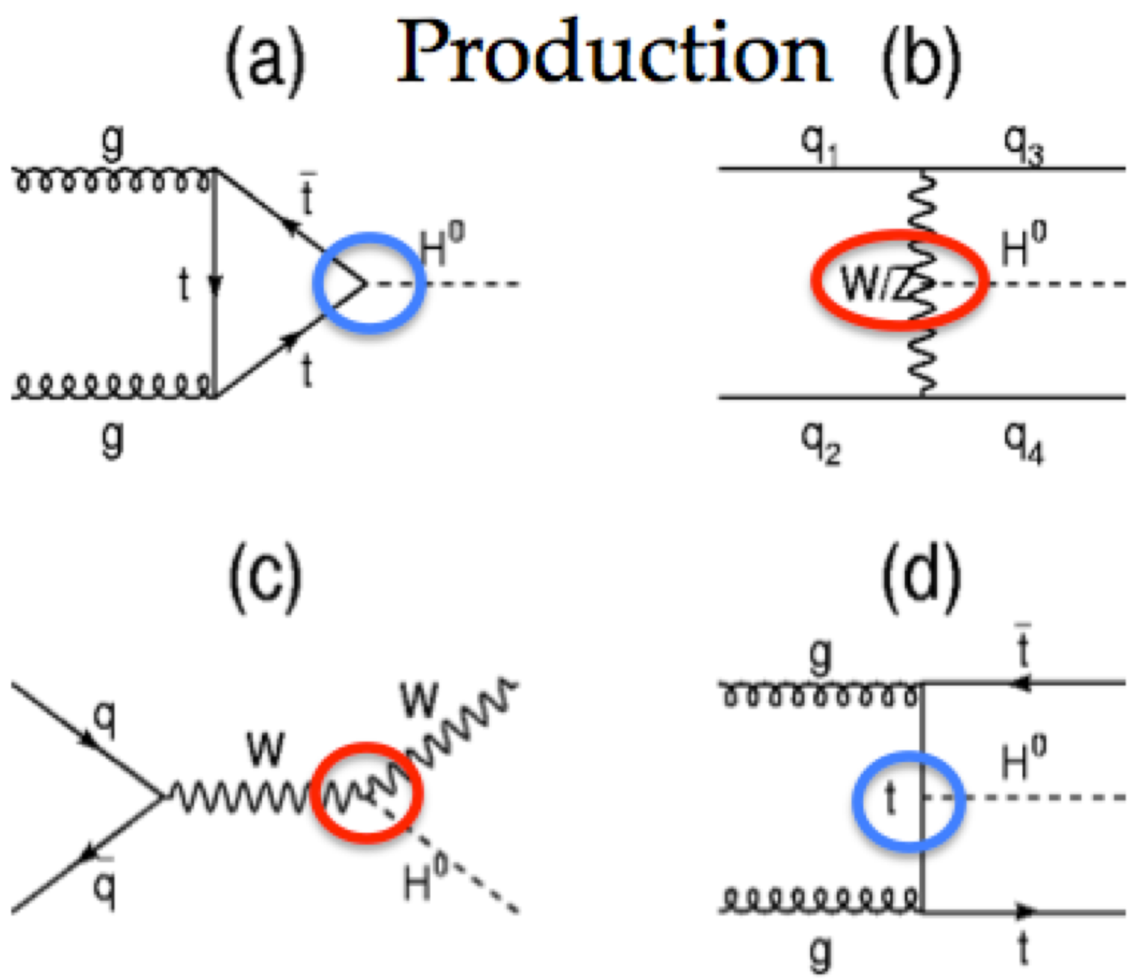
Effective Couplings: diagrams



(a) gluon fusion (19 pb @8 TeV)

(b) VBF (WW or ZZ fusion)

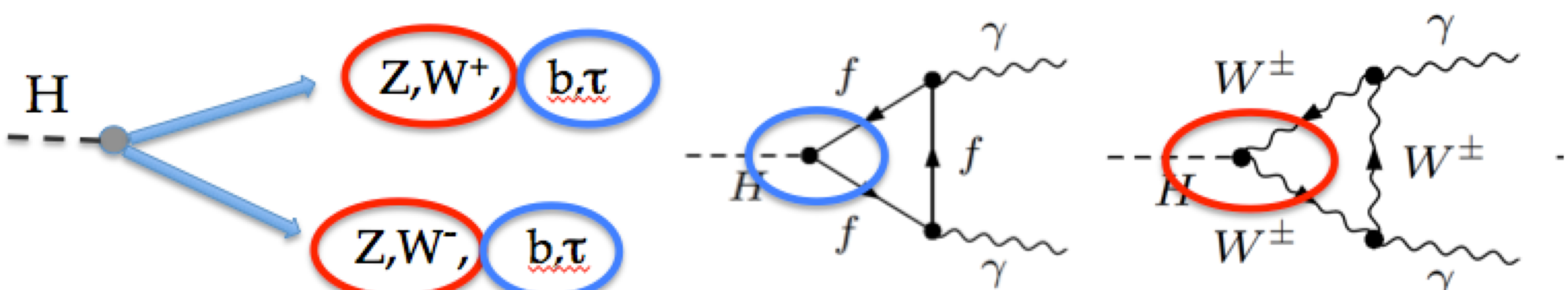
(c) Associated production (VH)

(d) ttH production

Fermions

Bosons

Decay



Combining different categories : master formula

$$n_s^c = (\sum_{i,f} \mu_i \, \sigma_i^{SM} \times A_{if}^c \times \varepsilon_{if}^c \times \mu_f \, \mathrm{BR}_f^{SM}) \times \mathcal{L}^c$$

Category is a sample of events selected by analysis cuts

- μ_c is the ratio between the observed cross section and the one predicted by the SM
- The production index i ∈ {ggH, VBF, VH, ttH}
- The decay index f ∈ {γγ,WW, ZZ, bb, τ τ}
- σ_{SM}^i and BR_{SM}^f are the corresponding production cross sections, decay branching fractions assuming that the Higgs boson is that of the SM.
- A^c_{if} and ε^c_{if} are the signal acceptance and the reconstruction efficiency for given production and decay modes in the category c. L^c is the integrated luminosity used for that specific category.

Combination means fitting scale parameters needed to realise the best agreement between data and (modified SM) expectations across different categories & experiments. Includes Signal Regions & Control Regions

There are different ways of combining different categories of different experiments, different ways correspond to different assumptions (which generally means simplifications).

Combining different categories : master formula

Category is a sample of events selected by analysis cuts (+ subcategories)

$$n_s^c = (\sum_{i,f} \mu_i \, \sigma_i^{SM} \times A_{if}^c \times \varepsilon_{if}^c \times \mu_f \, \mathrm{BR}_f^{SM}) \times \mathcal{L}^c$$

VH=WH+ZH

$i \in$ {ggH, VBF, VH, ttH}
$f \in$ {γγ,WW, ZZ, bb, τ τ}
5 values of i
5 values of f

	$\gamma\gamma$	ZZ (4ℓ)	WW $(\ell\nu\ell\nu)$	$\tau^+\tau^-$	$b\bar{b}$
ggF (high p_T^H)	A	A	—	A	—
ggF (incl. or low p_T^H)	A - C	A - C	A - C	—	—
ggF 1-jet	—	C	A - C	C	—
VBF	A - C	A - C	A - C	A - C	C
WH (1-ℓ)	A - C	A	A - C	C	A - C
WH (two jets)	A - C	A - C	A - C	—	—
ZH (0-ℓ)	A - C	A	—	—	A - C
ZH (2-ℓ)	A - C	A	A - C	C	A - C
ZH (two jets)	A - C	A - C	A - C	—	—
ttH (1-ℓ)	A - C	—	A - C	A - C	A - C
ttH (2-ℓ)	—	—	A - C	A - C	A - C
ttH (hadronic)	A - C	—	—	—	A

A – ATLAS
C - CMS

Possible ways of Fitting:

1. $\mu_i \times \mu_f$ are 25 free parameters
2. a reference process is defined: **H decay to ZZ in the ggf production mode**.
   σ(ggf→H →ZZ) + σ_i/σ_{ggf} + BR_f/BR_{ZZ},
   9 parameters (10-2+1)
3. Further assumptions (see later)
4. Effective Lagrangian, introduce vertex modifiers

Signal strength (μ)

The luminosity collected by ATLAS & CMS gives

Category is a sample of events selected by analysis cuts

Production mechanism	ggf	VBF	VH/ZH	ttH
# events produced LHC	500K	40K	20K	3K
# selected events	O(100)	O(100)	O(10)	
# events produced Tevatron	10K		2K	

For each decay channel "c" we define categories to maximize the sensitivity of the analysis to one particular production mode. However a mixture of different mechanisms in one category is inevitable. This implies the cross section of one category is not the cross section of one production mechanism.

$$n_s^c = (\sum_{i,f} \mu_i \, \sigma_i^{SM} \times A_{if}^c \times \varepsilon_{if}^c \times \mu_f \, \mathrm{BR}_f^{SM}) \times \mathcal{L}^c$$

Where μ_c is ration between measured & expected events in that category and

i=ggf,VBF,VH,tth and f=γγ,WW,ZZ,bb,ττ

Measurement of μ_c gives an indication of how well SM describes data

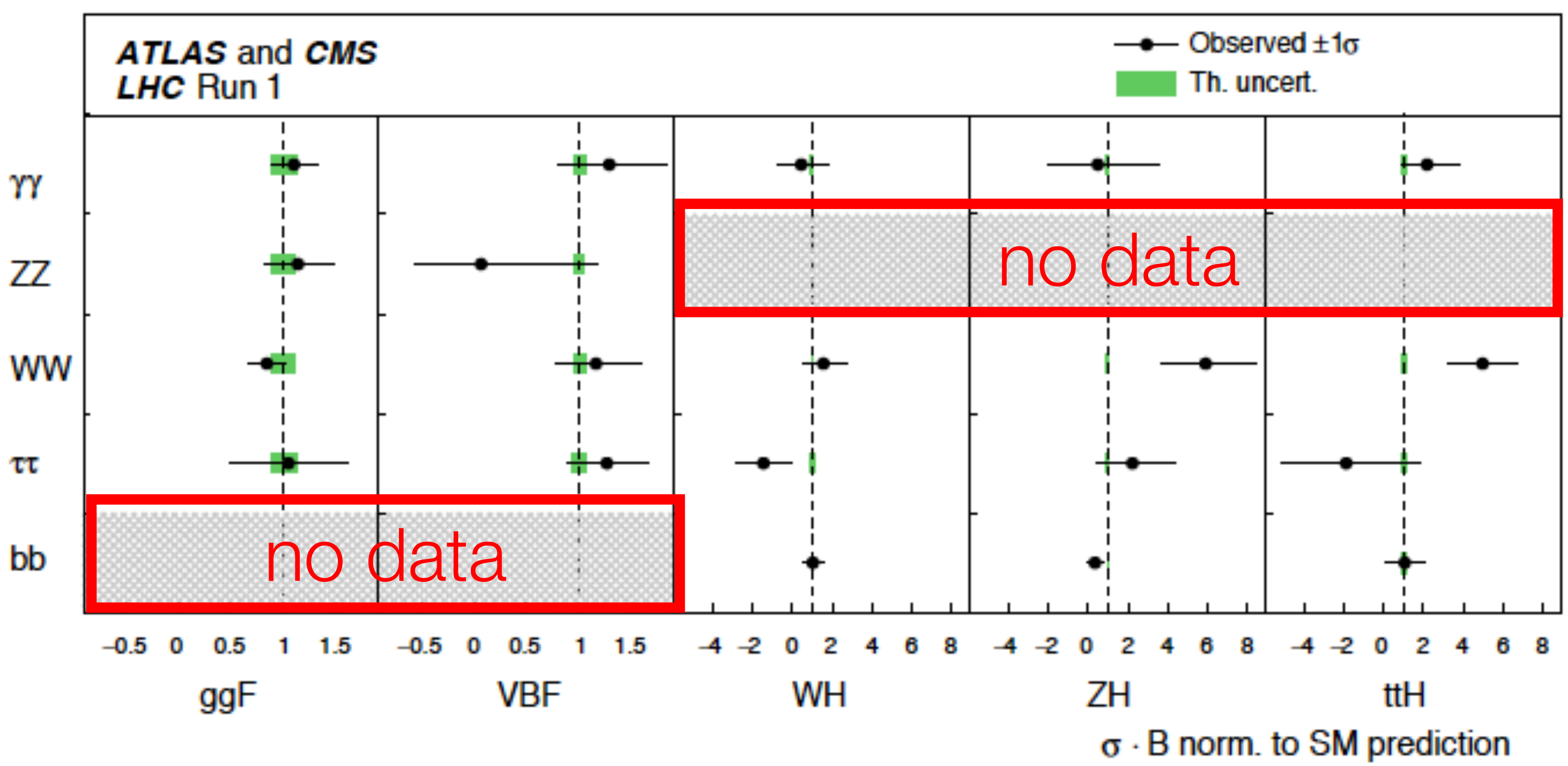
Combination type 1, most general fit

The signal strength $\mu = (\sigma \cdot \mathcal{B})_{\text{obs}}/(\sigma \cdot \mathcal{B})_{\text{SM}}$

