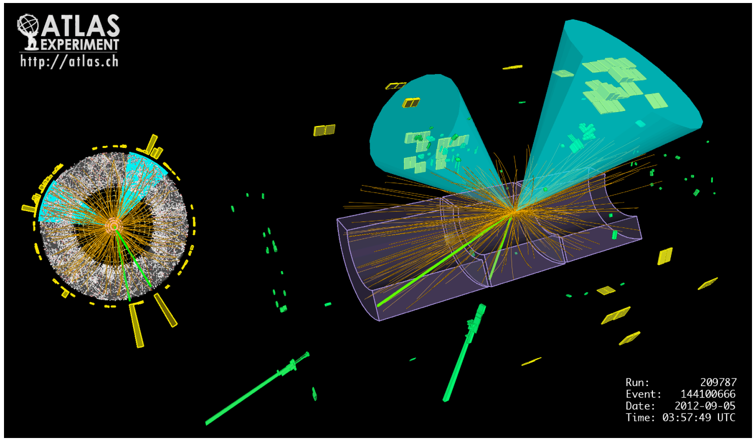
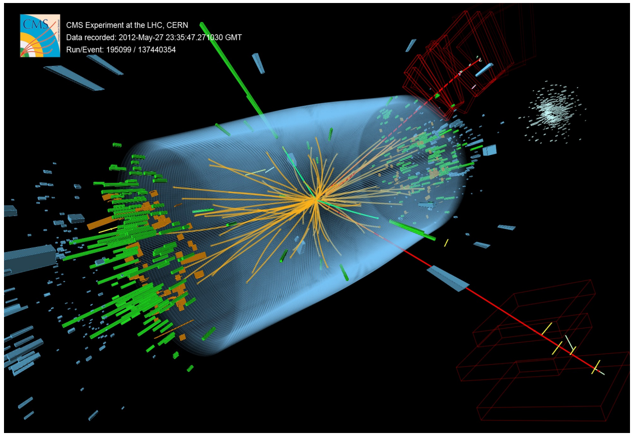




Higgs Results from LHC: ATLAS and CMS

Toni Baroncelli - INFN Sezione Roma TRE

On the behalf of ATLAS and CMS Collaborations

Outline of the talk

- Introduction
- Higgs production and decay

- Properties
  - Mass measurements
  - Spin – Parity determination
  - Coupligs
  - (Differential cross-sections in $\gamma\gamma$ final states)
  - Search for Physics beyond SM
- Conclusions

Bibliography

ATLAS: http://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults
CMS: http://cms.web.cern.ch/org/cms–papers–and–results

- Phys.Lett. B 716 (Discovery)
- arXiv:1307.1432 Sub. Phys.Lett. B (Spin)
- arXiv:1307.1427 Sub. Phys.Lett. B (Couplings)
- ATLAS-CONF 2013-014 (Mass combination)
- 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,H to bb)
- ATLAS–CONF 2013-072 (H to $\gamma\gamma$, diff σ)
- ATLAS–PHYS-PUB 2012-001/002 (HL-LHC)

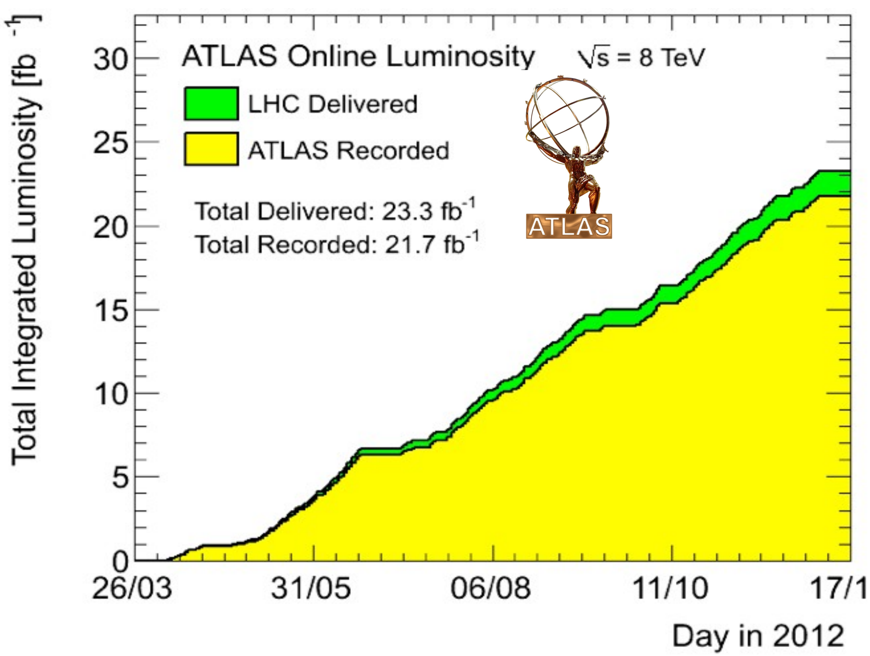
- Phys. Le] . B 716 (Discovery)
- arXiv:1212.6639 – Phys. Rev. Lett. 110 (ZZ*, Spin)
- CSM–PAS–HIG–13–016 (Properties $\gamma\gamma$)
- CMS–PAS–HIG–13–018 (ZH, Z invisible)
- CMS–PAS–HIG–13–005 (Mass,Couplings)
- CMS–PAS–HIG–13–012 (H to bb)
- CMS–PAS–HIG–13–001 ($\gamma\gamma$)
- CMS–PAS–HIG–13–002 (ZZ*, Spin)
- CMS–PAS–HIG–13–003 (WW*)
- CMS–PAS–HIG–13–004 ($\tau\tau$)
- CMS–NOTE–2012–006 (HL-LHC)

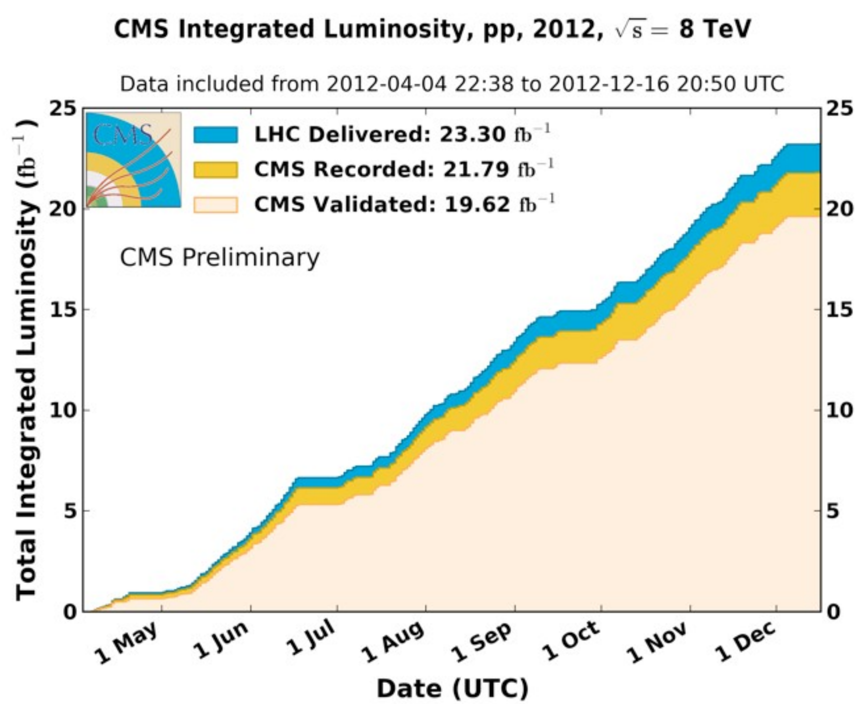
- **LHC – XS Higgs wg:**
- http://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections
  - arXiv:1307.1347 (Yellow Report 3: σ, BR and coupling and spin/CP fit-models models)

LHC data

Excellent machine and detector performance resulted in large amount of data with very high quality: ~95% of delivered data are recorded, and ~90% of those are certified and used in physics publications!

About 5+20 fb^{-1} of good quality data (2011+2012) used by both Collaborations



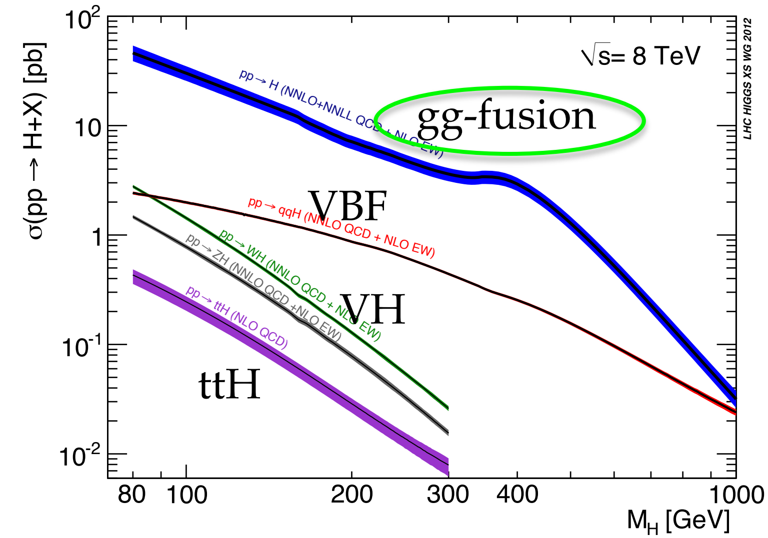


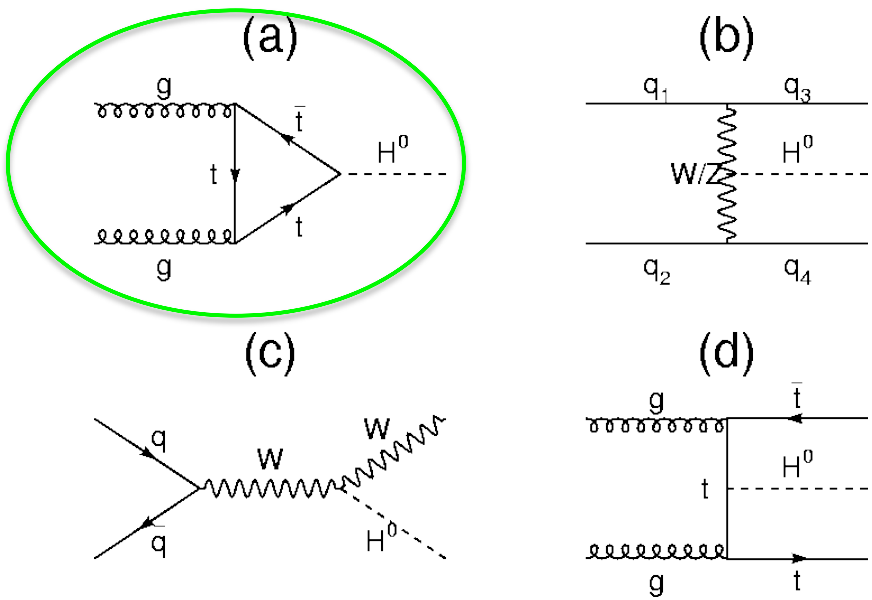
Higgs Boson Production

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

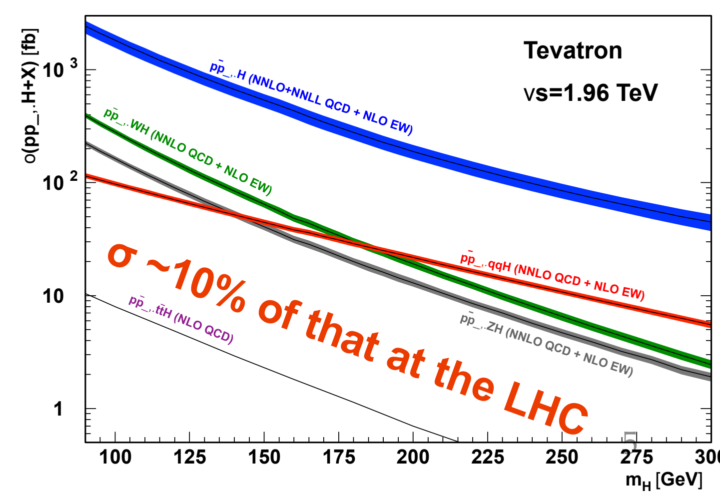
The following four mechanisms can be tested at the LHC and the Tevatron:

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





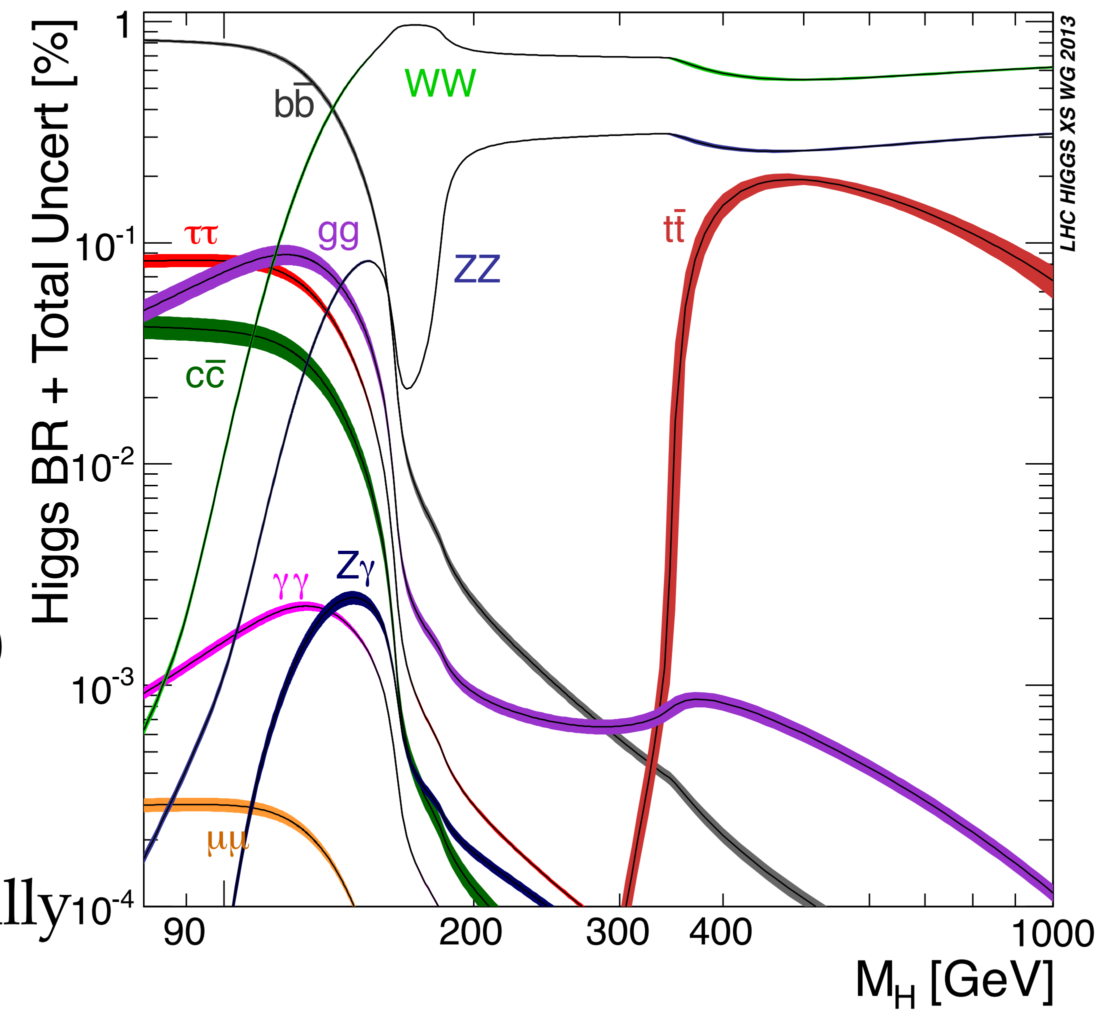
Baglio, Djouadi
JHEP 10 (2010) 064



Higgs Boson Decay

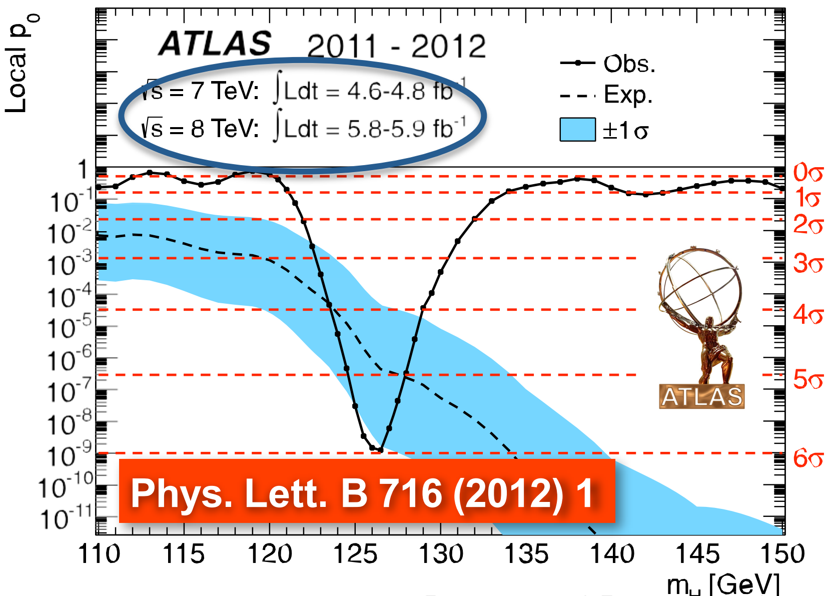
According to the SM for a M_H~125 GeV:

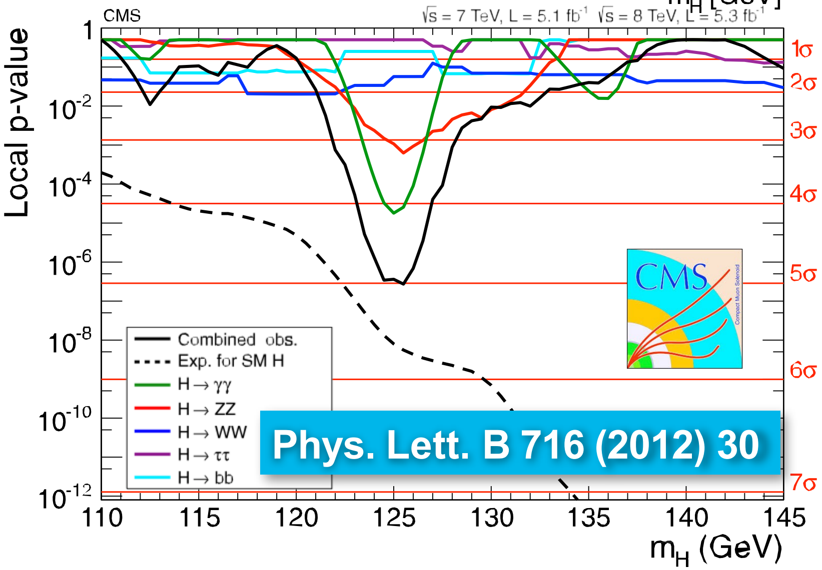
- H(bb) – 57% (hard)
- H(WW) - 22%
- H($\tau\tau$) - 6.2%
- H(ZZ) - 2.8% (easy)
- H($\gamma\gamma$) - 0.23% (easy)

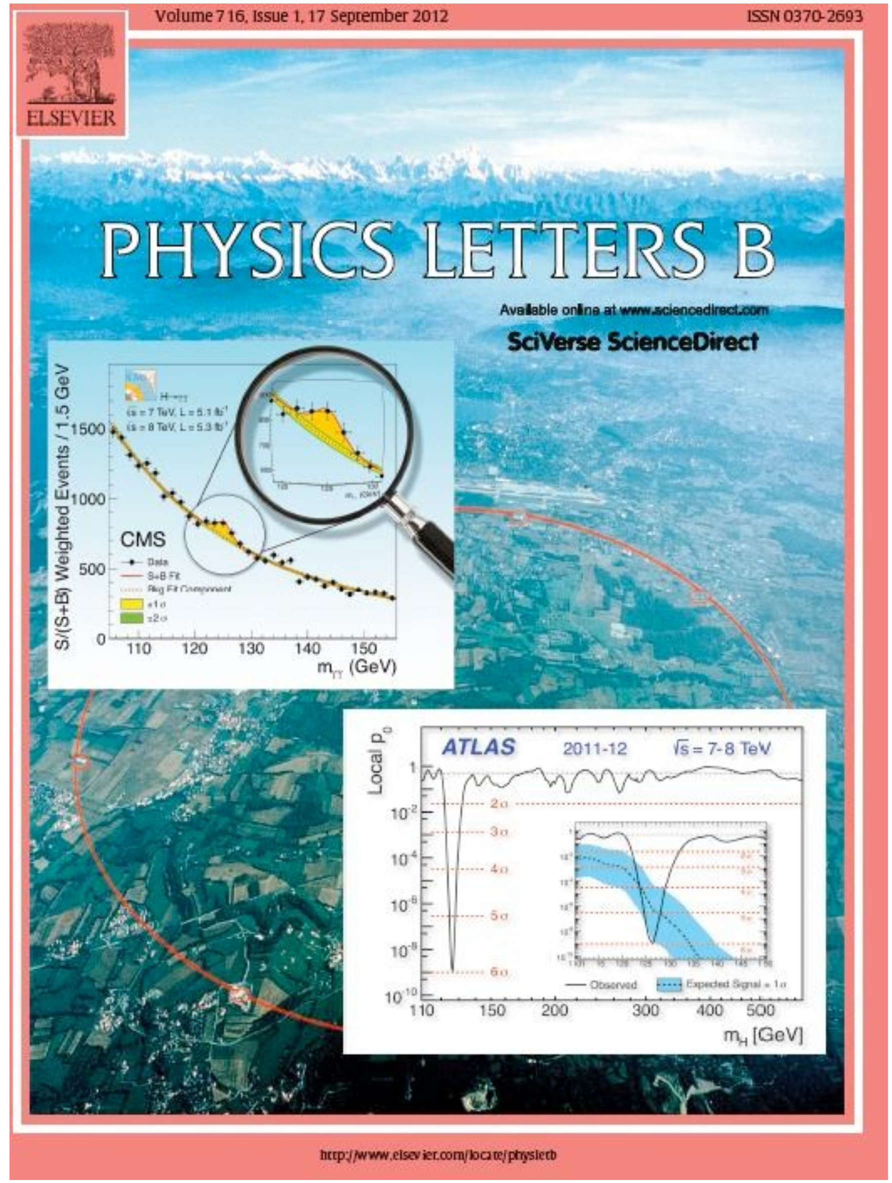


This means that several channels are experimentally accessible!

