Higgs couplings and properties with ATLAS

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Introduction

In short:

- July 2012 observation of a new particle
- Followed by combined measurements of the properties (mass, couplings, spin, parity)

What we have:

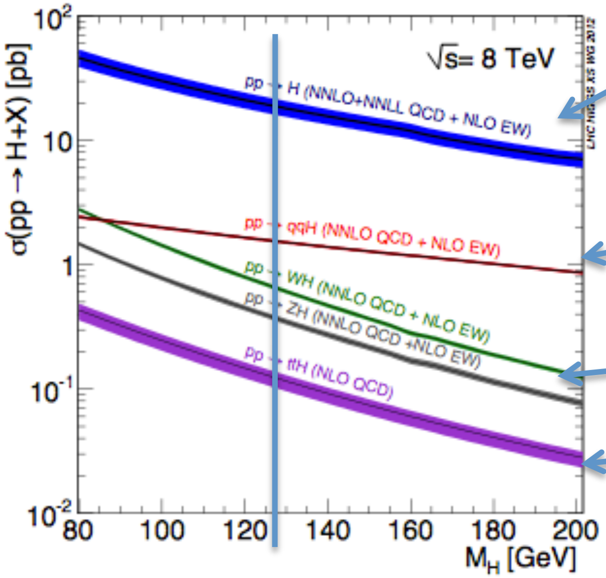
- 4.6 - 4.8 fb^{-1} data @ 7 TeV and 20.7 fb^{-1} data @ 8 TeV

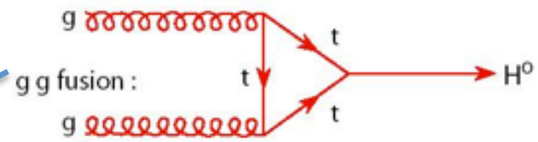
Outline: Overview of the Higgs properties

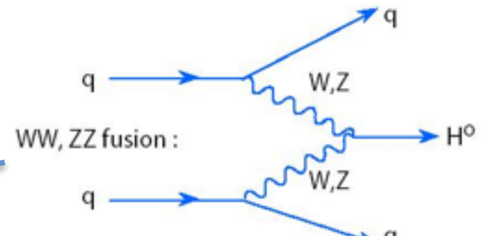
- Mass ATLAS-CONF-2013-014
- Spin/Parity http://arxiv.org/pdf/1307.1432v1.pdf
- Couplings: ATLAS-CONF-2014-009.pdf
  ATLAS-CONF-2014-010.pdf

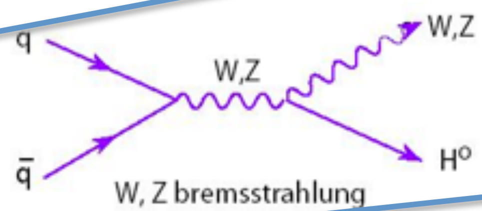
NEW CHANNELS :
H-> ττ and H-> bb-bar

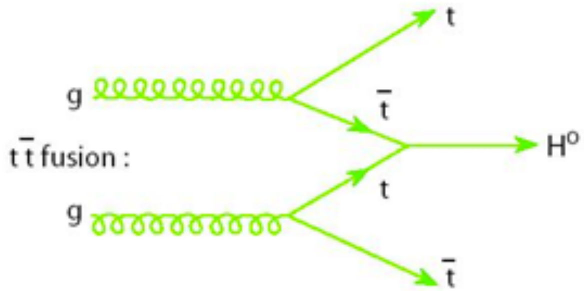
Higgs production and decay modes



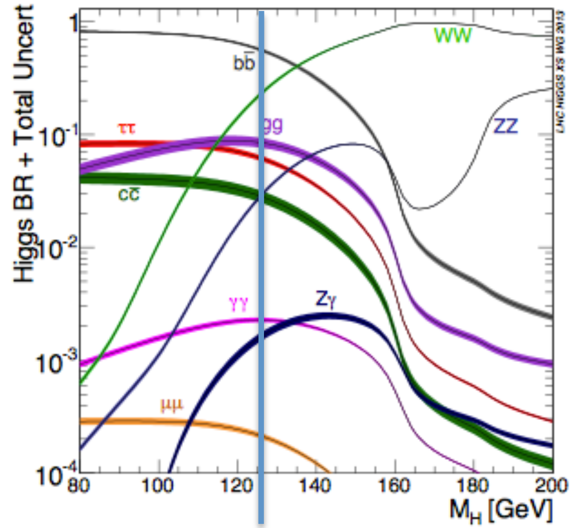








- H->ZZ*: very clean channel but low statistic
- H->yy : simple final state but low branching ratio
- H->WW*: broad sensitivity, low mass resolution
- H->bb-bar, H->ττ : allows fermions coupling but challenging backgrounds

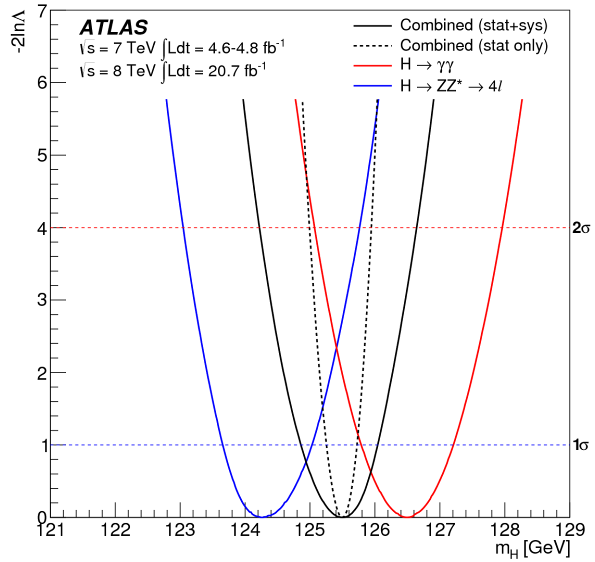


Higgs Mass Measurement

- Higgs mass is the only free parameter in the SM
- Use the two channels with best mass resolution:

$$m_H^{4l} = 124.3^{+0.6}_{-0.5}(\text{stat})^{+0.5}_{-0.3}(\text{sys})\ \text{GeV}$$

$$m_H^{\gamma\gamma} = 126.8 \pm 0.2(\text{stat}) \pm 0.7(\text{sys})\ \text{GeV}$$



- Combination: use profile likelihood ratio $\Lambda(m_H)$
- Channel signal strengths are varied independently
- Ratio of the cross sections of different production modes fixed to SM values

$$m_H^{\gamma\gamma+4l} = 125.5 \pm 0.2(\text{stat})^{+0.5}_{-0.6}(\text{sys})\ \text{GeV}$$

Values used in spin and coupling studies.

- Check the consistency between $m^{\gamma\gamma}$ and m^{4l} with a data fit on $\Lambda(\Delta m_H)$:

$$\Delta m_H = m_H^{\gamma\gamma} - m_H^{4l} = 2.3^{+0.6}_{-0.7}(\text{stat}) \pm 0.6(\text{sys})\ \text{GeV}$$

Compatible with **Δm_H = 0 at a level of 2.4σ**

Spin and Parity Measurement

- In the SM the Higgs boson is a spin-0 CP-even particle: $J^P = 0^+$
- Test the following hypothesis:

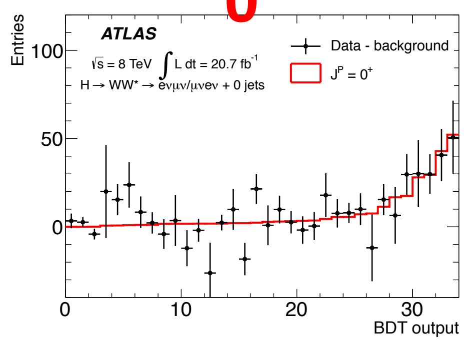
  0^-, 1^+ , 1^- and 2^+_m (graviton like model with minimal coupling)

- Landau-Yang theorem forbids the direct decay of an on-shell spin-1 particle into a pair of photon -> Spin-1 hypothesis strongly disfavored

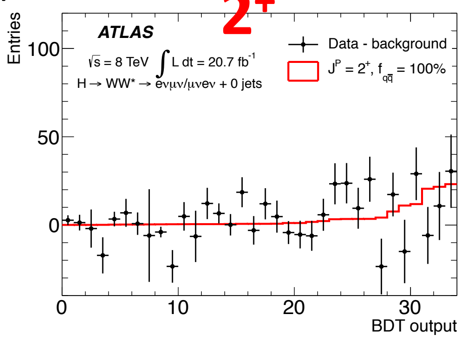
Higgs channels	Variables sensitive to spin-information	Input to the Likelihood fit
H->WW*	ΔΦ(ll), m(ll), pT(ll) mT	Combined on a BTD
H->ZZ*	m_{12} , m_{23} , 2 production angles and 3 decay angles	Combined on a BDT
H-> yy	|cosθ*| of the photons wrt the z-Axis of the Colin-Soper frame	|cosθ*|

H->WW* 1-dim BDT output for background subtracted data using best fit values for the spin hypothesis

0^+



2^+



Spin and Parity Results

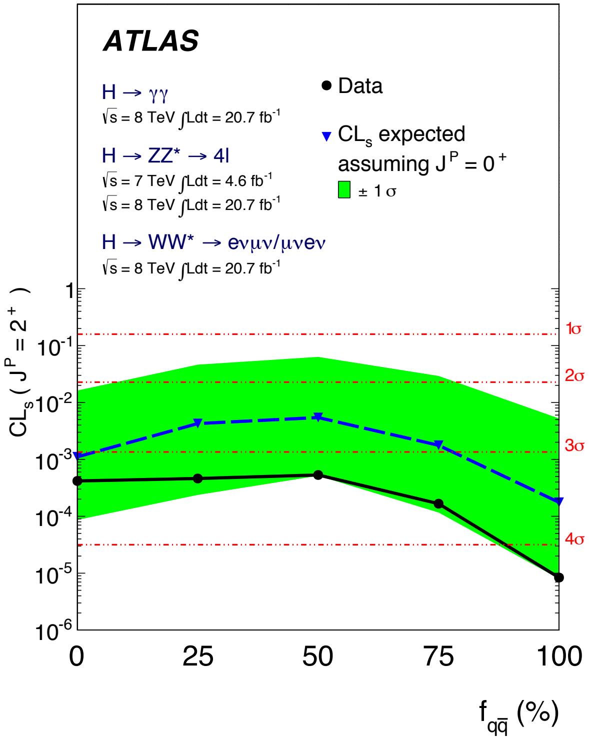
- The exclusion of a spin hypothesis $J^P_{alt} = (0^-, 1^+, 1^-, 2_m^+)$ in favor of the SM $J^P=0^+$ is evaluated in terms of corresponding $CL_S(J^P_{alt})$: $\mathrm{CL_s}(J^P_{\mathrm{alt}}) = \frac{p_0(J^P_{\mathrm{alt}})}{1 - p_0(0^+)}$