	$\gamma\gamma$	ZZ (4ℓ)	WW $(\ell\nu\ell\nu)$	$\tau^+\tau^-$	$b\bar{b}$	Comb.
ggF	$1.10^{+0.22+0.07}_{-0.21-0.05}$	$1.13^{+0.33+0.09}_{-0.30-0.07}$	$0.84^{+0.12+0.12}_{-0.12-0.11}$	$1.00^{+0.4+0.4}_{-0.4-0.4}$	—	$1.03^{+0.16}_{-0.14}$
VBF	$1.3 \pm 0.5^{+0.2}_{-0.1}$	$0.1^{+1.1+0.2}_{-0.6-0.2}$	$1.2^{+0.4+0.2}_{-0.3-0.2}$	$1.3^{+0.3+0.2}_{-0.3-0.2}$	—	$1.18^{+0.25}_{-0.23}$
WH	$0.5^{+1.3+0.2}_{-1.2-0.1}$	—	$1.6^{+1.0+0.6}_{-0.9-0.5}$	$-1.4^{+1.2+0.7}_{-1.1-0.8}$	$1.0^{+0.4+0.3}_{-0.4-0.3}$	$0.89^{+0.40}_{-0.38}$
ZH	$0.5^{3.0}_{-2.5}{}^{+0.5}_{-0.2}$	—	$5.9^{+2.3+1.1}_{-2.1-0.8}$	$2.2^{+2.2+0.8}_{-1.7-0.6}$	$0.4^{+0.3+0.2}_{-0.3-0.2}$	$0.79^{+0.38}_{-0.36}$
ttH	$2.2^{1.6}_{-1.3}{}^{+0.2}_{-0.1}$	—	$5.0^{+1.5+1.0}_{-1.5-0.9}$	$-1.9^{+3.2+1.9}_{-2.7-1.8}$	$1.1^{+0.5+0.8}_{-0.5-0.8}$	$2.3^{+0.7}_{-0.6}$
Comb.	$1.14^{+0.19}_{-0.18}$	$1.29^{+0.26}_{-0.23}$	$1.09^{+0.18}_{-0.16}$	$1.11^{+0.24}_{-0.22}$	$0.70^{+0.29}_{-0.27}$	$\boxed{1.09^{+0.11}_{-0.10}}$

3 missing

2 missing



- No deviation SM
- 25 – 5 = 20 parameters determined

Combination type 2, less general fit

i = production, f = decay

All is referred to the gluon fusion production mechanism in the H → ZZ decay mode

$$\mu_i = \frac{\sigma_i}{\sigma_{ggF}\sigma_i^{SM}} \boxed{\times \mu_{gg\to H\to ZZ}}$$

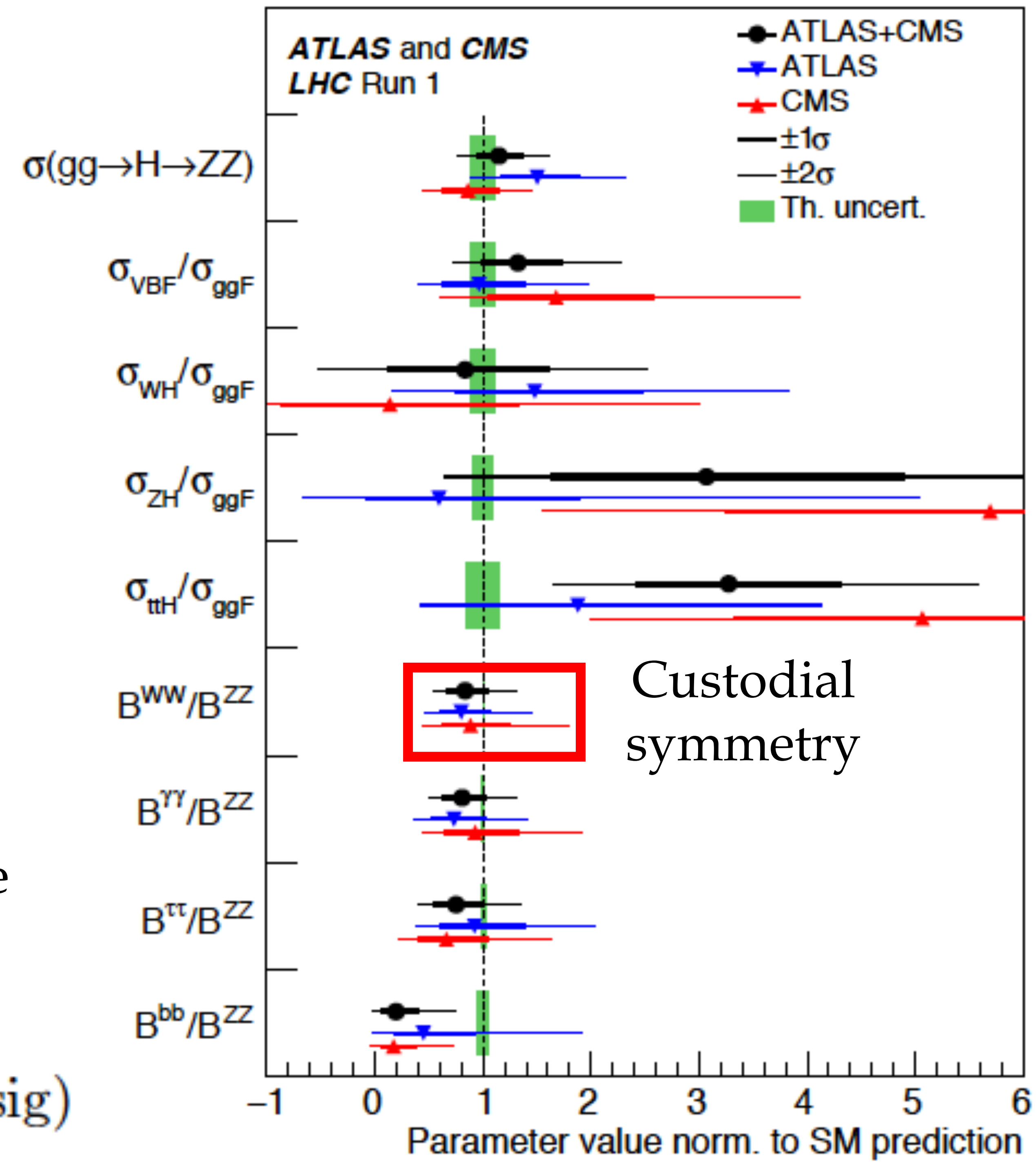
$$\mu_f = \frac{\mathrm{BR}_i}{\boxed{\mathrm{BR}_{ZZ}}\mathrm{BR}_i^{SM}}$$

$$\mu_{gg\to H\to ZZ} = \boxed{\mu_{ggF}} \times \mu_{ZZ} \times \sigma_i^{SM} \times \mathrm{BR}_f^{SM}$$

Then, the master formula applies with the following parameters for all i and f indices except when both **i = ggF and f = ZZ**

→ 8 + 1 parameters

Improved precision stemming from fewer parameters shows no deviation from SM

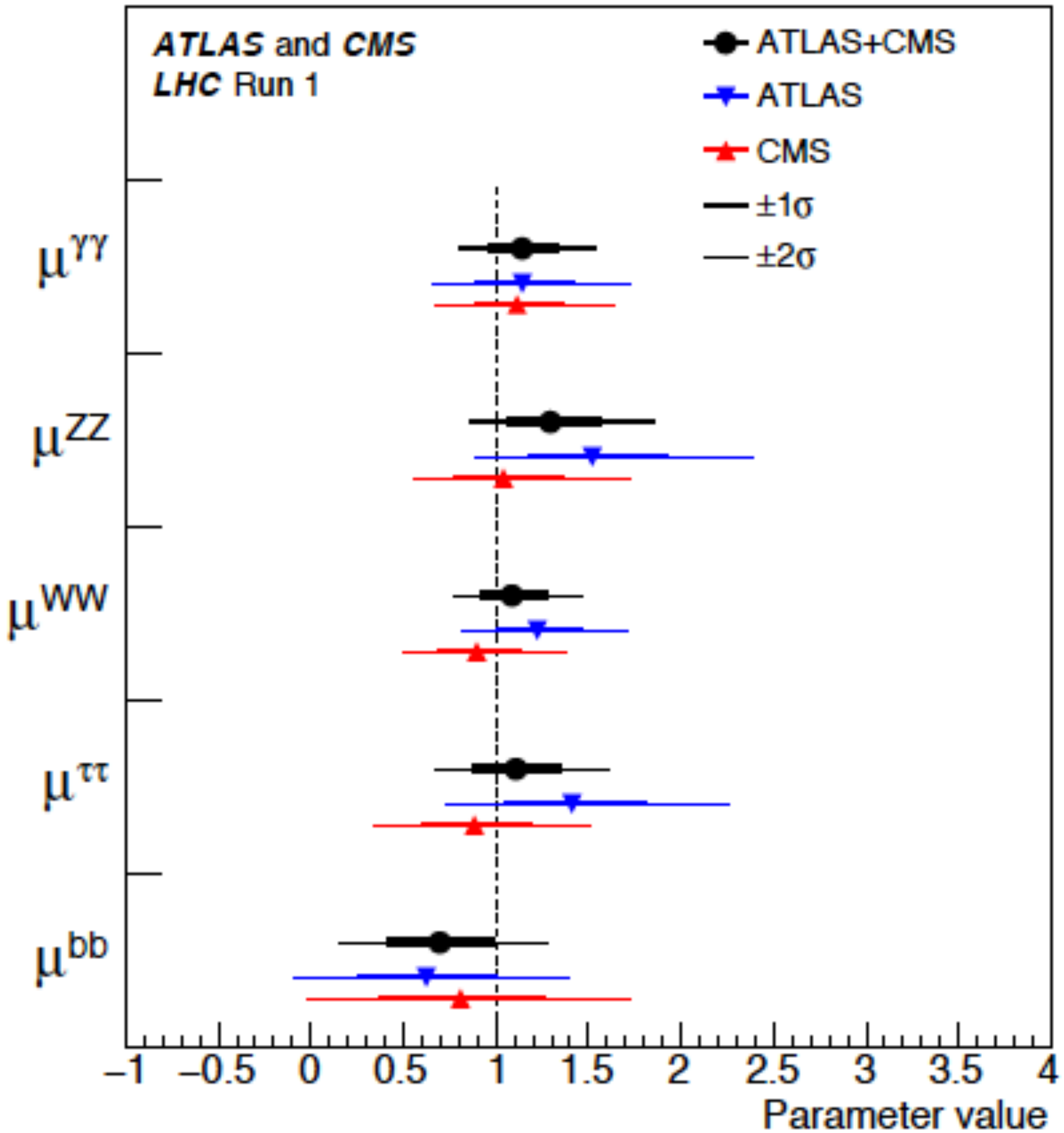


Finally if all deviations are included in a single parameter $\boxed{\mu = 1.09 \pm 0.07\ (\mathrm{stat})}$

$$\pm\, 0.04\ (\mathrm{expt})\ \pm 0.03\ (\mathrm{th.\,bkg})\ \pm 0.07\ (\mathrm{th.\,sig})$$

