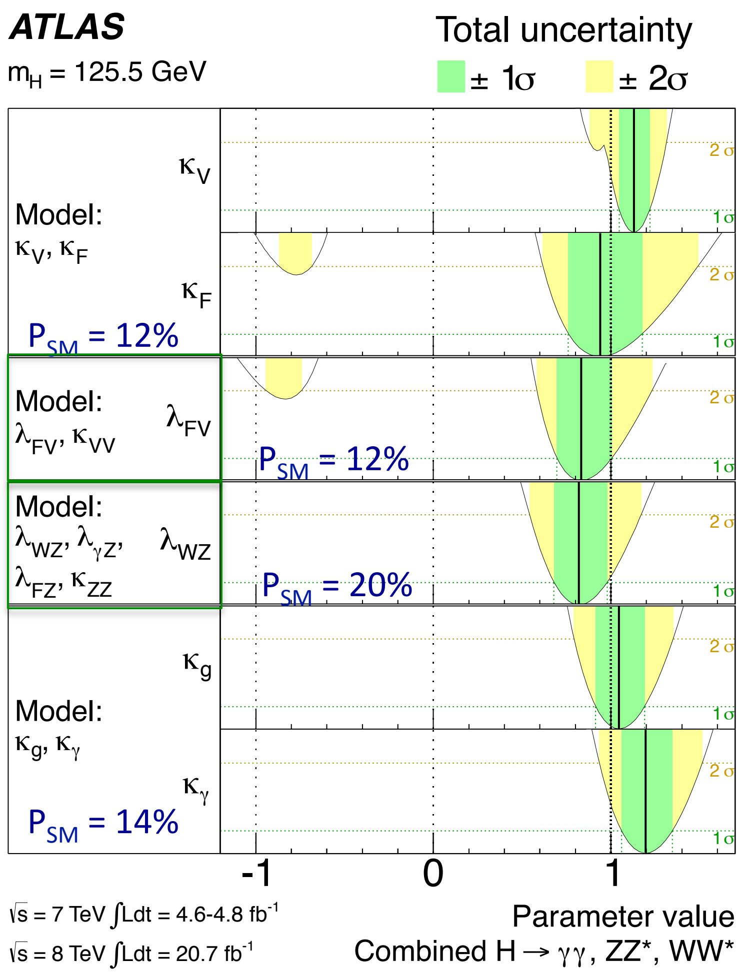
  $BR_{BSM} = \Gamma_{BSM}/\Gamma_H$
- This quantity is sensitive also to other *undetectable* decay modes: H → light hadrons
- ATLAS:
  - *Assumptions* three-level couplings: $\kappa_b = \kappa_W .. = 1$
  - 3 Fitted Par.: κ_γ κ_g + BR_{BSM}
  - **BR_{BSM} < 0.60 @ 95% CL** (0.67 exp.)
- CMS:
  - *Assumption*: $\kappa_V \leq 1$ (motivated by EWSB)
  - 7 Fitted Par.: κ_V κ_b κ_τ κ_t κ_γ κ_g + BR_{BSM}
  - **BR_{BSM} < 0.64 @ 95% CL** (0.66 exp.)





Couplings Overview



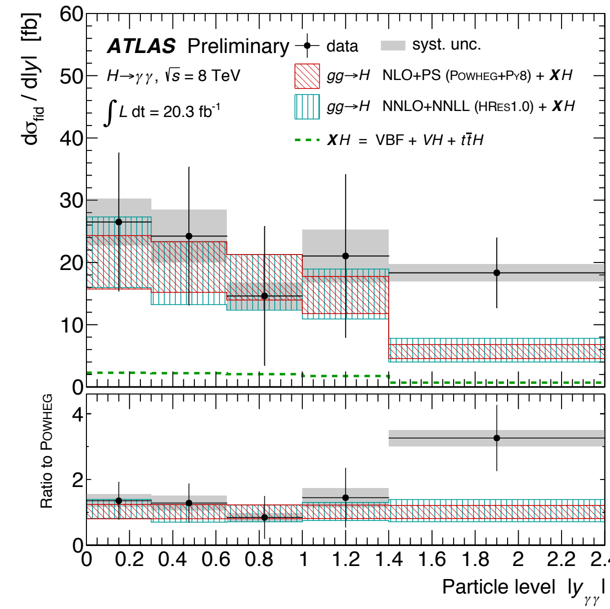


- Different *Sectors* of the New Boson Couplings tested: P_{SM}>12%

All compatible with SM Higgs expectations

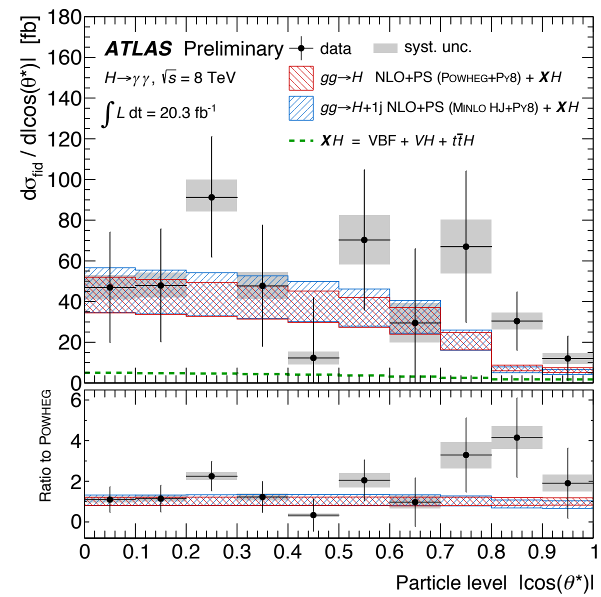
Differential Cross sections in $\gamma\gamma$ final state

- ATLAS: fiducial differential cross-sections
  - **$d\sigma/dP_{T\gamma\gamma}$, $d|y_{\gamma\gamma}|$, $d|\cos(\theta^*)|$, dN_{jets}, $d\phi_{JJ}$, ...**
  - Unfolded to particle level
  - Sensitive to: PDF, QCD, production mechanism, spin, Lagrangian tensor structure, ...



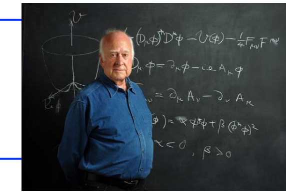
Probabilities of χ^2 compatibility tests for Data vs Predictions for different observables

	N_{jets}	$p_T^{\gamma\gamma}$	$\lvert y^{\gamma\gamma}\rvert$	$\lvert\cos\theta^*\rvert$	$p_T^{j_1}$	$\Delta\phi_{jj}$	$p_T^{\gamma\gamma jj}$
POWHEG	0.54	0.55	0.38	0.69	0.79	0.42	0.50
MINLO	0.44	–	–	0.67	0.73	0.45	0.49
HRES 1.0	–	0.39	0.44	–	–	–	–



Data in agreement with tested predictions (Powheg, MINLO, Hres1.0) within current experimental accuracy

Conclusions



- 1 year after the discovery properties of the New boson measured with increasing precision thanks to outstanding LHC performance and improved analysis from CDF and D0:
  - Mass measured at the 3 per mill level
  - Evidence for scalar nature 0^+ (though CP mixing not excluded)
  - Evidence for couplings to Fermions: *direct* $>3\sigma$ and *indirect* $>5\sigma$
  - Evidence for V-mediated and VBF production
  - Coupling Tests compatible with SM predictions
  - No sign (yet ?) for BSM contributions: invisible decays, Γ_{BSM}, loop couplings ..

All measured properties compatible with the SM Higgs boson

- Coming soon: final RUN1 publications from CMS and ATLAS
- In 2015 LHC will increase E_{CM} (σ_H~2.6) and Luminosity ($10^{34}cm^{-2}s^{-1}$)
  - Increase sensitivity to challenge the SM predictions:

This is just the *beginning* of a

***rich* and *exciting* "Higgs physics program" !**

Thanks to Parallel Sessions Speakers !