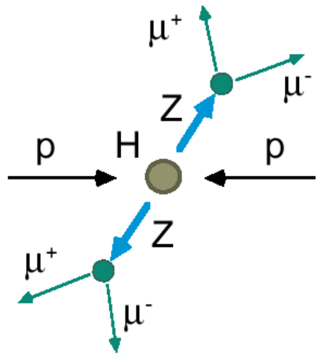
Higgs Boson Discovery







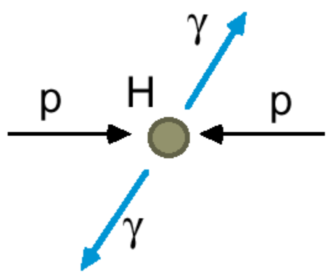
Distinguishing Different Final States



Higgs to ZZ to 4l

Selection cuts: isolated leptons within $|\eta| < 2.5$, $P_{T(1,2)} > 20$ GeV and $P_{T\,(3,4)} > 7$ GeV, one lepton pair around Z mass.

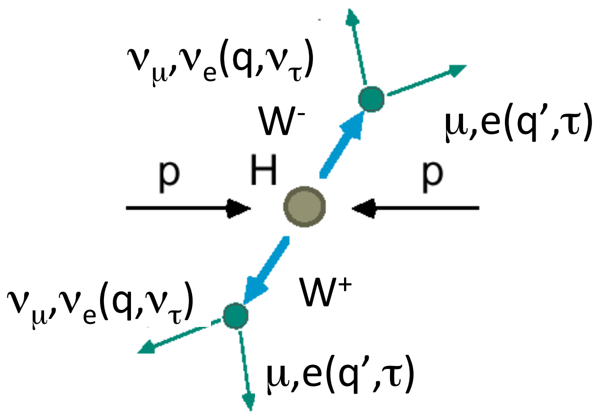
Backgrounds: continuum production $(Z^{(*)}/\gamma)$ $(Z^{(*)}/\gamma)$ which includes the single resonance **Z to 4l**, referred to as **ZZ**$^{(*)}$



Higgs to γγ

Selection cuts: isolated photons within $|\eta| < 2.5$, $P_{T(1,2)} >$ 40,30 GeV and 100 GeV$<m_{\gamma\gamma}<$160 GeV. Narrow resonance on continuous background.

Backgrounds: 2γ-production, γ-jet and dijet production



Higgs to WW

Selection cuts: 2 high energy OS isolated leptons. Missing energy, (MET), no b-jet, Z-mass veto, 3rd lepton veto small $\Delta\phi$(l1,l2)

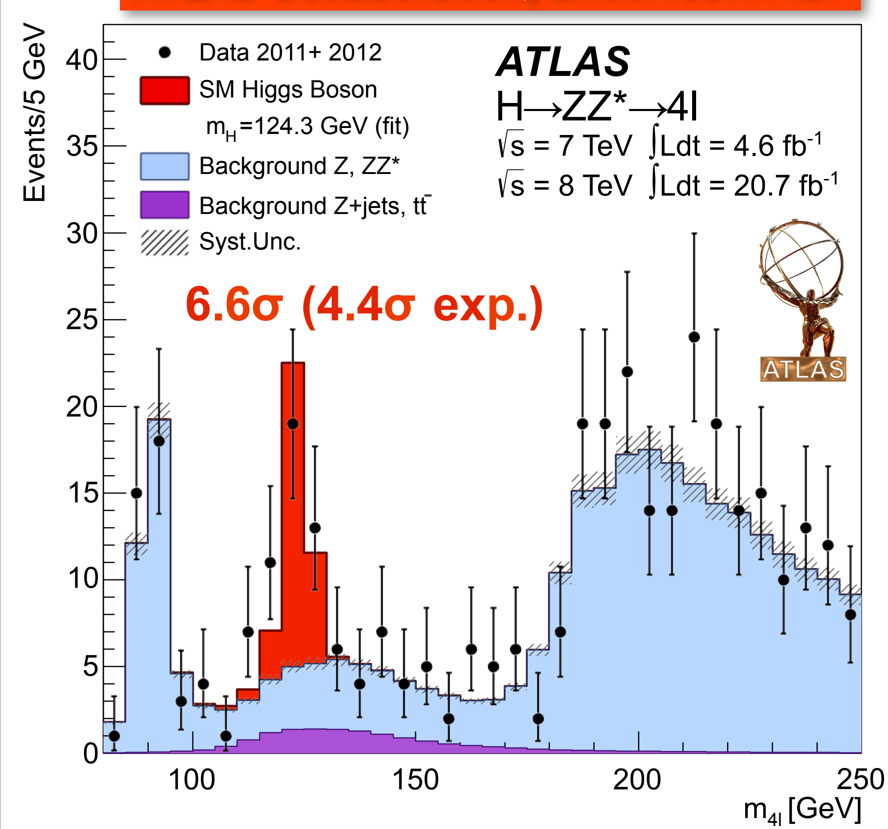
Backgrounds:QCD multijet, W+jets, WW, WZ

Higgs to 4 Leptons

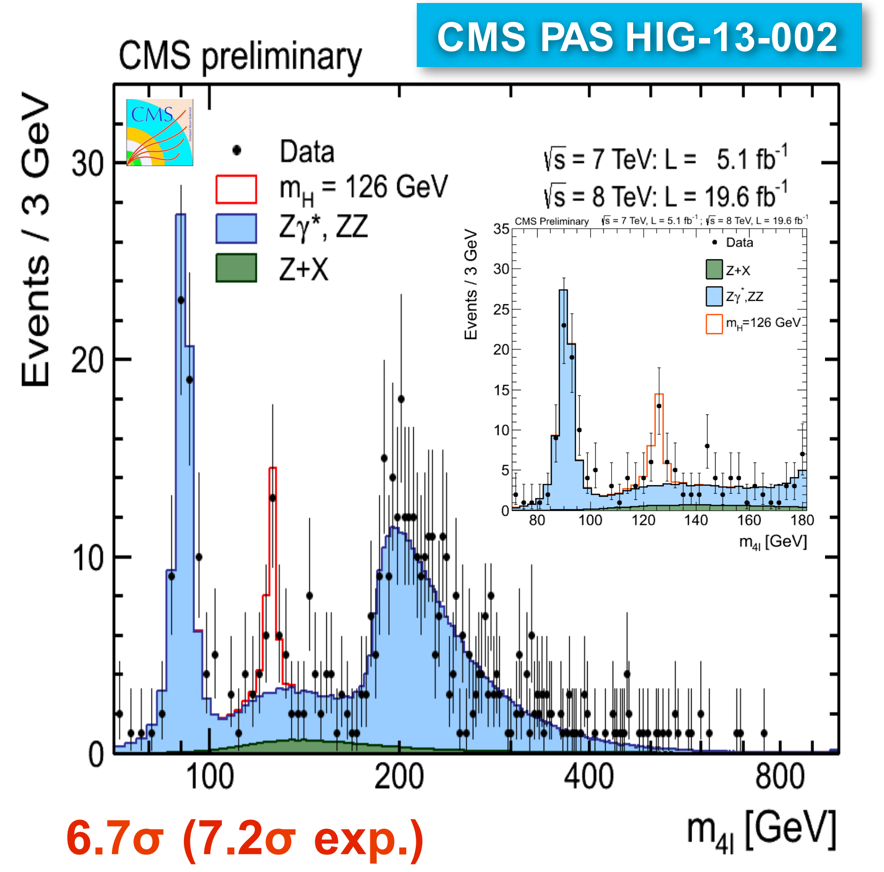
Most sensitive, high-resolution channel for a 125 GeV Higgs

- ATLAS: Cut-in-categories, FSR accounting, untagged + VBF+ VH
- CMS: MELA (angular analysis), FSR recovery, untagged + VBF

ATLAS Collaboration, arXiv:1307.1427

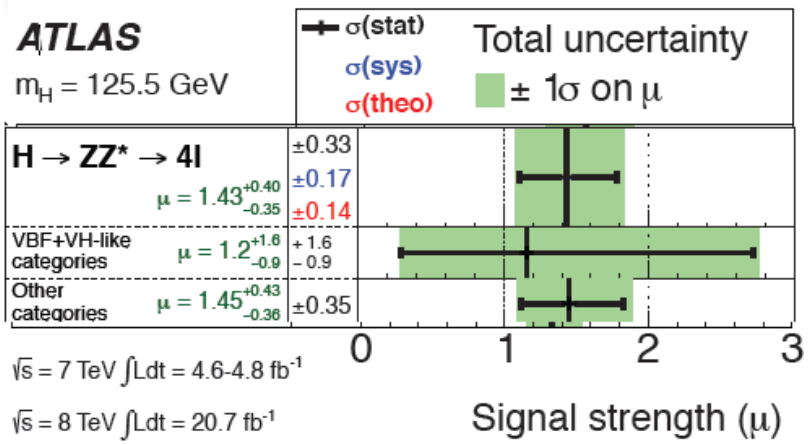


CMS PAS HIG-13-002

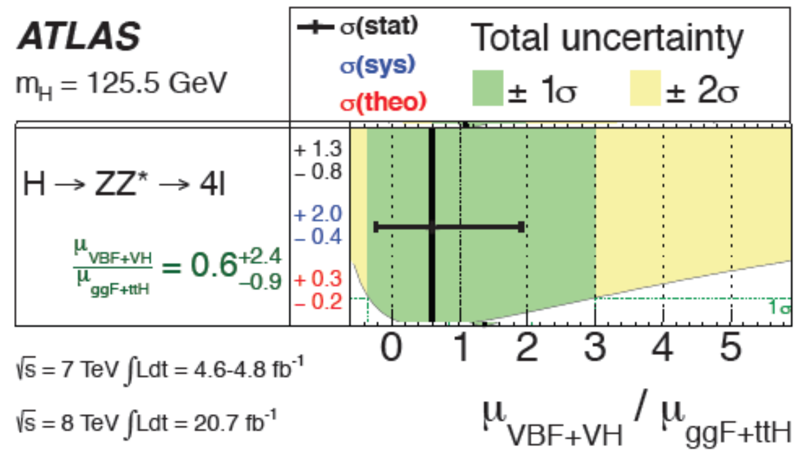


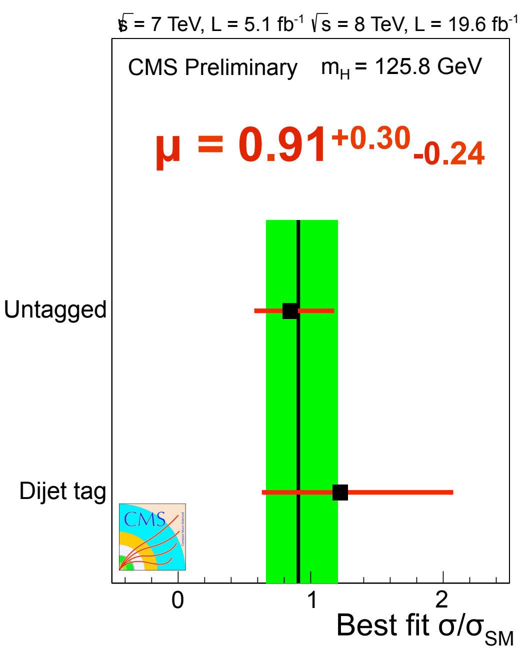
Higgs to 4 Leptons : Results

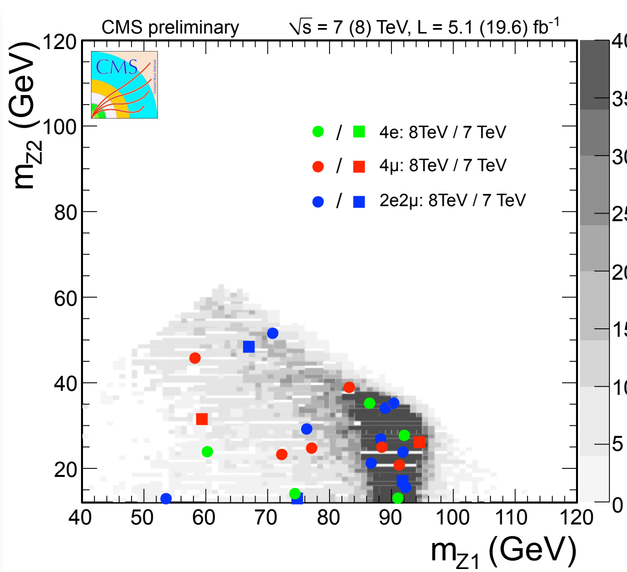
ATLAS Collaboration, arXiv:1307.1427

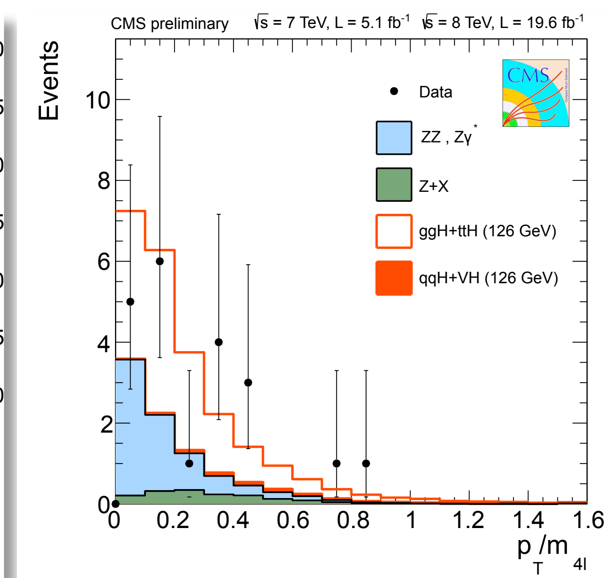


$m_H = 124.3^{+0.6}_{-0.5}{}^{+0.5}_{-0.3}$ GeV







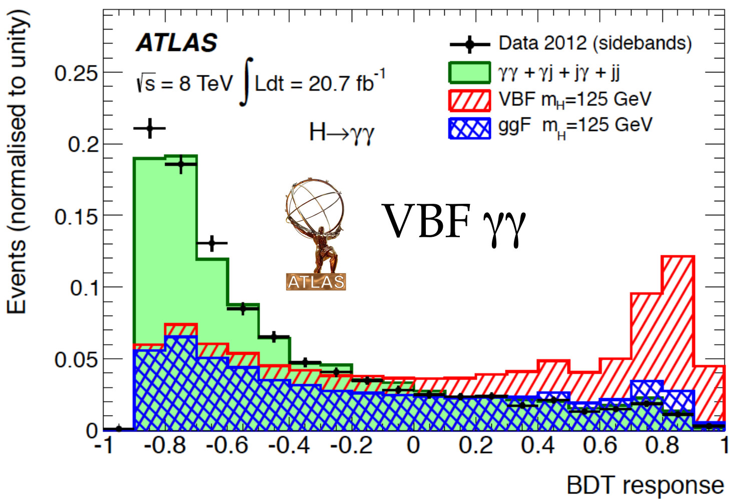


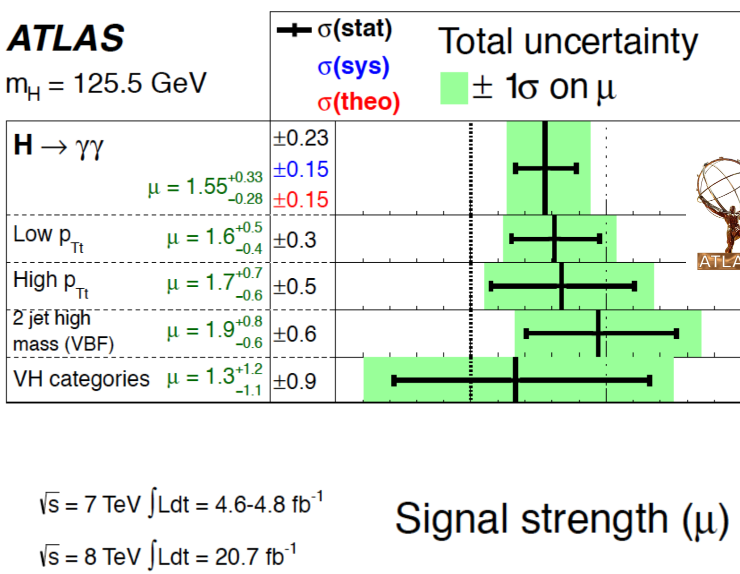
CMS PAS HIG-13-002

m_H = 125.8 ± 0.5 ± 0.2 GeV

Higgs to γγ: ATLAS Results

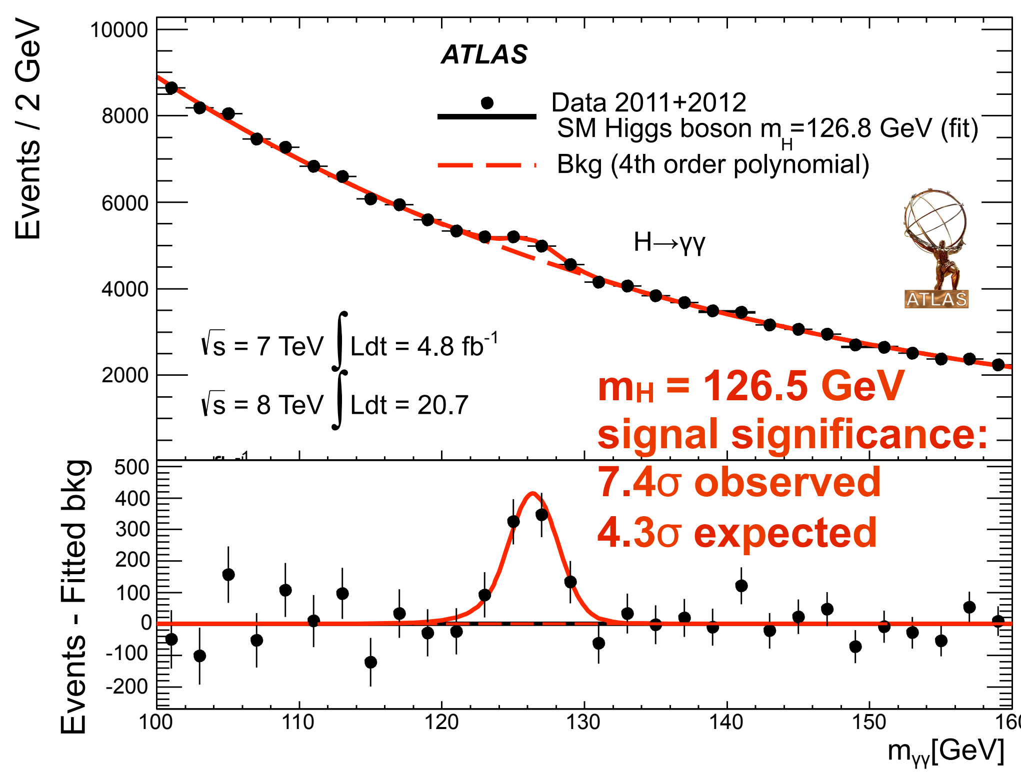
ATLAS Collaboration, arXiv:1307.1427





m_H = 126.8 ± 0.2 ± 0.7 GeV

Category	N_D	N_B	N_S	ggF	VBF	WH	ZH	ttH
Untagged	14248	13582	350	320	19	7.0	4.2	1.0
Loose high-mass two-jet	41	28	5.0	2.3	2.7	< 0.1	< 0.1	< 0.1
Tight high-mass two-jet	23	13	7.7	1.8	5.9	< 0.1	< 0.1	< 0.1
Low-mass two-jet	19	21	3.1	1.5	< 0.1	0.92	0.54	< 0.1
E_T^{miss} significance	8	4	1.2	< 0.1	< 0.1	0.43	0.57	0.14
Lepton	20	12	2.7	< 0.1	< 0.1	1.7	0.41	0.50
All categories (inclusive)	13931	13205	370	330	27	10	5.8	1.7