Assume all production cross sections are SM ones

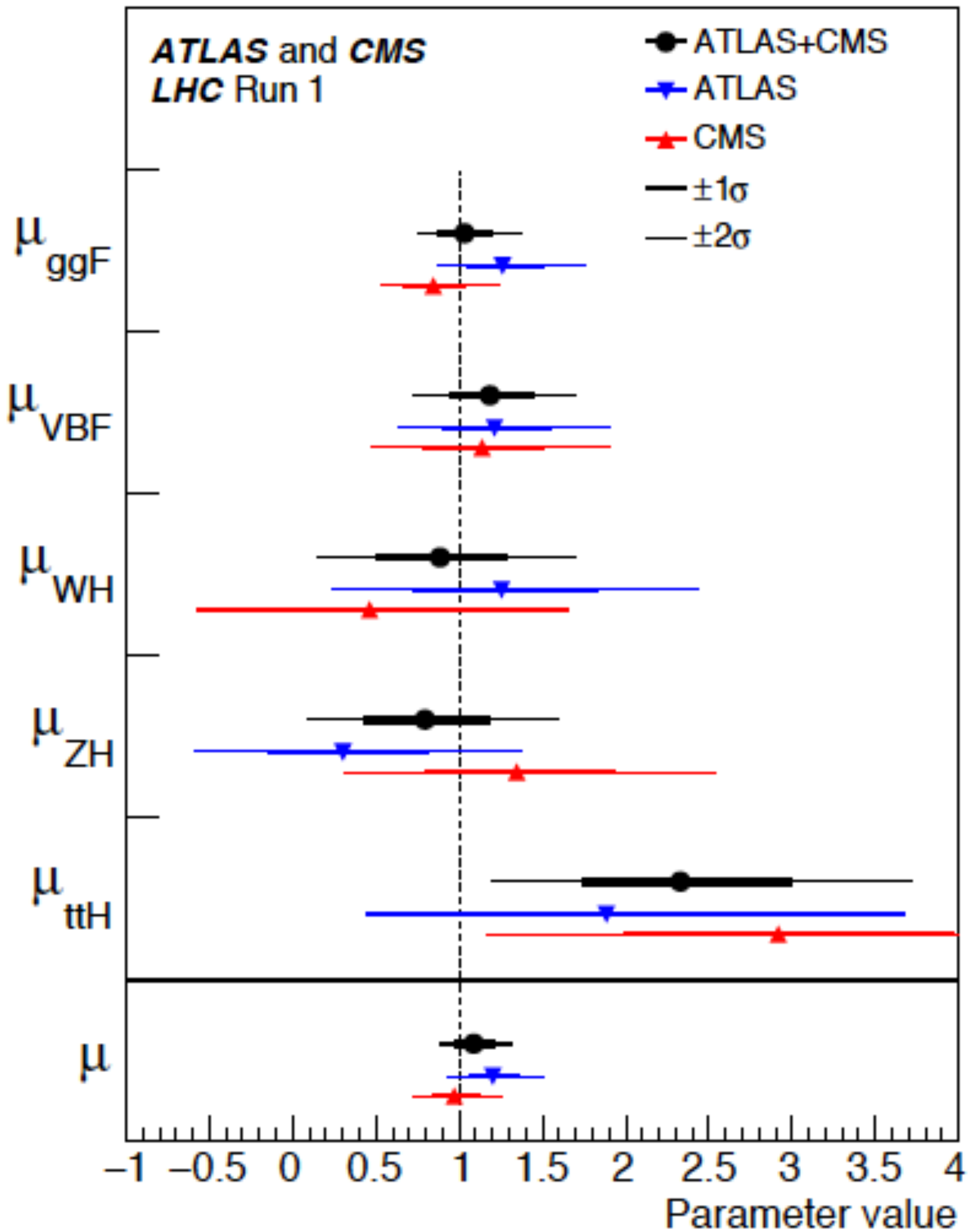
→ only decay modes!



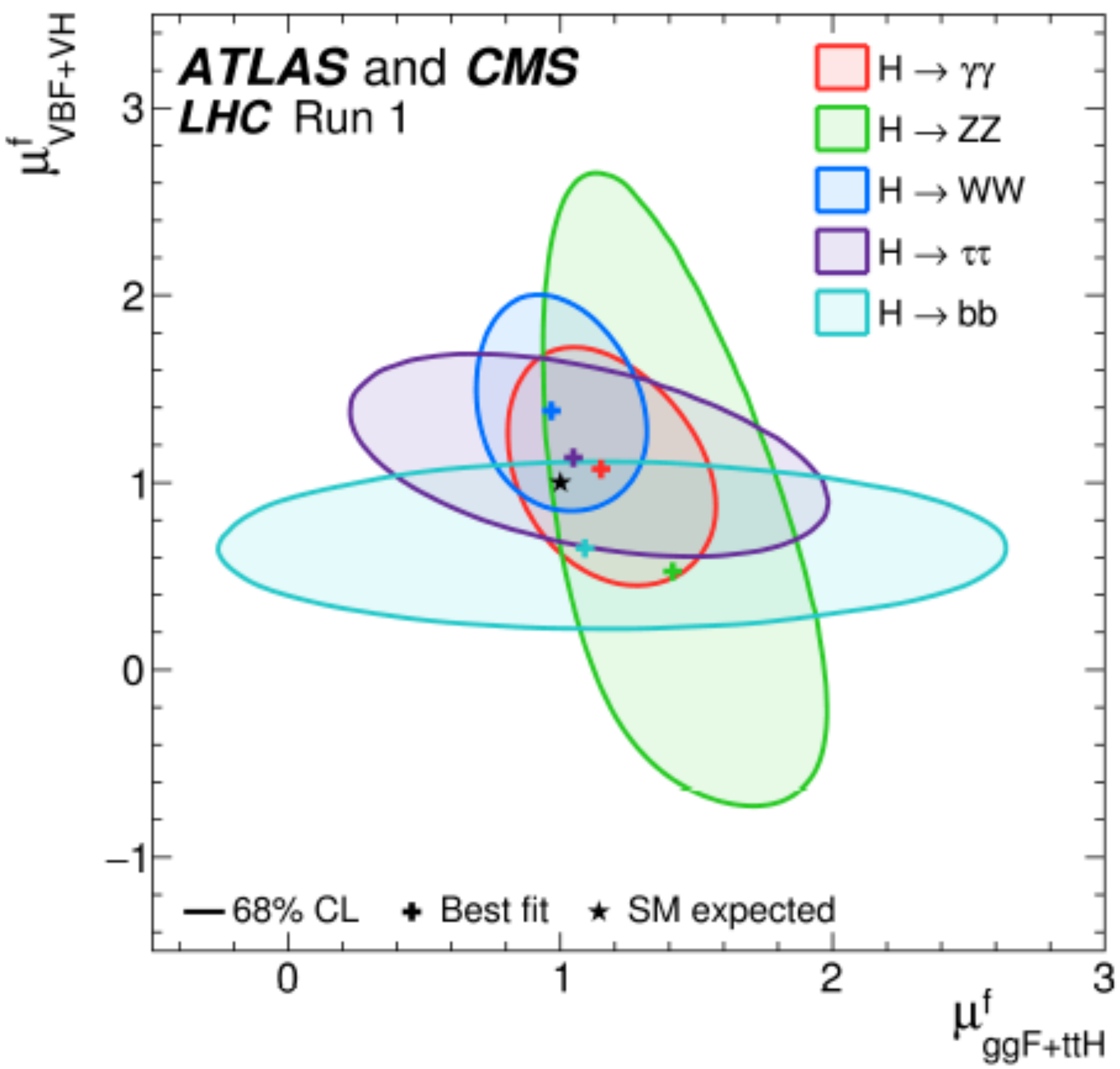
	Expected Z	Observed Z
$\gamma\gamma$	4.6σ (ATLAS) 5.3σ (CMS)	5.2σ (ATLAS) 4.6σ (CMS)
ZZ	6.2σ (ATLAS) 6.3σ (CMS)	8.1σ (ATLAS) 6.5σ (CMS)
WW	5.9σ (ATLAS) 5.4σ (CMS)	6.5σ (ATLAS) 4.7σ (CMS)
$\tau^+\tau^-$	3.4σ (ATLAS) 3.9σ (CMS)	4.5σ (ATLAS) 3.8σ (CMS)
$b\bar{b}$	2.6σ (ATLAS) 2.5σ (CMS)	1.4σ (ATLAS) 2.1σ (CMS)
$\tau^+\tau^-$ (Combined)	5.0σ	5.5σ
$b\bar{b}$ (Combined)	3.7σ	2.6σ

Assume all BR fractions are SM ones

→ only production modes!



One more assumption: vertices VHF & VH scale with one μ and ggF and ttH with another μ



Estimators of Effective Couplings

The measurement of the parameters of interest is carried out using a statistical test based on the profile likelihood ratio

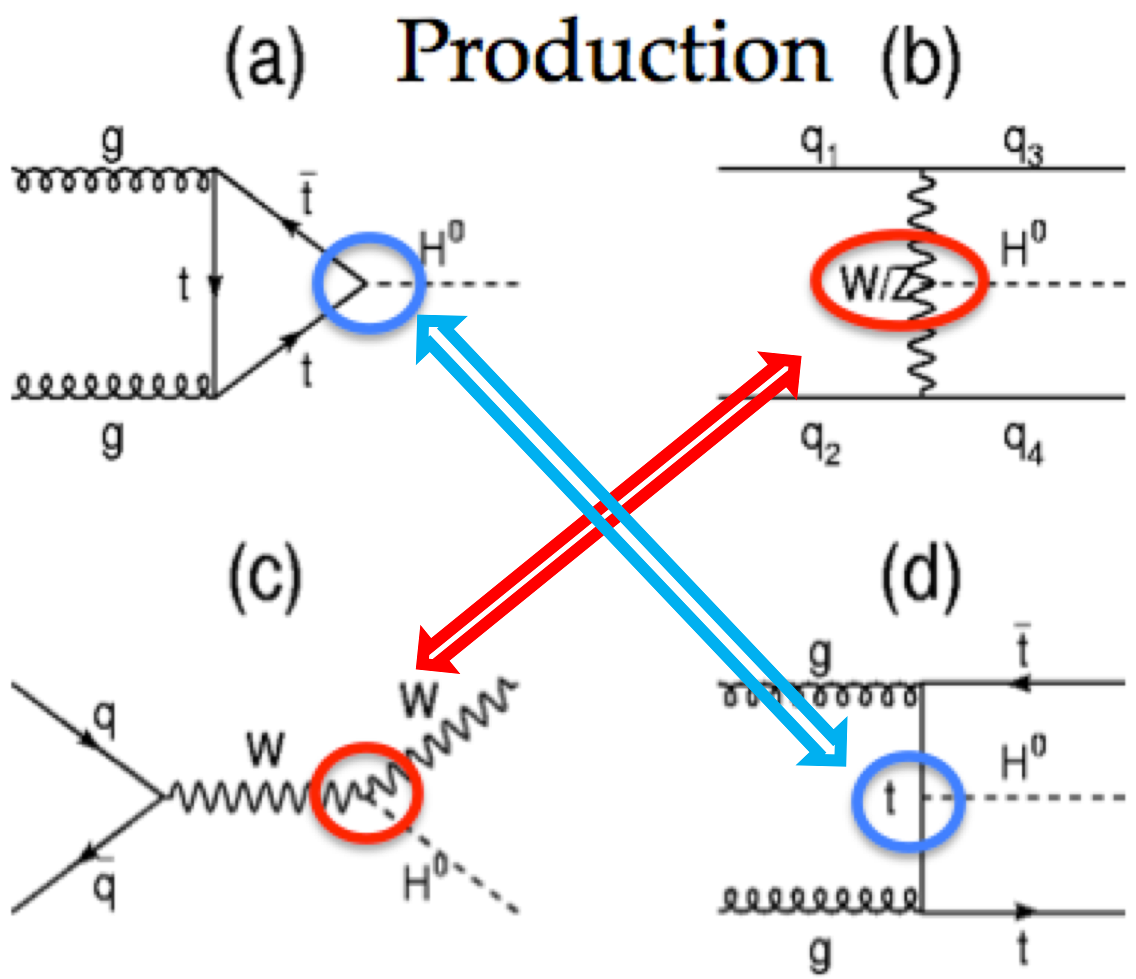
$$\Lambda(\boldsymbol{\alpha}) = \frac{L(\boldsymbol{\alpha}, \hat{\hat{\boldsymbol{\theta}}}(\boldsymbol{\alpha}))}{L(\hat{\boldsymbol{\alpha}}, \hat{\boldsymbol{\theta}})}$$

where α and θ are respectively the parameters of interest and the nuisance parameters.