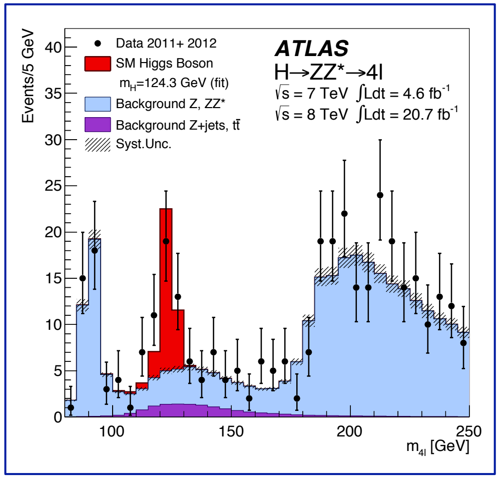
- Material from the excellent talks in parallel session:

J.B. De Vivie, D.M Sheafer, C. Botta, M. Donega, K.N. Herner, D.O'Neil, M. De Gruttola, M. Bluj, F. Margaroli, M. Kucharchizyk, D. Lopez Mateos, M. Dueherssen, J. Bendavid, J. Elmsheuser, N. Kostantinidis

BACKUP SLIDES

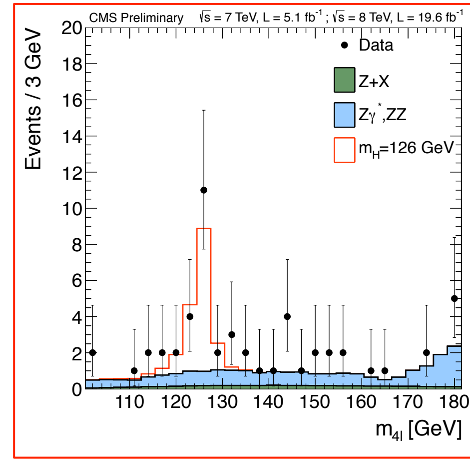
Mass Measurements

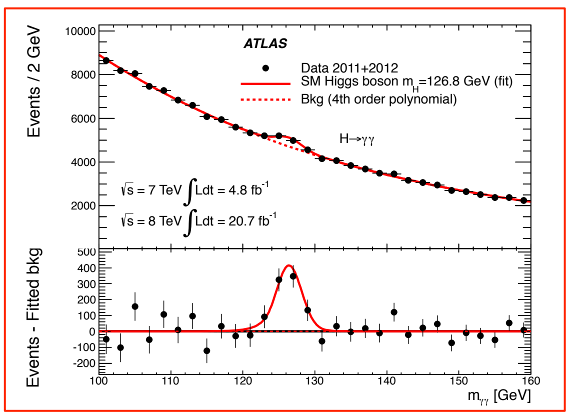
From $\gamma\gamma$ and $ZZ^*(4\ell)$ mass spectra



ATLAS: $M_H = 124.3 \pm 0.6_{stat} \pm 0.4_{sys}$ GeV

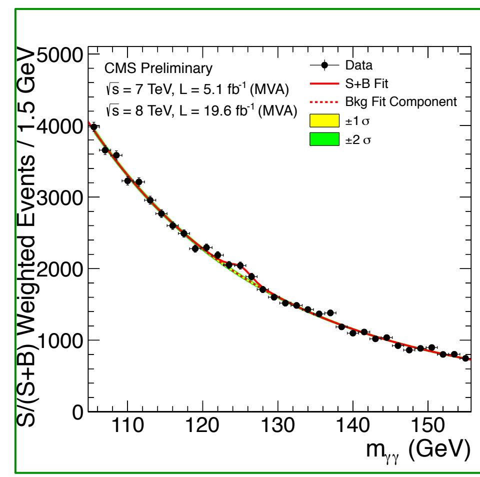
CMS: $M_H = 125.8 \pm 0.5_{stat} \pm 0.2_{sys}$ GeV





ATLAS: $M_H = 126.8 \pm 0.2_{stat} \pm 0.7_{sys}$ GeV

CMS: $M_H = 125.4 \pm 0.5_{stat} \pm 0.6_{sys}$ GeV



ATLAS: $M_H = 125.5 \pm 0.2_{stat} \pm 0.6_{sys}$ GeV

CMS: $M_H = 125.7 \pm 0.3_{stat} \pm 0.3_{sys}$ GeV

Mass Measurement: ATLAS

ATLAS tension between $\gamma\gamma$ and $ZZ^*(4\ell)$ mass measurements

- Dedicated Likelihood with different mass parameterization:

$$M_H \text{ and } \Delta M_H$$

- $\Delta M_H = 2.3 \pm 0.7_{stat} \pm 0.6_{sys}$ GeV $= 2.3 \pm 0.9_{tot}$ (M_H "profiled")
- Probability to observe such a large (or larger) difference if $\Delta M_H = 0$ evaluated at 1.5% (2.4σ)
- If main systematics on Electromagnetic-Energy Scale shifted by 1σ probability increases to 8%
- Updates final $\gamma\gamma$ and $ZZ^*(4\ell)$ publications this fall:
  - better EES calibration (material description, ..), improved ZZ* mass analysis (MVA techniques, event by event errors, ..)

Spin-Parity determination

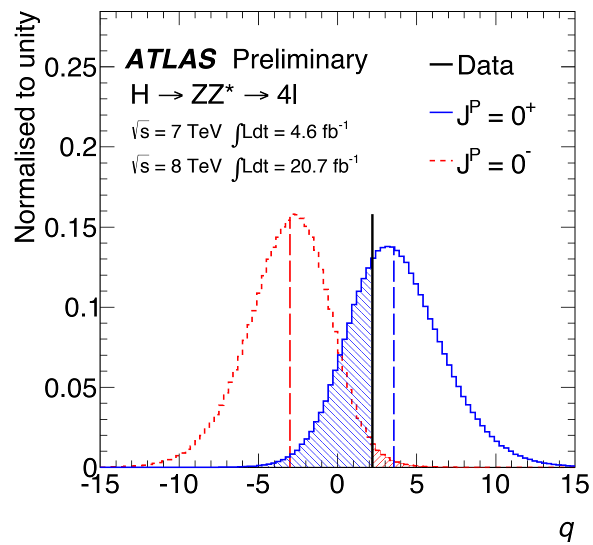
- Used as test statistics the likelihood ratio q:

$$\mathcal{L}(J^P,\mu,\theta) = \prod_{j}^{N_{chann.}} \prod_{i}^{N_{bins}} P(N_{i,j} \mid \mu_j \cdot S_{i,j}^{(J^P)}(\theta) + B_{i,j}(\theta)) \times \mathcal{A}_j(\theta)$$

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

- Signal strengths μ_{JP} treated as independent Nuisance-Parameter for each channel and each spin hypothesis
- Probability distributions for different J^P hypothesis derived via pseudo-experiments
- When deriving exclusions use CL_s:

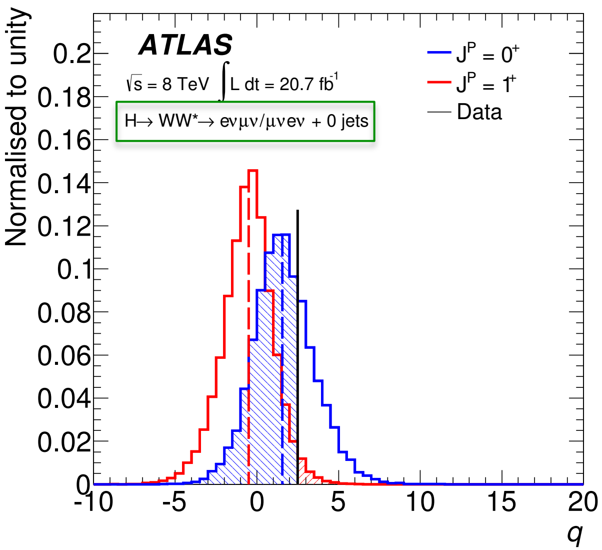
$$\mathrm{CL_s}(J^P_{\rm alt}) = \frac{p_0(J^P_{\rm alt})}{1 - p_0(0^+)}$$



Test of 0^+ vs 1^+ / 1^-

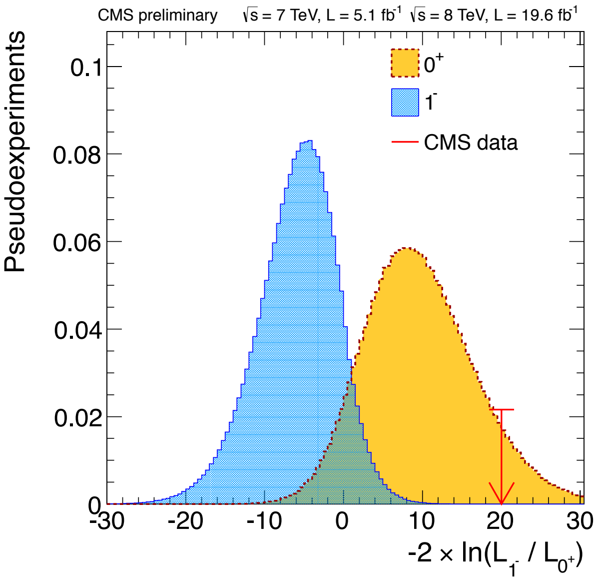
ATLAS: **combined** WW*→νℓνℓ + ZZ*→4ℓ

- 1^+ Excluded at 99.97% CL (exp. 99.95%)
- 1^- Excluded at 99.7% CL (exp. 99.4%)