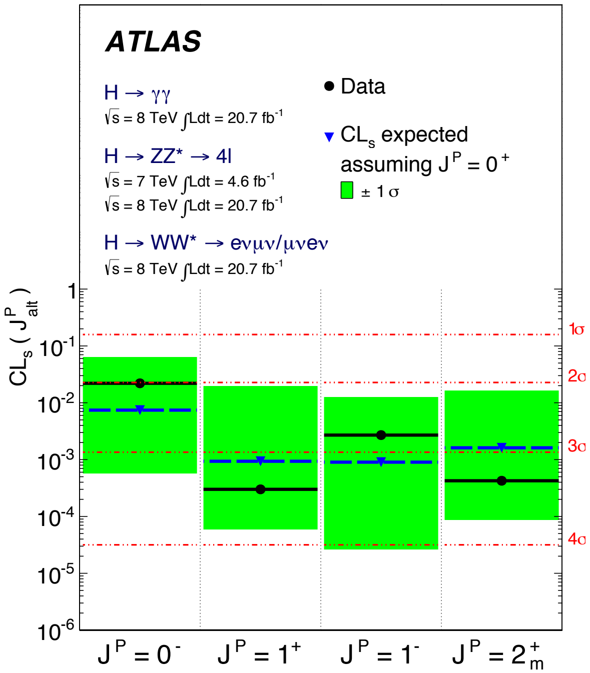
$p_0\,(J^P_{alt})$: prob. that the given observation is a positive fluctuation of the tested hypothesis

- 2^+_m hypothesis tested as a function of f_{qq} (gg main production mode at LO)

Resulting exclusion of alternative hypotheses using CL_S (f_{qq} = 0% for 2^+_m)

J^P	Inputs	CL_s [%]
0^-	ZZ*	97.8
1^+	ZZ*, WW*	99.97
1^-	ZZ*, WW*	99.7
2^+_m	ZZ*, WW*, γγ	99.9





Global Signal Strength

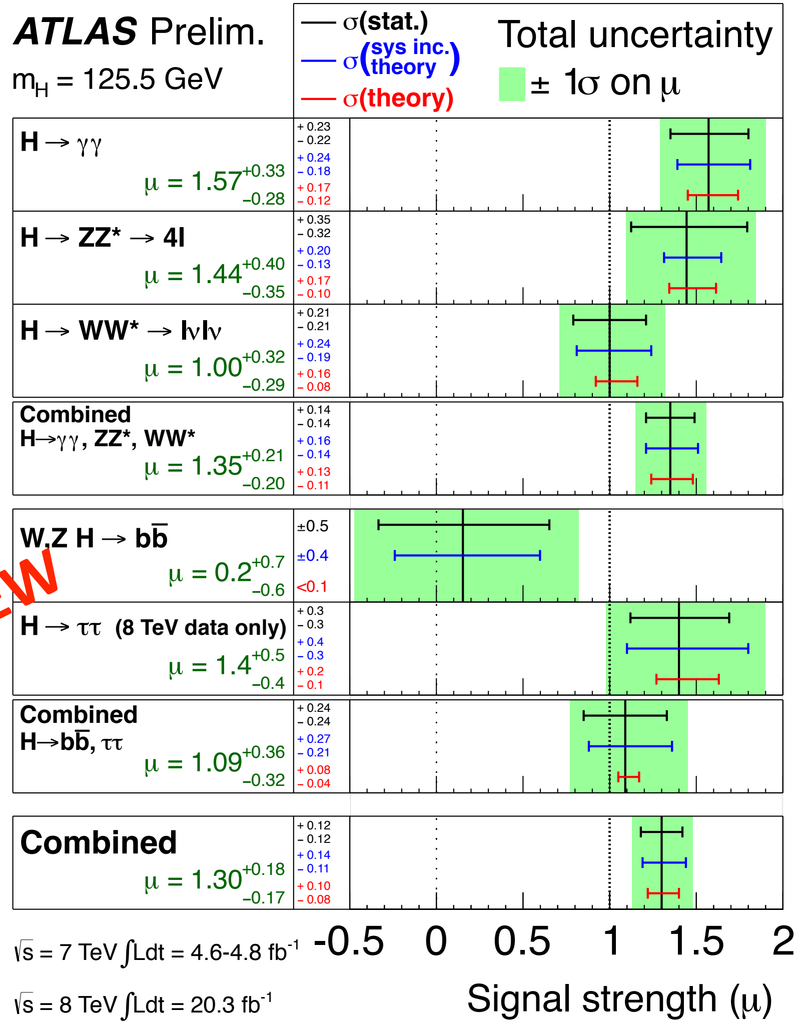
- $\mu = \sigma_{obs}/\sigma_{SM}$ determined with a likelihood ratio fit
- Common signal strength scale factors account for all productions and decay modes
- New channels (see C. Lee talk)
  H->ττ : observed with 4.1σ significance
  H->bb-bar : no excess over background
- Combination of H->bb-bar and H->ττ :

$$\mu^{bb,\tau\tau} = 1.09 \pm 0.24\,(\text{stat})\,^{+0.27}_{-0.21}\,(\text{sys})$$

-> **3.7 σ evidence** for direct decay to fermions

- Combining all the channels:

$$\mu = 1.30 \pm 0.12\,(\text{stat})\,^{+0.14}_{-0.11}$$



NEW

Compatibility of ~7% with SM (μ=1)

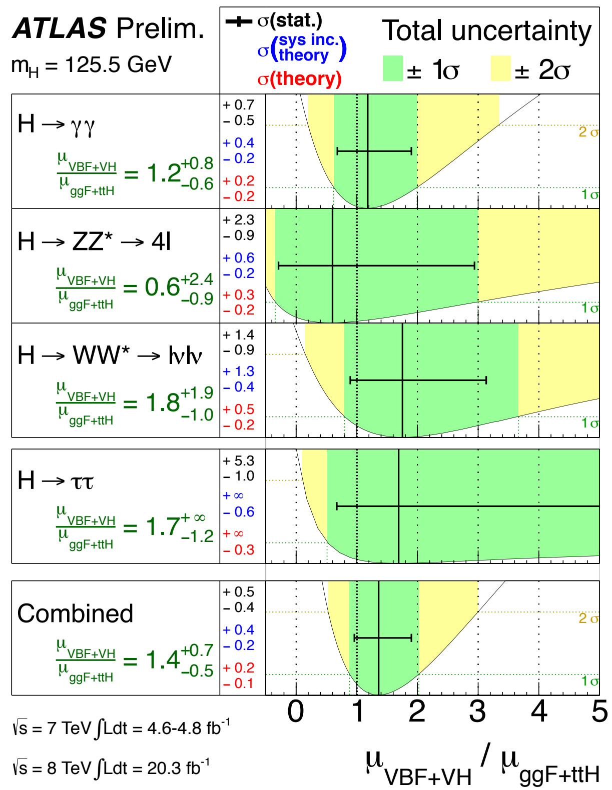
Signal Strength: production mode

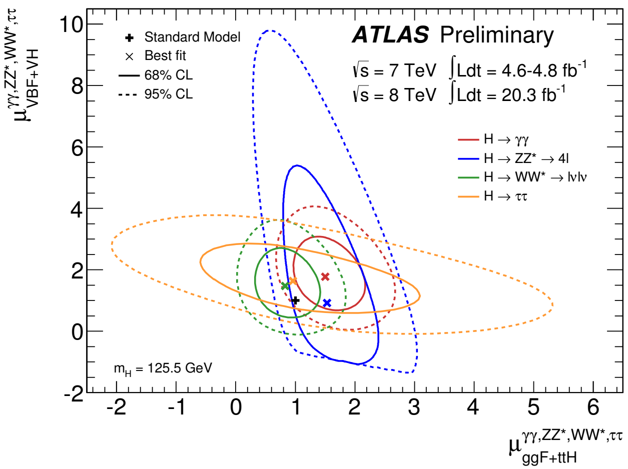
- Measure relative contributions of the different Higgs production mode to the same decay channel

- Two signal strength parameter for Higgs couplings

  - to vector boson: $\mu^f_{VBF+VH} = \mu^f_{VBF} = \mu^f_{VH}$
  - to fermions: $\mu^f_{ggF+ttH} = \mu^f_{ttH} = \mu^f_{ggF}$

H->bb-bar not included





Fit to data the likelihood $\Lambda(\mu_{VBF+VH}/\ \mu_{ggF+ttH})$ with no assumption on the Higgs boson branching ratios

Combined results:

$$\mu_{\mathrm{VBF+VH}}/\mu_{\mathrm{ggF}+ttH} = 1.4^{+0.5}_{-0.4}\,(\mathrm{stat})\ ^{+0.4}_{-0.2}\,(\mathrm{sys})$$

95% CL contours compatible with SM

Probe the VBF production by profiling (μ_{VH})

$$\mu_{\mathrm{VBF}}/\mu_{\mathrm{ggF}+ttH} = 1.4^{+0.5}_{-0.4}\,(\mathrm{stat})\ ^{+0.4}_{-0.3}\,(\mathrm{sys})$$

-> Evidence of VBF production at **4.1σ**

Couplings Measurement

- Basic assumptions:

 - Signal in different channels originated from single resonance at m =125.5 GeV

- width of the Higgs is neglected (narrow-width approx.) for decoupling of production and decay

$\sigma \cdot BR(xx \to H \to yy) = \sigma(xx) \cdot \Gamma_{yy} / \Gamma_{tot}$

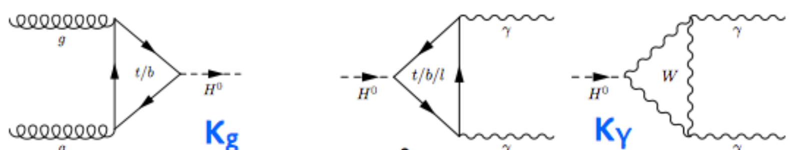
- same tensor structure of the SM Higgs boson, allow only for modification of the coupling strength