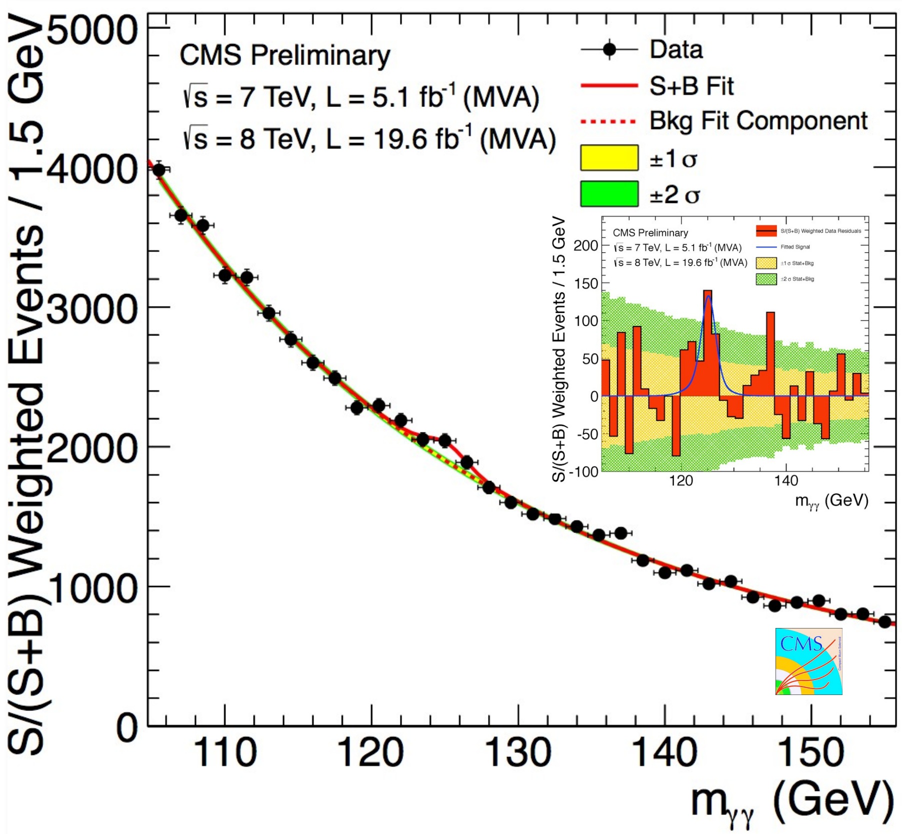
Higgs to γγ: CMS Results - 1

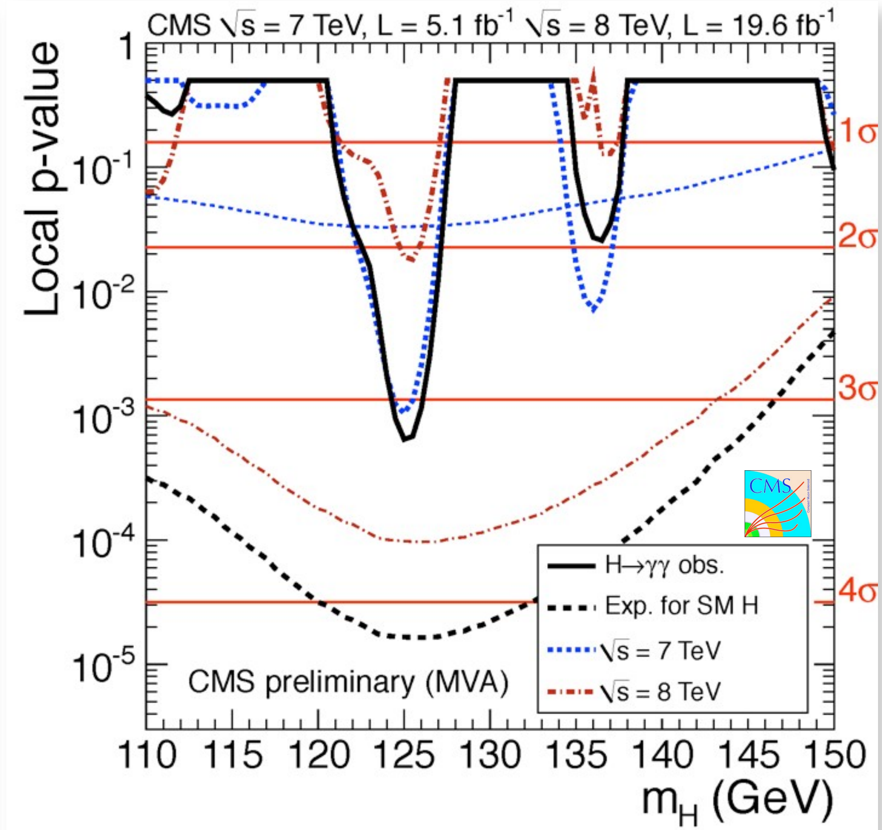
Main analysis: MVA; cross-check: cut-in-categories (CiC)

- **Significances:**
  - MVA: 3.2σ (4.2σ expected)
  - CiC: 3.9σ (3.5σ expected)
- **Mass: 125.4 ± 0.8 GeV**

μ-values:

	MVA analysis (at m_H=125 GeV)	cut-based analysis (at m_H=124.5 GeV)
7 TeV	$1.69^{+0.65}_{-0.59}$	$2.27^{+0.80}_{-0.74}$
8 TeV	$0.55^{+0.29}_{-0.27}$	$0.93^{+0.34}_{-0.32}$
7 + 8 TeV	$0.78^{+0.28}_{-0.26}$	$1.11^{+0.32}_{-0.30}$



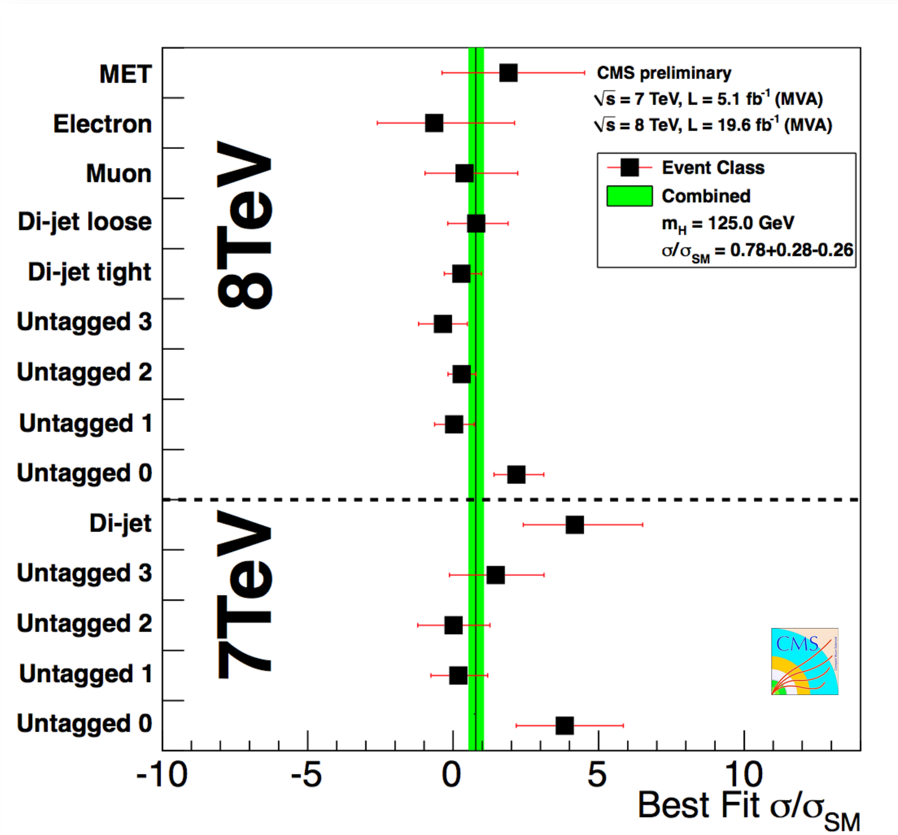


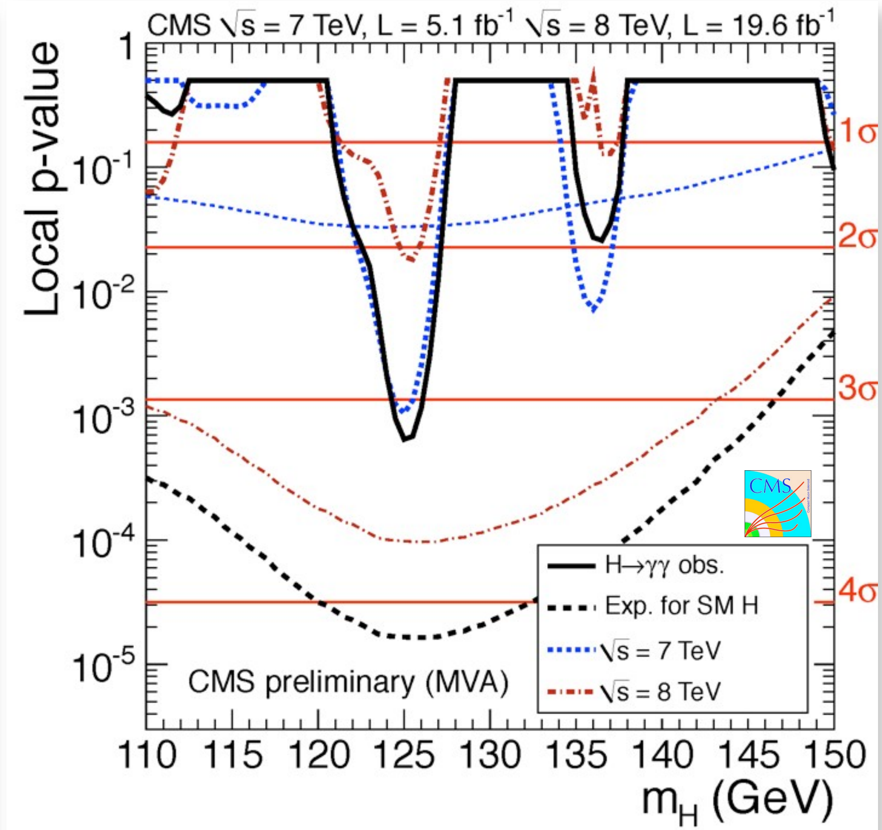
Higgs to γγ: CMS Results - 2

- Main analysis: MVA; cross-check: cut-in-categories (CiC)
  - Significances:
    - MVA: 3.2σ (4.2σ expected)
    - CiC: 3.9σ (3.5σ expected)
  - Mass: **125.4 ± 0.8 GeV**

μ-values:

	MVA analysis (at m_H=125 GeV)	cut-based analysis (at m_H=124.5 GeV)
7 TeV	$1.69^{+0.65}_{-0.59}$	$2.27^{+0.80}_{-0.74}$
8 TeV	$0.55^{+0.29}_{-0.27}$	$0.93^{+0.34}_{-0.32}$
7 + 8 TeV	$0.78^{+0.28}_{-0.26}$	$1.11^{+0.32}_{-0.30}$





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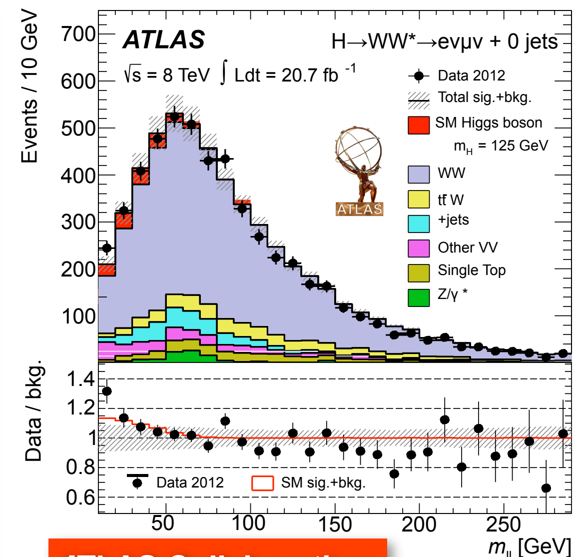
Higgs to WW to 2 Leptons and 2 Neutrinos

High-yield, low-resolution channel

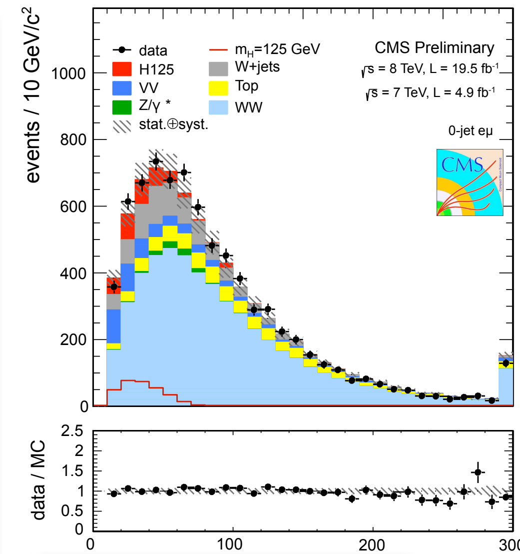
Most discriminating variables: M_{ll} and M_T (dilepton transverse mass) Search done in 0-, 1-, and 2-jet categories; in the ee, eμ, and μμ channels

ATLAS: fit to the M_T distribution

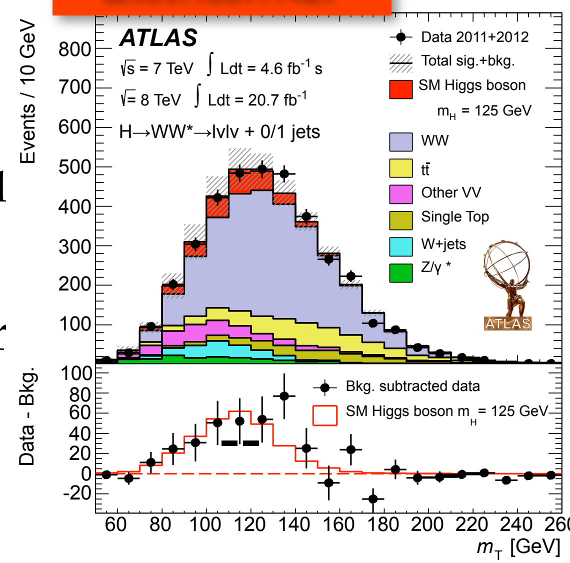
CMS: 2D analysis in M_{ll} vs M_T for the eμ channel and cut-based analysis for the same-flavor channels (also as a cross-check in eμ)

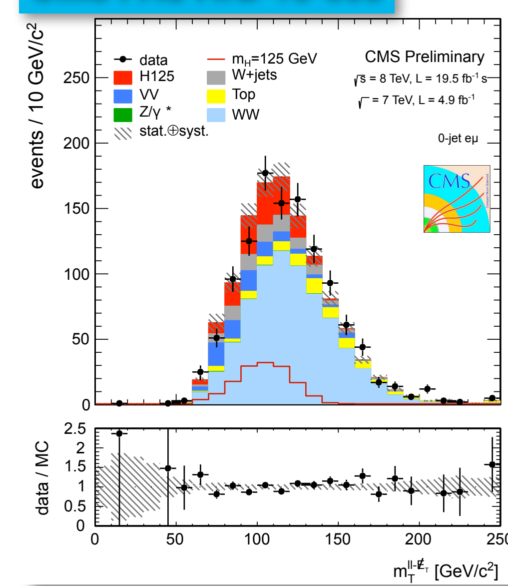


ATLAS Collaboration arXiv:1307.1427



CMS PAS HIG-13-003

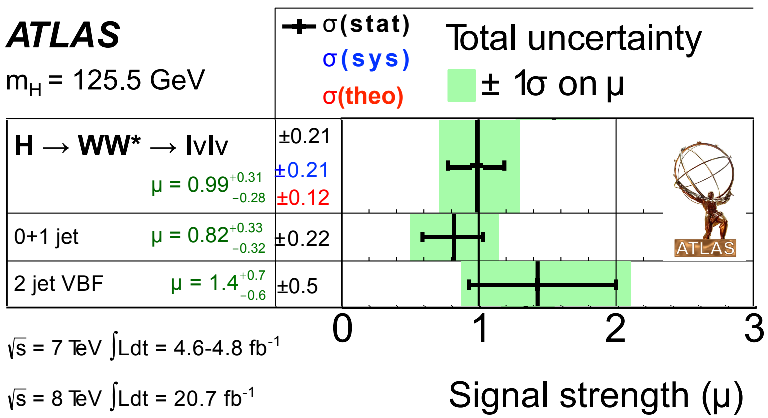


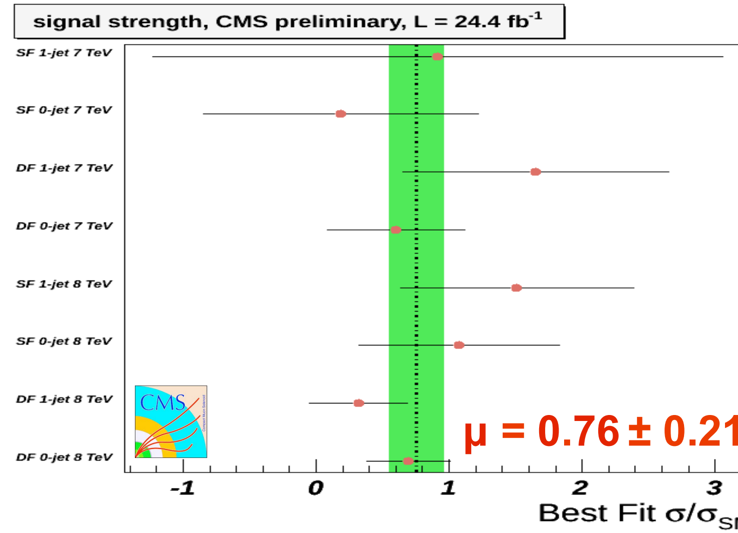


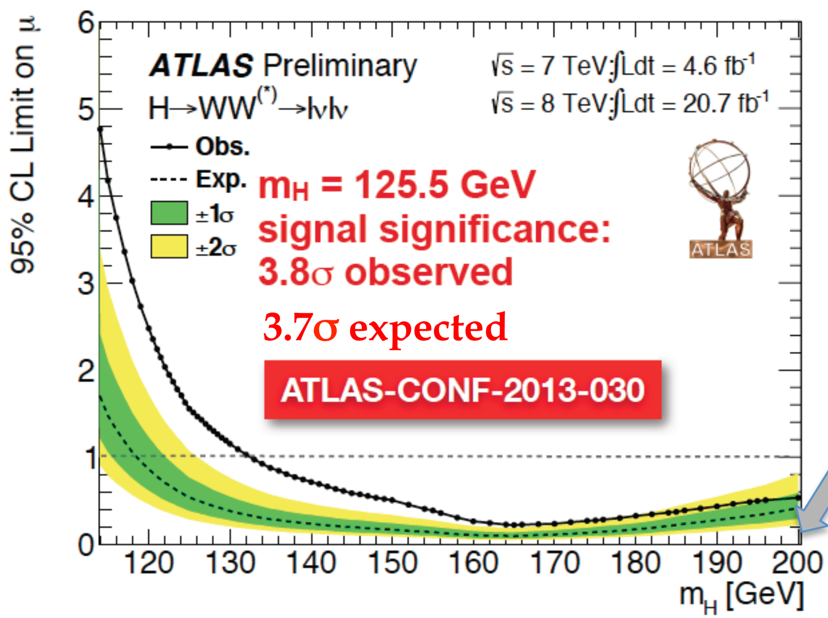
Higgs to WW to lνlν

◆ Significant excess is observed:

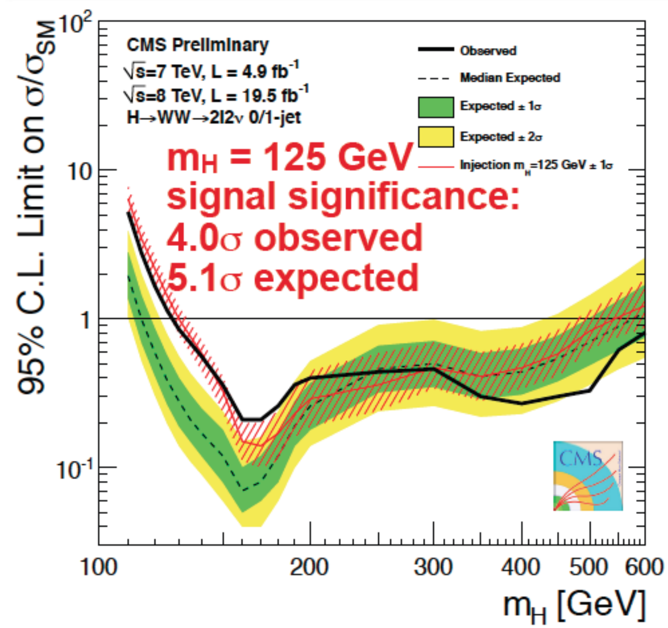
ATLAS Collaboration
arXiv:1307.1427







More later on !



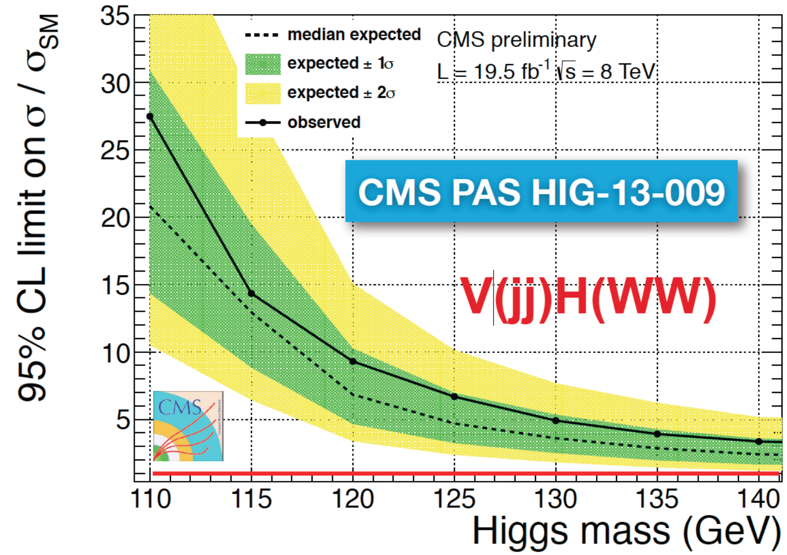
CMS PAS HIG-13-003

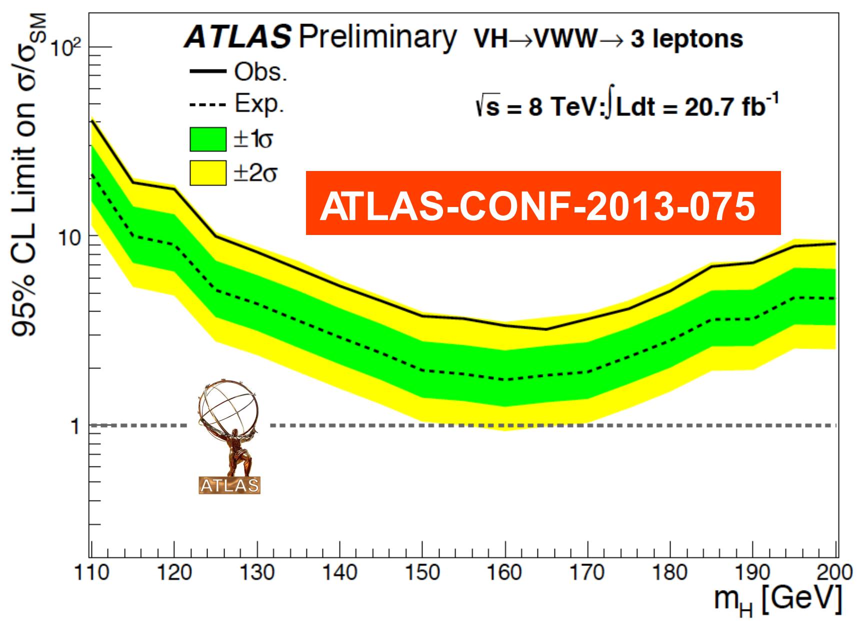
INFN ROMA Tre

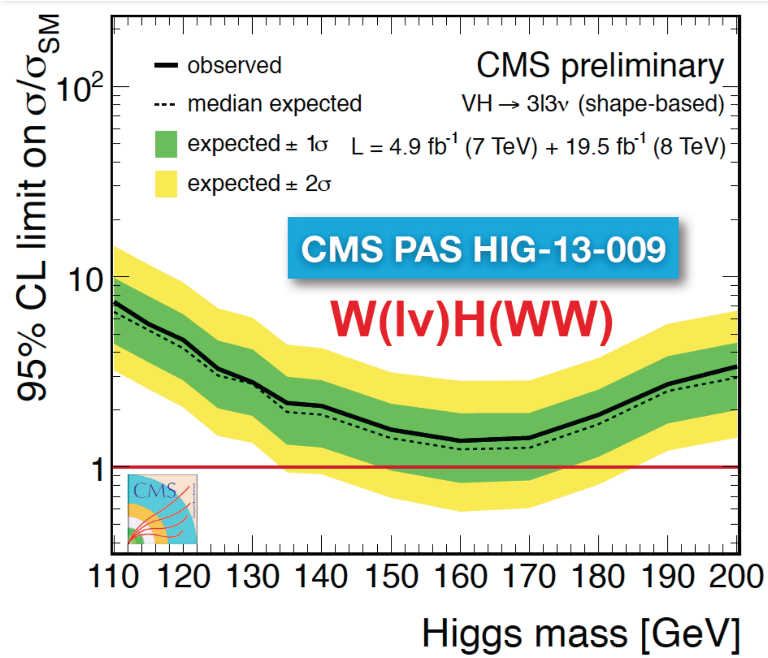
Associate Production VH(WW)