CMS: ZZ*→4ℓ

- 1^+ Excluded at >99.9% CL (exp. 99.7%)
- 1^- Excluded at >99.9% CL (exp. 99.5%)



Compatible with SM Higgs 0^+

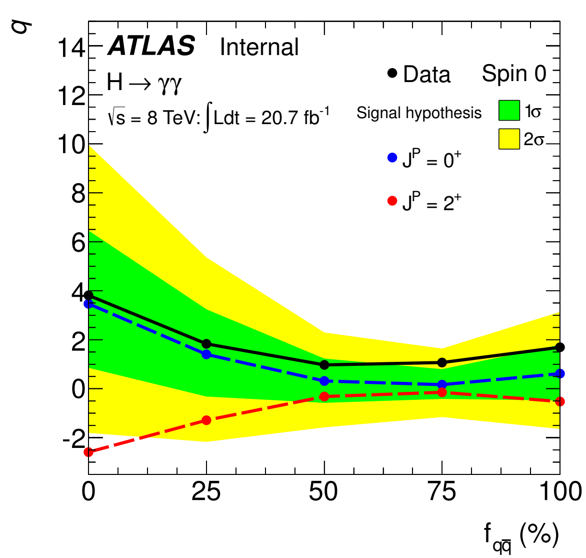
Test of 0^+ vs 2^+_m f_{qq} scan

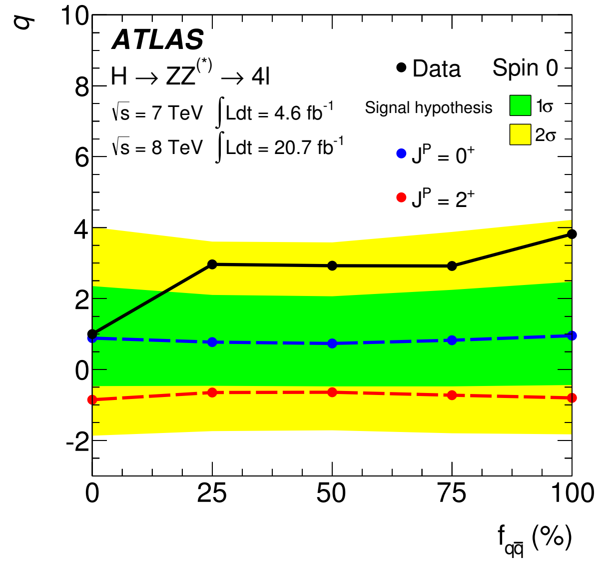
Graviton inspired with minimal couplings to SM particles

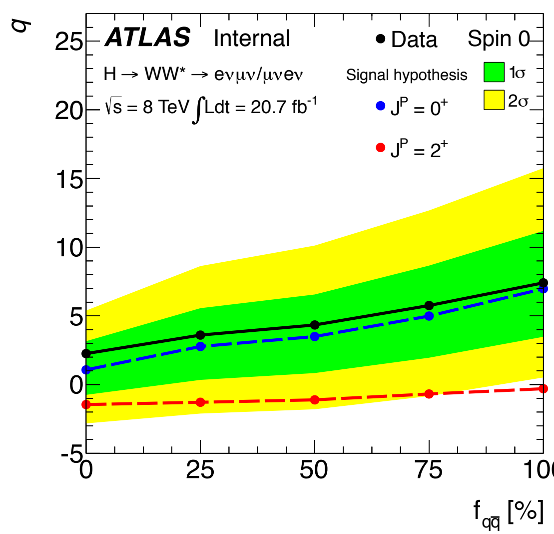
Tensor can be produced via gg or qq annihilation

ATLAS: γγ + WW* + ZZ*

- 2^+_m (100% qq) Excluded at >99.99% CL (exp. >99.99%)
- 2^+_m (100% gg) Excluded at 99.98% CL (exp. 99.94%)







Channels/Categories used in the coupling tests

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
$\gamma\gamma$	untagged	$\gamma\gamma$ (4 diphoton classes)	4 + 4	1-2%	5.1	19.6
	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
$ZZ \to 4\ell$	$N_{jet} < 2$ $N_{jet} \geq 2$	4e, 4μ, 2e2μ	3 + 3 3 + 3	1-2%	5.1	19.6
$WW \to \ell\nu\ell\nu$	0/1-jets	(DF or SF dileptons) × (0 or 1 jets)	4 + 4	20%	4.9	19.5
	VBF-tag	$\ell\nu\ell\nu + (jj)_{VBF}$ (DF or SF dileptons for 8 TeV)	1 + 2	20%	4.9	12.1
	WH-tag	$3\ell 3\nu$ (same-sign SF and otherwise)	2 + 2		4.9	19.5
$\tau\tau$	0/1-jet 1-jet VBF-tag	(eτ_h, $\mu\tau_h$, eμ, $\mu\mu$)× (low or high p_T^τ) $\tau_h\tau_h$ (eτ_h, $\mu\tau_h$, eμ, $\mu\mu$, $\tau_h\tau_h$) + $(jj)_{VBF}$	16 + 16 1 + 1 5 + 5	15%	4.9	19.6
	ZH-tag WH-tag	(ee, $\mu\mu$) × ($\tau_h\tau_h$, eτ_h, $\mu\tau_h$, eμ) $\tau_h\mu\mu$, τ_heμ, e$\tau_h\tau_h$, $\mu\tau_h\tau_h$	8 + 8 4 + 4		5.0	19.5
bb	VH-tag	($\nu\nu$, ee, $\mu\mu$, eν, $\mu\nu$ with 2 b-jets)× (low or high p_T(V) or loose b-tag)	10 + 13	10%	5.0	12.1
	ttH-tag	(ℓ with 4, 5 or ≥6 jets) × (3 or ≥4 b-tags); (ℓ with 6 jets with 2 b-tags); ($\ell\ell$ with 2 or ≥3 b-tagged jets)	6 + 6 3 + 3		5.0	5.1

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} $\oplus$ {ℓ-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

CDF - arXiv:1303.6346 Subm. Phys Rev. D

Channel		Luminosity (fb^{-1})
$WH \to \ell\nu b\bar{b}$ 2-jet channels 4×(5 b-tag categories)	$H \to b\bar{b}$	9.45
$WH \to \ell\nu b\bar{b}$ 3-jet channels 3×(2 b-tag categories)		9.45
$ZH \to \nu\bar{\nu}b\bar{b}$ (3 b-tag categories)		9.45
$ZH \to \ell^+\ell^- b\bar{b}$ 2-jet channels 2×(4 b-tag categories)		9.45
$ZH \to \ell^+\ell^- b\bar{b}$ 3-jet channels 2×(4 b-tag categories)		9.45
$WH + ZH \to jjb\bar{b}$ (2 b-tag categories)		9.45
$t\bar{t}H \to W^+bW^-\bar{b}b\bar{b}$ (4 jets,5 jets,≥6 jets)×(5 b-tag categories)		9.45
$H \to W^+W^-$ 2×(0 jets)+2×(1 jet)+1×(≥2 jets)+1×(low-$m_{\ell\ell}$)	$H \to W^+W^-$	9.7
$H \to W^+W^-$ (e-τ_{had})+(μ-τ_{had})		9.7
$WH \to WW^+W^-$ (same-sign leptons)+(tri-leptons)		9.7
$WH \to WW^+W^-$ (tri-leptons with 1 τ_{had})		9.7
$ZH \to ZW^+W^-$ (tri-leptons with 1 jet,≥2 jets)		9.7
$H \to \tau^+\tau^-$ (1 jet)+(≥2 jets)	$H \to \tau^+\tau^-$	6.0
$H \to \gamma\gamma$ 1×(0 jet)+1×(≥1 jet)+3×(all jets)	$H \to \gamma\gamma$	10.0
$H \to ZZ$ (four leptons)	$H \to ZZ$	9.7