--> Deviation from SM predictions with multiplicative modifiers K for production, decay and total width K_H or their ratios λ

$$\kappa_i^2 = \frac{\sigma_i}{\sigma_i^{SM}} \qquad \kappa_j^2 = \frac{\Gamma_j}{\Gamma_j^{SM}} \qquad \kappa_H^2 = \frac{\sum \kappa_j^2 \Gamma_j^{SM}}{\Gamma_H^{SM}} \qquad \frac{\sigma \cdot \mathrm{B}(gg \to H \to \gamma\gamma)}{\sigma_{\mathrm{SM}}(gg \to H) \cdot \mathrm{B}_{\mathrm{SM}}(H \to \gamma\gamma)} = \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

- Assume BSM contributions in:
  - the total decay width, K_H (SM only: $K_H^2 \sim 0.25 K_V^2 + 0.75 K_F^2$)
  - gluon and photon vertex loops coupling modifiers (K_g, K_γ)

-> $K_g^2 \sim 1.06\, K_t^2 - 0.07\, K_t K_b + 0.01\, K_b^2$
-> $K_\gamma^2 \sim 1.59\, K_W^2 - 0.66\, K_W K_t + 0.07\, K_t^2$



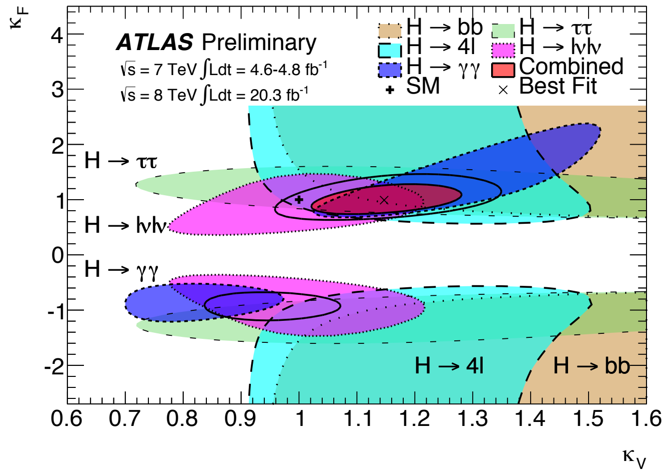
Effective loop-induced coupling modifiers

Fermions vs Bosons Couplings

- Fit parameters are the coupling scale factors for all fermions k_F and for all vectors k_V

$$K_V = k_W = k_Z \quad \text{and} \quad K_F = K_t = K_b = K_\tau$$

- K_g and K_y are parametrized with tree-level scale factors (no BSM) and with no BSM contribution to K_H



BEST FIT VALUES: $K_V = 1.15^{+0.08}_{-0.08}$ $K_F = 0.99^{+0.17}_{-0.15}$

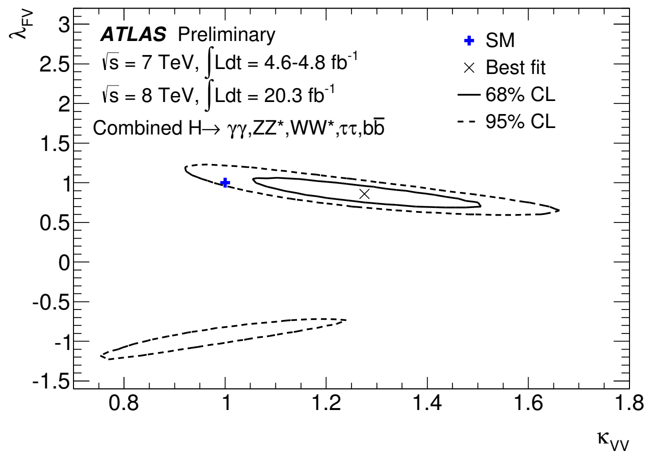
- Best fit prefers positive coupling, good compatibility with the SM (~12%)

- No assumption on the total width done (strong constraint on the fermion couplings)

- Repeat fit, possible only in the ratio K_F/K_V

BEST FIT VALUES : $\lambda_{FV} = K_F/K_V = 0.86^{+0.14}_{-0.12}$

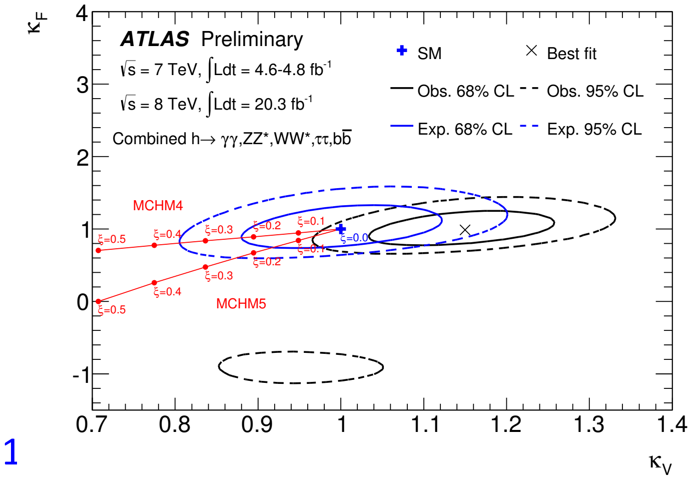
$K_{VV} = K_V{*}K_V/K_H = 1.28^{+0.16}_{-0.15}$



Comp. with SM: 10%

Minimal Composite Higgs Models (MCHM)

- MCHM represent a possible explanation of the scalar naturalness problem
- Higgs is a composite boson (pseudo Nambu-Goldston)
- Higgs couplings to boson and fermions modified with a compositness scale, f, combined into the parameter $\xi = v^2/f^2$ (SM $\xi = 0$, f->∞)
- Consider two models with measured couplings scale factors expressed as function of ξ:



MCHM4

$$\kappa = \kappa_V = \kappa_F = \sqrt{1-\xi}$$

MCHM5

$$\kappa_V = \sqrt{1-\xi}$$

$$\kappa_F = \frac{1-2\xi}{\sqrt{1-\xi}}.$$

Best fit: MCHM4: $\xi = -0.30^{+0.17}_{-0.18}$; MCHM5: $\xi = -0.08^{+0.11}_{-0.1}$

Obs (exp) 95% CL upper limit: MCHM4: f > 710 GeV (460 GeV); MCHM5: f > 640 GeV (550GeV)

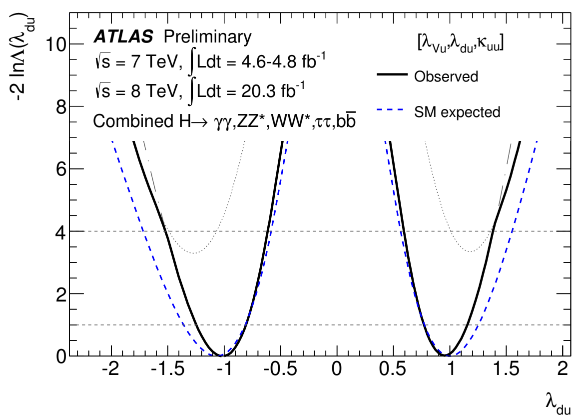
Probing relation within fermionic coupling sector

- New channels H->bb-bar and H->ττ allows to probe fermionic sector (K_V fixed)

Probe the ratio between up and down fermion couplings modifiers:

Around the SM–like Minimum:

$$\lambda_{du}=K_d/K_u = 0.95^{+0.20}_{-0.18}$$

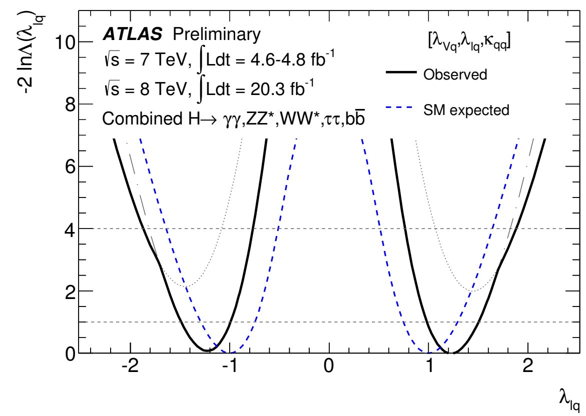


~3.6σ evidence Higgs coupling to d-type fermions

Probe the ratio between lepton and quarks couplings modifiers:

Around the SM–like Minimum:

$$\lambda_{lq} = K_l/K_q = 1.22^{+0.28}_{-0.24}$$



λ_{du}, λ_{lq} used **with other couplings SF to test** 2HDM and MSSM models (more in D. Sidorov talk)

~15% compatibility of the SM hypothesis with the best fit point

Mass dependence of the coupling

- Probe the mass dependence of the Higgs boson couplings to other particles using the measured coupling to the SM particles (K_W,K_Z, K_b K_t, K_τ)
- Express the coupling scale factors to different fermions (f,i) and bosons (V,j)

$$\kappa_{f,i} = v\frac{m_{f,i}^{\epsilon}}{M^{1+\epsilon}}$$

$$\kappa_{V,j} = v\frac{m_{V,j}^{2\epsilon}}{M^{1+2\epsilon}}$$

v = SM vacuum expectation value ~ 246 GeV

SM with : M=*v* -> $K_{f,l} = K_{V,j} = 1$

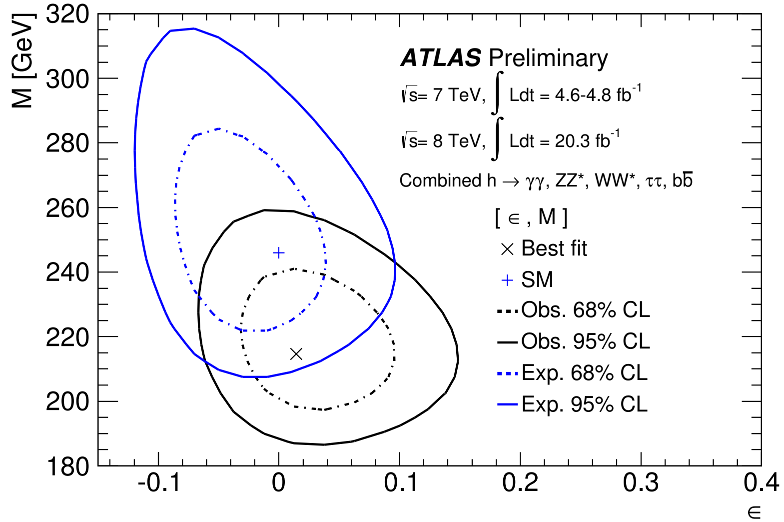
- Parameter of interest are

M : vacuum expectation value

ε : mass scaling parameter

Combined fit to the measured rates gives:

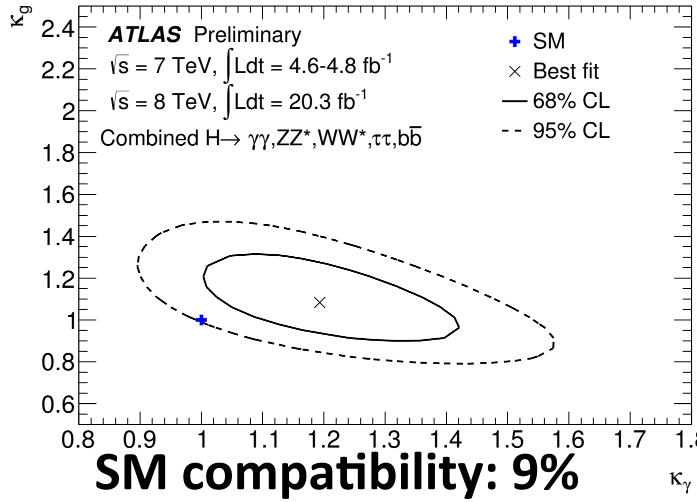
- Best fit point compatible with SM within ~1.5σ
- ε close to 0 -> coupling to fermions and bosons consistent with linear and quadratic mass dependence



Probing BSM contributions

- Higgs loop-induced processes are very sensitive to heavy unknown particle
- Free parameters are K_g and K_γ
- Higgs total width (K_H) only from SM particles

$K_g = 1.08^{+0.15}_{-0.13}$ $K_\gamma = 1.19^{+0.15}_{-0.12}$

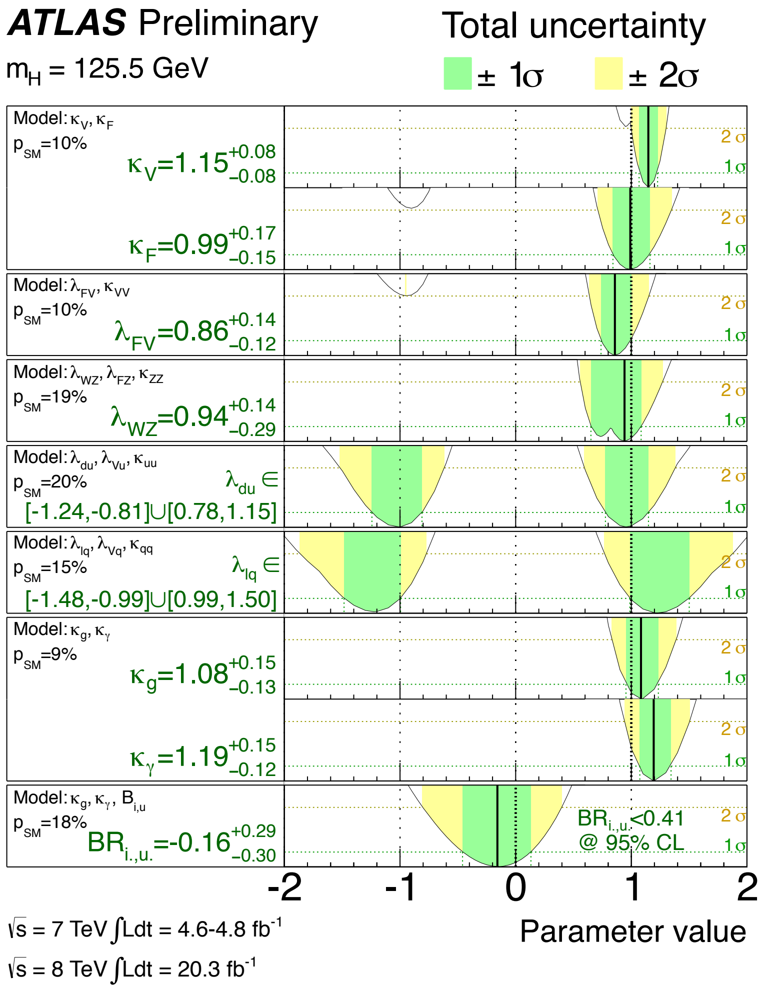


SM compatibility: 9%

- Probe non SM decay with a branching ratio, $BR_{i,.,u.}$ from invisible or undetected final states parametrizing the total Higgs width as: $\Gamma_H = \frac{\kappa_H^2(\kappa_i)}{(1 - BR_{i.,u.})}\Gamma_H^{SM}$
- Best-fit values are : $K_g = 1.00^{+0.23}_{-0.16}$ $K_\gamma = 1.17^{+0.16}_{-0.13}$ $Br_{i.,u.} = -0.16^{+0.29}_{-0.30}$
- Using the physical constraint $BR_{i,.,u.} > 0$ the 95% CL upper limit is:

$Br_{i.,u} < 0.41$ (SM exp. < 0.55)

Other Results

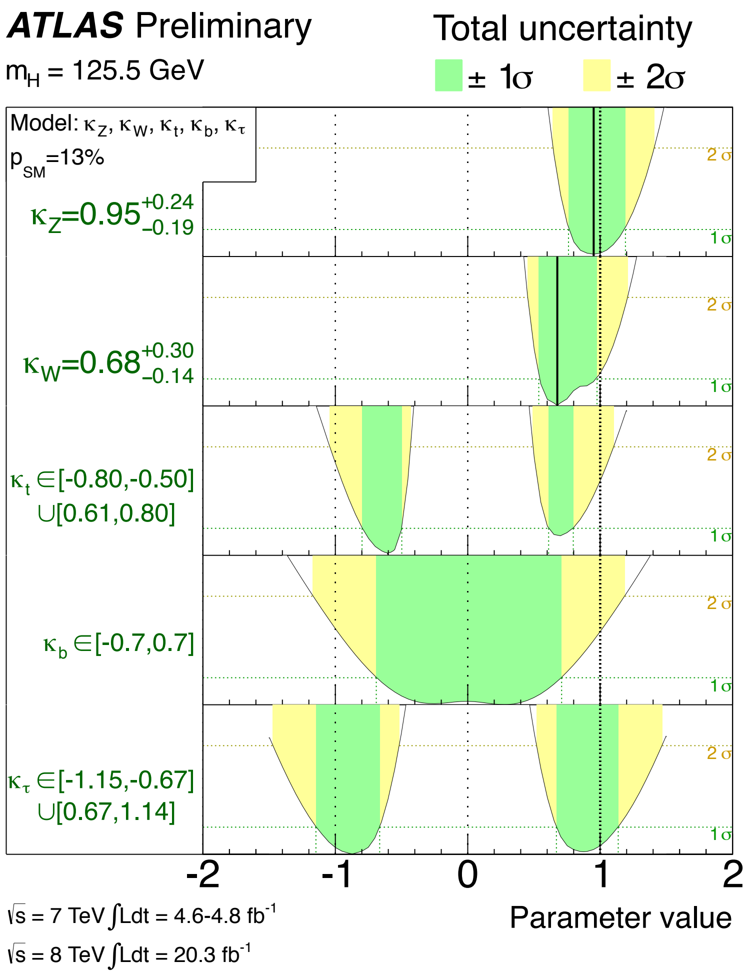


Summary of the Higgs boson coupling scale factors measurements for m_H = 125.5 GeV.

The Higgs boson coupling measurements have been used to search indirectly for new physics:

- Custodial Symmetry
- Additional electroweak singlett
- Two-Higgs-doublet models
- Simplified MSSM
- Higgs portal to dark matter

Couplings Summary



Summary of the couplings

Scale factors for generic model:

- only SM particles in loops
- total width fixed to SM value

Conclusions

- After the discovery, the Higgs boson study has entered a new phase of precise measurement of its properties
- Combined mass measurement $m_H^{\gamma\gamma+4l} = 125.5 \pm 0.2(\text{stat})^{+0.5}_{-0.6}(\text{sys})\ \text{GeV}$
- Evidence for the spin-0 nature of the Higgs boson with positive parity strongly preferred ($J^p = 0^-, 1^+, 1^-, 2^+$ excluded at CL above 97.8%)
- New channels H->ττ and H->bb-bar with combined signal strength

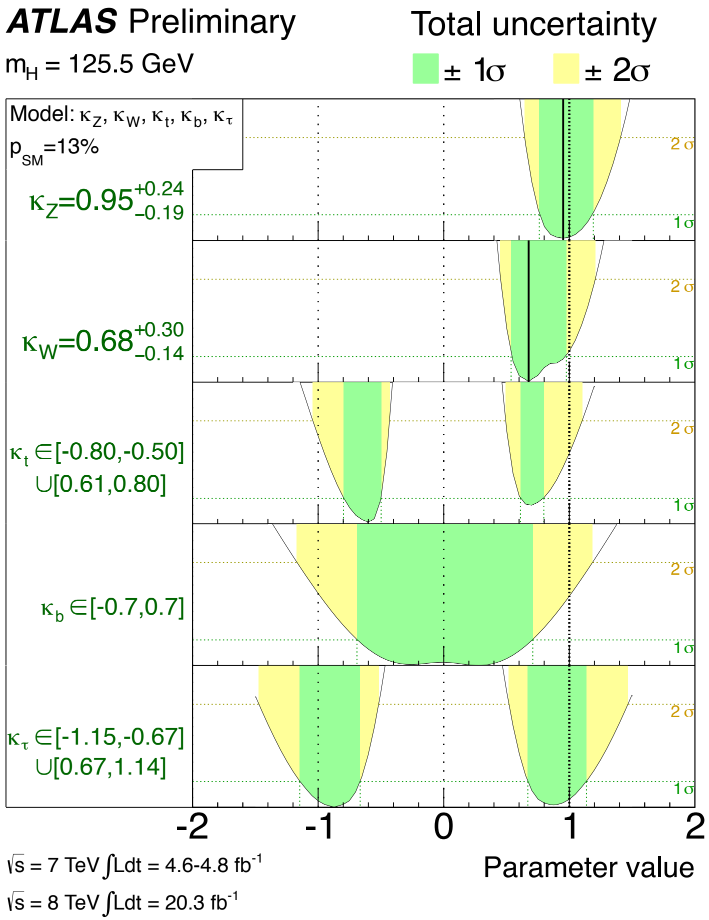
$$\mu^{bb,\tau\tau} = 1.09 \pm 0.24\,(\text{stat})\,^{+0.27}_{-0.21}\,(\text{sys})$$