VH(WW) is an important test of the Higgs nature. It has been studied in 3-lepton (ATLAS+CMS), 4-lepton (ATLAS), and lljj (CMS) final states

ATLAS: combination with the H(WW) analysis: gives 4.0 σ (3.8 σ exp.) significance at m_H = 125 GeV

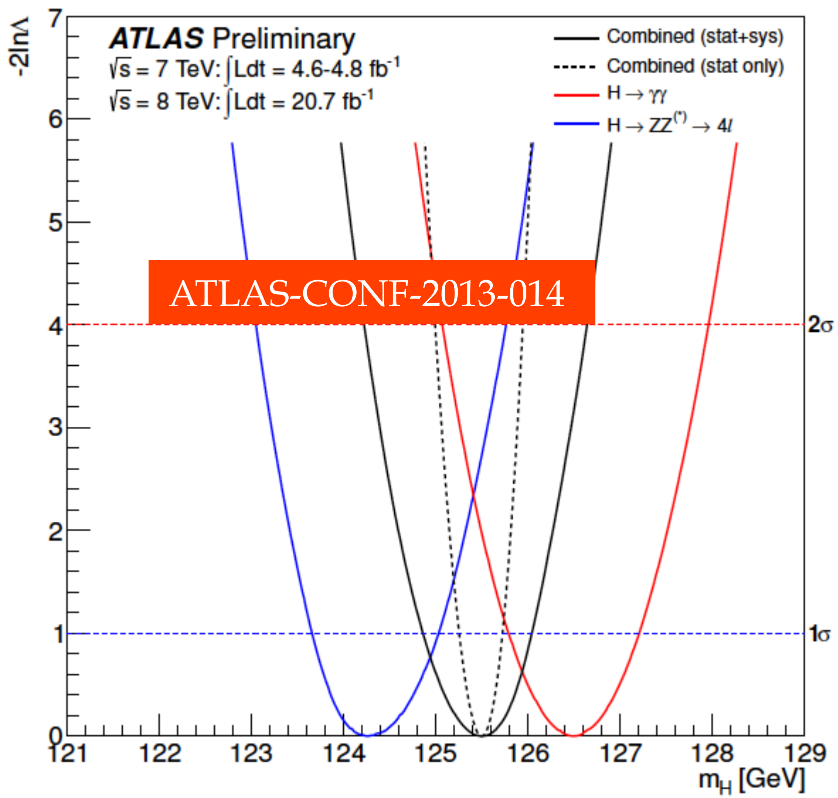




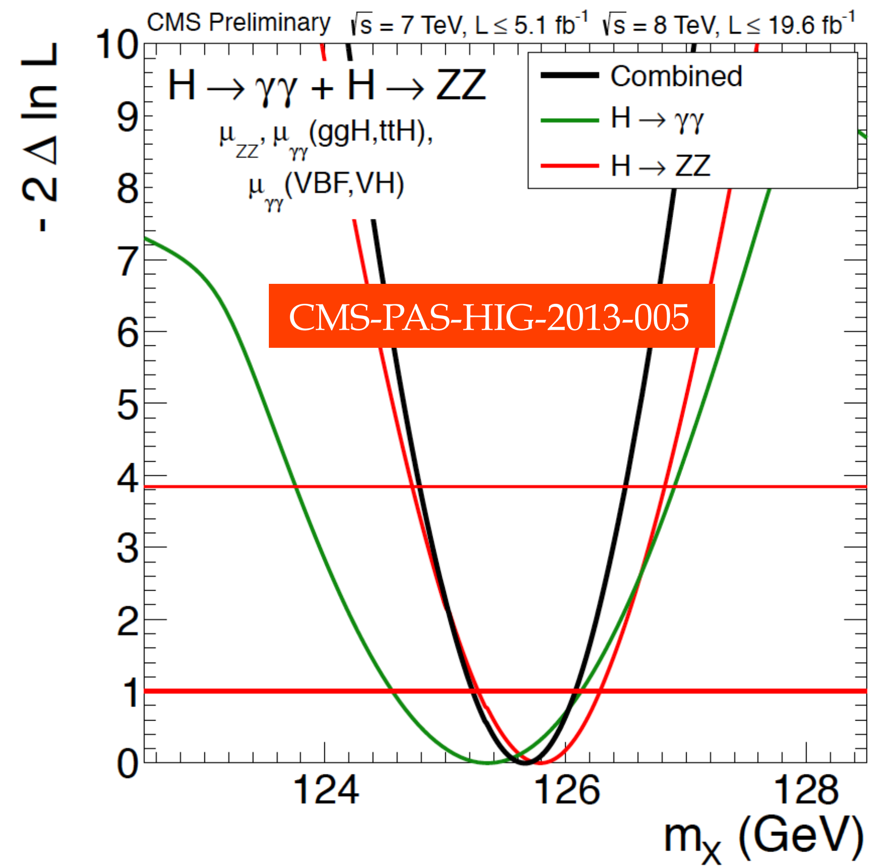


Higgs Mass Measurement

Measured from γγ and ZZ*(4l) mass spectra: needed to predict σxBR



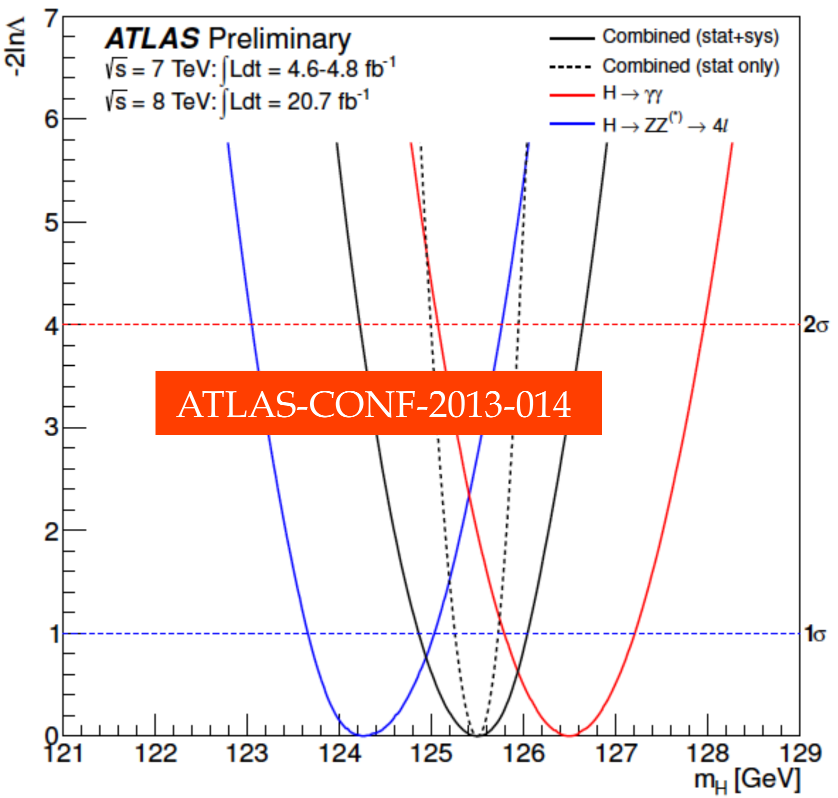
$$ATLAS : M_H = 125.5 \pm 0.2_{stat} \pm 0.6_{syst} GeV$$



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

$$From - \gamma\gamma : \Gamma_H < 6.9 GeV @ 95\% CL (direct)$$

Any tension between ZZ and γγ mass measurements?



$$\Delta M_H = 2.3 \pm 0.7_{stat} \pm 0.6_{sys}\ \text{GeV}$$
$$= 2.3 \pm 0.9_{tot}$$

Probability to observe such a large (or larger) difference if $\Delta M_H = 0$ evaluated at 1.5% (2.4σ)

If main systematics on EM energy scale shifted by 1σ the probability increases to 8%

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

Spin – Parity Determination (SM 0^+)

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

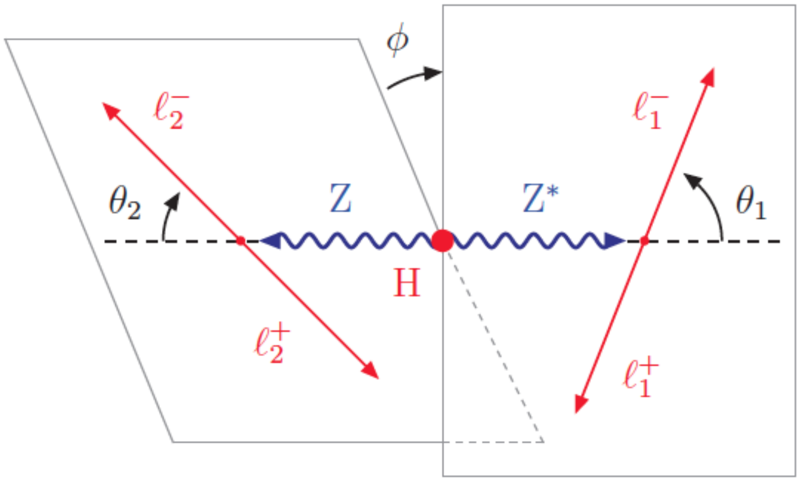
Spin - Parity

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

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

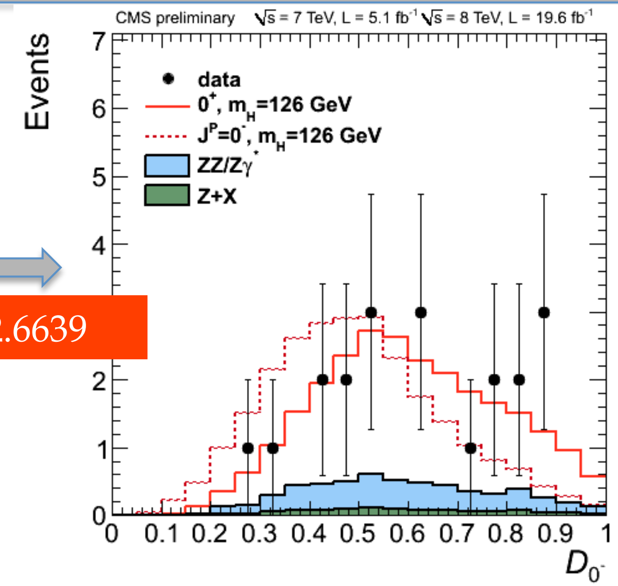
Several observables of H to WW* to $l\nu l\nu$ are sensitive to J^P: $\Delta\phi_{ll}$, M_{ll}, .. Combined with Boosted-Decision-Tree (BDT) technique

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}



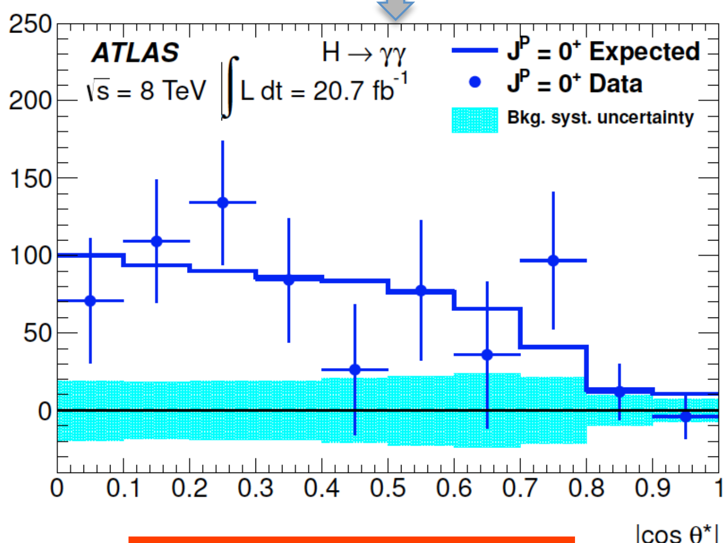
Spin – Parity, 0^+ vs 0^-

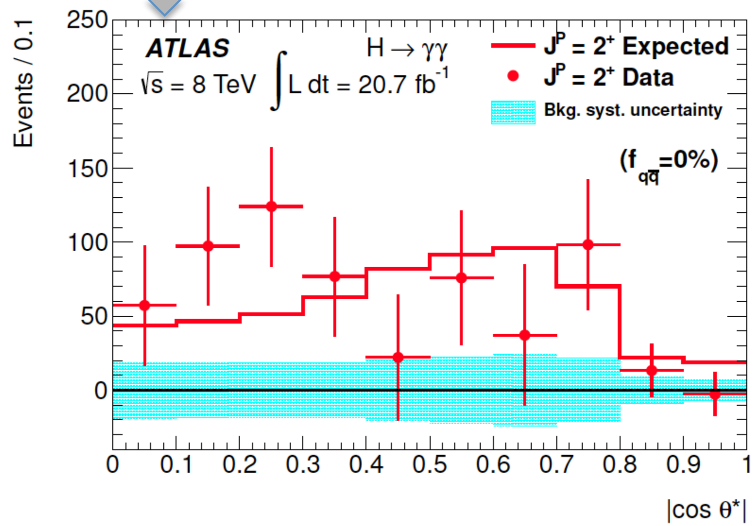
CMS 2 masses and 5 angles in H to ZZ* decay combined in a BDT output D_{JP}.



CMS:arXiv:1212.6639

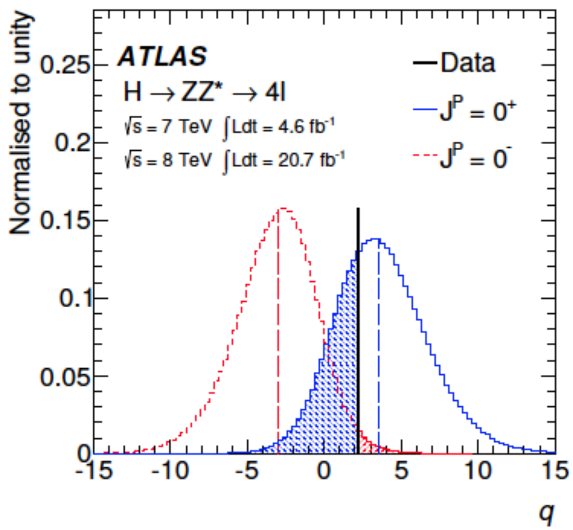
ATLAS: cos(Θ*) in H to γγ decay compared to 0^+ 2^+ distributions.

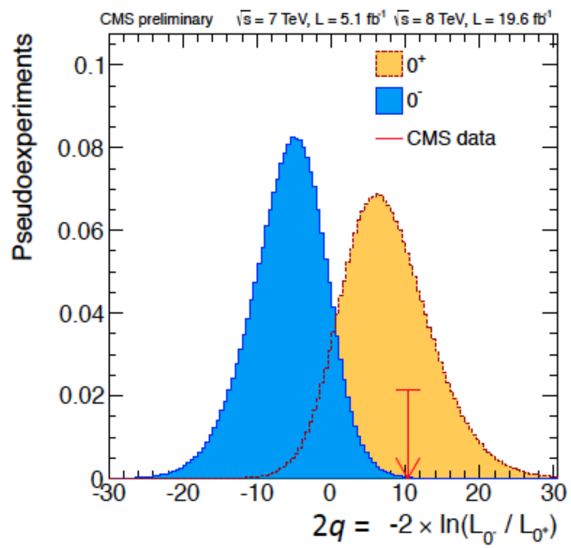


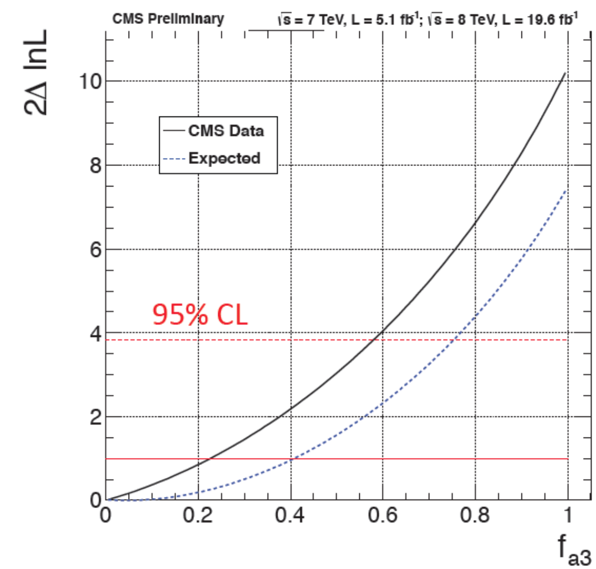


ATLAS-CONF-2013-040

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

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

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

INFN ROMA Tre

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

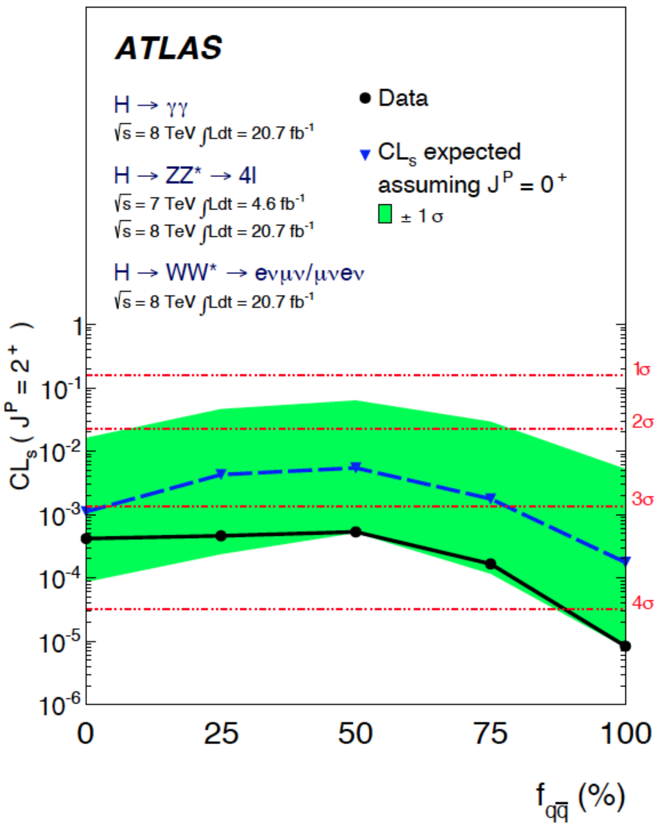
$$dN / d\cos\vartheta^* = 1 - \cos^4\vartheta^* \,(gluon - gluon - fusion)$$

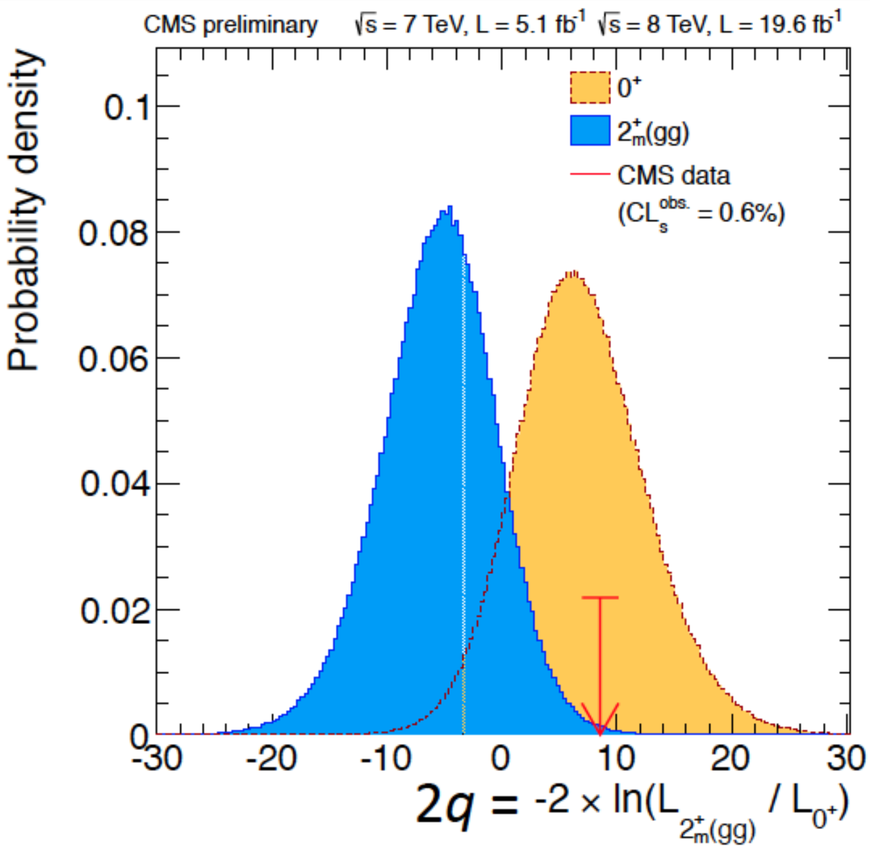
and

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

- 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





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

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

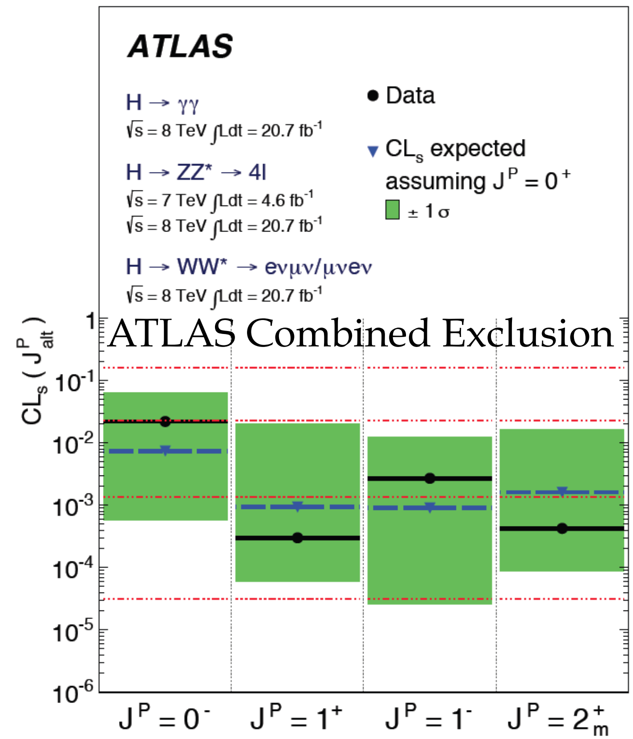
$$ATLAS - CombinedExclusion(\gamma\gamma, ZZ^*, WW^*): 2^+(100\% q\bar{q}) 99.9\% CL (expected\ 99.9\%)$$