D0 - arXiv:1303.6346 Subm. Phys Rev. D

Channel		Luminosity (fb^{-1})
$WH \to \ell\nu b\bar{b}$ 2-jet channels 2×(4 b-tag categories)	$H \to b\bar{b}$	9.7
$WH \to \ell\nu b\bar{b}$ 3-jet channels 2×(4 b-tag categories)		9.7
$ZH \to \nu\bar{\nu}b\bar{b}$ (2 b-tag categories)		9.5
$ZH \to \ell^+\ell^- b\bar{b}$ 2×(2 b-tag)×(4 lepton categories)		9.7
$H \to W^+W^- \to \ell^\pm\nu\ell^\mp\nu$ 2×(0 jets,1 jet,≥2 jets)	$H \to W^+W^-$	9.7
$H + X \to W^+W^- \to \mu^\mp\nu\tau^\pm_{had}\nu$ (3 τ categories)		7.3
$H \to W^+W^- \to \ell\bar{\nu}jj$ 2×(2 b-tag categories)×(2 jets, 3 jets)		9.7
$VH \to e^\pm\mu^\pm + X$		9.7
$VH \to \ell\ell\ell + X$ ($\mu\mu e$, 3 × $e\mu\mu$)		9.7
$VH \to \ell\bar{\nu}jjjj$ 2×(≥4 jets)		9.7
$VH \to \tau_{had}\tau_{had}\mu + X$ (3 τ categories)	$H \to \tau^+\tau^-$	8.6
$H{+}X \to \ell^\pm\tau^\mp_{had}jj$ 2×(3 τ categories)		9.7
$H \to \gamma\gamma$ (4 categories)	$H \to \gamma\gamma$	9.6

Production/Decay with *Signa*l above 2σ

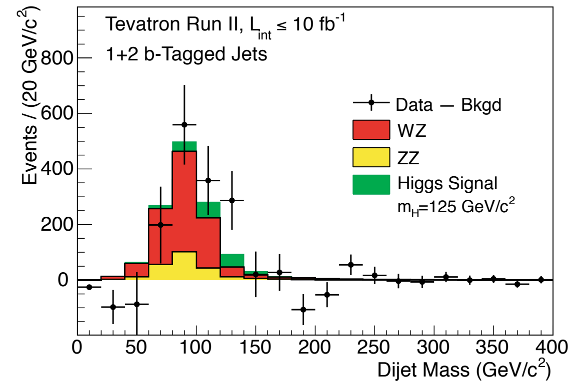
- Measure: Yields → Production x Decay
  - Production modes: gg, VBF, W/ZH, ttH
  - Decay Channels: $\gamma\gamma$, WW*, ZZ*, bb, $\tau\tau$, $\mu\mu$, Zγ

Observations Above 2σ:

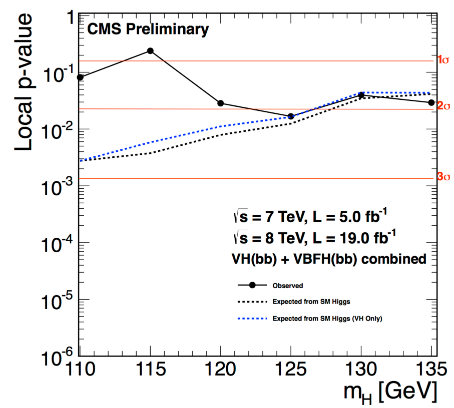
- ATLAS:
  - Production Modes: gluon-gluon(>5σ), VBF(>3σ), VH
  - Decay Channels: WW*(3.8σ), ZZ* (>5σ), $\gamma\gamma$(>5σ)
- CMS:
  - Production Modes: gluon-gluon(>5σ), VH, VBF, (V+VBF)H(>3σ)
  - Decay Channels: WW*(4σ), ZZ*(>5σ), $\gamma\gamma$(>3σ), $\tau\tau$, bb, *combined* $\tau\tau$+bb (>3σ)
- D0+CDF:
  - Production Modes: VH(>3σ)
  - Decay Channels: bb(>3σ)

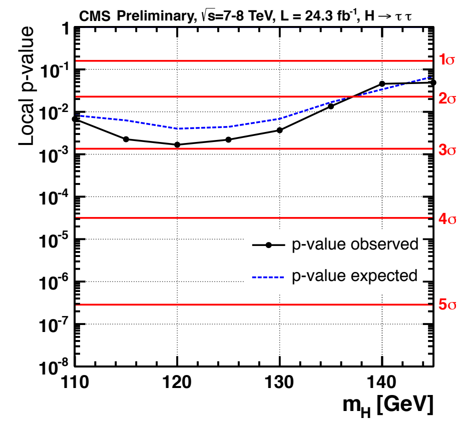
Evidence for Direct Couplings to Fermions

- TEVATRON: CDF+D0 Combined VH→bb
  - 2.1σ excess
  - $\sigma(VH)\times BR(H\rightarrow bb)$ = (0.19 ± 0.09) pb - SM for M_H=125 GeV → (0.12 ± 0.01) pb

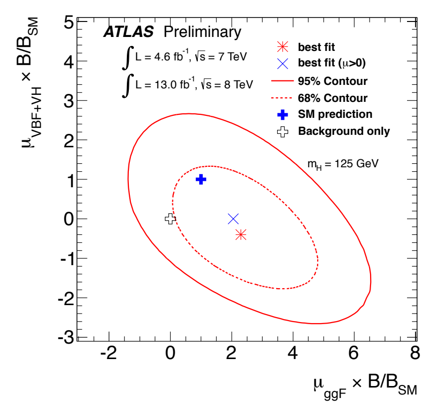


- CMS (for M_H=125 GeV):
  - (VBF+V)H → bb combination 2.1σ excess
  - H→ ττ 2.85σ excess
  - Combined H→ (ττ + bb) 3.4σ excess





- 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)



The Couplings fit

- Loop contributions can:
  - Expressed as a function of SM couplings
  - Treated as free parameter (test possible BSM contributions)

- Total width Γ_H two kind of assumptions
  - Only SM particles contribute to $\Gamma_H(\Gamma_i)$
  - Measure ratio of couplings λ

Production modes

$$\frac{\sigma_{ggH}}{\sigma_{ggH}^{SM}} = \begin{cases} \kappa_g^2(\kappa_b, \kappa_t, m_H) \\ \kappa_g^2 \end{cases} \quad (3)$$

$$\frac{\sigma_{VBF}}{\sigma_{VBF}^{SM}} = \kappa_{VBF}^2(\kappa_W, \kappa_Z, m_H) \quad (4)$$

$$\frac{\sigma_{WH}}{\sigma_{WH}^{SM}} = \kappa_W^2 \quad (5)$$

$$\frac{\sigma_{ZH}}{\sigma_{ZH}^{SM}} = \kappa_Z^2 \quad (6)$$

$$\frac{\sigma_{t\bar{t}H}}{\sigma_{t\bar{t}H}^{SM}} = \kappa_t^2 \quad (7)$$

LHC-XS wg

Detectable decay modes

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

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

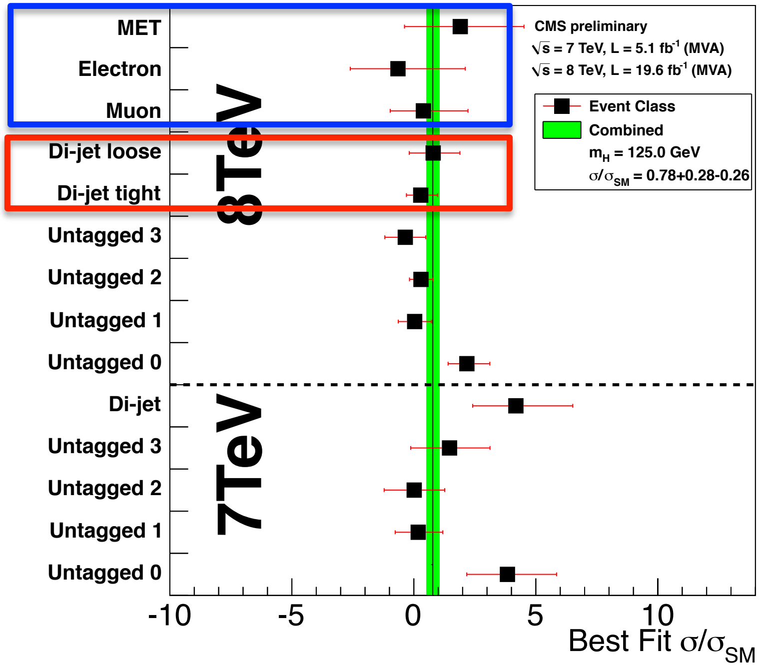
$$\frac{\Gamma_{b\bar{b}}}{\Gamma_{b\bar{b}}^{SM}} = \kappa_b^2$$