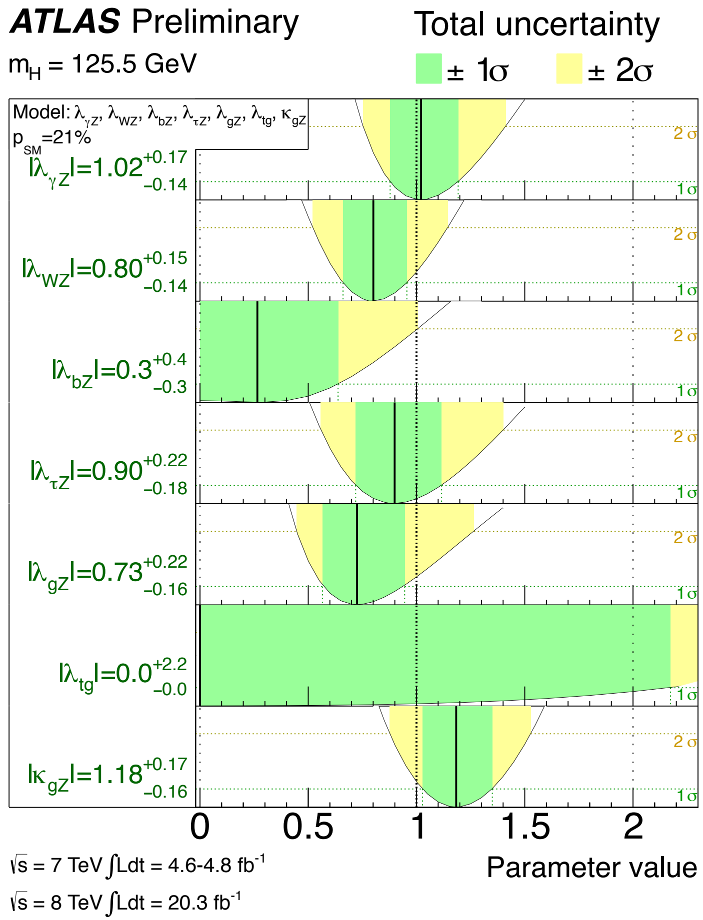
-> 3.7σ evidence for the direct decay of the Higgs to fermions

- Combined signal strength: $\mu = 1.30 \pm 0.12\,(\text{stat})\,^{+0.14}_{-0.11}$
- New channels allowed the direct probe of the relations within the fermionic coupling sector
- Coupling measurements are consistent with SM expectation within the present uncertainties

BACK UP

Coupling Scale Factors Summary

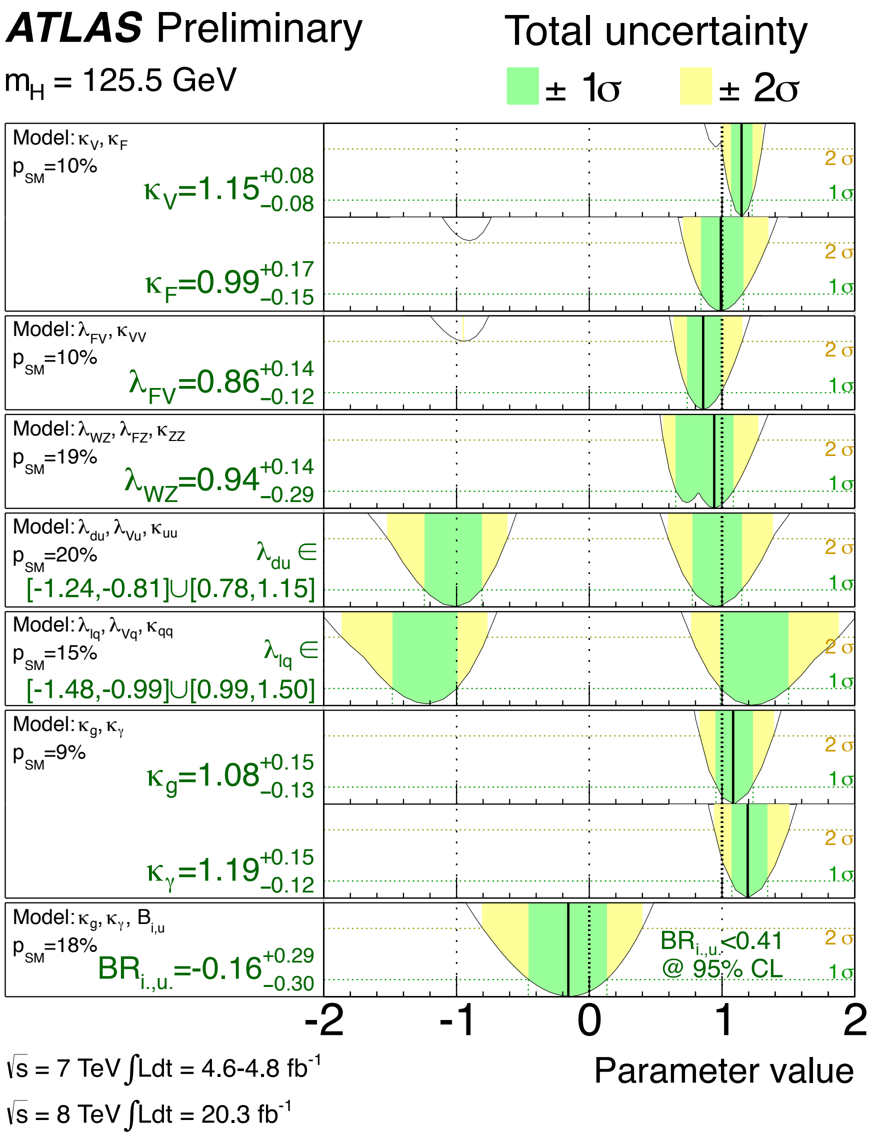




Generic model:
- only SM particles in loops
- total width fixed to SM value

Generic model:
- Independent Kγ, Kg
- no assumption on the total width
(only ratios of coupling scale factors can be measured)

Coupling Scale Factors Summary



SM fermion and boson coupling scale factors

Ratio of fermion and boson coupling scale factors
(Free total Higgs width)

Custodial symmetry SM

p down fermions couplings , free fermion scale factors

Lepton quark couplings, free fermion scale factors

BSM contribution in H->gg and gg->H
Total width only from SM

BR to invisible or undetected
no assumption on total width

Custodial Symmetry

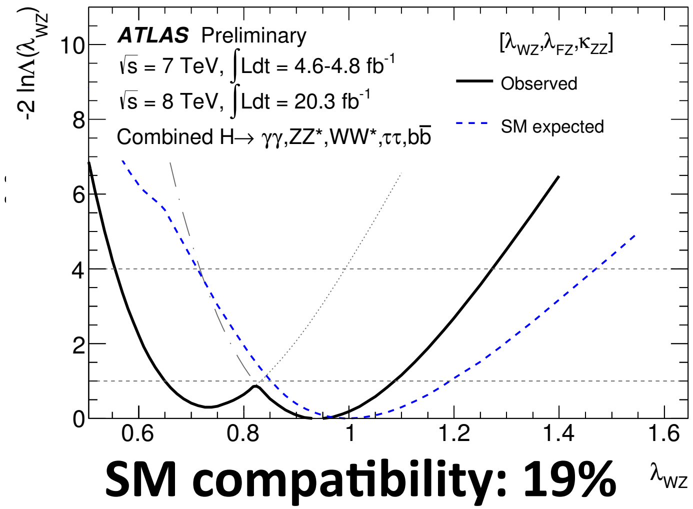
- Custodial symmetry fixes the ratio between the W and Z couplings to the SM one

- Probe the coupling ratio of W and Z (K_F=K_t=K_b=K_τ):

  $\lambda_{WZ} = K_W/K_Z$, $\lambda_{FZ} = K_F/K_Z$, $K_{ZZ}=K^2_Z/K_H$

- Only SM particle in loop (no BSM contributions):

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



SM compatibility: 19%

MORE GENERAL:

- Allow possible BSM contributions to the H -> γγ loop by adding an effective scale factor ratio $\lambda_{\gamma Z}$ which is profiled in the λ_{WZ} measurement

-> λ_{WZ} in agreement with the expectation of custodial symmetry

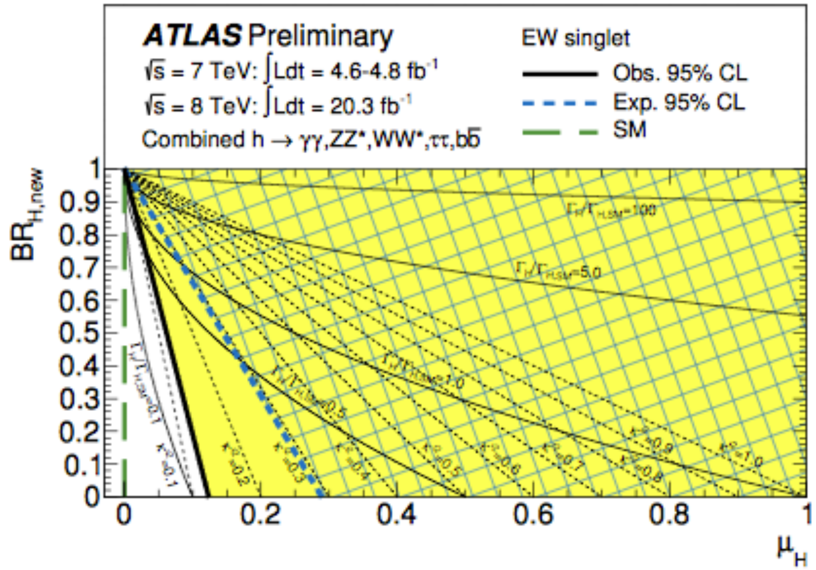
Additional EW Singlet

- The simplest extension to the SM Higgs sector involves the addition of an EW singlet field to the doublet Higgs field of the SM (possible answer to the dark matter problem)
- Two CP-even non-degenerate Higgs bosons, where *h* (H) denotes the lighter (heavier) of the pair
- h is assumed to have identical production and decay modes to those of the SM Higgs boson but with rates modified
- The overall signal strength for H can be written as:

$$\mu_H = \frac{\sigma_H \times BR_H}{(\sigma_H \times BR_H)_{SM}} = \kappa'^2 (1 - BR_{H,new})$$

And:

$$\kappa'^2 = 1 - \mu_h.$$



- Resulting k'^2 using the measured μ_h:

$K'^2 = -0.30^{+0.17}_{-0.18}$ (exp: $0.00^{+0.15}_{-0.17}$)