Summary of Spin Parity Results

CMS ZZ*(4ℓ)

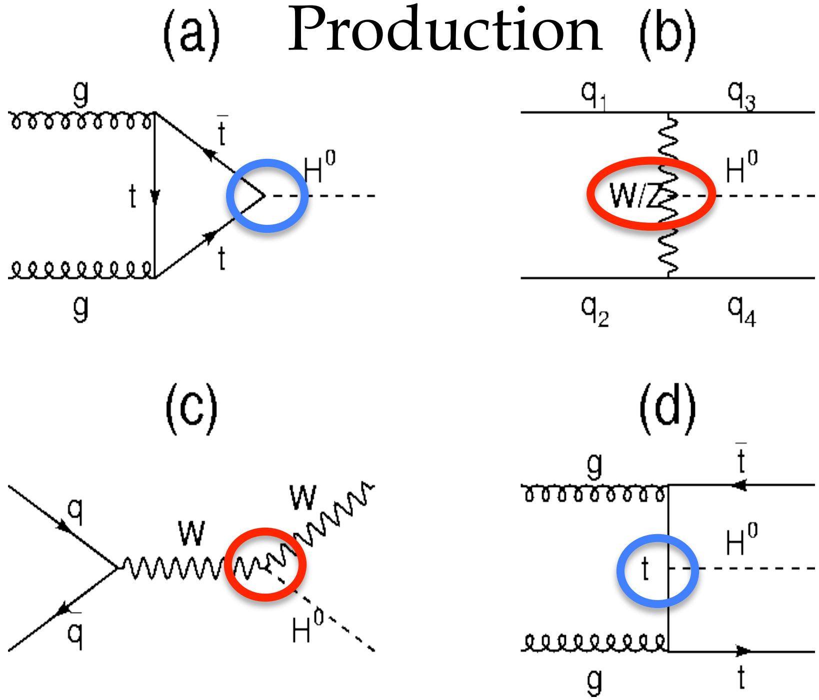
J^P	production	comment	expect (μ=1)	obs. 0^+	obs. J^P	CL_s
0^-	$gg \to X$	pseudoscalar	2.6σ (2.8σ)	0.5σ	3.3σ	0.16%
0_h^+	$gg \to X$	higher dim operators	1.7σ (1.8σ)	0.0σ	1.7σ	8.1%
2_{mgg}^+	$gg \to X$	minimal couplings	1.8σ (1.9σ)	0.8σ	2.7σ	1.5%
$2_{mq\bar{q}}^+$	$q\bar{q} \to X$	minimal couplings	1.7σ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



Effective Couplings: diagrams

Production

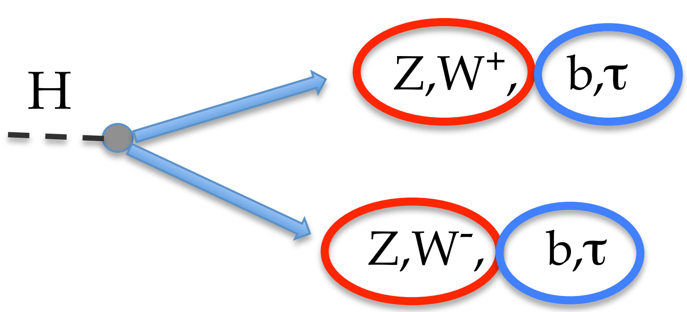


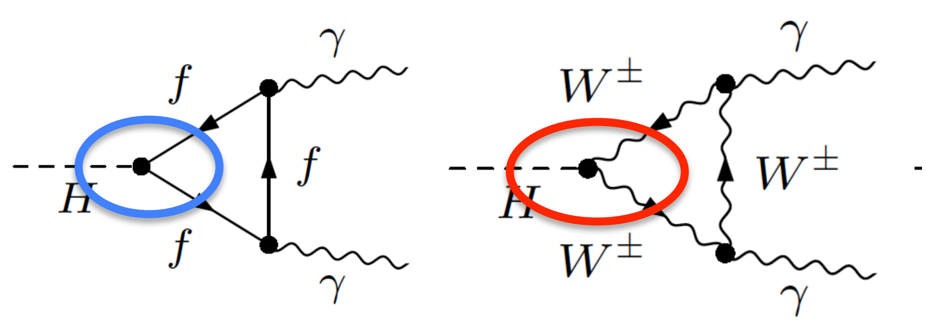
(a) gluon fusion (19 pb @8 TeV)
(b) VBF (WW or ZZ fusion)
(c) Associated production (VH)
(d) ttH production

Fermions

Bosons

Decay





Estimators of Effective Couplings

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

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

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

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}

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

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 $\lambda_{du}=k_d/k_u$ $\lambda_{WZ}=k_W/k_Z$

A bit of gymnastic (skip this slide)

$$
\begin{aligned}
\sigma(gg \to H) * \mathrm{BR}(H \to \gamma\gamma) &\sim \mu_{\mathrm{ggF}+t\bar{t}H;H\to\gamma\gamma} \\
\sigma(qq' \to qq'H) * \mathrm{BR}(H \to \gamma\gamma) &\sim \mu_{\mathrm{ggF}+t\bar{t}H;H\to\gamma\gamma} \cdot \mu_{\mathrm{VBF}+VH}/\mu_{\mathrm{ggF}+t\bar{t}H} \\
\sigma(gg \to H) * \mathrm{BR}(H \to ZZ^{(*)}) &\sim \mu_{\mathrm{ggF}+t\bar{t}H;H\to ZZ^{(*)}} \\
\sigma(qq' \to qq'H) * \mathrm{BR}(H \to ZZ^{(*)}) &\sim \mu_{\mathrm{ggF}+t\bar{t}H;H\to ZZ^{(*)}} \cdot \mu_{\mathrm{VBF}+VH}/\mu_{\mathrm{ggF}+t\bar{t}H} \\
\sigma(gg \to H) * \mathrm{BR}(H \to WW^{(*)}) &\sim \mu_{\mathrm{ggF}+t\bar{t}H;H\to WW^{(*)}} \\
\sigma(qq' \to qq'H) * \mathrm{BR}(H \to WW^{(*)}) &\sim \mu_{\mathrm{ggF}+t\bar{t}H;H\to WW^{(*)}} \cdot \mu_{\mathrm{VBF}+VH}/\mu_{\mathrm{ggF}+t\bar{t}H} \\
\sigma(gg \to H) * \mathrm{BR}(H \to \tau\tau) &\sim \mu_{\mathrm{ggF}+t\bar{t}H;H\to\tau\tau} \\
\sigma(qq' \to qq'H) * \mathrm{BR}(H \to \tau\tau) &\sim \mu_{\mathrm{ggF}+t\bar{t}H;H\to\tau\tau} \cdot \mu_{\mathrm{VBF}+VH}/\mu_{\mathrm{ggF}+t\bar{t}H}
\end{aligned} \tag{3}
$$

where $\mu_{\mathrm{ggF}+t\bar{t}H;H\to XX}$ is defined as

$$
\mu_{\mathrm{ggF}+t\bar{t}H;H\to XX} = \frac{\sigma(\mathrm{ggF}) \cdot \mathrm{BR}(H \to XX)}{\sigma_{\mathrm{SM}}(\mathrm{ggF}) \cdot \mathrm{BR}_{\mathrm{SM}}(H \to XX)} = \frac{\sigma(t\bar{t}H) \cdot \mathrm{BR}(H \to XX)}{\sigma_{\mathrm{SM}}(t\bar{t}H) \cdot \mathrm{BR}_{\mathrm{SM}}(H \to XX)} \tag{4}
$$

and $\mu_{\mathrm{VBF}+VH}/\mu_{\mathrm{ggF}+t\bar{t}H}$ is the parameter of interest giving the ratio between VBF + VH and ggF + $t\bar{t}H$ scale factors.

Higgs Signal Strength, ATLAS & CMS

$$CMS-Combined(\gamma\gamma,\tau\tau,bb,WW^*,ZZ^*):\mu=0.80\pm0.14$$

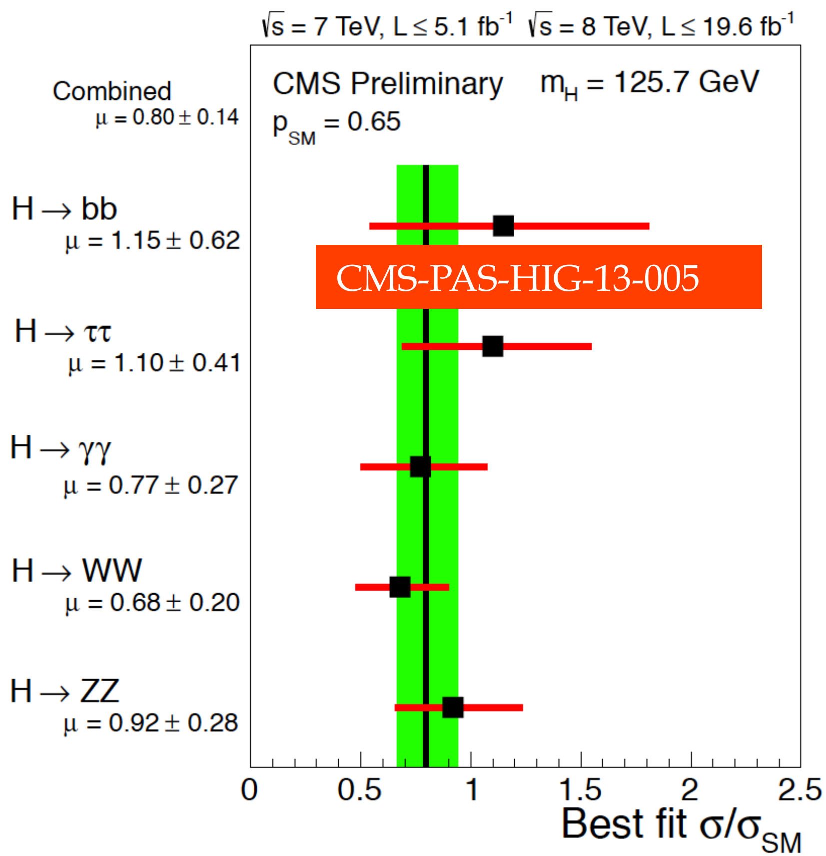
$$ATLAS-Combined(\gamma\gamma,WW^*,ZZ^*):\mu=1.33^{+0.21}_{-0.18}$$

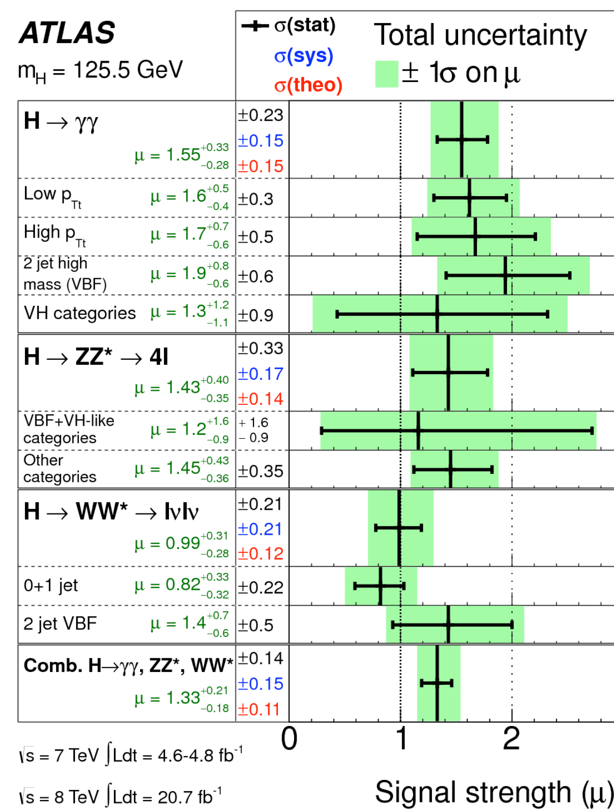
$$ATLAS-Combined(\gamma\gamma,\tau\tau,bb,WW^*,ZZ^*):\mu=1.23\pm0.18$$

$$TEVATRON-Combined(\gamma\gamma,\tau\tau,bb,WW^*):\mu=1.44\pm0.60$$

Compatible with SM

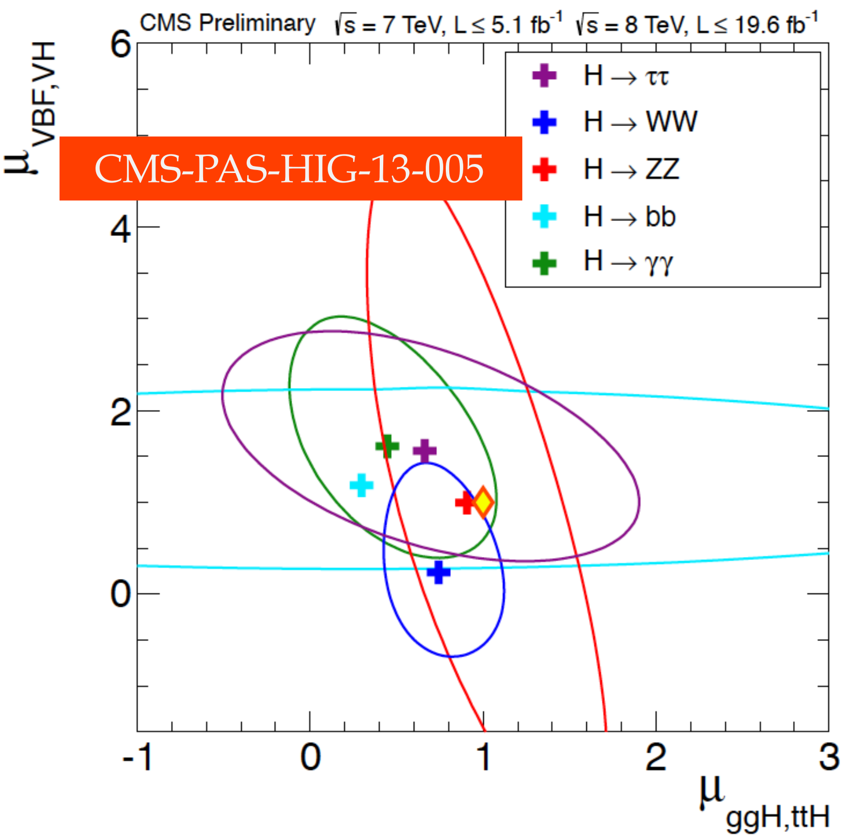
arXiv:1307.1427v1

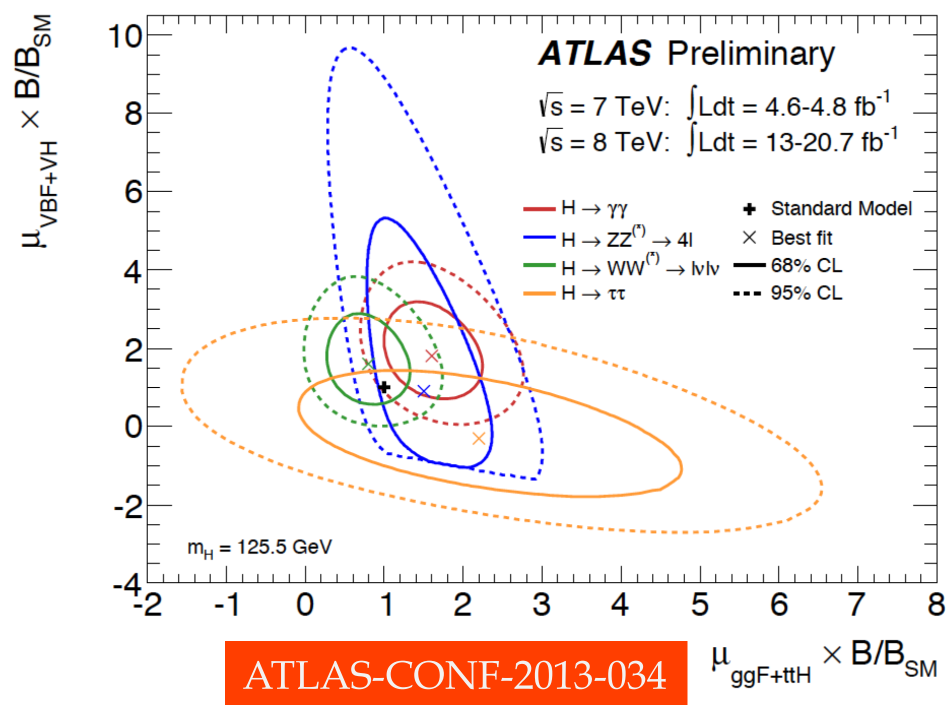




μ_{VBF+VH} vs $\mu_{ggF+ttH}$

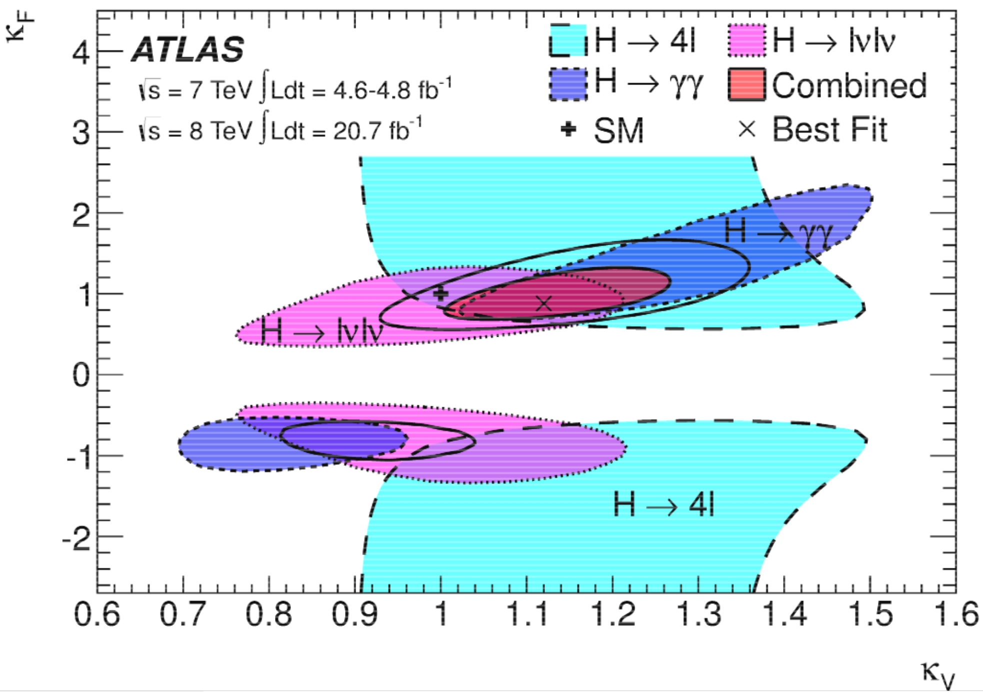
Look at signal strenghts of different Higgs production mechanisms. Put ggF+ttH together as they both scale mostly with ttH in the SM. Similarly put VBF and VH together

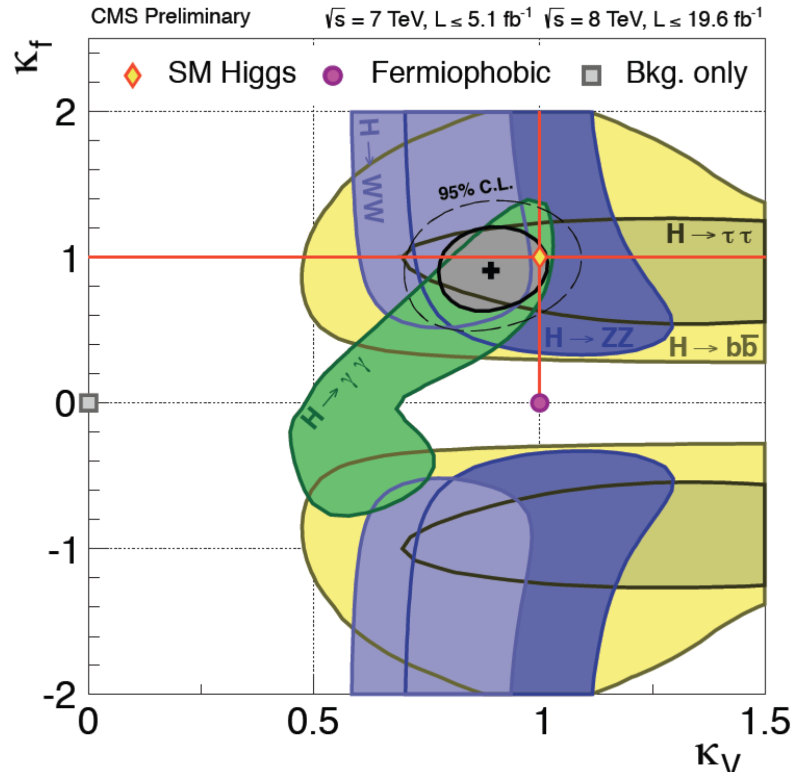




Vector Boson and Fermion Couplings

Al fermions couplings scale as k_F $(k_t=k_b=k_\tau\ldots)$
All Vector Boson couplings scale as k_V $(k_W=k_Z)$
No BSM contribution to Γ_H