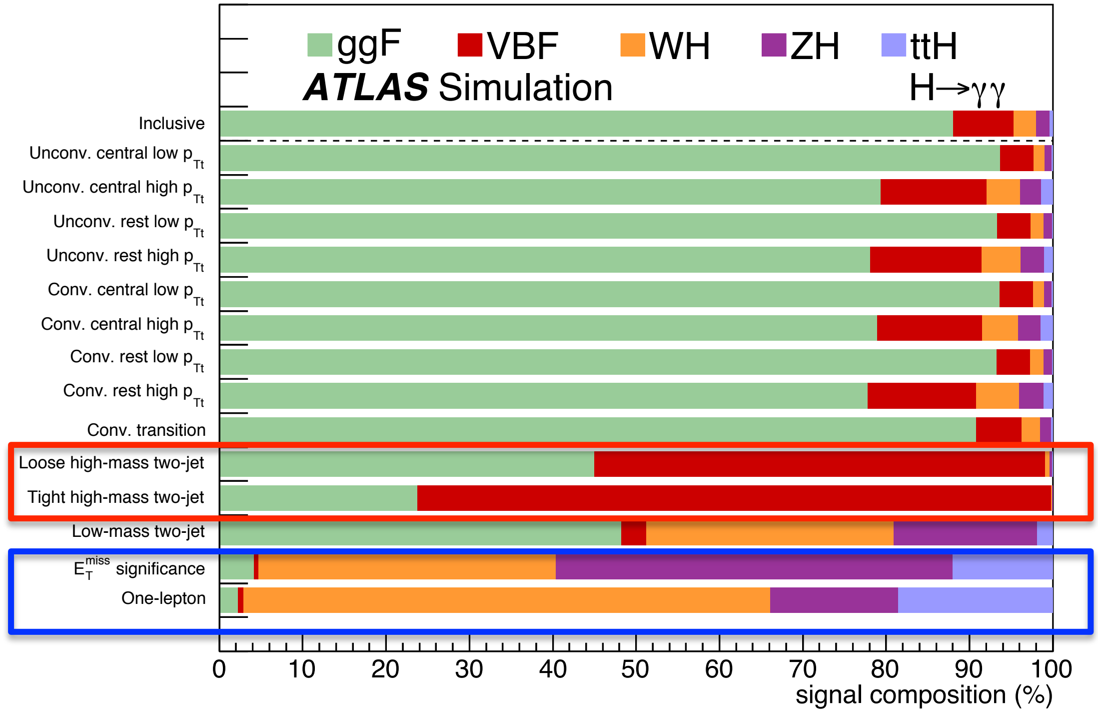
$$\frac{\Gamma_{\tau^-\tau^+}}{\Gamma_{\tau^-\tau^+}^{SM}} = \kappa_\tau^2$$

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

$$\kappa^2_{\gamma\gamma} = (1.6\,\kappa^2_W + 0.07\,\kappa^2_t - 0.67\,\kappa_W\kappa_t)$$

Inputs to the Fit





- Input to coupling fit: event yields per category *k* (list of channels/category used in backup)
  - $N^k = n^k_{\text{signal}} + n^k_{\text{background}}$
- Signal scaling factors per Production *i* and Decay *f*

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

LHC Coupling Fit: statistical approach

- Use profile likelihood ratio: $q(a) = -2\ln\frac{\mathcal{L}(\text{obs}\,|\,s(a)+b,\,\hat{\hat{\theta}}_a)}{\mathcal{L}(\text{obs}\,|\,s(\hat{a})+b,\,\hat{\theta})}$.

- a Parameter(s) of Interest: Signal Strength, Coupl. scale factor, Mass, …
- θ Nuisance parameter(s): Systematics, …

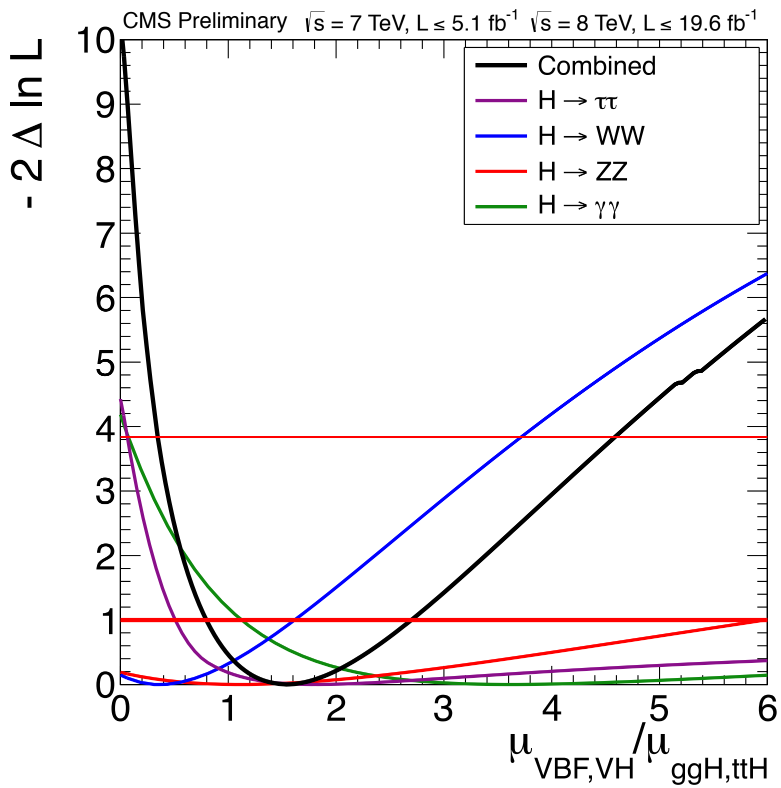
- CL intervals: Asymptotic approximation:
  - 1D: 68% $q(a) = 1$ - 95% $q(a) = 3.84$
  - 2D: 68% $q(a_i,a_j) = 2.3$ - 95% $q(a_i,a_j) = 6$
  - Cross checked with "pseudo-experiments"

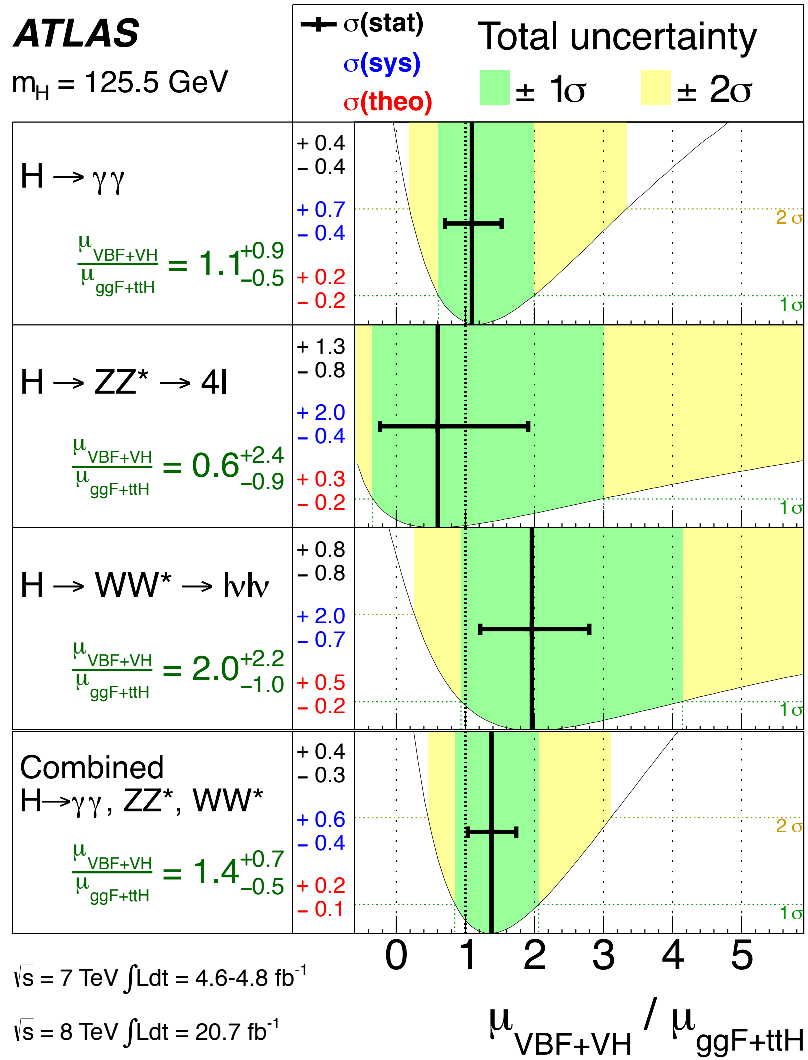
$$q_\mu = -2\,\Delta\ln\mathcal{L} = -2\ln\frac{\mathcal{L}(\text{data}\,|\,\mu,\hat{\hat{\theta}}_\mu)}{\mathcal{L}(\text{data}\,|\,\hat{\mu},\hat{\theta})}$$