- Observed (expected) 95% CL upper limit of

$K'^2 < 0.12\ (0.29)$

Couplings and BSM models

	Model	Coupling Parameter	Description	Measurement
1	MCHM4, EW singlet	μ_h	Overall signal strength	$1.30^{+0.18}_{-0.17}$
		$\kappa = \sqrt{\mu_h}$	Universal coupling	$1.14^{+0.09}_{-0.08}$
2	MCHM5, 2HDM Type I	κ_V	Vector boson (W, Z) coupling	1.15 ± 0.08
		κ_F	Fermion $(t, b, \tau, \ldots)$ coupling	$0.99^{+0.17}_{-0.15}$
3	2HDM Type II, MSSM	$\lambda_{Vu} = \kappa_V/\kappa_u$	Ratio of vector boson & up-type fermion $(t, c, \ldots)$ couplings	$1.21^{+0.24}_{-0.26}$
		$\kappa_{uu} = \kappa_u^2/\kappa_h$	Ratio of squared up-type fermion coupling & total width scale factor	$0.86^{+0.41}_{-0.21}$
		$\lambda_{du} = \kappa_d/\kappa_u$	Ratio of down-type fermion $(b, \tau, \ldots)$ & up-type fermion couplings	$[-1.24, -0.81] \cup [0.78, 1.15]$
4	2HDM Type III	$\lambda_{Vq} = \kappa_V/\kappa_q$	Ratio of vector boson & quark $(t, b, \ldots)$ couplings	$1.27^{+0.23}_{-0.20}$
		$\kappa_{qq} = \kappa_q^2/\kappa_h$	Ratio of squared quark coupling & total width scale factor	$0.82^{+0.23}_{-0.19}$
		$\lambda_{lq} = \kappa_l/\kappa_q$	Ratio of lepton (τ, μ, e) & quark couplings	$[-1.48, -0.99] \cup [0.99, 1.50]$
5	Mass scaling parametrization	κ_Z	Z boson coupling	$0.95^{+0.24}_{-0.19}$
		κ_W	W boson coupling	$0.68^{+0.30}_{-0.14}$
		κ_t	t quark coupling	$[-0.80, -0.50] \cup [0.61, 0.80]$
		κ_b	b quark coupling	$[-0.7, 0.7]$
		κ_τ	τ lepton coupling	$[-1.15, -0.67] \cup [0.67, 1.14]$
6	Higgs portal (without $Zh \to \ell\ell + E_T^{miss}$)	κ_g	Gluon effective coupling	$1.00^{+0.23}_{-0.16}$
		κ_γ	Photon effective coupling	$1.17^{+0.16}_{-0.13}$
		BR_i	Invisible branching ratio	$-0.16^{+0.29}_{-0.30}$
7	Higgs portal (with $Zh \to \ell\ell + E_T^{miss}$)	κ_g	Gluon effective coupling	–
		κ_γ	Photon effective coupling	–
		BR_i	Invisible branching ratio	-0.02 ± 0.20

Measurements of Higgs boson coupling scale factors in different coupling parametrizations , along with the BSM models or parametrizations they are used to probe.

Input to the Couplings Combination

Higgs boson Decay	Subsequent Decay	Sub-Channels	$\int L\,dt$ [fb^{-1}]	Ref.
		2011 $\sqrt{s}$ =7 TeV		
$H \to \gamma\gamma$	–	10 categories $\{p_{Tt} \otimes \eta_{\gamma} \otimes \text{conversion}\} \oplus \{\text{2-jet VBF}\}$	4.8	[3]
$H \to ZZ^*$	4ℓ	$\{4e, 2e2\mu, 2\mu2e, 4\mu, \text{2-jet VBF}, \ell\text{-tag}\}$	4.6	[3]
$H \to WW^*$	$\ell\nu\ell\nu$	$\{ee, e\mu, \mu e, \mu\mu\} \otimes \{\text{0-jet, 1-jet, 2-jet VBF}\}$	4.6	[3]
$VH \to Vbb$	$Z \to \nu\nu$	$E_T^{miss} \in \{120-160, 160-200, \geq 200 \text{ GeV}\} \otimes \{\text{2-jet, 3-jet}\}$	4.6	[5]
	$W \to \ell\nu$	$p_T^W \in \{< 50, 50-100, 100-150, 150-200, \geq 200 \text{ GeV}\}$	4.7	
	$Z \to \ell\ell$	$p_T^Z \in \{< 50, 50-100, 100-150, 150-200, \geq 200 \text{ GeV}\}$	4.7	
		2012 $\sqrt{s}$ =8 TeV		
$H \to \gamma\gamma$	–	14 categories: $\{p_{Tt} \otimes \eta_{\gamma} \otimes \text{conversion}\} \oplus$ $\{\text{loose, tight 2-jet VBF}\} \oplus \{\ell\text{-tag}, E_T^{miss}\text{-tag, 2-jet VH}\}$	20.3	[3]
$H \to ZZ^*$	4ℓ	$\{4e, 2e2\mu, 2\mu2e, 4\mu, \text{2-jet VBF}, \ell\text{-tag}\}$	20.3	[3]
$H \to WW^*$	$\ell\nu\ell\nu$	$\{ee, e\mu, \mu e, \mu\mu\} \otimes \{\text{0-jet, 1-jet, 2-jet VBF}\}$	20.3	[3]
$VH \to Vbb$	$Z \to \nu\nu$	$E_T^{miss} \in \{120-160, 160-200, \geq 200 \text{ GeV}\} \otimes \{\text{2-jet, 3-jet}\}$	20.3	[5]
	$W \to \ell\nu$	$p_T^W \in \{<90, 90\text{-}120, 120\text{-}160, 160\text{-}200, \geq 200 \text{ GeV}\} \otimes \{\text{2-jet, 3-jet}\}$	20.3	
	$Z \to \ell\ell$	$p_T^Z \in \{<90, 90\text{-}120, 120\text{-}160, 160\text{-}200, \geq 200 \text{ GeV}\} \otimes \{\text{2-jet, 3-jet}\}$	20.3	
$H \to \tau\tau$	$\tau_{lep}\tau_{lep}$	$\{ee, e\mu, \mu\mu\} \otimes \{\text{boosted, 2-jet VBF}\}$	20.3	[6]
	$\tau_{lep}\tau_{had}$	$\{e, \mu\} \otimes \{\text{boosted, 2-jet VBF}\}$	20.3	
	$\tau_{had}\tau_{had}$	$\{\text{boosted, 2-jet VBF}\}$	20.3	

Statistical Procedure

- Likelihood function constructed for each individual channel

$$L_c(\mathcal{D}_c|\nu_c,\boldsymbol{\theta}_c) = \mathrm{Pois}(n_c|\nu_c)\prod_{e_c=1}^{n_c} f_c(x_{e_c}|\boldsymbol{\theta}_c)\cdot\prod_{p} g_{p,c}(a_{p,c}|\theta_{p,c})$$

expected evt #

systematics: nuisance parameter (NP)

constraint on NPs

observed evt #

observable

estimated central value of $\theta_{p,c}$

- Combination by taking product of the likelihood of individual channels and correlating systematics, if necessary

individual likelihood excluding constraint

not simple product of $g_{p,c}$

$$L(\mathcal{D}|\boldsymbol{\nu},\boldsymbol{\theta}) = \prod_{c}\tilde{L}_c(\mathcal{D}_c|\nu_c,\boldsymbol{\theta}_c)\prod_{p} g_p(a_p|\theta_p)$$

- Hypothesis testing based on the profile likelihood ratio

$$\Lambda(\mu) = \frac{L(\mu,\hat{\hat{\theta}}(\mu))}{L(\hat{\mu},\hat{\theta})}$$

conditional minimum for a given μ

unconditional(global) minimum

μ: parameter of interest, e.g

- signal strength (μ_i)
- mass (m_H) and mass difference (Δm_H)
- coupling scale factors λ_i, κ_i

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Statistical Procedure II

$$\Lambda(\alpha) = \frac{L(\alpha\,,\,\hat{\hat{\theta}}(\alpha))}{L(\hat{\alpha},\hat{\theta})}.$$

PROFILE LIKELIHHOD RATIO

- Likelihood fits to the observed data are done for the parameters of interest.
- Systematic uncertainties and their correlations are modelled by introducing nuisance parameters θ described by likelihood functions associated with the estimate of the corresponding effect
- parameters being "profiled", i.e., similarly to nuisance parameters they are set to the values that maximizes the likelihood function for the given fixed values of the parameters of interest.

$$-2\ln\Lambda(\alpha)$$

TEST STATISTIC

- Test statistic of several parameters of interests is distributed asymptotically as χ^2 distribution

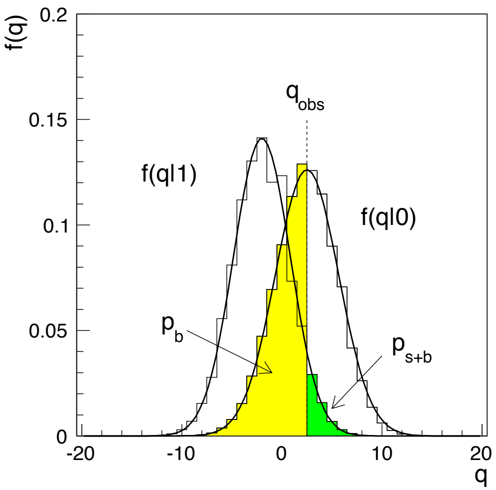
100(1 − β)% CONFIDENCE LEVEL (CL) CONTOURS

- Defined by $-2\ln\Lambda(\alpha) < k_\beta,$ where k_β satisfies $P(\chi^2_n > k_\beta) = \beta.$

P_{SM} COMPATIBILITY WITH THE SM

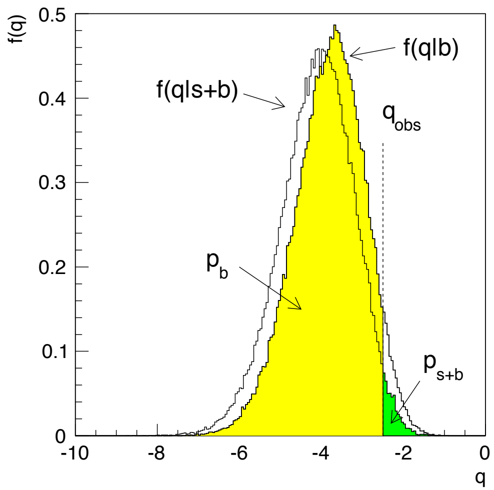
- Quantified using the *p-value* obtained from the profile likelihood ratio $\Lambda(\alpha = \alpha_{SM})$, where α is the set of parameters of interest and α_{SM} are their Standard Model values

CLs



$$p_b = P(q \leq q_{\rm obs}|b) = \int_{-\infty}^{q_{\rm obs}} f(q|b)\, dq\ .$$

$$p_{s+b} = P(q \geq q_{\rm obs}|s+b) = \int_{q_{\rm obs}}^{\infty} f(q|s+b)\, dq\ .$$