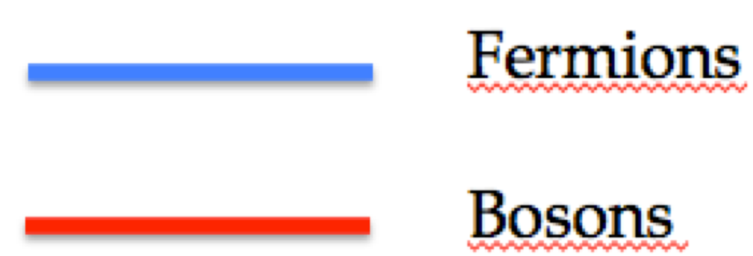
In the numerator, the nuisance parameters are set to their profiled values $\hat{\vartheta}(\alpha)$, which maximize the likelihood function for fixed values of the parameters of interest α.

In the denominator, both the parameters of interest and the nuisance parameters are set to the values $\hat{\alpha}$ and $\hat{\vartheta}(\alpha)$ respectively which jointly maximize the likelihood.

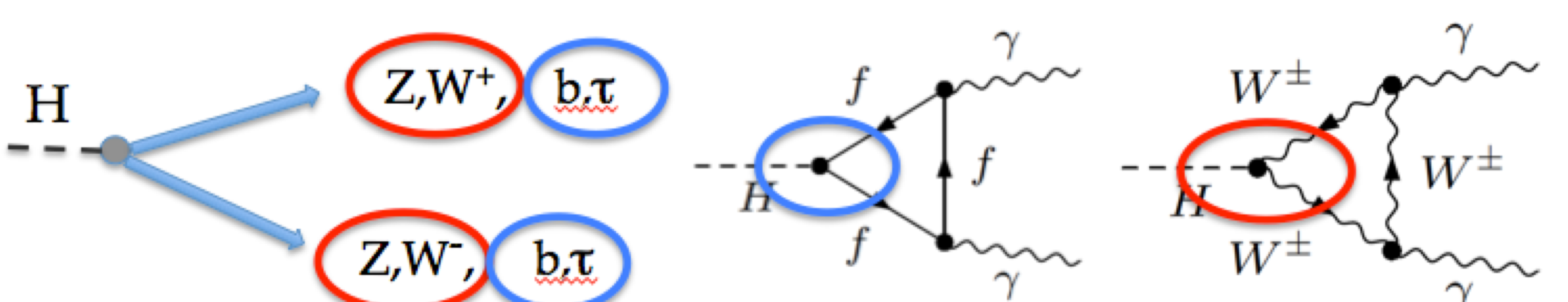
Effective Couplings: diagrams (1° slide)



(a) gluon fusion (19 pb @8 TeV)
(b) VBF (WW or ZZ fusion)
(c) Associated production (VH)
(d) ttH production



Decay



Estimators of Effective Couplings

Nuisance parameters

Best value

$$q_0 = -2\ln\frac{\mathcal{L}(\text{obs}\,|\,b,\hat{\theta}_0)}{\mathcal{L}(\text{obs}\,|\,\hat{\mu}\cdot s+b,\hat{\theta})},$$

b,s background, signal; $\hat{\Theta}$ "nuisance parameters"; $\hat{\mu}$ signal strength modifier

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

'a' is quantity of interest, profile it. $q_0(a)$ is best fit of q(a) with fit nuisance parameters

Value at "a"

$$\hat{\mu} = \hat{\sigma}/\sigma_{SM}$$

Signal strength. The best fit value for the common signal strength modifier provides the first compatibility test. μ is 0 in absence of H, 1 in case of SM H.

- Test $\mu_{\gamma\gamma}$, μ_{ZZ} … $\mu_{ggF+ttH}$ and μ_{VBF+VH}

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

ii and *ff* couplings modified by k_i^2 and k_f^2 Example:

$$\sigma\cdot\mathrm{BR}\,(gg\to\mathrm{H}\to\gamma\gamma) = \sigma_{\mathrm{SM}}(gg\to\mathrm{H})\cdot\mathrm{BR}_{\mathrm{SM}}(\mathrm{H}\to\gamma\gamma)\cdot\frac{\kappa_g^2\cdot\kappa_\gamma^2}{\kappa_{\mathrm{H}}^2}$$

- Test $\lambda_{WZ}=k_W/k_Z$ ("costudial symmetry", ==1 in SM)
- Test $\lambda_{du}=k_d/k_u$ $\lambda_{WZ}=k_W/k_Z$

Coupling properties of the Higgs Boson

Elaborate even more: introduce modifiers k_x of vertices in the Lagrangian. In this way production and decay vertices are treated on the same footing.

Remember

- In SM H does not couple to massless particles directly (only via loops).

$$\begin{aligned}\mathcal{L} = & \boxed{\kappa_3} \frac{m_H^2}{2v} H^3 + \boxed{\kappa_Z} \frac{m_Z^2}{v} Z_\mu Z^\mu H + \boxed{\kappa_W} \frac{2m_W^2}{v} W_\mu^+ W^{-\mu} H \\ & + \boxed{\kappa_g} \frac{\alpha_s}{12\pi v} G_{\mu\nu}^a G^{a\mu\nu} H + \boxed{\kappa_\gamma} \frac{\alpha}{2\pi v} A_{\mu\nu} A^{\mu\nu} H + \boxed{\kappa_{Z\gamma}} \frac{\alpha}{\pi v} A_{\mu\nu} Z^{\mu\nu} H \\ & + \boxed{\kappa_{VV}} \frac{\alpha}{2\pi v} \left(\cos^2\theta_W Z_{\mu\nu} Z^{\mu\nu} + 2\, W_{\mu\nu}^+ W^{-\mu\nu} \right) H \\ & - \left(\boxed{\kappa_t} \sum_{f=u,c,t} \frac{m_f}{v} f\overline{f} + \boxed{\kappa_b} \sum_{f=d,s,b} \frac{m_f}{v} f\overline{f} + \boxed{\kappa_\tau} \sum_{f=e,\mu,\tau} \frac{m_f}{v} f\overline{f} \right) H.\end{aligned}$$

Parametrizations in SM

$$(1-\cos^4\theta_W)\kappa_{VV} = \sin 2\theta_W \kappa_{Z\gamma} + \sin^2\theta_W \kappa_{\gamma\gamma}.$$

The κ_g, κ_γ and $\kappa_{Z\gamma}$, can be treated effectively as free parameters in the fit or in terms of the know SM field content and as a function of the SM coupling modifiers, in the following way:

Independent of SM expressions

$$\begin{aligned} \boxed{\kappa_g^2(\kappa_t,\kappa_b)} &= 1.06\cdot\kappa_t^2 - 0.07\cdot\kappa_t\kappa_b + 0.01\cdot\kappa_b^2 \\ \boxed{\kappa_\gamma^2(\kappa_F,\kappa_V)} &= 1.59\cdot\kappa_V^2 - 0.66\cdot\kappa_V\kappa_F + 0.07\cdot\kappa_F^2 \qquad (11.24) \\ \boxed{\kappa_{Z\gamma}^2(\kappa_F,\kappa_V)} &= 1.12\cdot\kappa_V^2 - 0.15\cdot\kappa_V\kappa_F + 0.03\cdot\kappa_F^2 \end{aligned}$$

These parametrizations are given for a Higgs boson mass hypothesis of 125 GeV.

The global fit is then performed expressing the μ_i and μ_f parameters in terms of a limited number of κ_k parameters or their ratios, under various assumptions. The parametrization for the production modes are: $\boxed{\mu_{ggF} = \kappa_g^2}$ for the gluon fusion; $\boxed{\mu_{VBF,VH} = \kappa_V^2}$ for the VBF and VH processes when the W and Z couplings are assumed to scale equally, and the following expression for the VBF production mode is used:

W & Z are assumed to scale differently

$$\boxed{\kappa_{VBF}^2(\kappa_W,\kappa_Z) = \frac{\kappa_W^2\sigma_{WWH} + \kappa_Z^2\sigma_{ZZH}}{\sigma_{WWH}+\sigma_{ZZH}}} \qquad (11.25)$$

Benchmarks considered

- Relative couplings to bosons and fermions. Introduce k_V and k_F
- **Couplings to Z and W**, ratio of couplings is a fundamental test of SM (custodial symmetry). Several production processes and decay modes may be used to test this assumptions. Ratio $\lambda_{WZ}=k_W/k_Z$ can be probed under a large number of conditions. First step is assuming all fermions scale as k_F and introduce K_{ZZ} which affects the total width. Second to be less dependent on loops, only decay channels to WW and ZZ have been considered (indetermination of sign but k_γ may give indication for the interference term between W and top in the loop)
- **Probing new physics**: it is assumed that no field distorts loop contributions of the H to gluons and photons. Possible deviations may indicate existence of new physics (new fields). This is done by assuming k_V and k_F equal to 1 in all expressions and leaving k_g and k_γ as free parameters of the fit

K_F vs K_V, *simplified* view: all fermions "F", bosons "V"