Evidence for different Production modes

Model independent fit to $\mu_{VBF+VH}/\mu_{gg+ttH}$ in different channels (BR's cancels out):

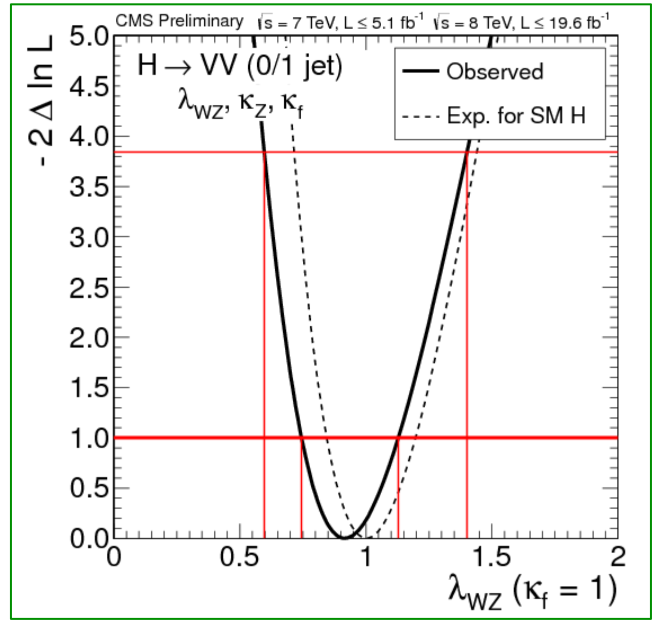
- ATLAS: Evidence for VBF production 3.1σ
- CMS: Evidence for V-boson mediated production



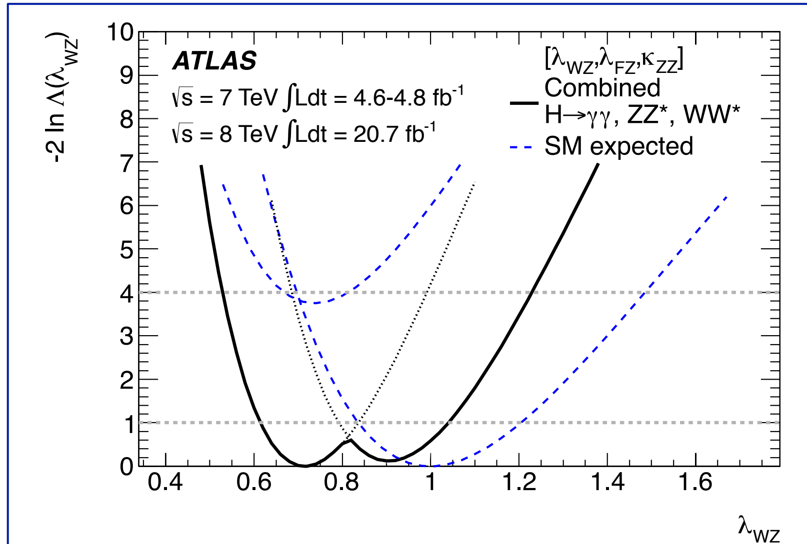


Test of W/Z coupling: $\lambda_{W/Z}$

- Ratio is independent of assumptions on Γ_H
- Tested under different assumptions
  - More *model independent*: using only *“untagged”* WW* and ZZ* channels
    - **CMS: $\lambda_{W/Z}$ [0.60,1.40] at 95% CL**
    - **ATLAS: $\lambda_{W/Z}$ = (0.81 ± 0.16) at 68% CL**



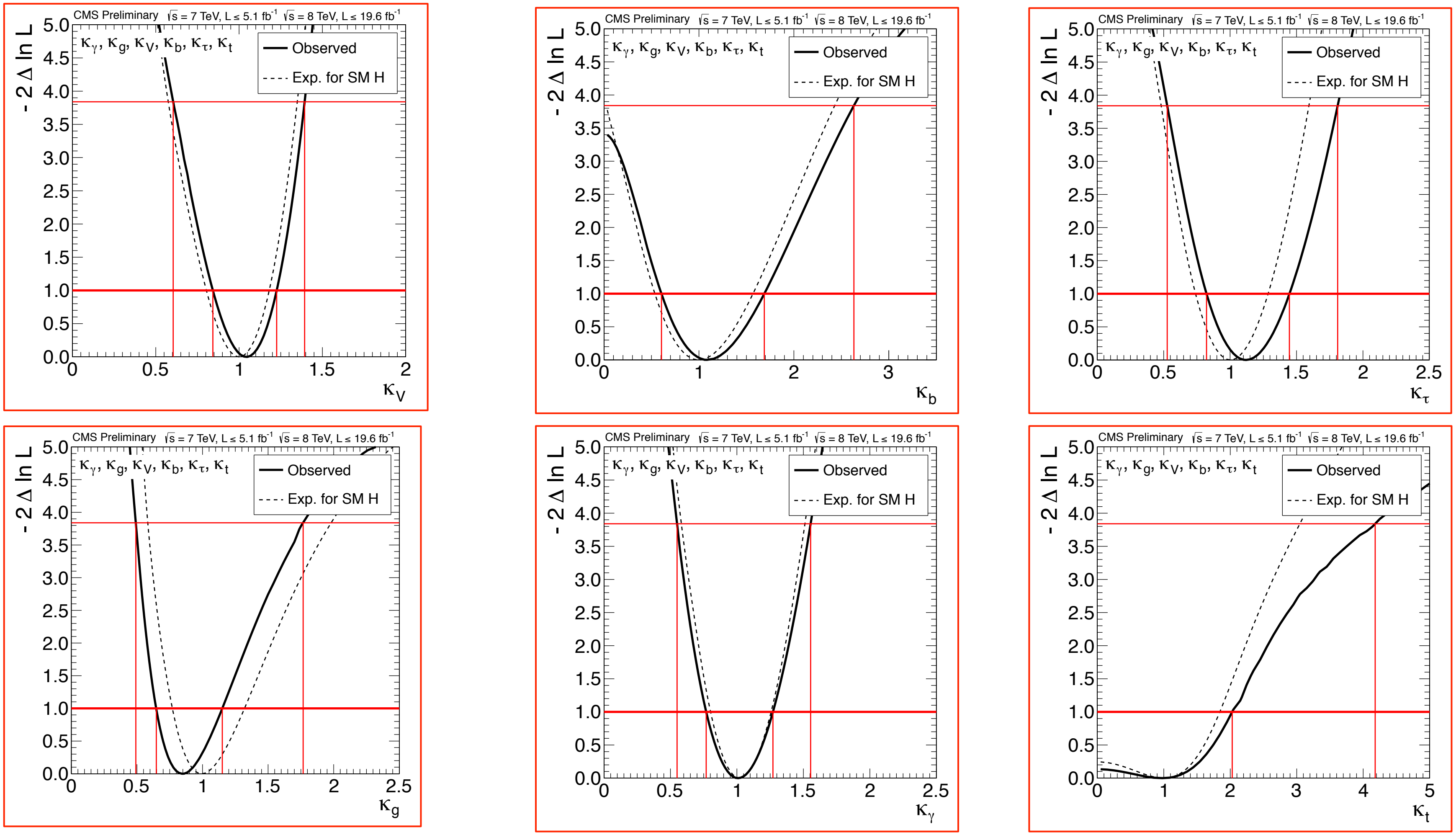
  - Assuming SM content in γγ loop and using VBF+VH production
    - **ATLAS: $\lambda_{W/Z}$ [0.61,1.04] at 68% CL**
    - **CMS: $\lambda_{W/Z}$ [0.62,1.19] at 95% CL**



Compatible with SM prediction:

Accuracy ~20%

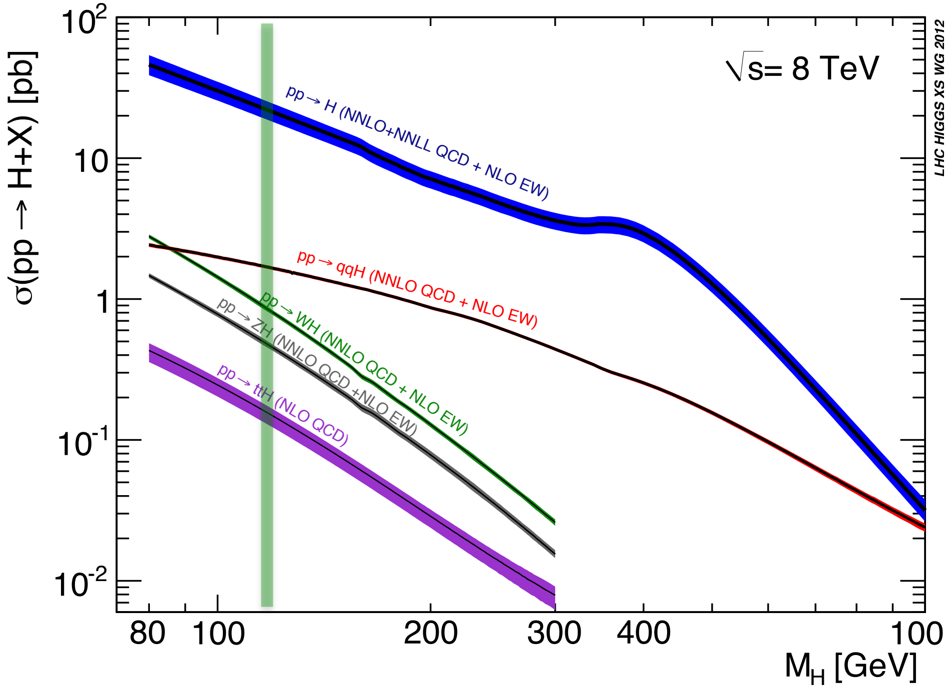
6 parameters fits: $\kappa_V\ \kappa_b\ \kappa_\tau\ \kappa_g\ \kappa_\gamma\ \kappa_t$

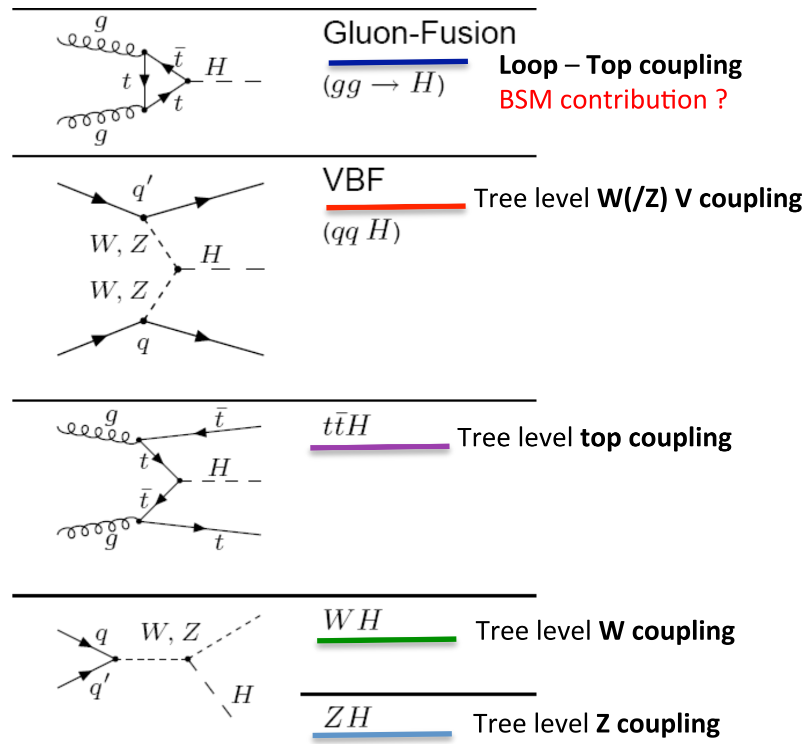


- 6 Parameters Fit: $\kappa_V\ \kappa_b\ \kappa_\tau\ \kappa_g\ \kappa_\gamma\ \kappa_t$ → Assumptions $\Gamma_{BSM} = 0$, $\kappa_W = \kappa_Z = \kappa_V$

Compatible with SM: Accuracy 20-100%

Higgs boson production at LHC





- Main production mode: ggH
- Access to top (direct and Loop), W and Z couplings via production cross section

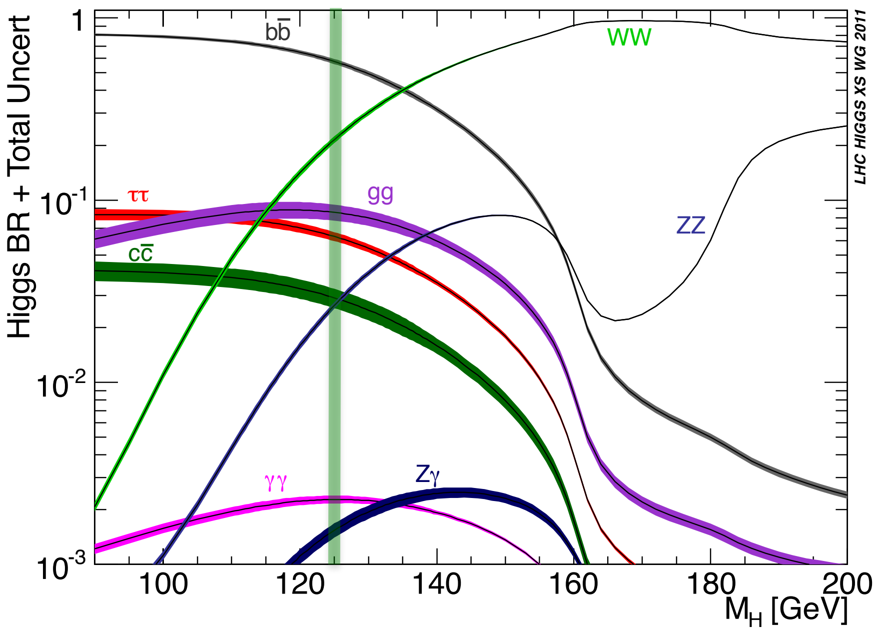
Higgs boson production at LHC

8 TeV

M_H(125 GeV)	σ(fb)	$\delta(th)_{TOT}$	$\delta(th)_{QCD-Scale}$	$\delta(th)_{PDF+\alpha s}$	$\delta\sigma/\delta M$(.5GeV)
ggH	19.5×10^3	**11%**	**8%**	**7%**	0.8%
VBF	1.58×10^3	3%	0.2%	3%	0.4%
WH	697	4%	0.5%	4%	1.3%
ZH	394	5%	1.5%	4%	1.3%
ttH	130	**11%**	**7%**	**8%**	1.9%

- Cross-sections are LARGE: LHC **is** the first Higgs Factory → Produced H~600k/Exp.
- Theory systematics more relevant for ggH and ttH - Mass dependency very weak

Higgs boson decay at LHC



- Experimentally accessible:
  - **bb, ττ, WW*, ZZ*, γγ, Zγ, μμ**
- Γ_H(125) ~4 MeV NO direct measure at LHC

M_H=125 GeV

Process	Branching ratio	Uncertainty	
H → bb	5.77 x 10-1	+3.2%	-3.3%
H → ττ	6.32 x 10-2	+5.7%	-5.7%
H → μμ	2.20 x 10-4	+6.0%	-5.9%
H → cc	2.91 x 10-2	+12.2%	-12.2%
H → gg	8.57 x 10-2	+10.2%	-10.0%
H → γγ	2.28 x 10-3	+5.0%	-4.9%
H → Zγ	1.54 x 10-3	+9.0%	-8.8%
H → WW	2.15 x 10-1	+4.3%	-4.2%
H → ZZ	2.64 x 10-2	+4.3%	-4.2%
Γ_H [GeV]	4.07 x 10-3	+4.0%	-3.9%

Mass dependency:

- δBR(bb)/0.5 GeV → 1%
- δBR(WW*)/0.5 GeV → 4%
- δBR(ZZ*)/0.5 GeV → 4%

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

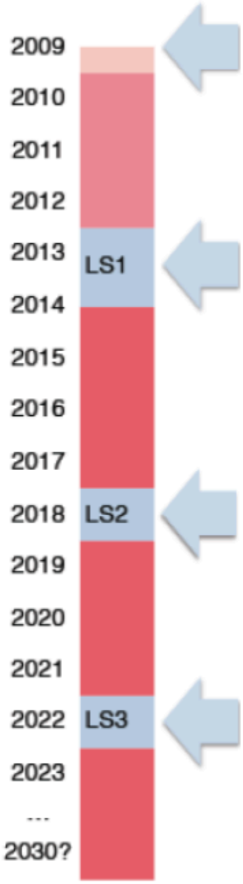
7+8 TeV
~ 30 fb^{-1}

LHC
Upgrade

14 TeV
~ 3000 fb^{-1}

results in backup slides

High Luminosity LHC: The timeline



✧ LHC startup, $\sqrt{s}$ = 900 GeV

$\sqrt{s}$=7~8 TeV, L=6x10^{33} cm^{-2} s^{-1}, bunch spacing 50 ns

Go to design energy, nominal luminosity (Phase-0)