Signal model (s+b) is excluded at a CL of 100*(1-α) if:

$$p_{s+b} < \alpha\ ,$$

Problem: one will exclude with probability close to α (i.e. 5%) hypothesis to which one has little or no sensitivity (s << b -> f(q|b) and f(q|s+b) almost overlapping)

-> Exclude model if: $$\mathrm{CL}_s \equiv \frac{p_{s+b}}{1-p_b} < \alpha\ .$$

IF: s << b -> f(q|b) and f(q|s+b) then $1-p_b << 1$

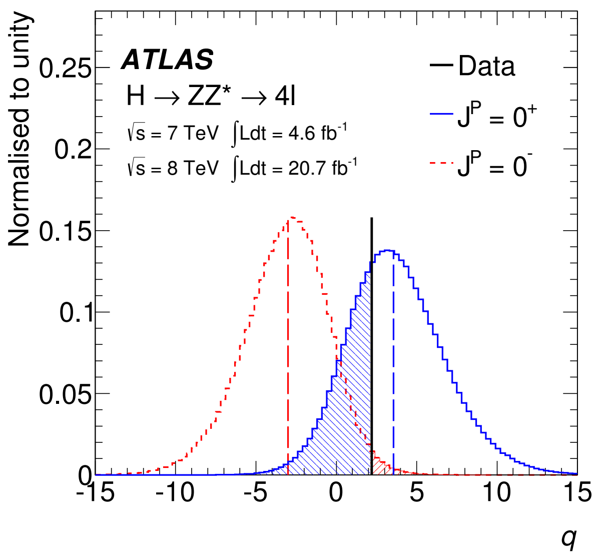
Spin and parity

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

Likelihood function that depends on the spin-parity assumption of the signal is constructed as a product of Conditional probabilities over binned distributions of the discriminant variables

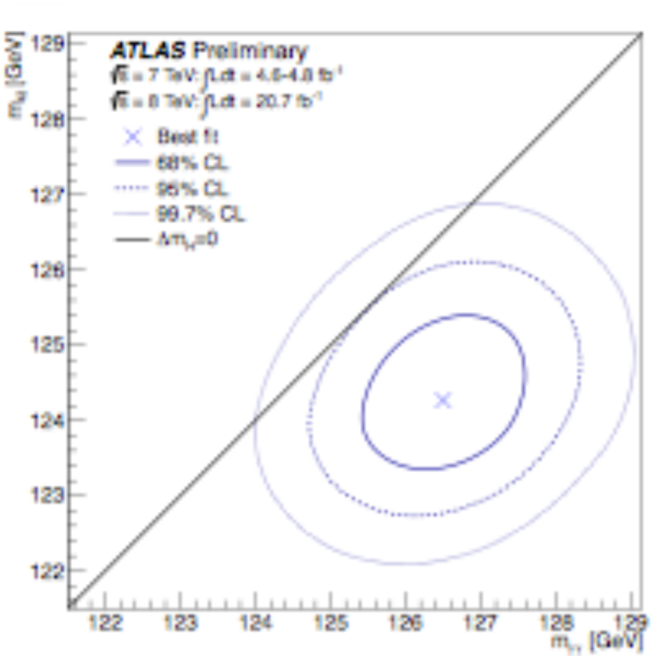
$$q = \log \frac{\mathcal{L}(J^P = 0^+, \hat{\hat{\mu}}_{0^+}, \hat{\hat{\theta}}_{0^+})}{\mathcal{L}(J^P_{\text{alt}}, \hat{\hat{\mu}}_{J^P_{\text{alt}}}, \hat{\hat{\theta}}_{J^P_{\text{alt}}})} ,$$

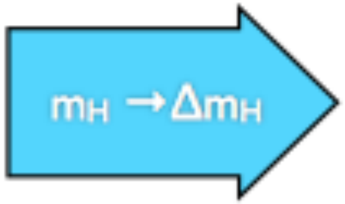
Test statistic used to distinguish between two signal spin-Parity hypothesis based on the ratio of likelihoods With values of the signal strength and nuisance parameters Fitted to data under eack Spin-CP hypothesis

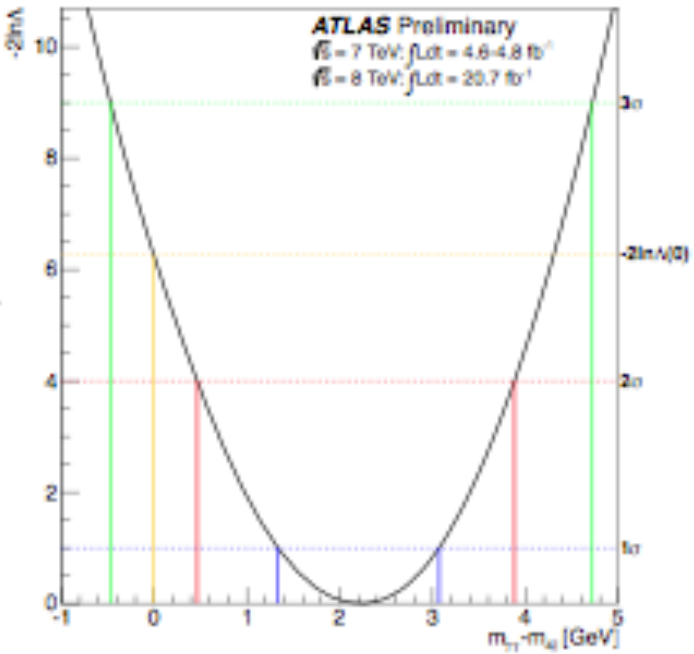


$$\text{CL}_s(J^P_{\text{alt}}) = \frac{p_0(J^P_{\text{alt}})}{1 - p_0(0^+)}$$

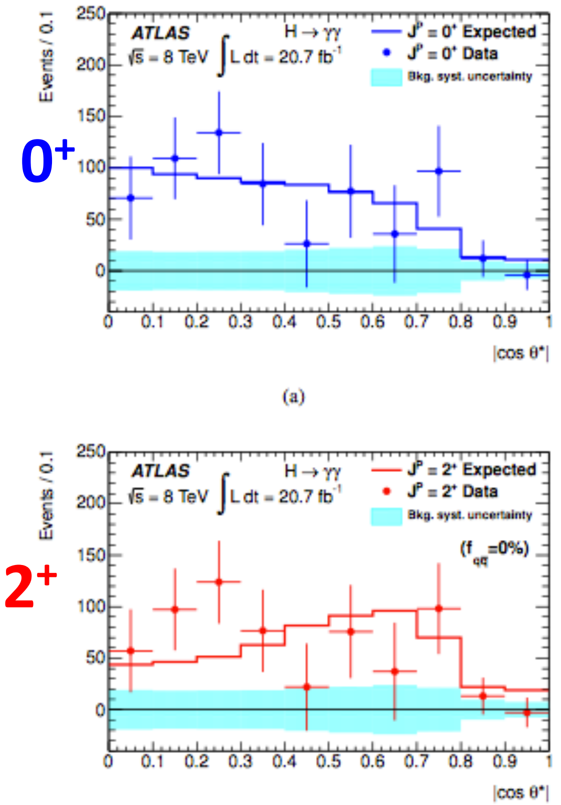
Mass Difference



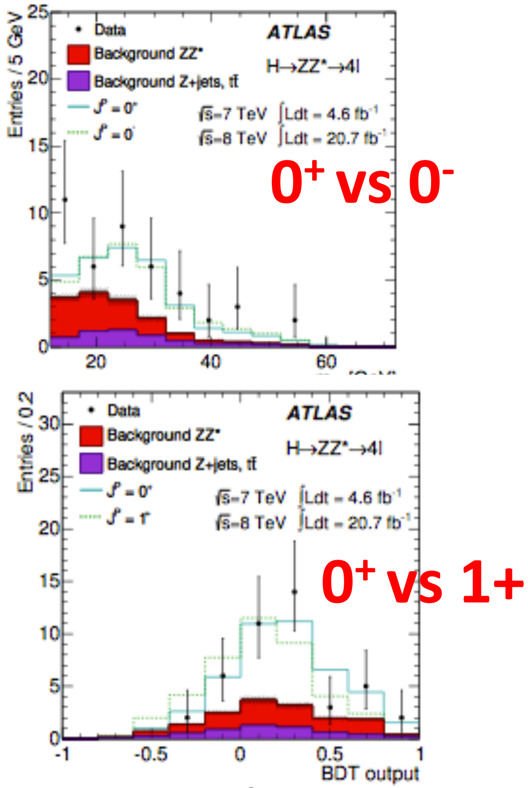




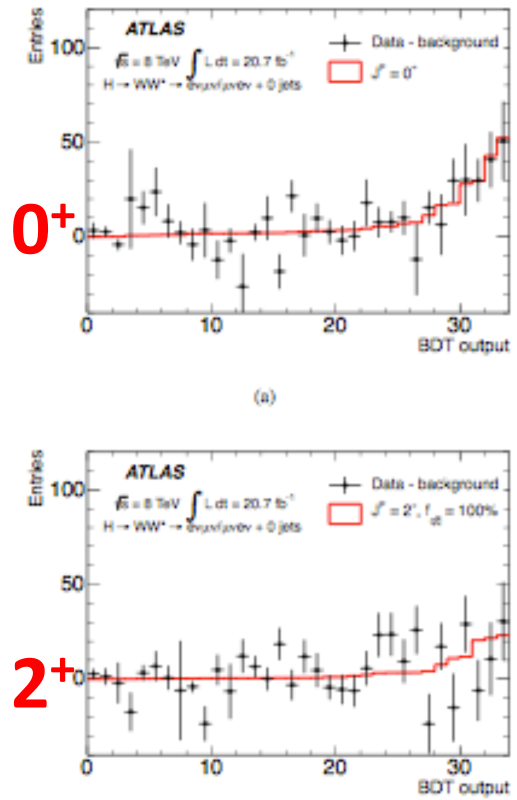
Spin and Parity Measurement



Distribution of |cosθ*| background subtracted data. Expected J^P distribution normalized to the fitted Data is overlaid as solid line



BDT output for m_{34} and $\cos\theta_1$. Signal contributions for each spin is scaled using the profiled value of μ