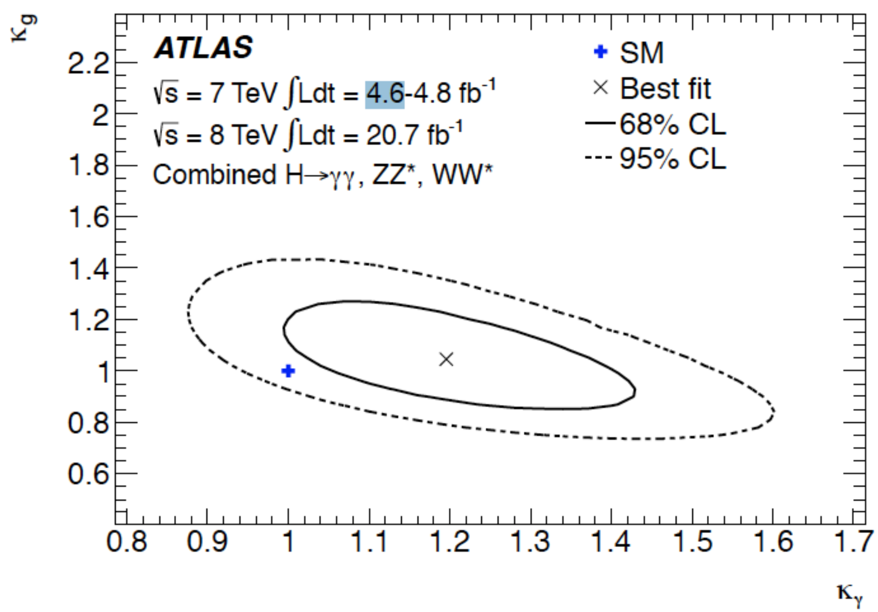
- **All experiments compatible with SM predictions: accuracy ~10-20%**
  - **ATLAS: κ_V [1.05,1.22] at 68% CL - κ_F [0.76,1.18] at 68% CL**
  - **CMS: κ_V [0.74,1.06] at 95% CL - κ_F [0.61,1.33] at 95% CL**
- κ_F=0 Excluded at >5σ (mainly indirect via gg loop)

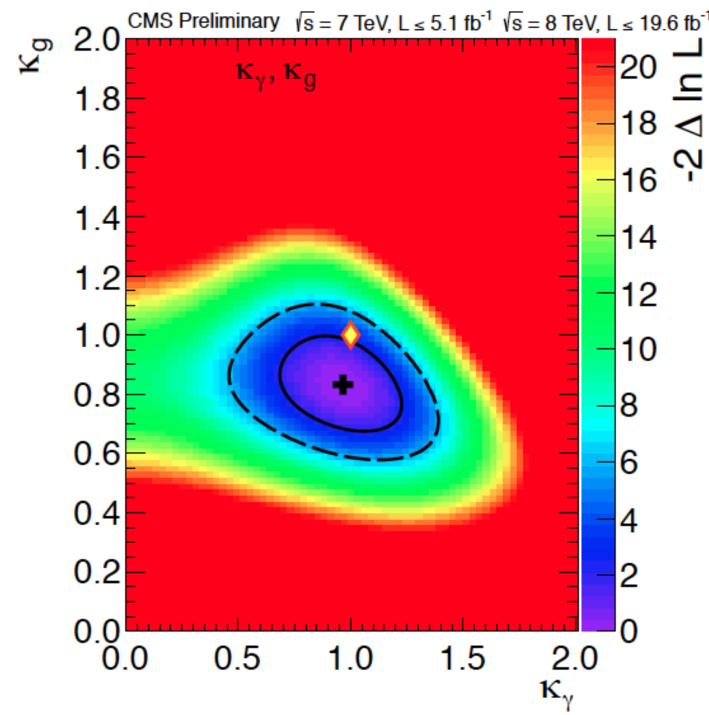
Test of loop induced couplings: k_g vs k_γ

Tree-level Coupling to SM particles as in SM:

$\kappa_b = \kappa_W = \kappa_Z = \kappa_\tau = \kappa_t = 1$; K_γ and K_g accommodate the effect of new particles

No BSM contributions to Γ_H

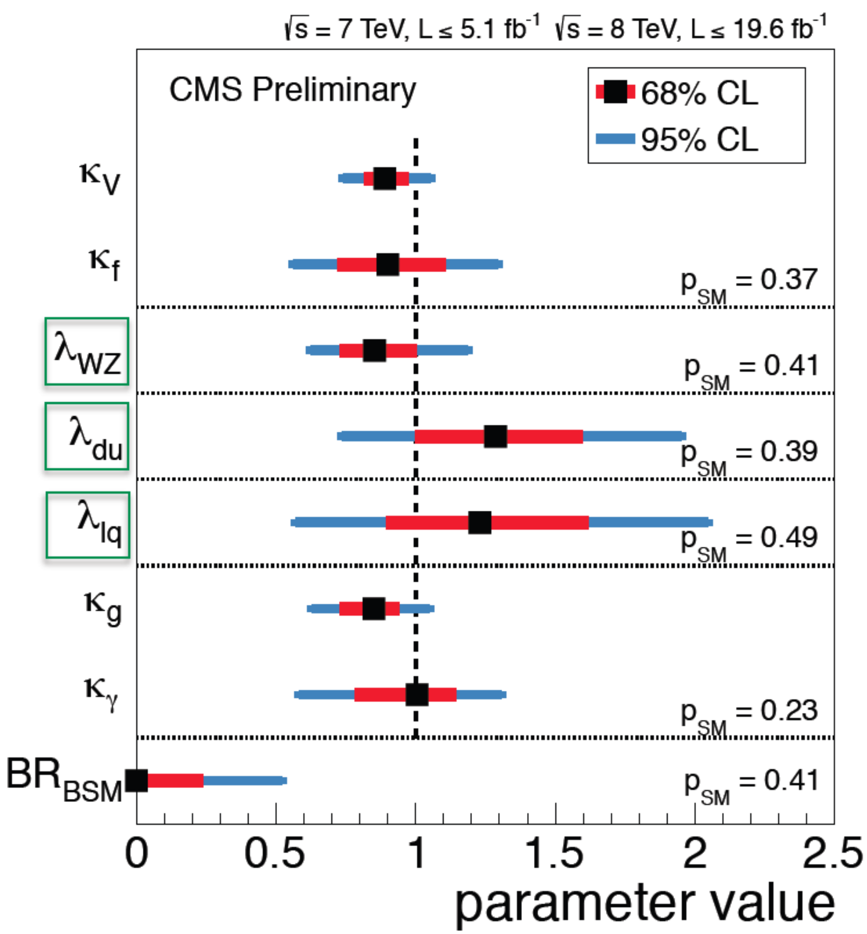


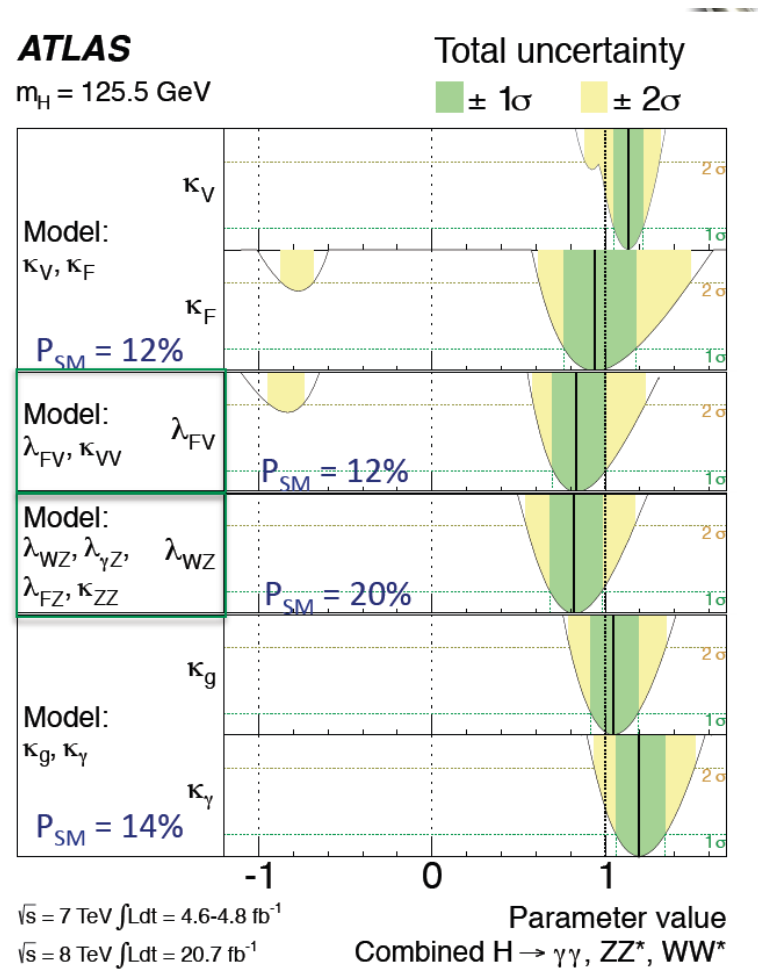


$$ATLAS : K_g = (1.04 \pm 0.14) at 68\% CL; K_\gamma = (1.20 \pm 0.15) at 68\% CL$$

$$CMS : K_g = [0.63, 1.05] at 68\% CL; K_\gamma = [0.59, 1.30] at 68\% CL$$

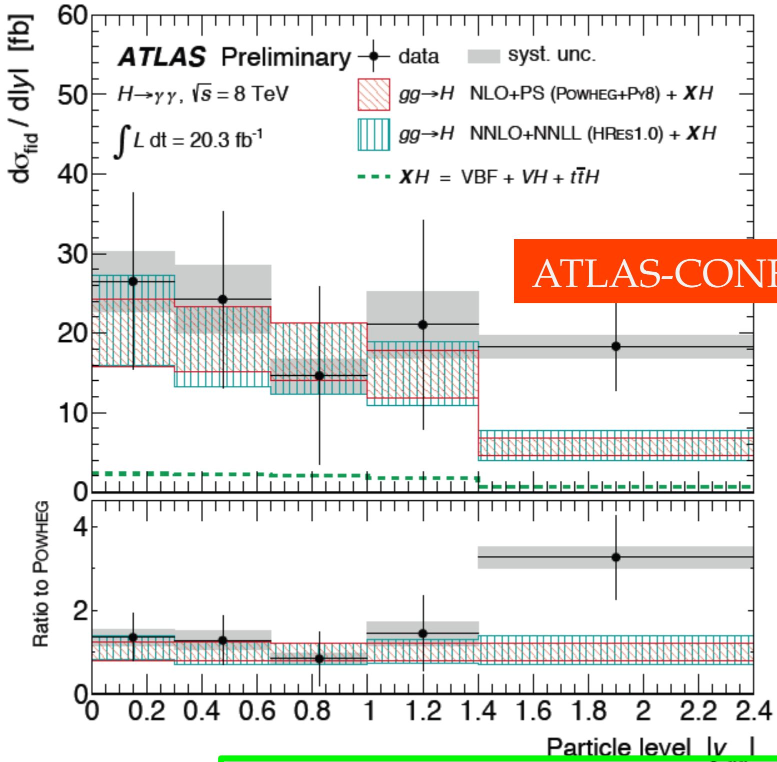
Overview of couplings



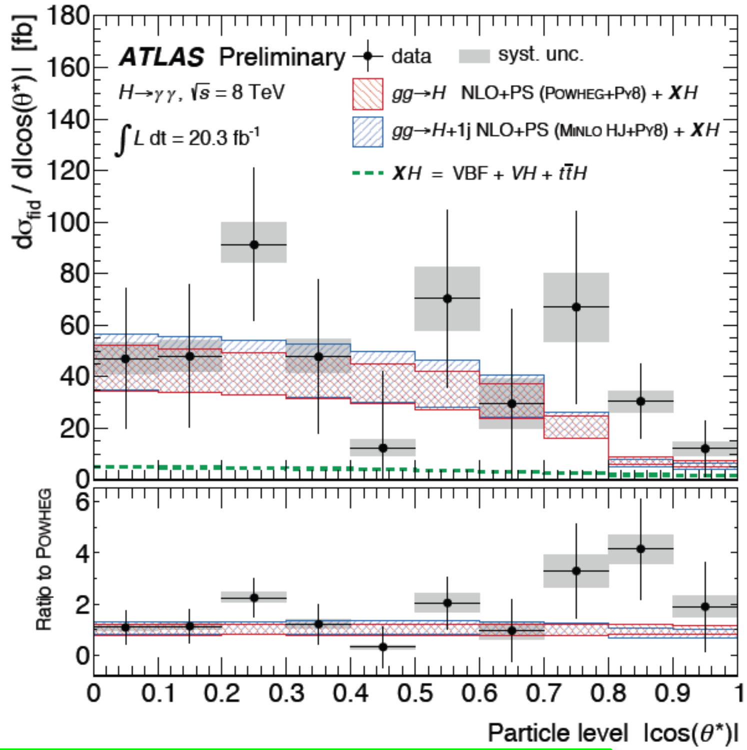


All findings are compatible with SM expectations

Differential Cross Sections in γγ final state



ATLAS-CONF-2013-072



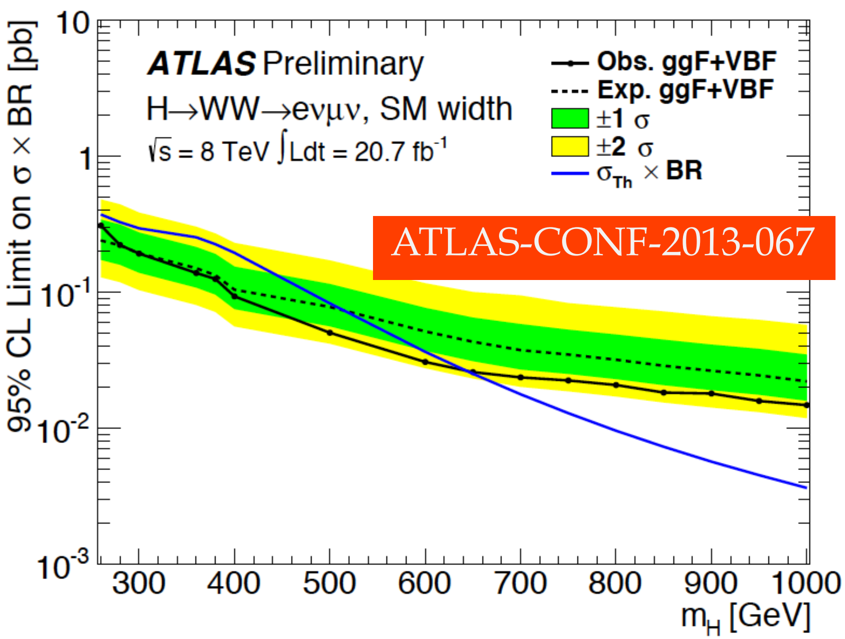
No significant deviation from SM observed

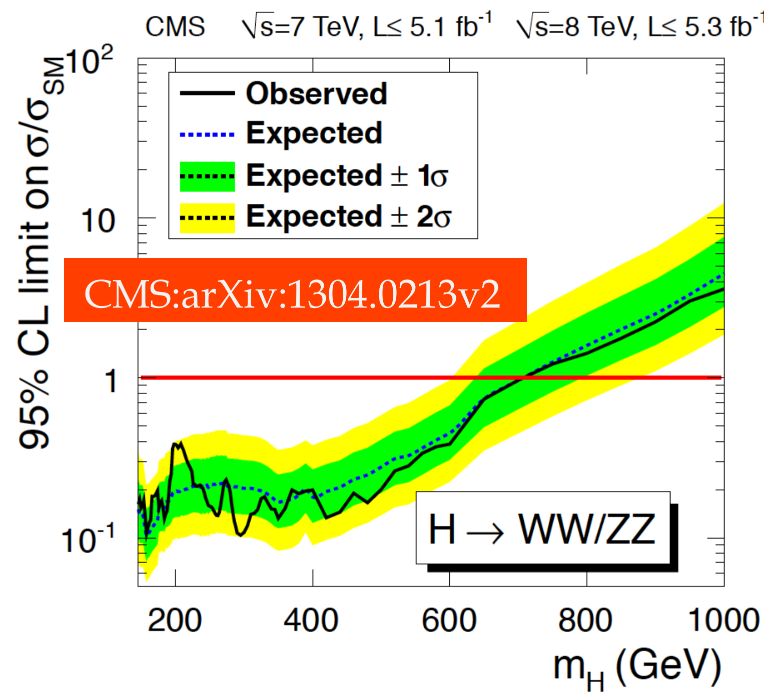
X^2 probability between data and MC for different observables

	N_{jets}	$p_T^{\gamma\gamma}$	$\|y^{\gamma\gamma}\|$	$\|\cos\theta^*\|$	$p_T^{j_1}$	$\Delta\phi_{jj}$	$p_T^{\gamma\gamma jj}$
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	–	–	–	–

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.



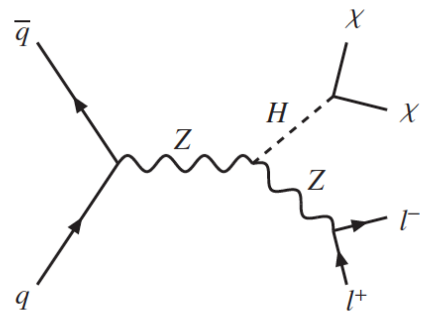


Finding one or more Higgs bosons at high mass would be an indication of something beyond SM. ATLAS and CMS have both, unsuccefully done so.

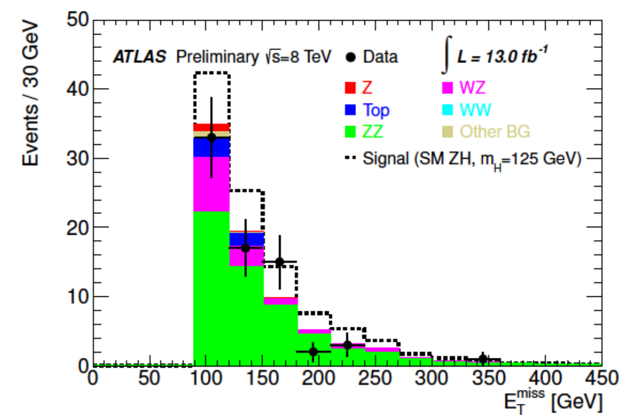
95% CL UL σxBR CMS: 145<M_H<710, ATLAS 260<M_H<640

From SM to BSM. Invisible Higgs decays

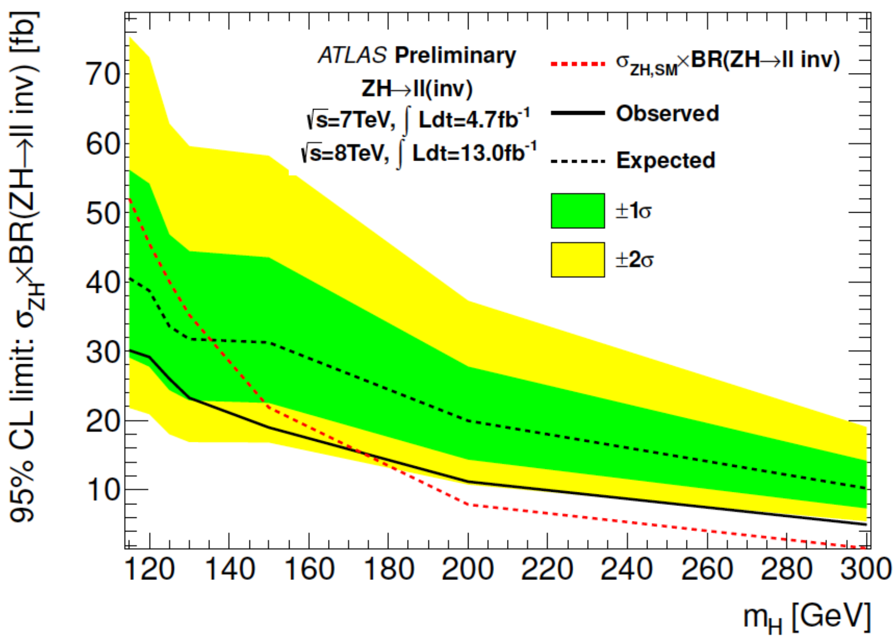
Another approach to some evidence of New Physics would be looking for invisible decays of the Higgs. There might be a contribution from dark particles as predicted by SUSY. Again search was, so far, unsuccesful.