$\sqrt{s}$=13~14 TeV, L~1x10^{34} cm^{-2} s^{-1}, bunch spacing 25 ns

Injector and LHC Phase-I upgrade to full design luminosity

$\sqrt{s}$=14 TeV, L~2x10^{34} cm^{-2} s^{-1}, bunch spacing 25 ns

HL-LHC Phase-II upgrade, IR, crab cavities

$\sqrt{s}$=14 TeV, L=5x10^{34} cm^{-2} s^{-1}, luminosity levelling

✔ Done

~20-25 fb^{-1}

~75-100 fb^{-1}

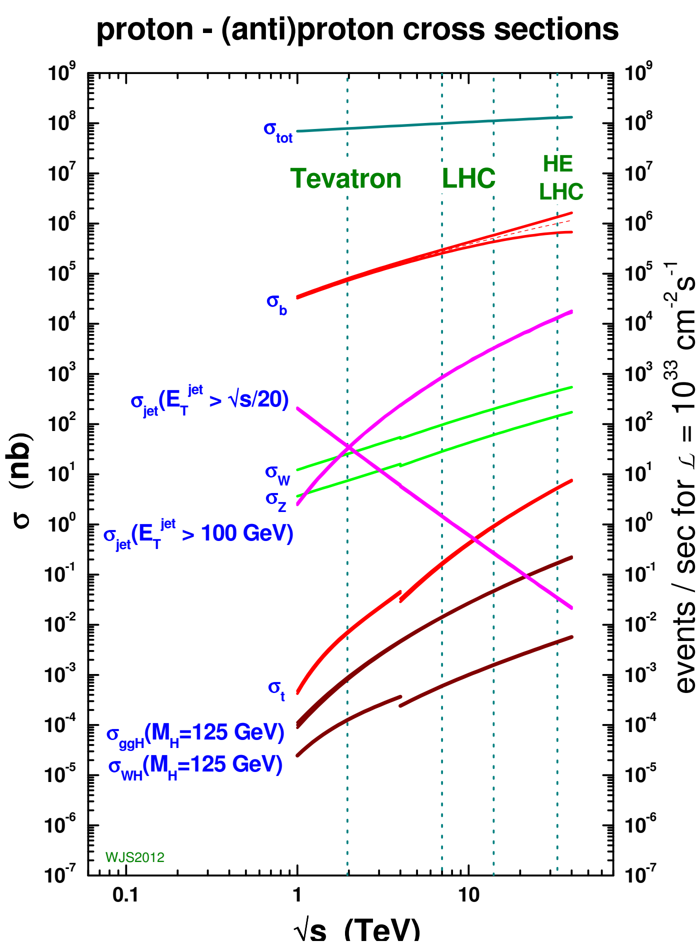
Approved
300 fb^{-1} at 14 TeV

HL-LHC:
3000 fb^{-1} at 14 TeV

High Luminosity LHC: the detectors upgrades

- Both detectors are planning **important upgrades** to stand the harsher running conditions at HL-LHC: pile-up, rates, radiation damage
  - Pile-up ~ 4-5 times more pile-up then today
- Plan: keep detector performance for main physics objects at the same level as we have today
  - Improved trigger system
  - New tracking systems
  - Improved forward detectors
  - ….
- CRUCIAL to profit of L increase

Signal σ and Yields: HL/HE



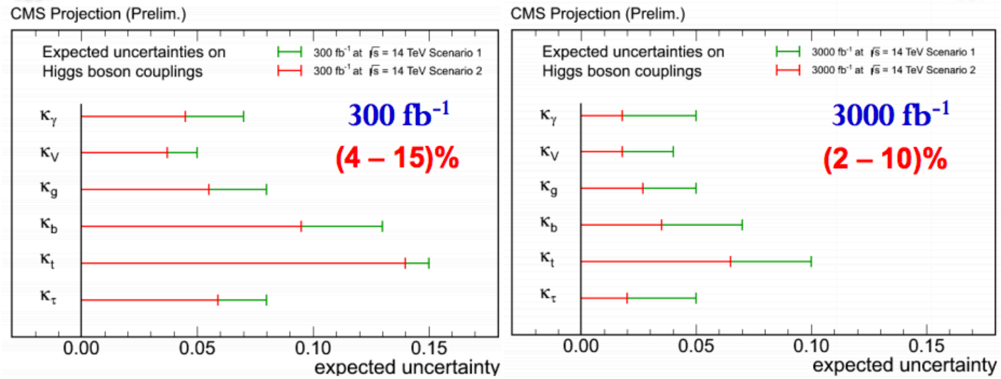
8 → 33 TeV: ggH x9.2   14 → 33 TeV: ggH→ HH x6

Process	3000 fb^{-1} 14 TeV	300 fb^{-1} 33 TeV
ggH→γγ	350k	123k
ggH→4ℓ	19k	6.7k
ttH→γγ	**42k**	**30k**
ttH→4ℓ/μμ	**0.2k/0.4k**	**0.16k/0.3k**
ggH→HH→bbγγ	**270**	**160**

LHC upgrades give access to rare decays
Better signal Yields at HL-LHC
BUT Pile-up and S/B better at HE-LHC

CMS: Couplings f 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

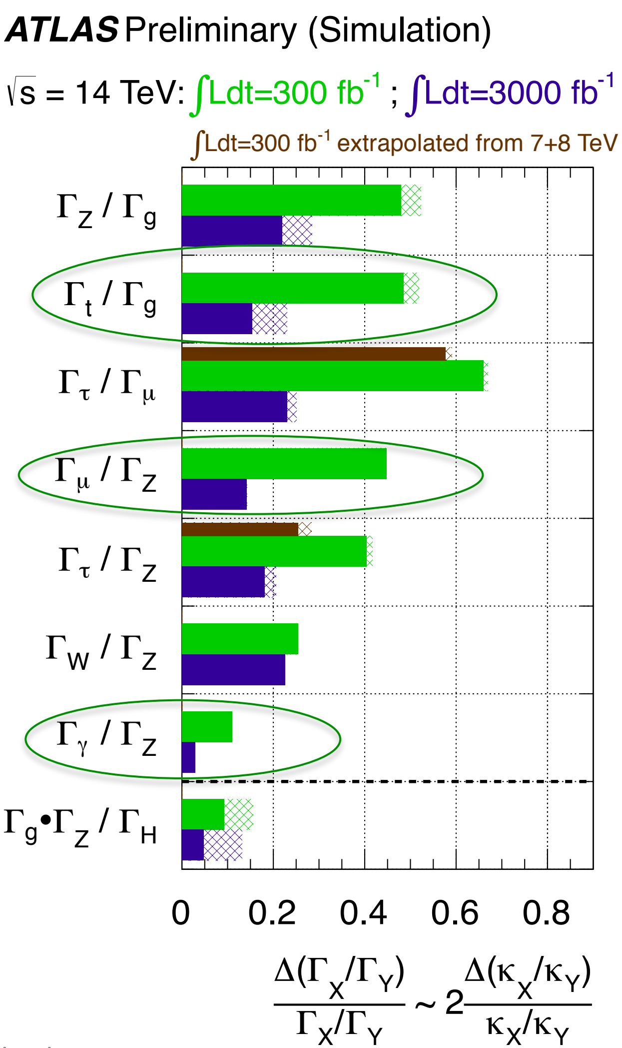
✓ γγ loop at 2-5% level

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

✓ direct top coupling at 7-10% level

✓ gg loop at 3-5% level

ATLAS: Coupling Ratios at HL-LHC



- Fit to coupling ratios:
  - No assumption BSM contributions to Γ_H
  - Some theory systematics cancels in the ratios
- Loop-induced Couplings γγ 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%

HL-LHC outlook

LHC 300 fb^{-1} at 14 TeV:

- Mass: <100 MeV (statistical)
- Coupling κ rel. precision*
  - Z, W, b, τ 10-15%
  - t, μ 3-2 σ observation
  - $\gamma\gamma$ and gg 5-11%

HL-LHC 3000 fb^{-1} at 14 TeV:

- Mass: << 50 MeV (statistical)
- Couplings κ rel. precision*
  - Z, W, b, τ, t, μ 2-10%
  - $\gamma\gamma$ and gg 2-5%

**Assuming sizeable (1/2) reduction of theory errors*

- "QCD scale" go to Higher order QCD computation ?
- gg "PDF" from LHC data ?

Mass Measurement:

Several exp./theory challenges to reach 50 MeV (e/γ/μ calibration E-scale, Interference, FSR, ..)