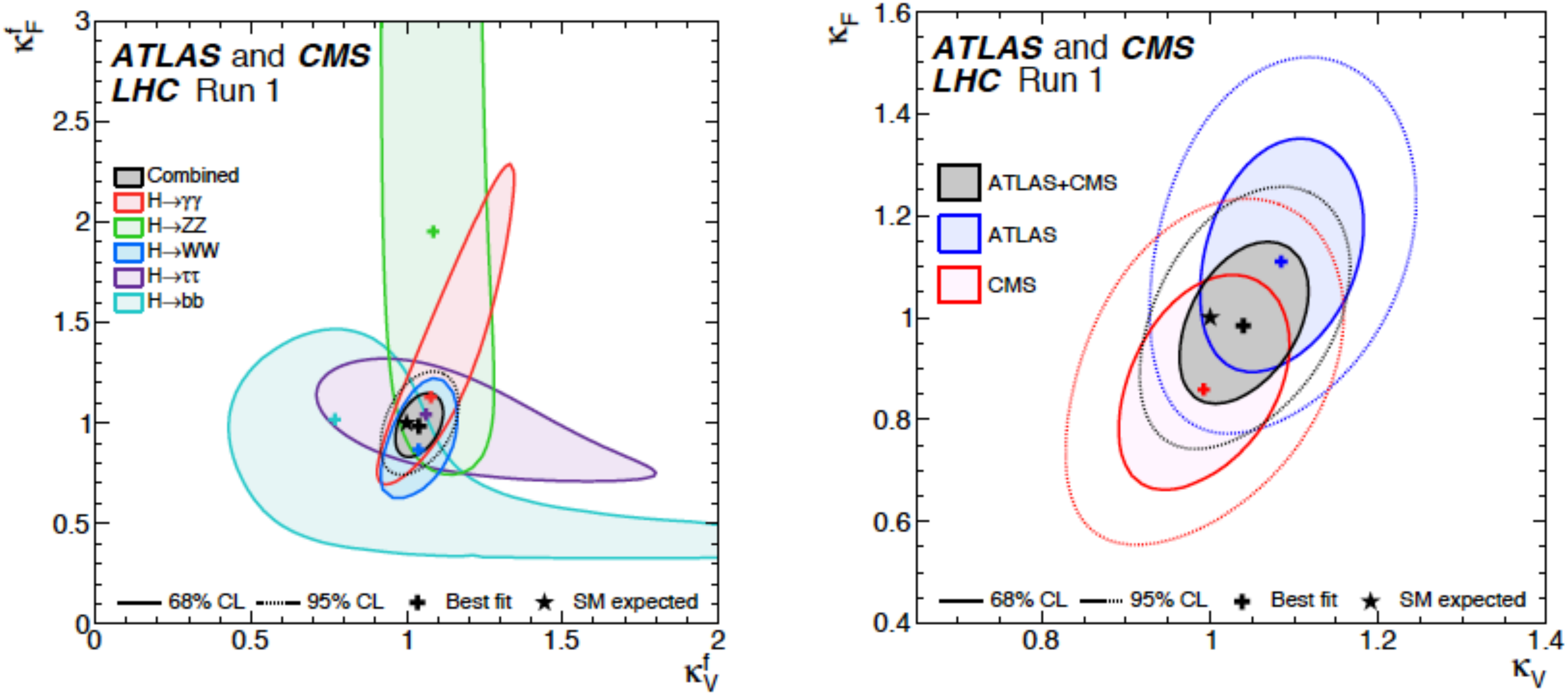
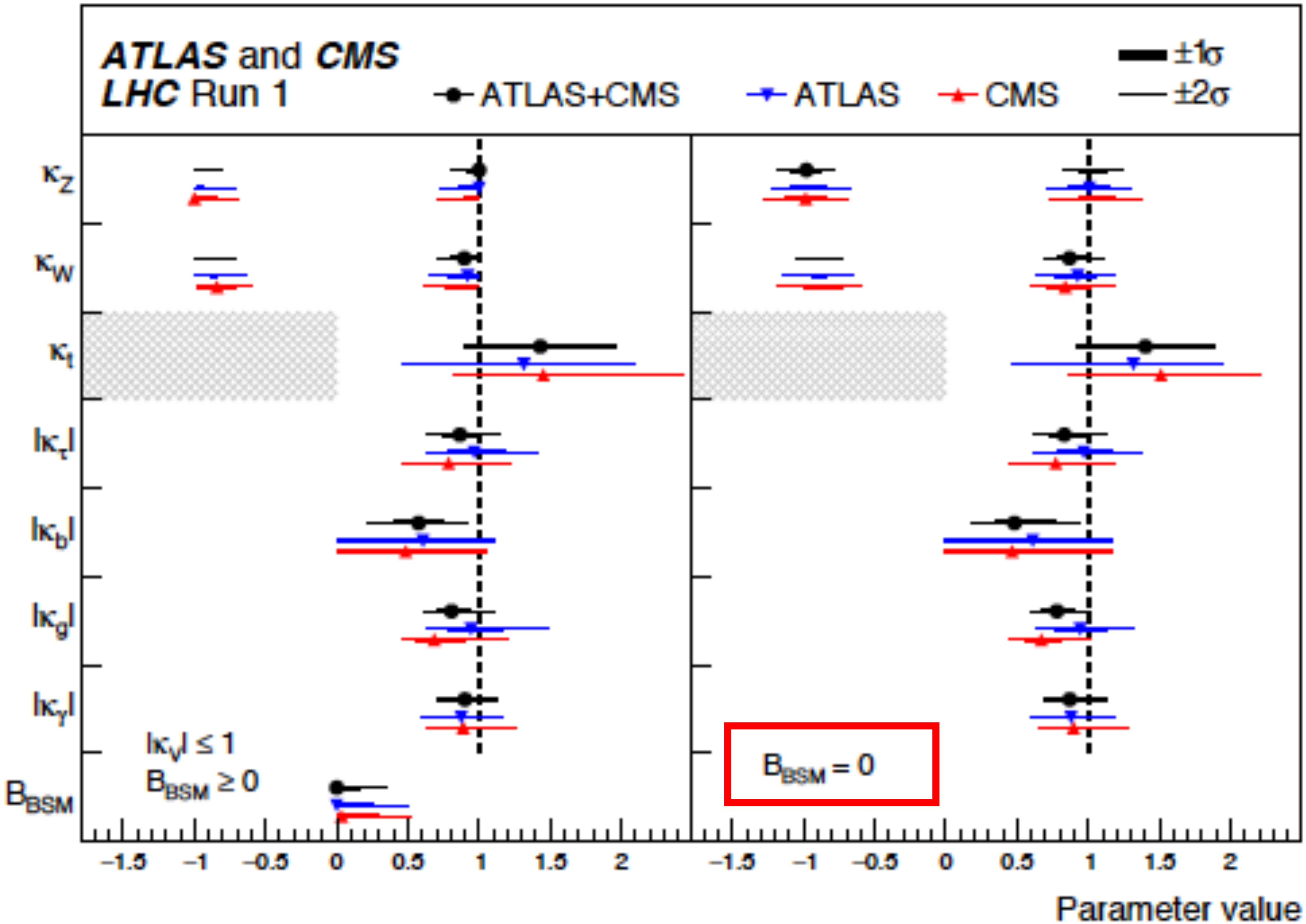


Figure 11.17: Likelihood contours in the (κ_F, κ_V) plane for the ATLAS-CMS combination for the main decay channels separately (left) and for the individual combination of all channels for ATLAS and CMS separately and the complete combined contour (right) [141].

Summary of the Higgs Boson coupling properties



Spin – Parity Determination (SM 0^+)

- Use observables that are sensitive to Spin and Parity of the New Boson independent of the coupling strengths
- Onshell decay of a spin=1 particle into $\gamma\gamma$ is forbidden by Landau-Yang theorem: spin=1 assignment strongly disfavoured
- Several alternative specific models: 0^-, 1^+, 1^-, 2^+ tested against the SM Higgs 0^+ hypothesis
- The spin-2 resonance can be produced either via gluon fusion (gg) or via P-wave quark-antiquark annihilation. Several scenarios corresponding to different admixtures of the production modes are considered.
- The discrimination between the spin hypotheses is enhanced when the spin-2 particle is produced predominantly via gluon fusion.

Spin - Parity

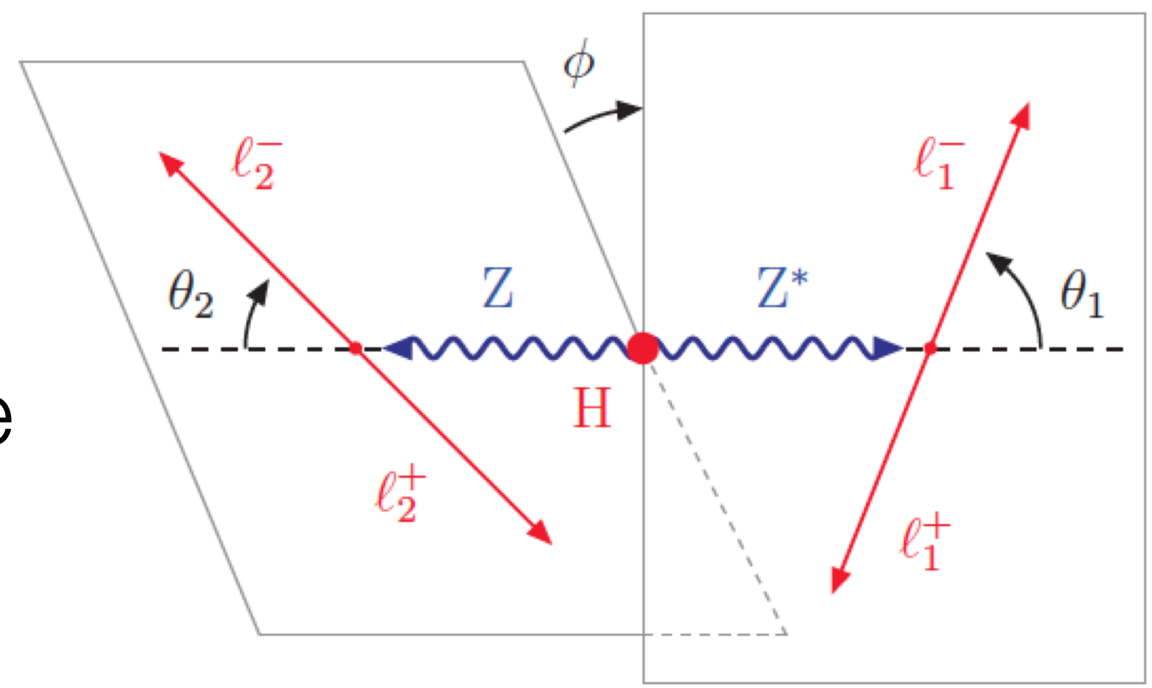
H to$\gamma\gamma$ decay angle cos(θ*) in Collins Soper frame sensitive to J

$$\cos\theta^* = \frac{\sinh(\eta_{\gamma_1} - \eta_{\gamma_2})}{\sqrt{1 + \left(p_T^{\gamma\gamma}/m_{\gamma\gamma}\right)^2}} \cdot \frac{2 p_T^{\gamma_1} p_T^{\gamma_2}}{m_{\gamma\gamma}^2}$$

The definition chosen for the polar angle in the rest frame is the Collins–Soper frame, which is defined as
the bisector axis of the momenta of the incoming protons in the diphoton rest frame

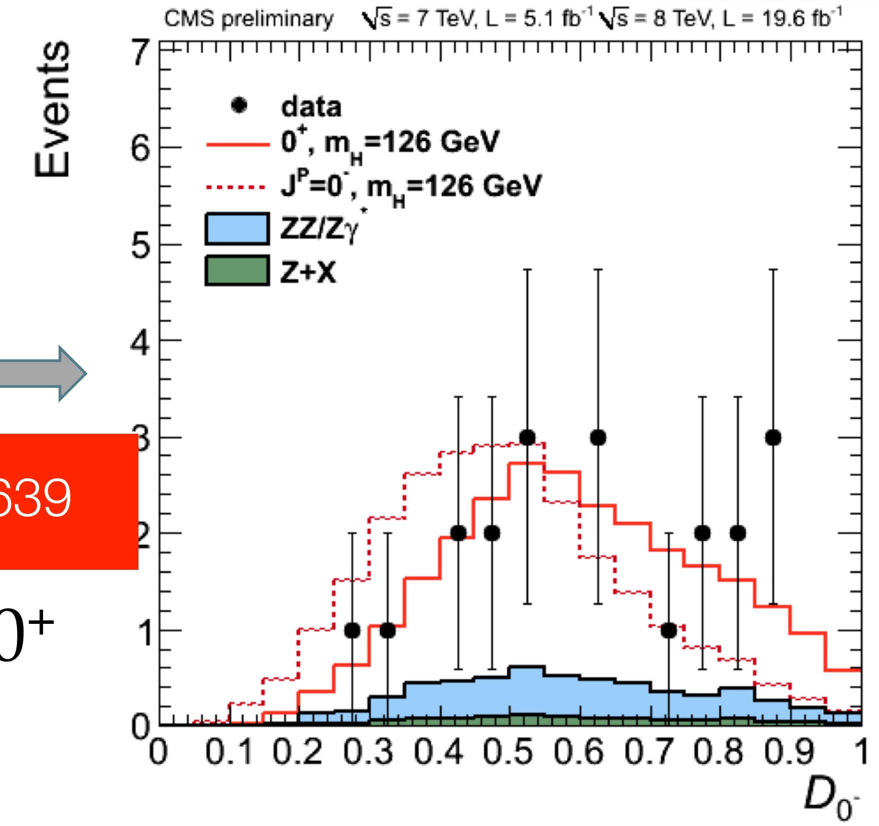
Several observables of H to WW* to $l\nu l\nu$ are sensitive to J^P : $\Delta\phi_{ll}$, M_{ll} , .. Combined with Boosted-Decision-Tree (BDT) technique

H to ZZ* to 4l: full final state reconstruction (2 masses, M_{Z1},M_{Z2}, and 5 angles) is sensitive to J^P. Combined with BDT or Matrix-Element discriminant D_{JP}