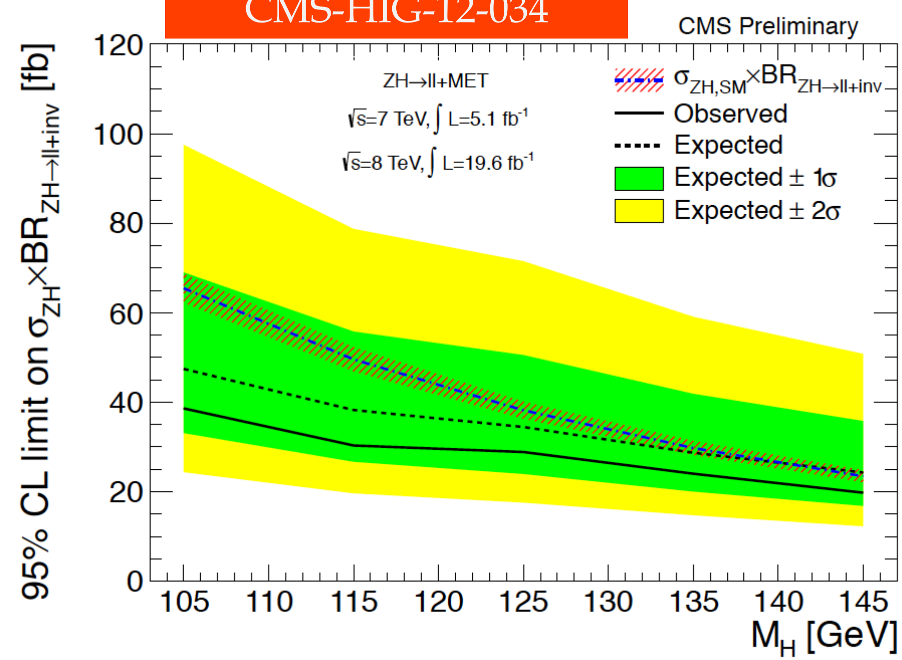
100% decay to invisible particles



ATLAS-CONF-2013-011



CMS-HIG-12-034



Conclusions

1 year after the discovery properties of the new boson have been measured with increasing precision thanks to outstanding LHC performance :

- 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 evidence of New Physics yet

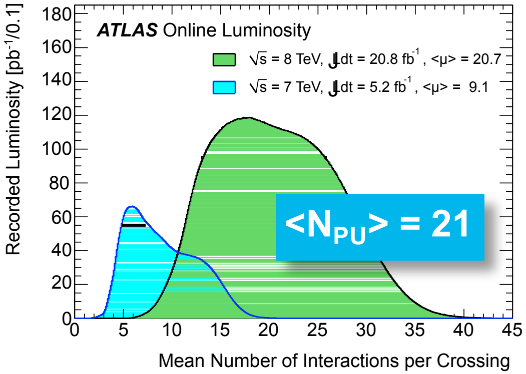
All measured properties are compatible with the SM Higgs boson

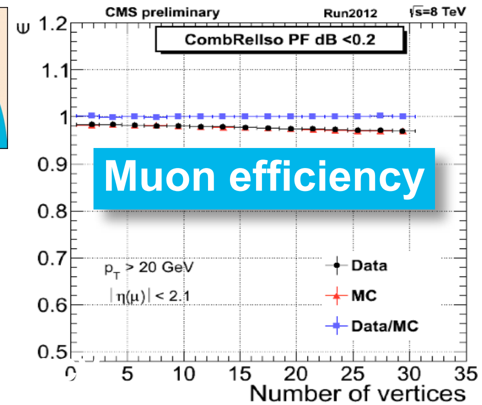
In 2015 LHC will increase E_{CM} (σ_H~2.6) and Luminosity ($10^{34}cm^{-2}s^{-1}$). This will allow to increase sensitivity to test SM predictions.

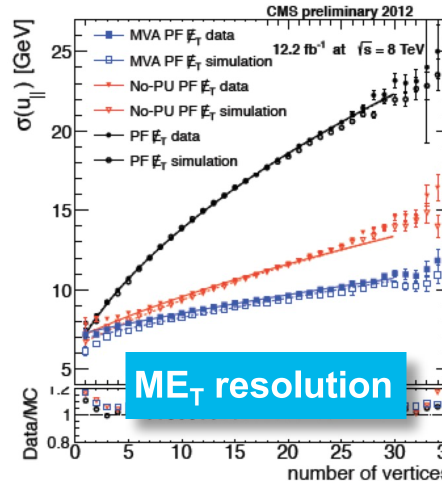
Thanks for your attention.

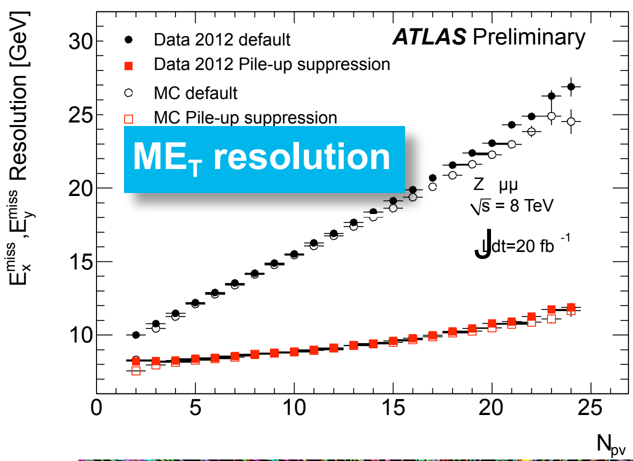
BACKUP Slides

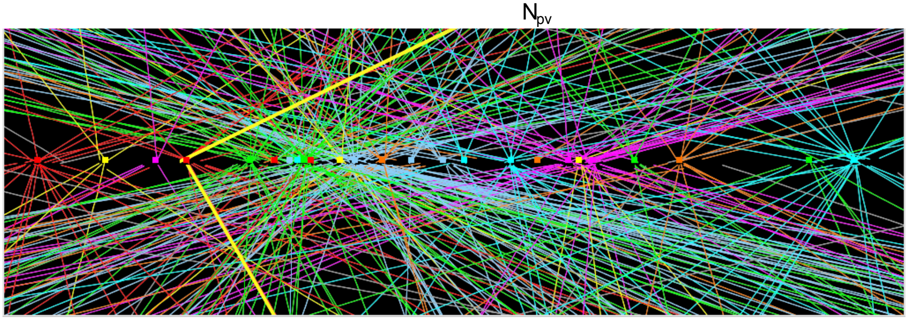
Pileup mitigation

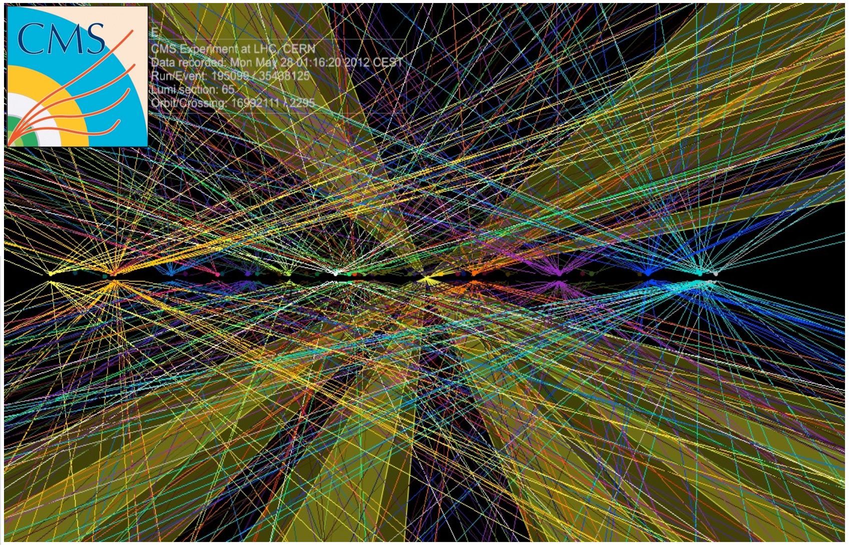






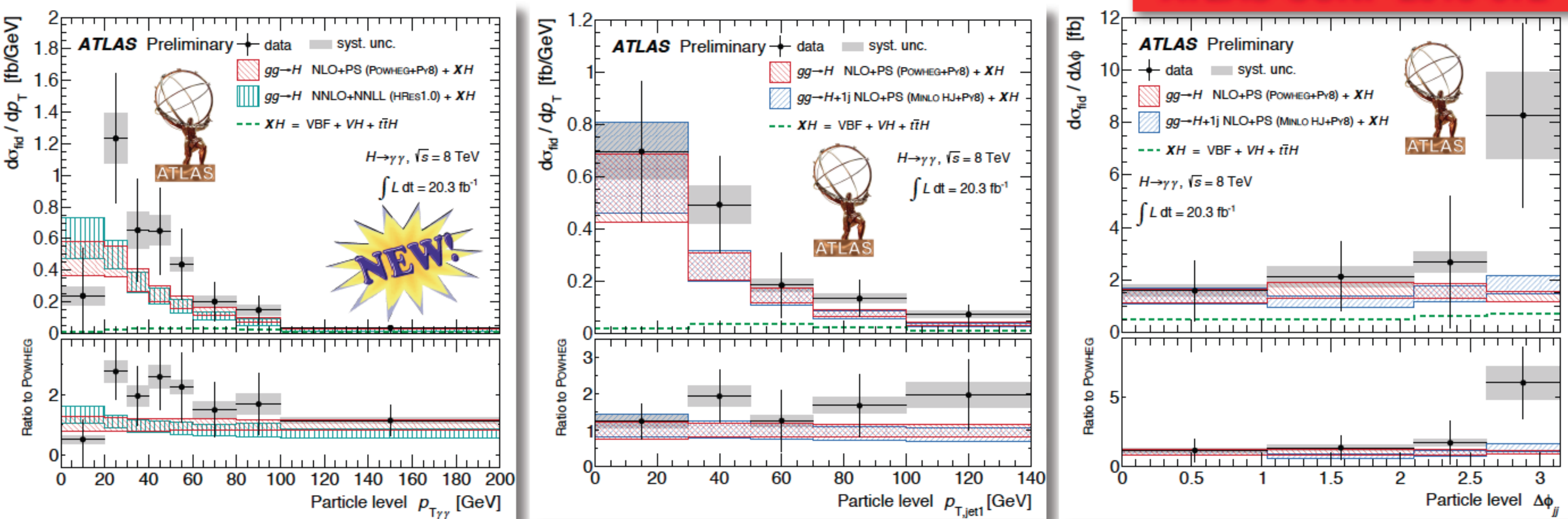




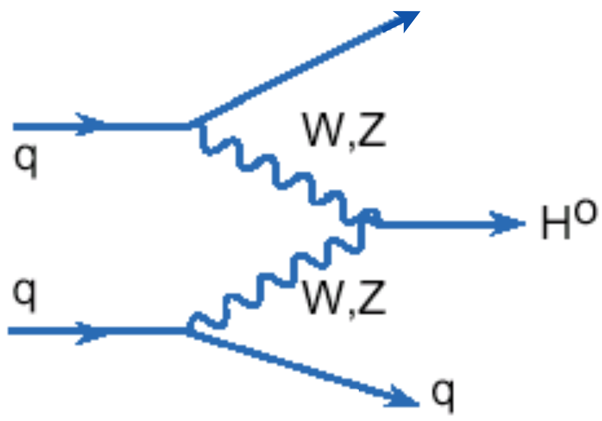


Higgs to γγ: Differential Distributions

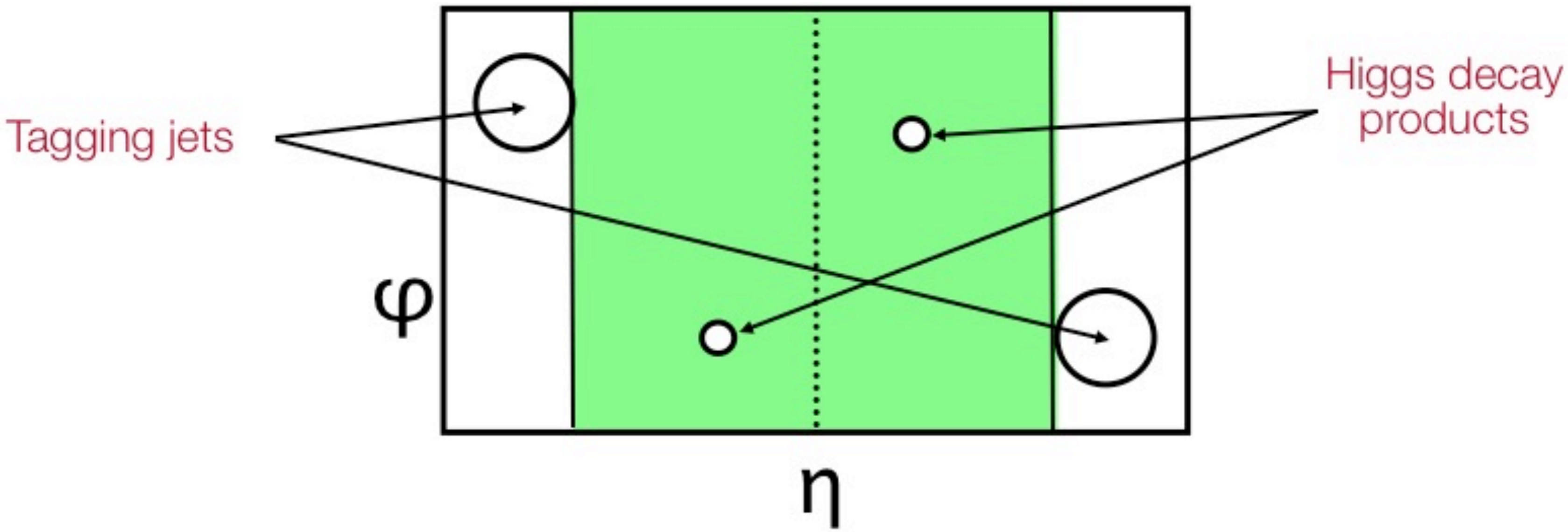
ATLAS-CONF-2013-072



Vector Boson Fusion (VBF)

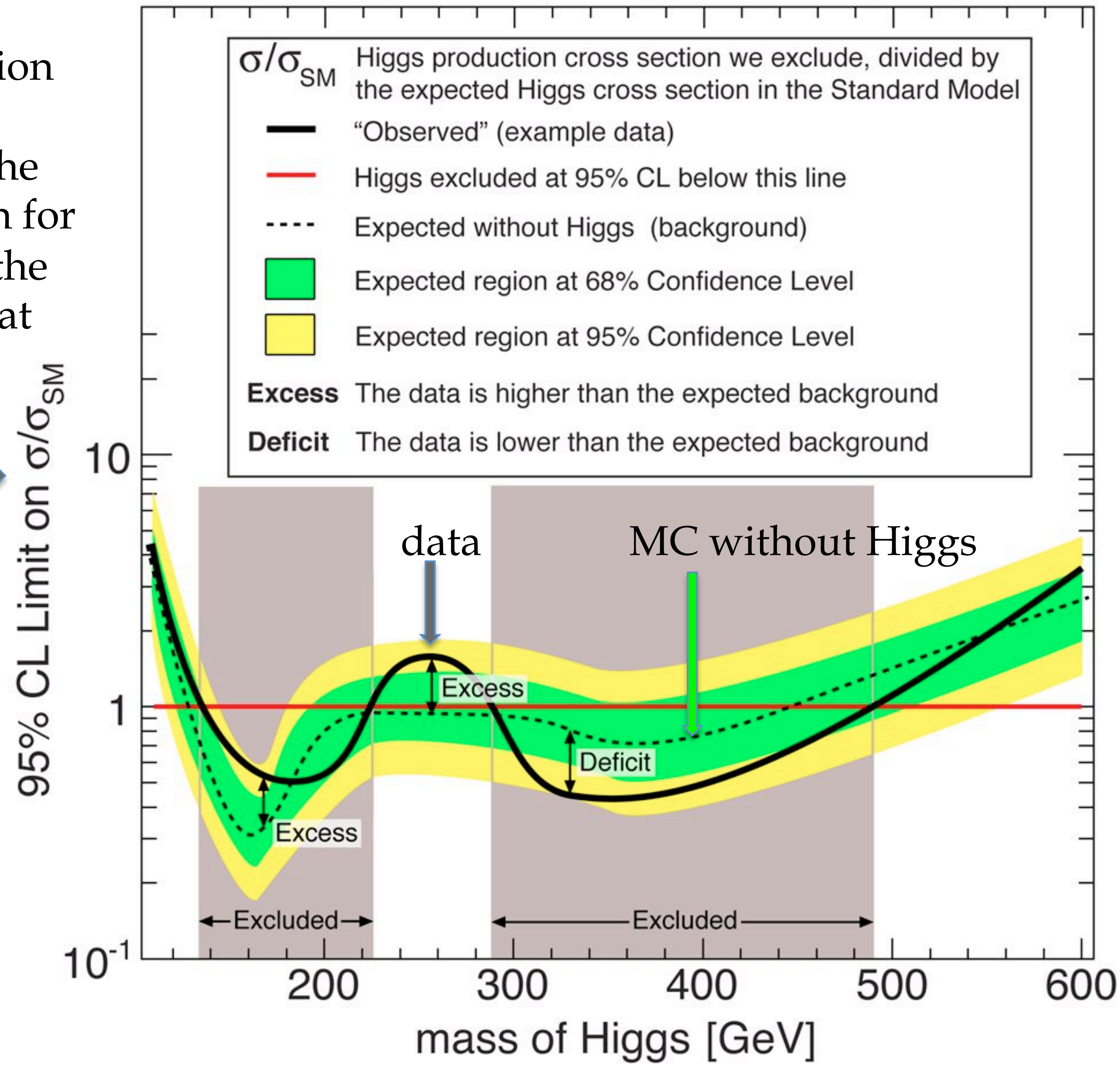


Distinctive signature:
- two forward jets (tagging jets)
- little (jet) activity in central region (central jet veto)



Exclusion Plots

Higgs boson production cross-section that we exclude, divided by the expected cross section for Higgs production in the Standard Model at that mass.



Exclusion Plots

The Standard Model does not predict the mass of the Higgs boson, but does predict the production cross section once the mass is known. The "cross section" is the likelihood of a collision event of a particular type.
ATLAS uses plots like this one to seek hints for the Higgs boson and also to exclude regions of mass where the Higgs is very unlikely to be found. This example is not real data, but is a simplified plot to show how we interpret the results of our searches for the Higgs boson. The vertical axis shows, as a function of the Higgs mass, **the Higgs boson production cross-section that we exclude, divided by the expected cross section for Higgs production in the Standard Model at that mass**. This is indicated by the solid black line. This shows a 95% confidence level, which in effect means the certainty that a Higgs particle with the given mass does not exist. The dotted black line shows the median (average) expected limit in the absence of a Higgs. The green and yellow bands indicate the corresponding 68% and 95% certainty of those values.
If the solid black line dips below the value of 1.0 as indicated by the red line, then we see from our data that the Higgs boson is not produced with the expected cross section for that mass. This means that those values of a possible Higgs mass are excluded with a 95% certainty. In this example, two regions would be ruled out at 95% certainty: approximately 135-225 GeV and 290-490 GeV.
If the solid black line is above 1.0 and also somewhat above the dotted black line (an excess), then there might be a hint that the Higgs exists with a mass at that value. If the solid black line is at the upper edge of the yellow band, then there may be 95% certainty that this is above the expectations. It could be a hint for a Higgs boson of that mass, or it could be a sign of background processes or of systematic errors that are not well understood. In this example, there is an excess and the solid black line is above 1.0 between about 225 and 290 GeV, but the excess has not reached a statistically significant level.
The red-gray shaded regions show what is excluded. The "bump" near a mass of 250 GeV could be a slight hint of a Higgs boson in this fictional example.

Limits Setting - 2

This plot shows hypothetical data and expectations that could be used in setting the limits shown in Figure A.The green curve shows (fictional) predicted results if there were a Higgs boson in addition to all the usual backgrounds. It could also represent the predictions of some other new physics. The dashed black curve shows what is expected from all background processes without a Higgs or some new physics. The black points show the hypothetical data.

In this case, the data points are too low to explain the Higgs boson hypothesis (or whatever new physics the green curve represents), so we can rule out that hypothesis. Nonetheless the data points are higher than the expectations for the background processes. This could yield an excess such as shown on the left in Figure A. There are three possible explanations for this excess:

It is a statistical fluctuation above the expected background processes.

It is a systematic problem due to an imperfect understanding of the background processes.

The excess is due to some different new physics (than that hypothesized) that would predict a smaller excess.

If instead, the black points lay close to the green curve, that could be evidence for the discovery of the Higgs boson (if it were statistically significant).

If the black points lay on or below the dashed black curve (the expected background), then there is no evidence for a Higgs boson and depending on the statistical significance, the Higgs boson might be ruled out at the corresponding mass.