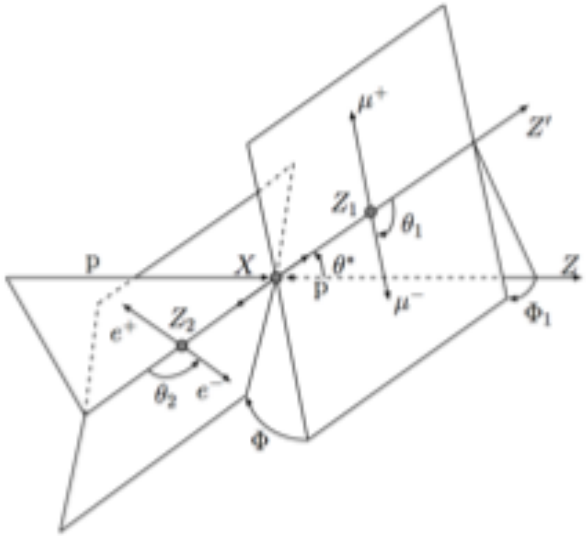
1-dim BDT output for background subtracted data using best fit values for the spin hypothesis

Spin and Parity Measurement

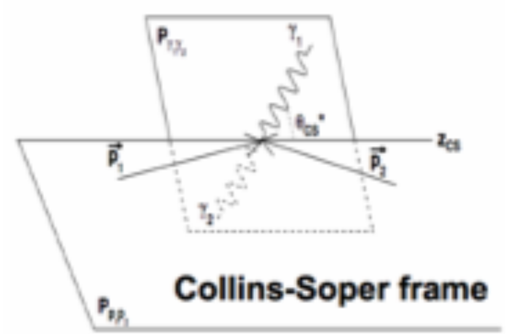
H→γγ – |cosθ*| is sensitive to the spin information

$$|\cos\theta^*| = \frac{|\sinh(\Delta\eta^{\gamma\gamma})|}{\sqrt{1+(p_T^{\gamma\gamma}/m_{\gamma\gamma})^2}} \frac{2p_T^{\gamma 1} p_T^{\gamma 2}}{m_{\gamma\gamma}^2}$$

H→ZZ* – reconstructed masses of two Z bosons, 1 production and 4 decay angles, serve as inputs to BDT

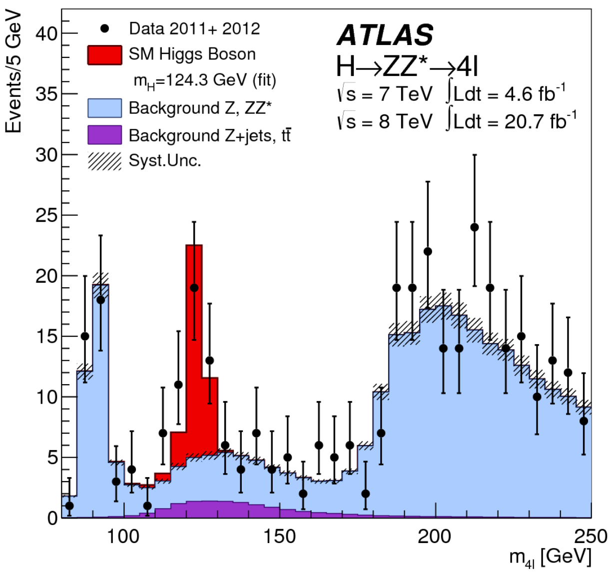


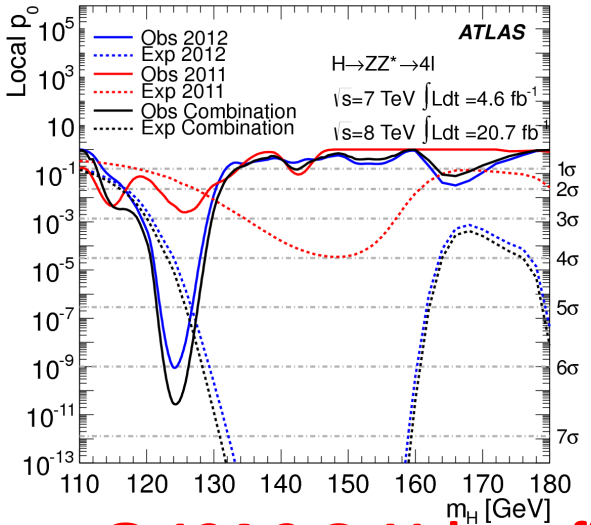
θ* - polar angle of the photons wrt the z-axis of the Collins-Soper frame



H -> ZZ*-> 4l

- 4 lepton selection: 2 pairs OS with pT > 20,15,10,7(e)/6(μ) GeV
- Events are split into 3 categories based on their production modes ggF, VBF and VH
- Background (ZZ, Z+jets, V) estimated from control regions, data or MC
- Signal extracted by fit to m4l





Observed: 6.6 σ

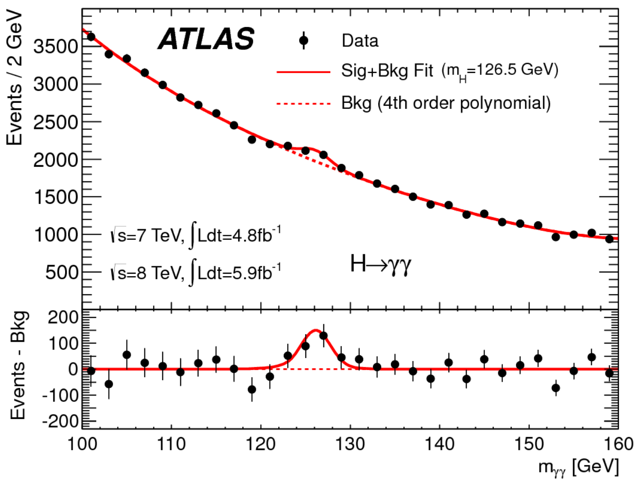
Expected: 4.4 σ

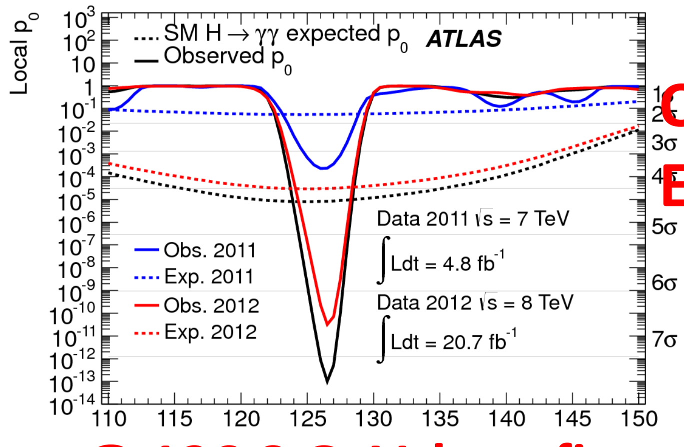
@ 124.3 GeV, best fit $\mu = 1.7^{+0.5}_{-0.4}$

H -> γγ

- Select two high E_T (30,40 GeV) isolated photons
- Backgrounds (background extrapolated from side bands in data: γγ, γ-jet and jet-jet
- Use 14 different categories to increase sensitivity and to separate production mode mode
- Signal extracted with $m_{\gamma\gamma}$ fit:

~21 pb^{-1} of 8 TeV
~5 pb^{-1} of 7 TeV



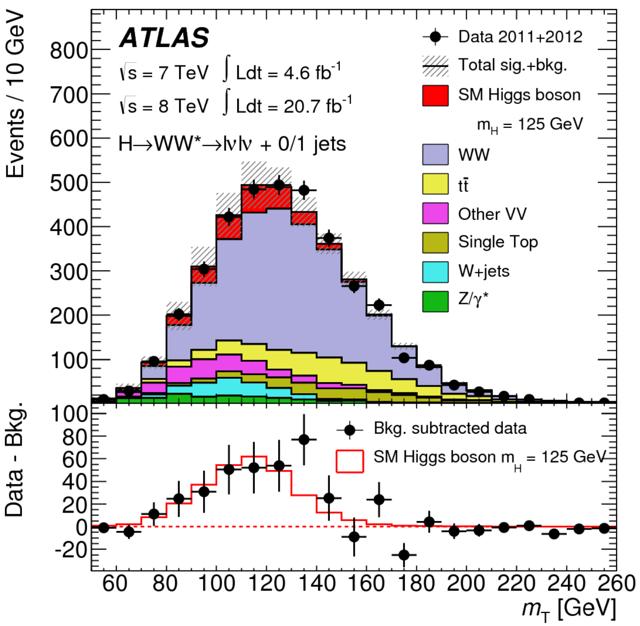


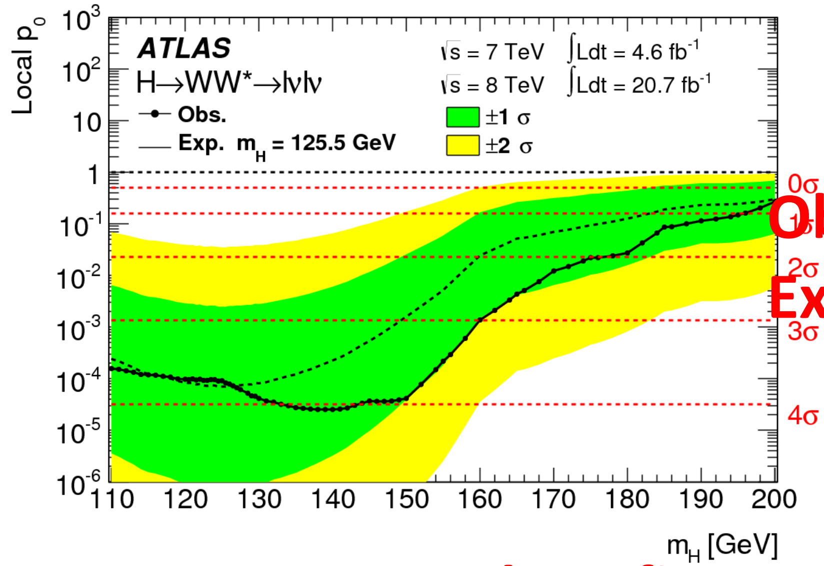
Observed: 7.4 σ
Expected: 4.1 σ

@ 126.8 GeV, best fit μ = 1.65 $^{+0.34}_{-0.30}$

H -> WW* -> lνlν

- Select two opposite sign well isolated leptons
- Missing transverse momentum (from 2 ν's) -> low mass resolution
- Background (WW, top, Wjets, Zjets) estimated from control regions and data
- Separate events into 3 different jet bin (0,1,2) to ggF and VBF production mode
- Signal extracted with m_T fit





Observed: 3.8 σ

Expected: 3.7 σ

@ 125 GeV, best fit μ = 1.01 $^{+0.31}_{-0.31}$