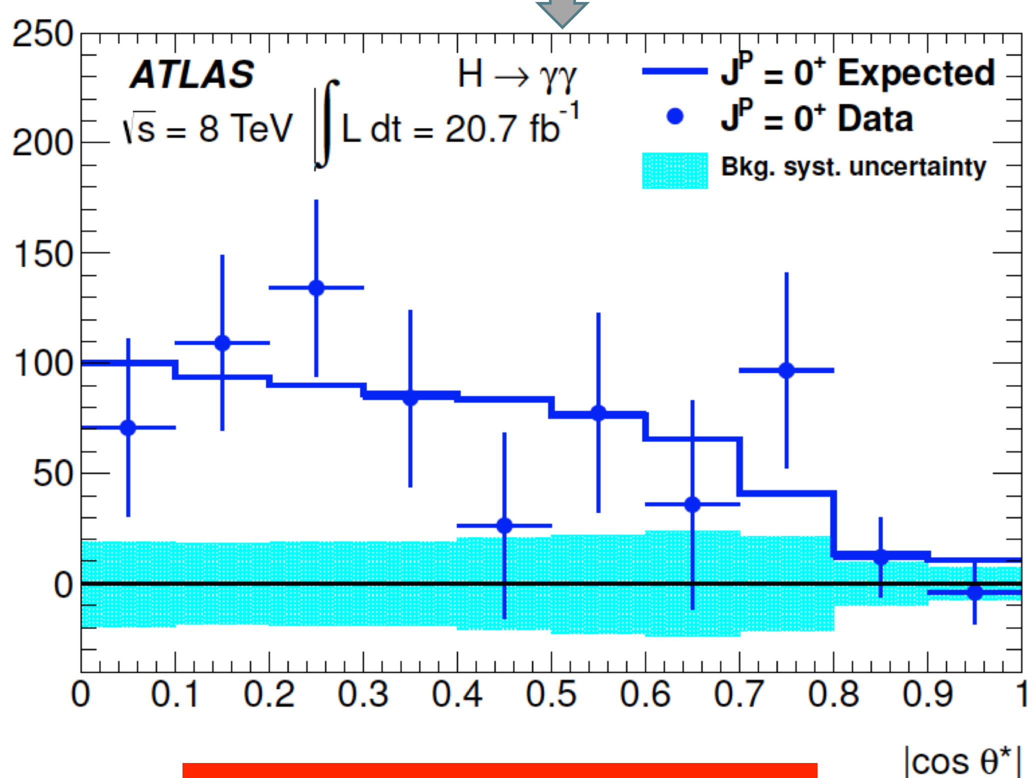
Spin – Parity, 0^+ vs 0^-

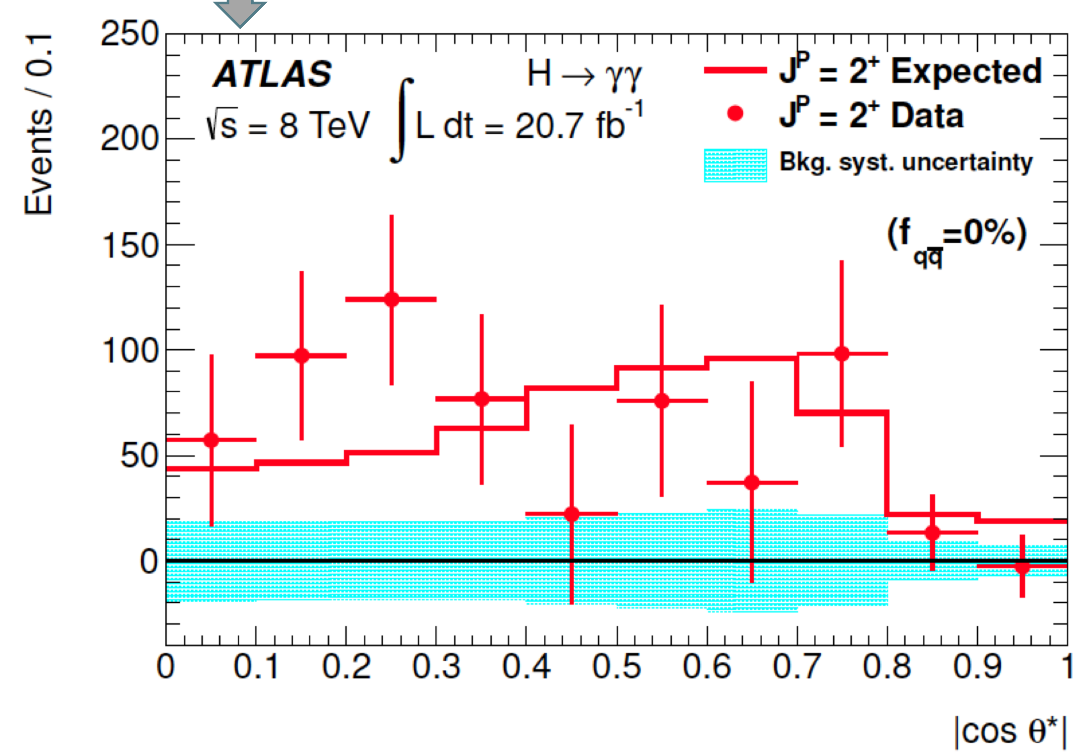
CMS 2 masses and 5 angles in H to ZZ* decay combined in a BDT output D_{JP}.



CMS:arXiv:1212.6639

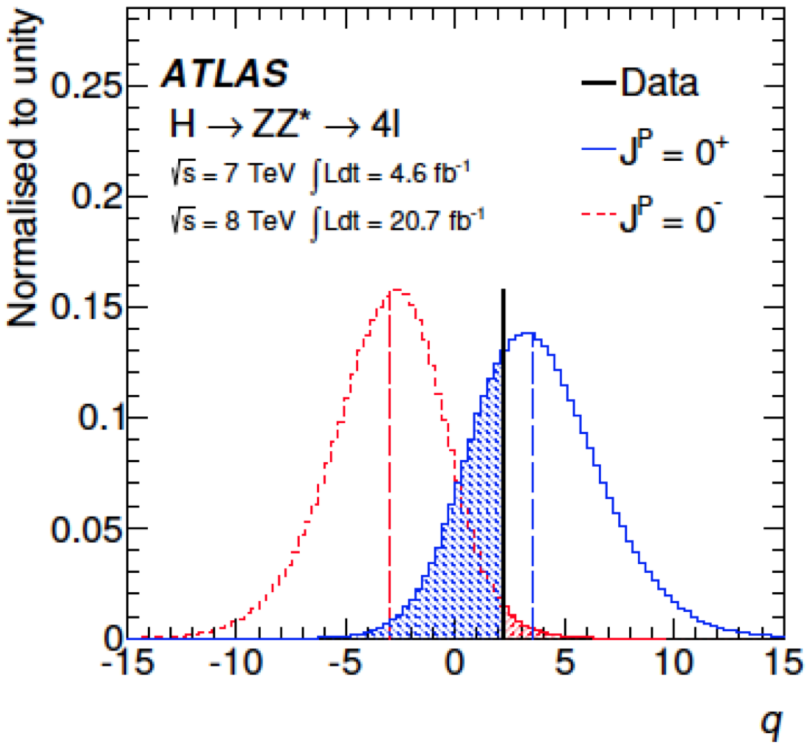
ATLAS: cos(Q*) in H to γγ decay compared to 0^+ 2^+ distributions.

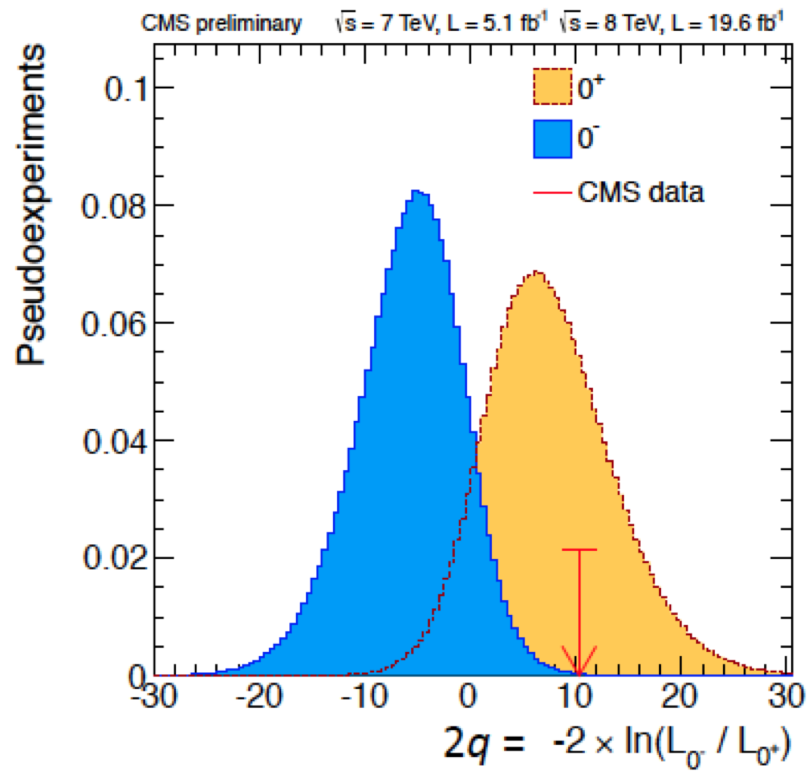


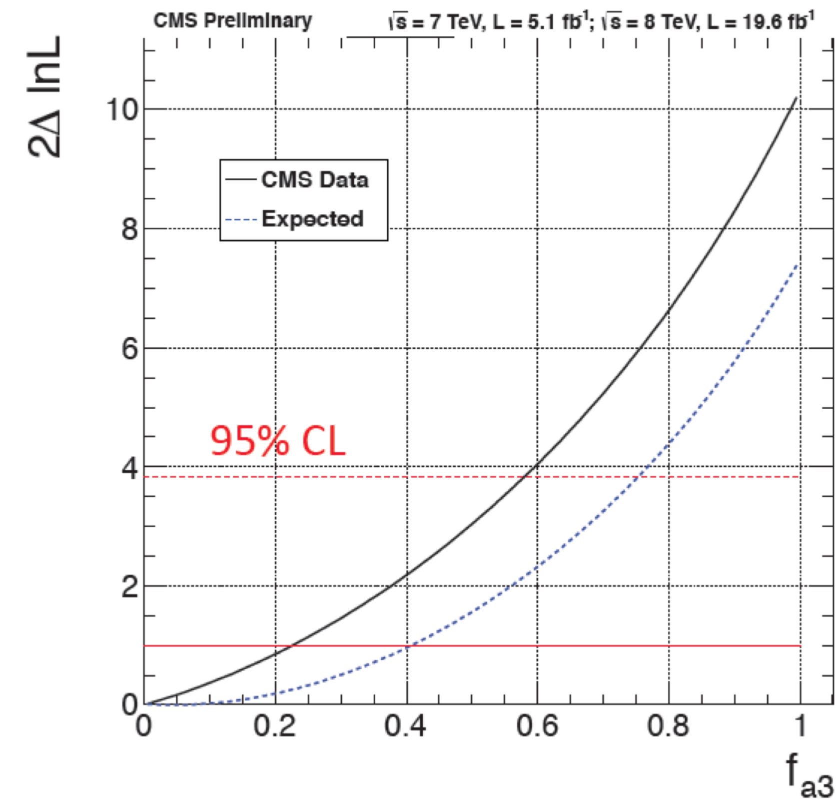


ATLAS-CONF-2013-040

Testing O^+, O^- in H to ZZ*







$$ATLAS : O^- Excluded @ 97.8\%CL(observed), 99.6\%CL(\exp ected)$$

$$CMS : O^- Excluded @ 99.8\%CL(observed), 99.5\%CL(\exp ected)$$

CMS also investigated the possibility of CP amplitudes other than SM: The most general decay amplitude for a spin-zero boson can be defined as: A_1(CP even)=1,A_2(Interference)=A_3(CP odd)=0

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

$$CMS : a_3 = 0.00^{+0.23}_{-0.00}; a_3 < 0.58 @ 95\%CL$$

Testing 0^+ vs 2^+

- A specific spin-2 "*graviton-like*" model with minimal couplings has been compared to the 0^+ predictions of the SM. In this specific model the spin-2 resonance can be produced either via gluon fusion (gg) or via P-wave quark-antiquark annihilation.

- The corresponding angular distributions follow

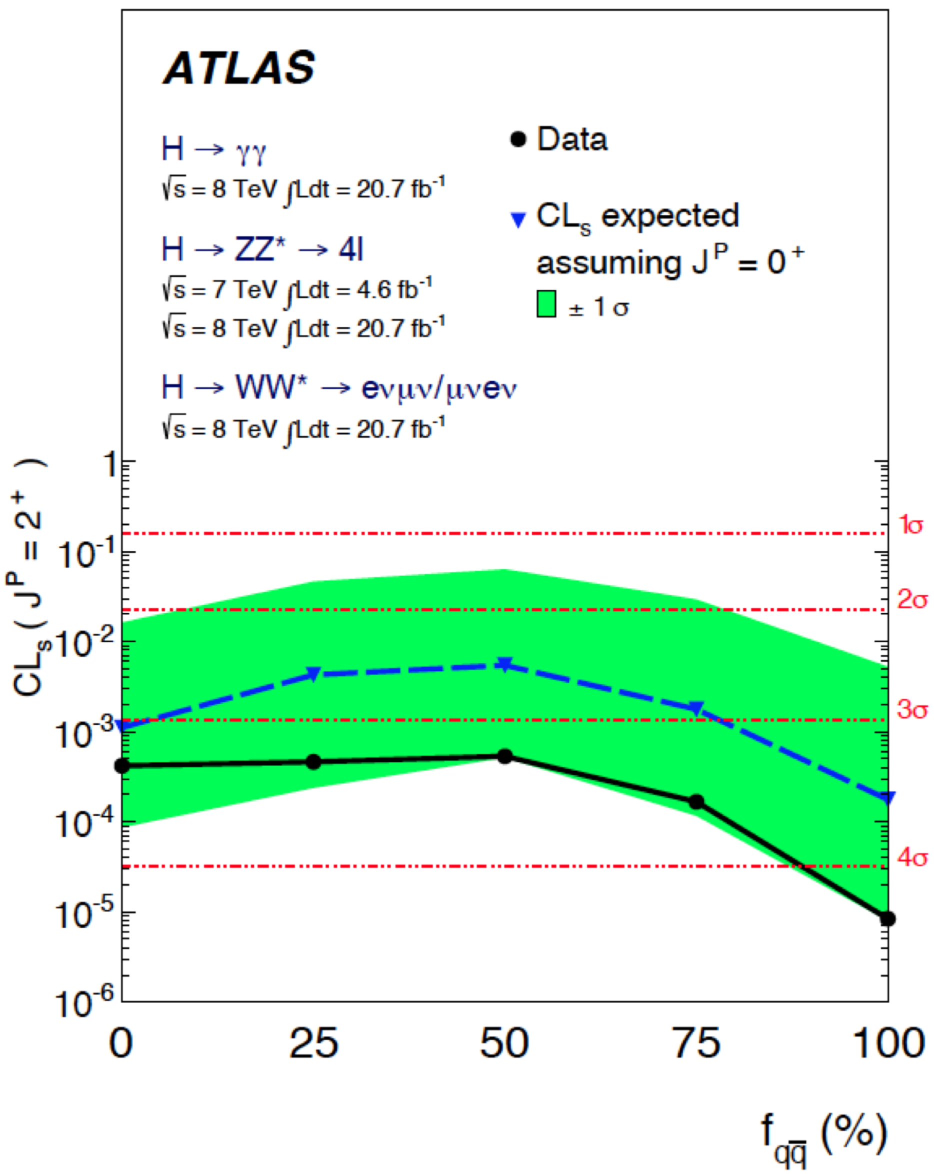
$$dN / d\cos\vartheta^* = 1 - \cos^4\vartheta^* (gluon - gluon - fusion)$$

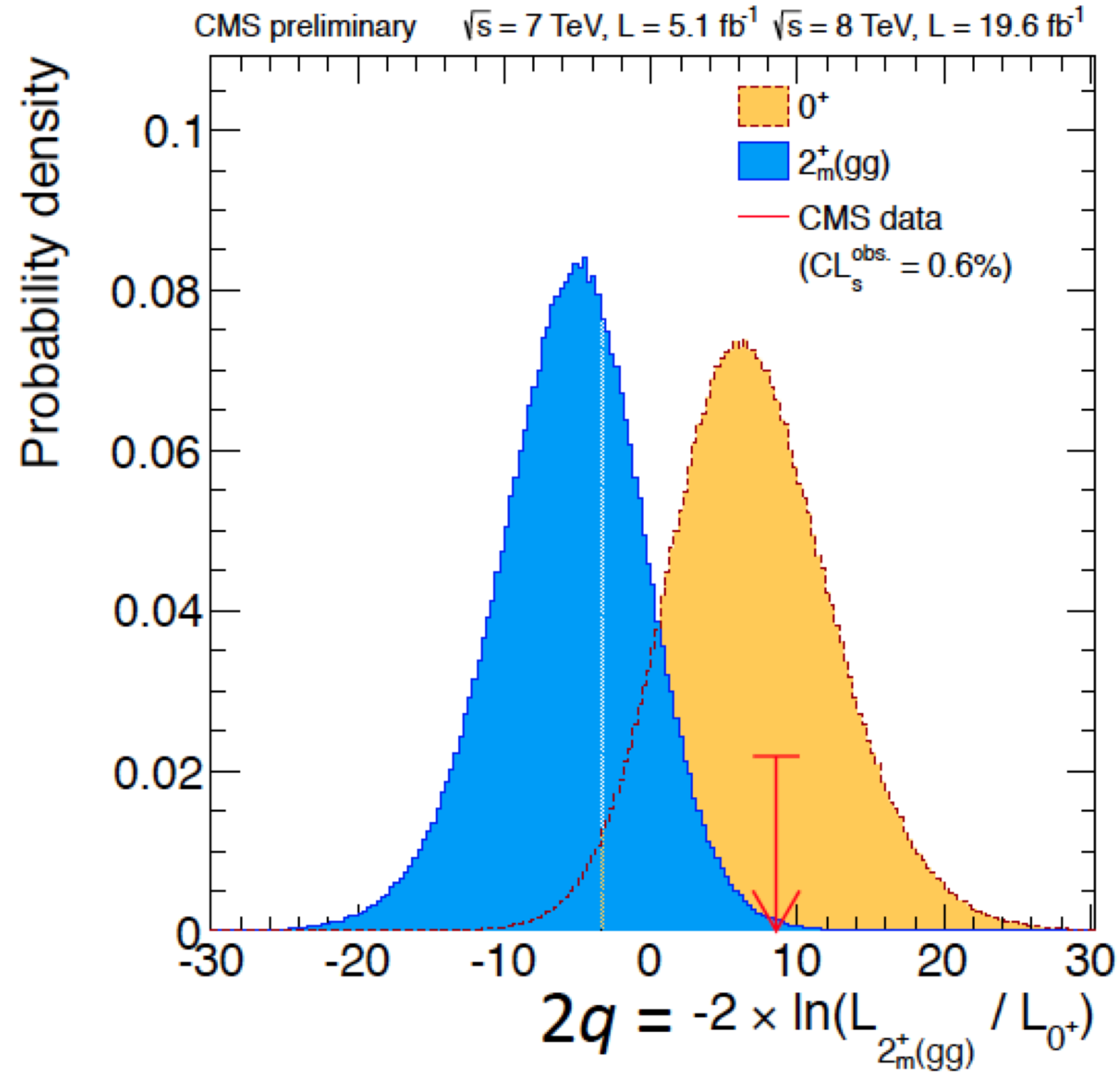
and

$$dN / d\cos\vartheta^* = 1 + 6\cos^2\vartheta^* + \cos^4\vartheta^* (q\bar{q} - production)$$

- Five scenarios corresponding to different admixtures of the production modes are considered. The discrimination between the spin hypotheses is enhanced when the spin-2 particle is produced predominantly via gluon fusion.

0^+ vs 2^+ Results





$$CMS - CombinedExclusion(ZZ^*, WW^*) : 2^+(100\% gg) 99.4\% CL (expected 98.8\%)$$

$$ATLAS - CombinedExclusion(\gamma\gamma, ZZ^*, WW^*) : 2^+(100\% gg) 99.9\% CL (expected 99.9\%)$$

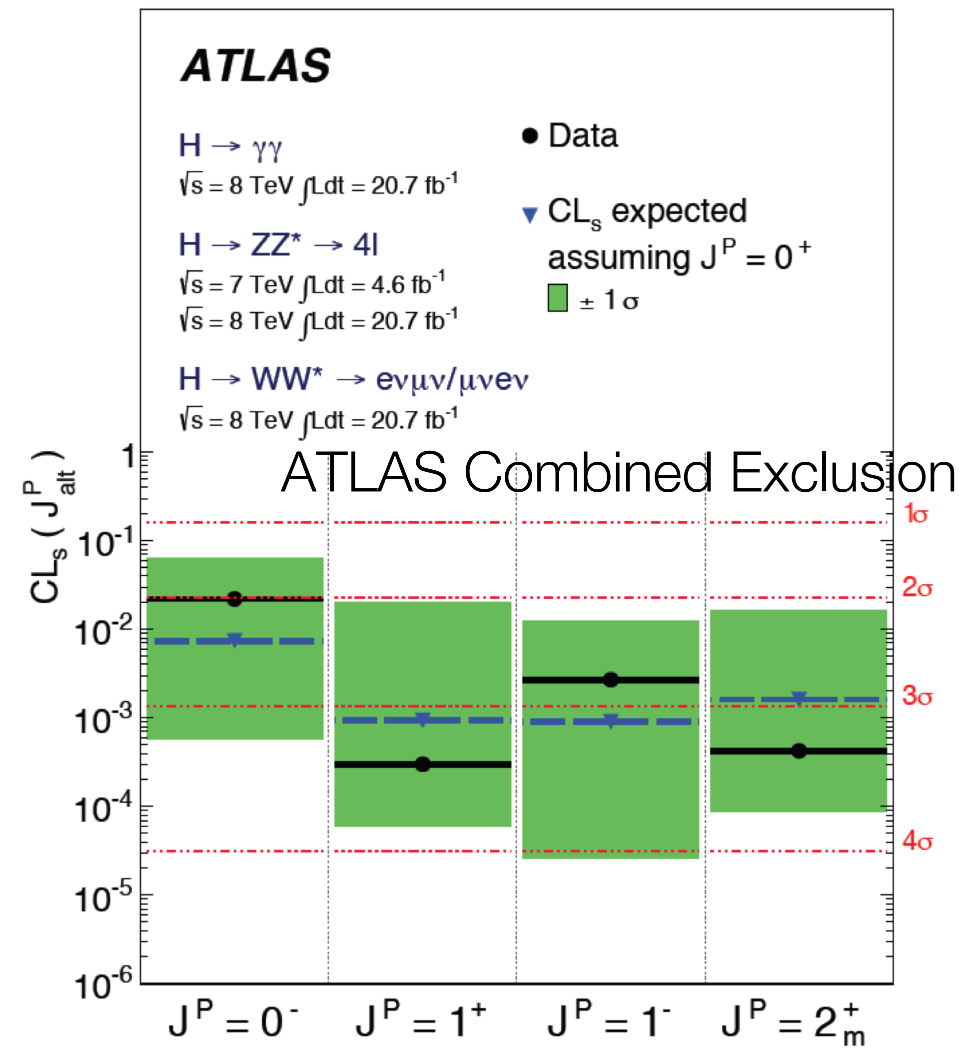
$$ATLAS - CombinedExclusion(\gamma\gamma, ZZ^*, WW^*) : 2^+(100\% q\bar{q}) 99.9\% CL (expected 99.9\%)$$

Summary of Spin Parity Results

CMS ZZ*(4ℓ)

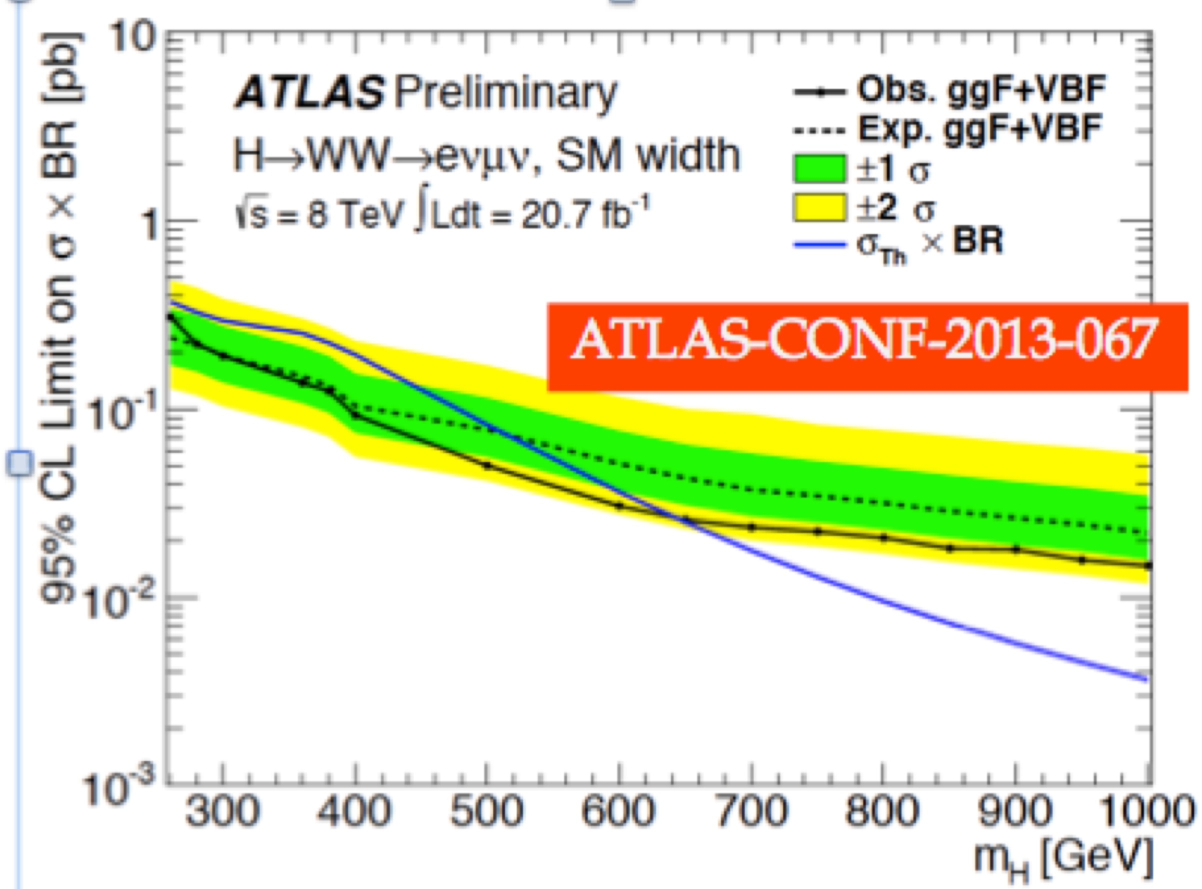
J^P	production	comment	expect (μ=1)	obs. 0^+	obs. J^P	CL_s
0^-	$gg \to X$	pseudoscalar	2.6σ (2.8σ)	0.5σ	3.3σ	0.16%
0_h^+	$gg \to X$	higher dim operators	1.7σ (1.8σ)	0.0σ	1.7σ	8.1%
2^+_{mgg}	$gg \to X$	minimal couplings	1.8σ (1.9σ)	0.8σ	2.7σ	1.5%
$2^+_{mq\bar{q}}$	$q\bar{q} \to X$	minimal couplings	1.7σ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

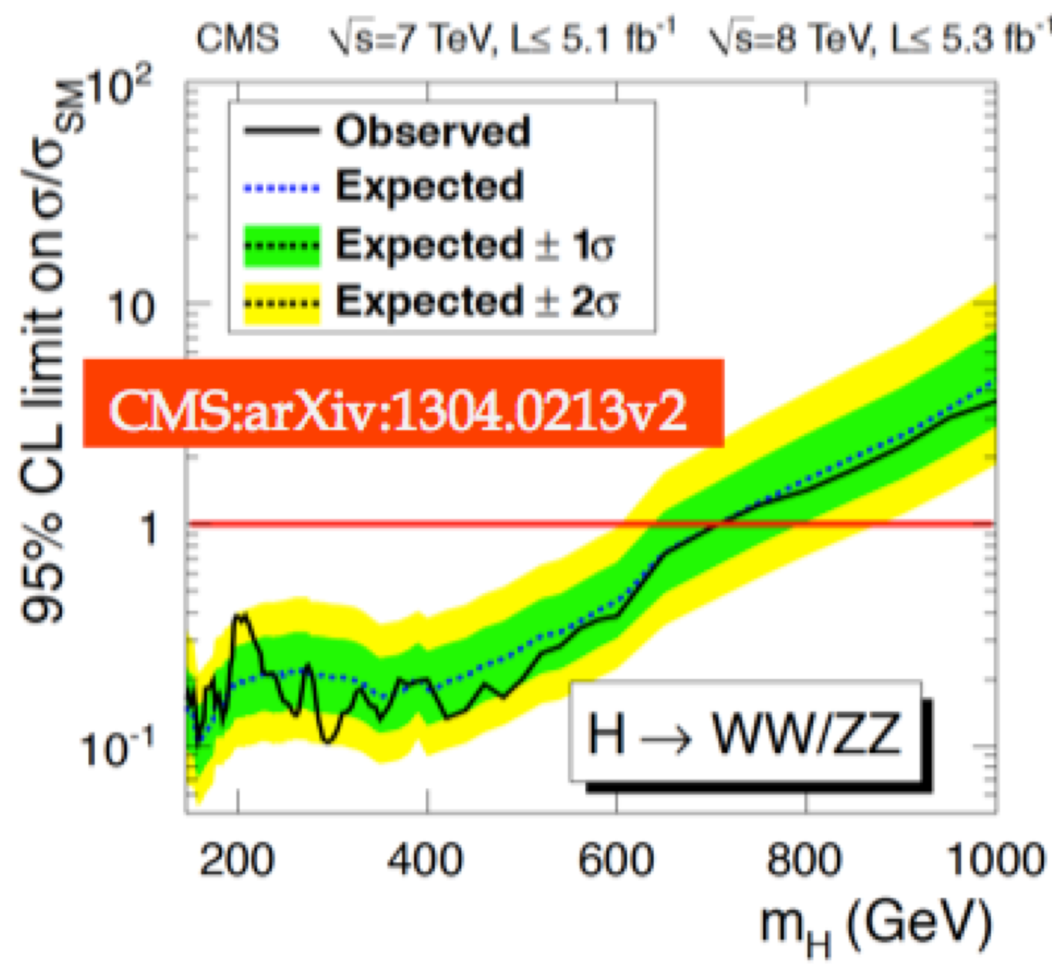
- Only bosonic decays used
- SM J^P quantum numbers strongly preferred wrt other assumptions
- Specific models excluded at more than 95%CL



From SM to BSM. High Mass Higgs

The most popular extension of the SM is SUSY. In this model there are 5 Higgs bosons, the lightest of which has the same behaviour of the unique SM Higgs.



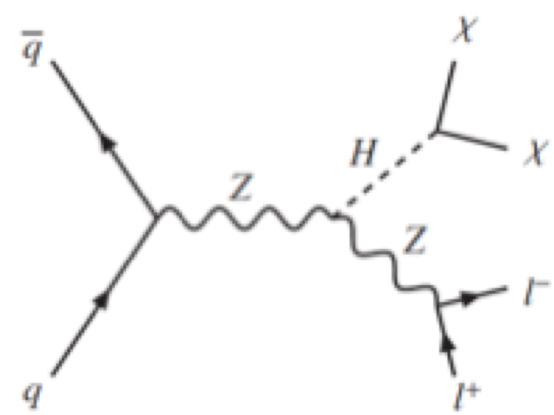


Finding one or more Higgs bosons at high mass would be an indication of something beyond SM. ATLAS and CMS have both, unsuccesfully done so.

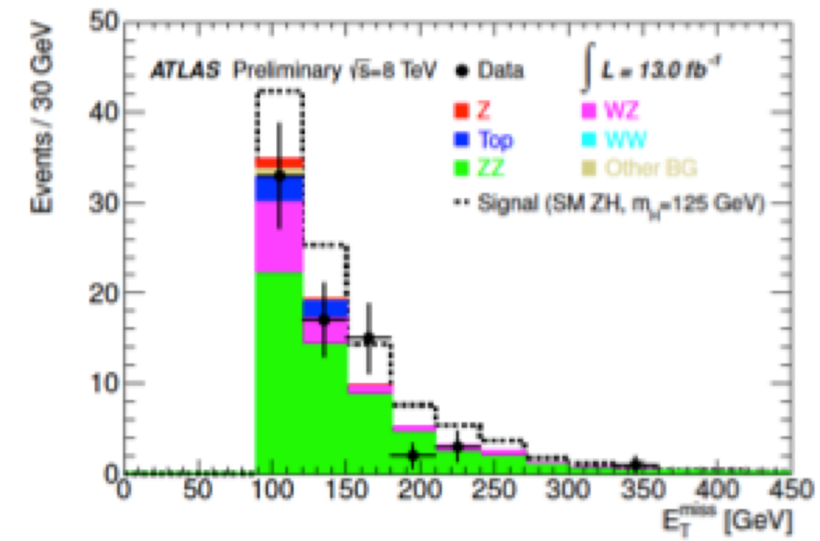
95% CL UL σxBR CMS: $145<M_H<710$, ATLAS $260<M_H<640$

From SM to BSM. Invisible Higgs decays

Another approach to some evidence of New Physics would be looking for invisible decays of the Higgs. There might be a contribution from dark particles as predicted by SUSY. Again search was, so far, unsuccesful.



100% decay to invisible particles



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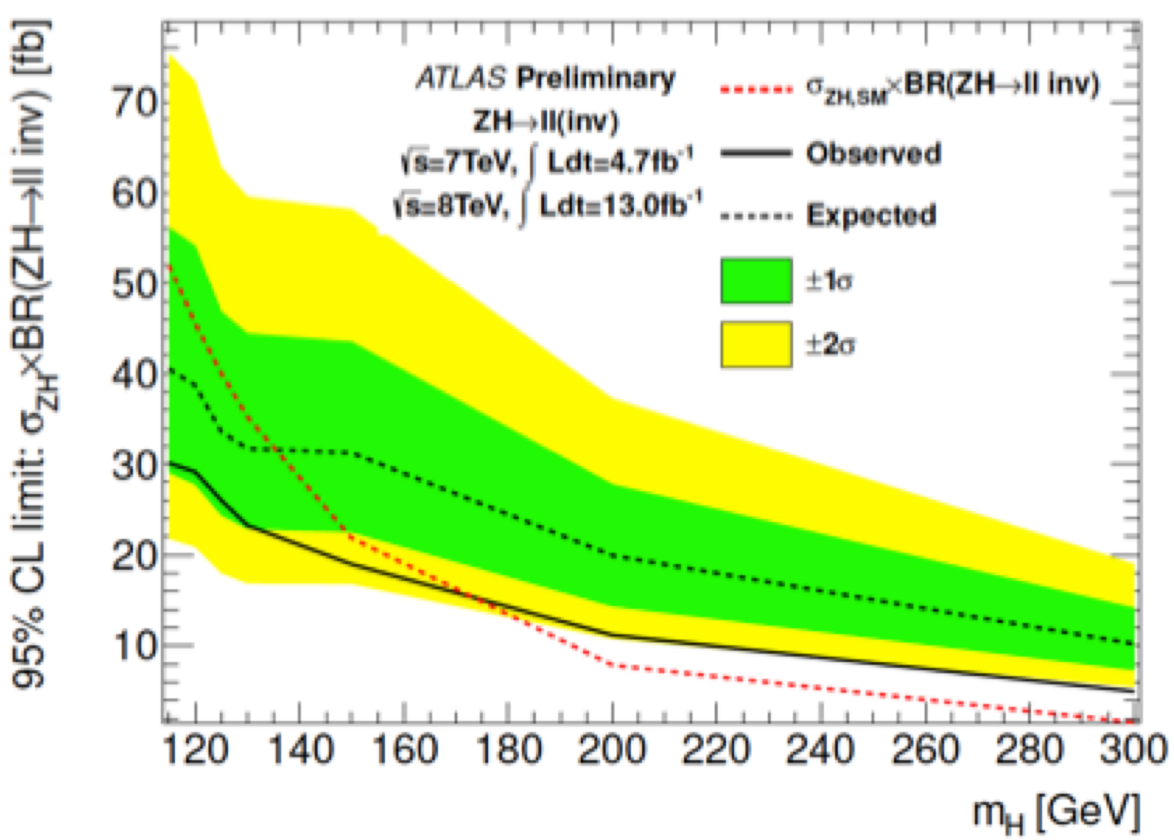

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