Limits - Setting

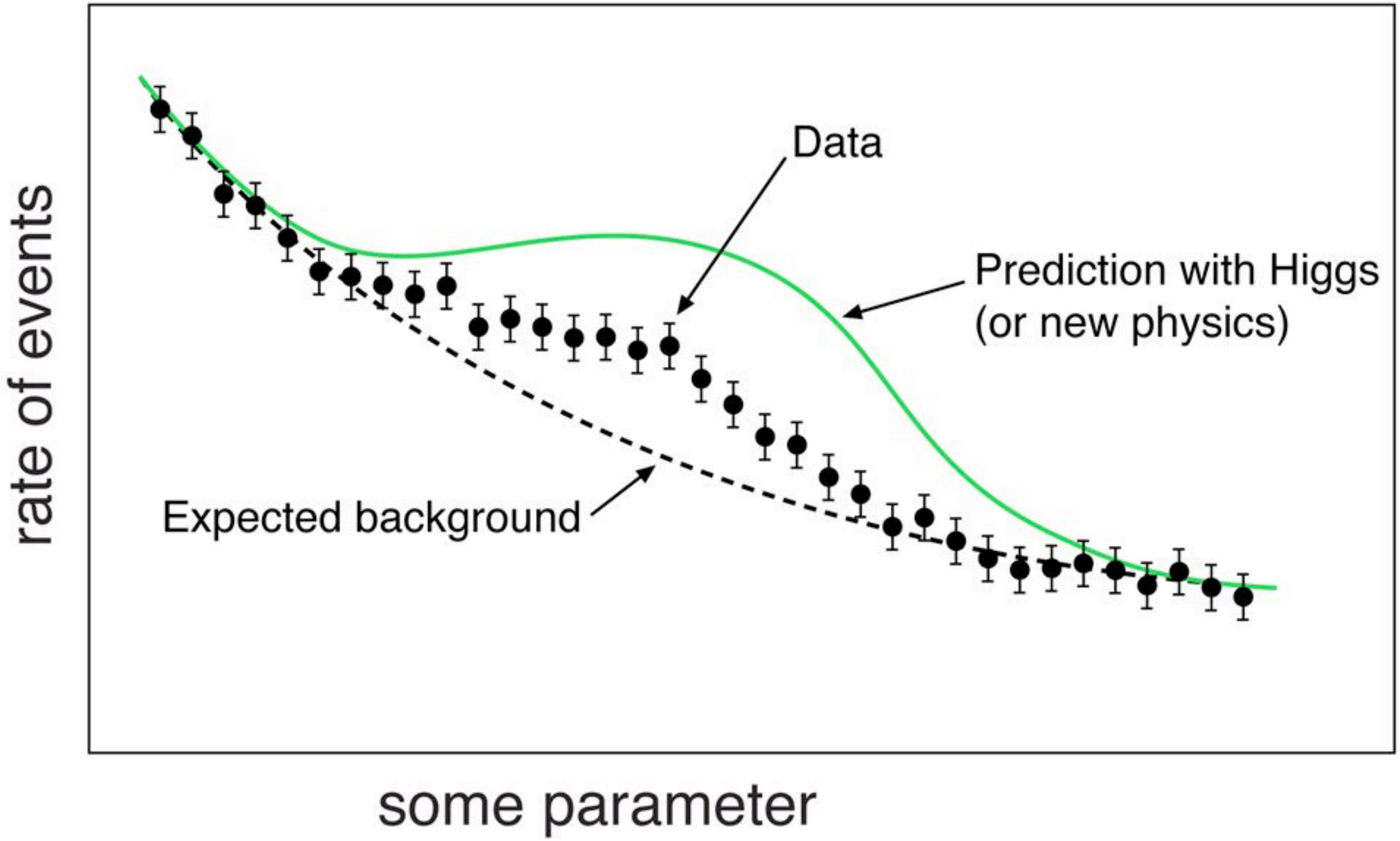
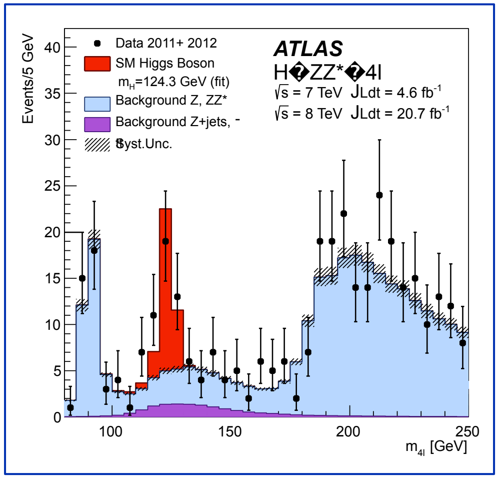


Figure B

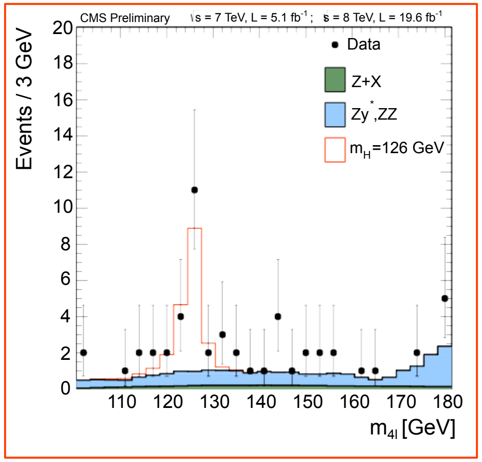
Mass Measurement
γγ and ZZ*

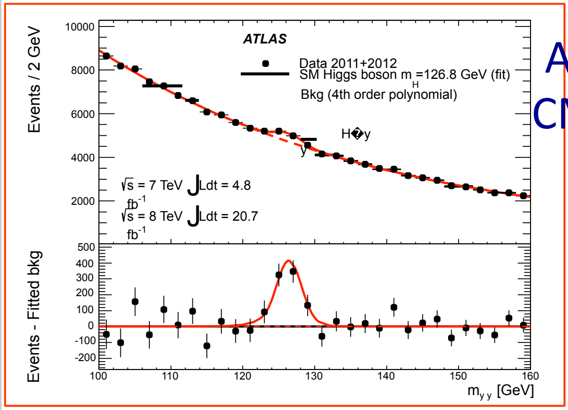
From γγ and ZZ*(4ℓ) mass spectra



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

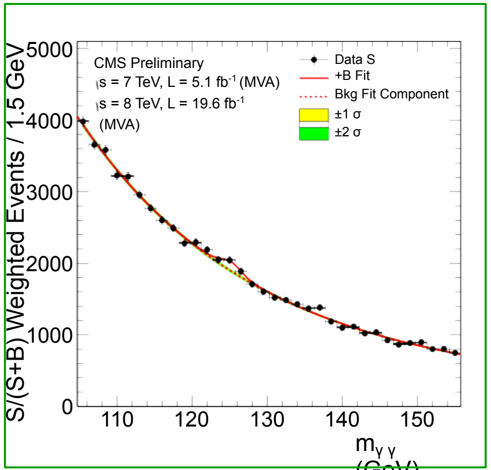
CMS: $M_H = 125.8 \pm 0.5_{stat} \pm 0.2_{sys}$ GeV





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

Spin Parity

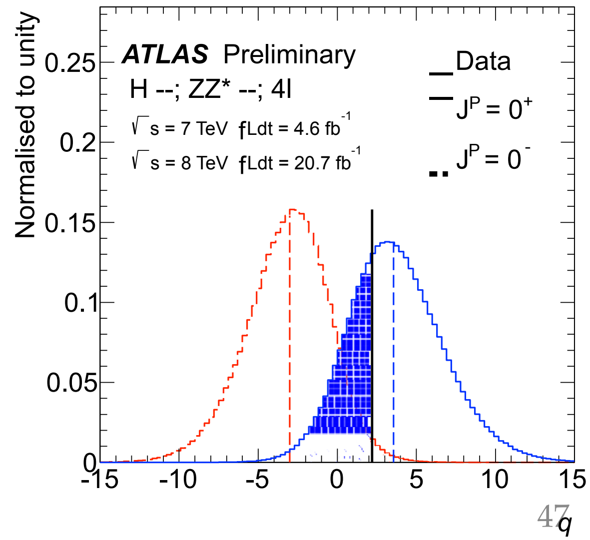
- Used as test statistics the likelihood ratio q:

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

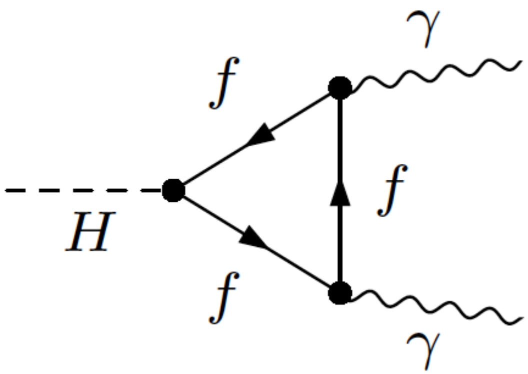
$$q = \log \frac{\mathcal{L}(J^P = 0^+, \hat{\hat{\mu}}_{0^+}, \hat{\hat{\theta}}_{0^+})}{\mathcal{L}(J^P_{\mathrm{alt}}, \hat{\hat{\mu}}_{J^P_{\mathrm{alt}}}, \hat{\hat{\theta}}_{J^P_{\mathrm{alt}}})}$$

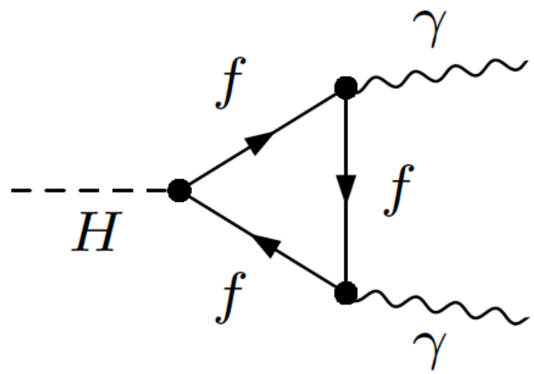
- Signal strengths μ_{JP} treated as independent Nuisance–Parameter for each channel and each spin hypothesis
- Probability distributions for different J^P hypothesis derived via pseudo–experiments
- When deriving exclusions use CL_s:

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

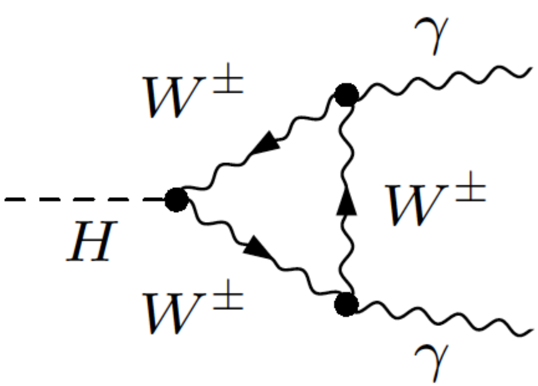


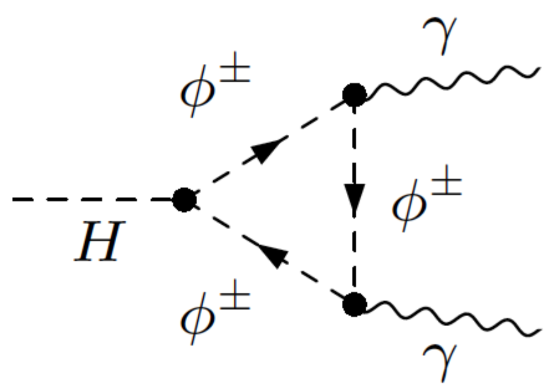
Higgs decay to 2 photons





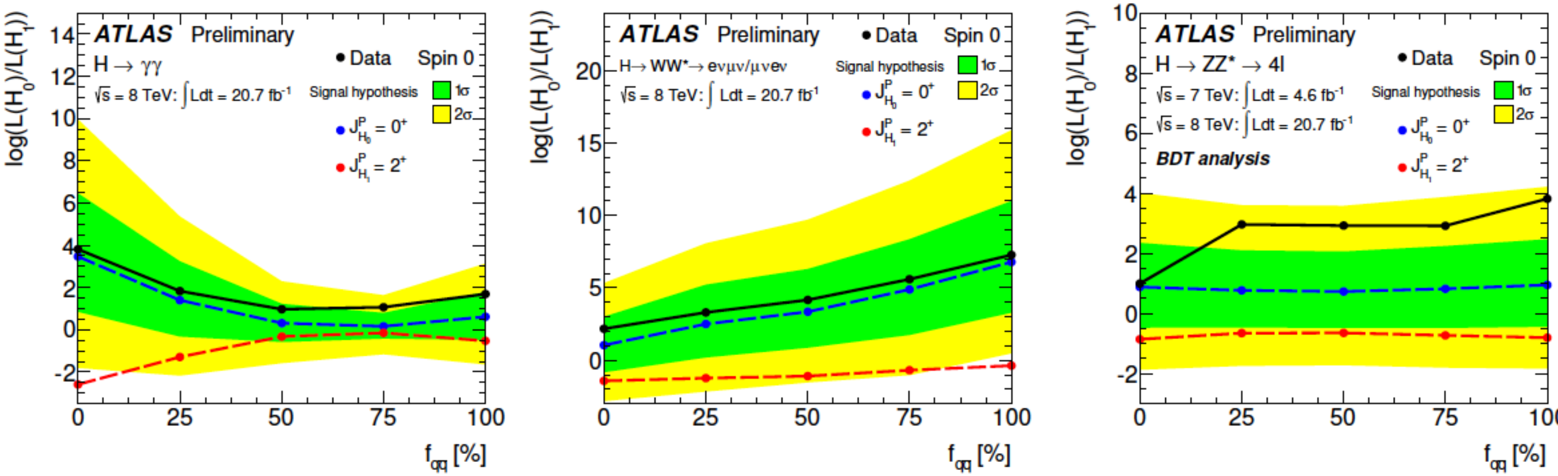
Only top quarks contribute, contributions from light fermions negligible





W-bosons, Goldstone-bosons and ghosts occur in the loops

ATLAS Spin 0^+ vs 2^+

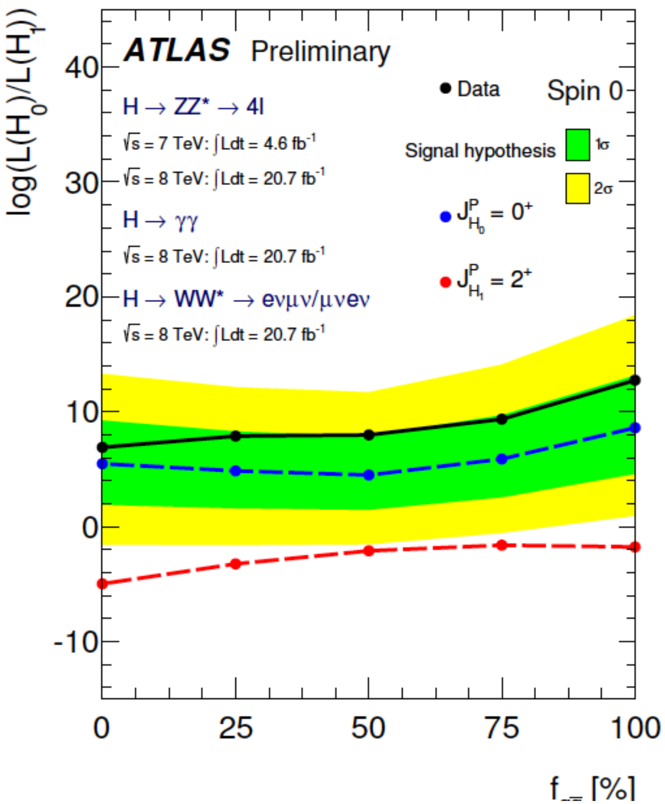


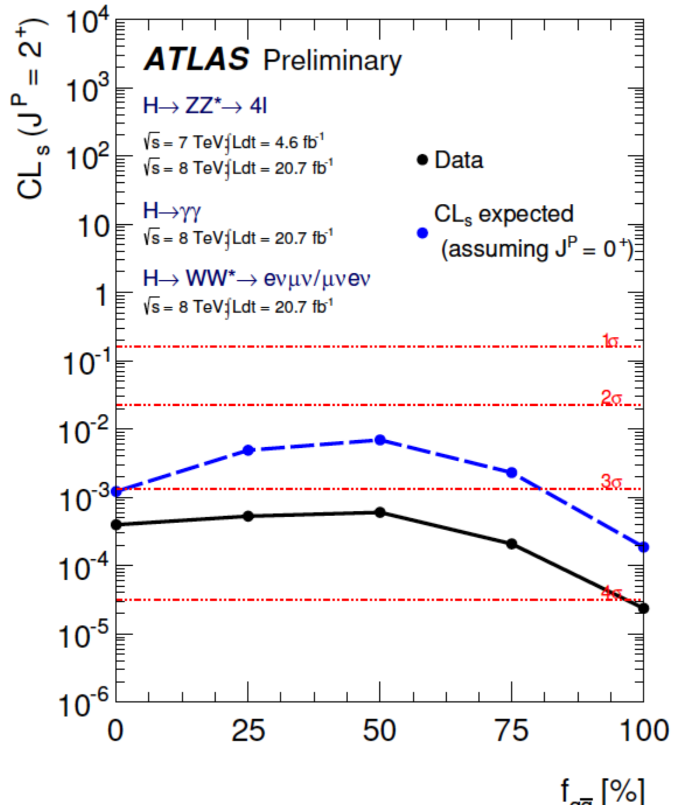
(a) $H \to \gamma\gamma$ (b) $H \to WW^* \to \ell\nu\ell\nu$ (c) $H \to ZZ^* \to 4\ell$

Table 3: Expected and observed p_0 values for $J^P = 0^+$ and $J^P = 2^+$ hypotheses as a function of the fraction $f_{q\bar{q}}$ of the $q\bar{q}$ spin-2 production mechanism. The values are calculated for the combination of the $H \to \gamma\gamma$, $H \to WW^* \to \ell\nu\ell\nu$ and $H \to ZZ^* \to 4\ell$ final states. The pseudo-experiments corresponding to the $J^P = 0^+$ hypothesis are generated following the Standard Model predictions for the signal strength in each channel.

$f_{q\bar{q}}$	Spin-2 assumed exp. $p_0(J^P = 0^+)$	Spin-0 assumed exp. $p_0(J^P = 2^+)$	obs. $p_0(J^P = 0^+)$	obs. $p_0(J^P = 2^+)$	$CL_s(J^P = 2^+)$
100%	$1.3 \cdot 10^{-2}$	$8.1 \cdot 10^{-3}$	0.99	$4.2 \cdot 10^{-6}$	$0.4 \cdot 10^{-3}$
75%	$2.3 \cdot 10^{-2}$	$1.3 \cdot 10^{-2}$	0.96	$3.7 \cdot 10^{-5}$	$1.0 \cdot 10^{-3}$
50%	$2.3 \cdot 10^{-2}$	$2.2 \cdot 10^{-2}$	0.97	$9.1 \cdot 10^{-5}$	$2.8 \cdot 10^{-3}$
25%	$1.0 \cdot 10^{-2}$	$2.1 \cdot 10^{-2}$	0.97	$1.0 \cdot 10^{-4}$	$4.1 \cdot 10^{-3}$
0%	$2.9 \cdot 10^{-3}$	$1.0 \cdot 10^{-2}$	0.95	$1.4 \cdot 10^{-4}$	$3.0 \cdot 10^{-3}$

ATLAS Spin 0^+ vs 2^+

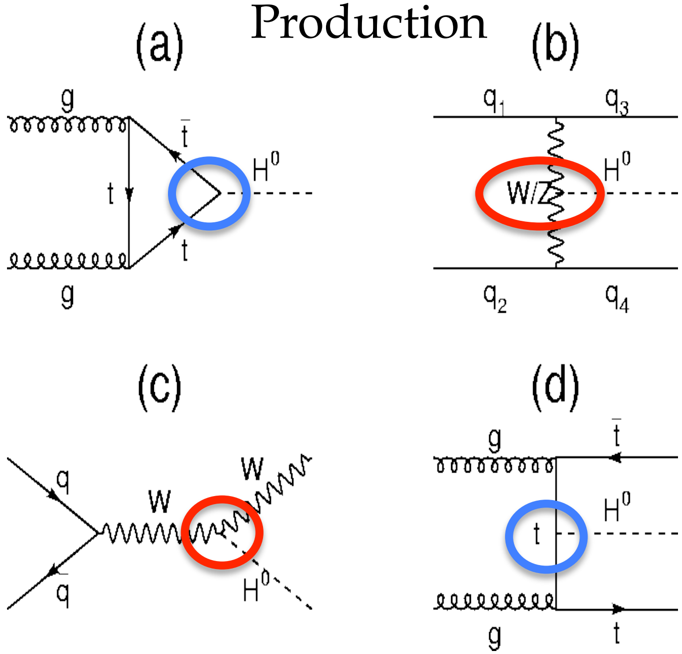




$f_{q\bar{q}}$	Spin-2 assumed exp. $p_0(J^P = 0^+)$	Spin-0 assumed exp. $p_0(J^P = 2^+)$	obs. $p_0(J^P = 0^+)$	obs. $p_0(J^P = 2^+)$	$\mathrm{CL_s}(J^P = 2^+)$
100%	$3.4 \cdot 10^{-3}$	$9.4 \cdot 10^{-5}$	0.82	$0.4 \cdot 10^{-5}$	$0.2 \cdot 10^{-4}$
75%	$1.0 \cdot 10^{-2}$	$1.1 \cdot 10^{-3}$	0.82	$3.7 \cdot 10^{-5}$	$2.1 \cdot 10^{-4}$
50%	$1.5 \cdot 10^{-2}$	$3.5 \cdot 10^{-3}$	0.85	$9.1 \cdot 10^{-5}$	$6.0 \cdot 10^{-4}$
25%	$6.8 \cdot 10^{-3}$	$2.4 \cdot 10^{-3}$	0.81	$1.0 \cdot 10^{-4}$	$5.3 \cdot 10^{-4}$
0%	$1.6 \cdot 10^{-3}$	$6.1 \cdot 10^{-4}$	0.65	$1.4 \cdot 10^{-4}$	$4.0 \cdot 10^{-4}$

Effective Couplings

Production

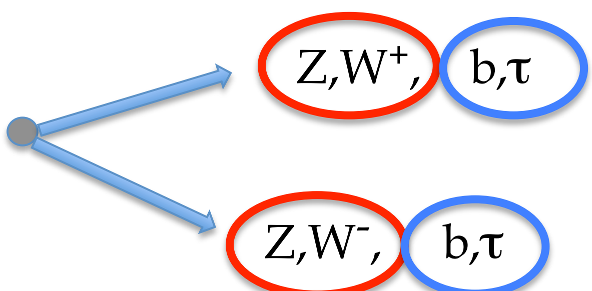


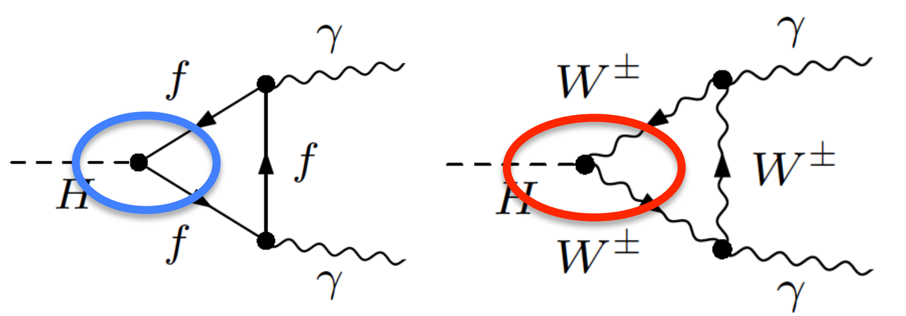
(a) gluon fusion (19 pb @8 TeV)
(b) VBF (WW or ZZ fusion)
(c) Associated production (VH)
(d) ttH production

Fermions

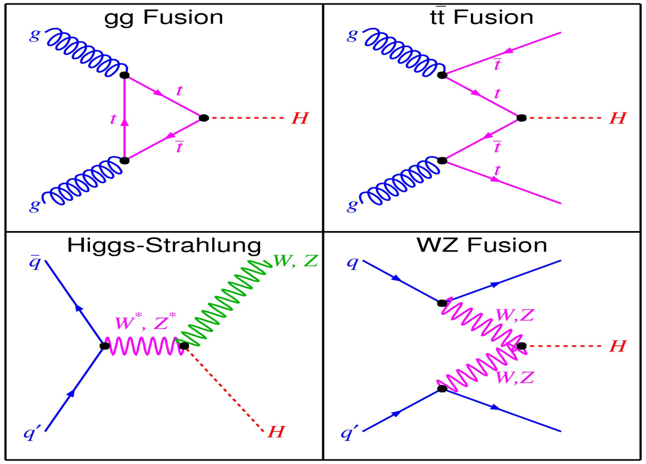
Bosons

Decay





Disantangle Higgs Production Modes

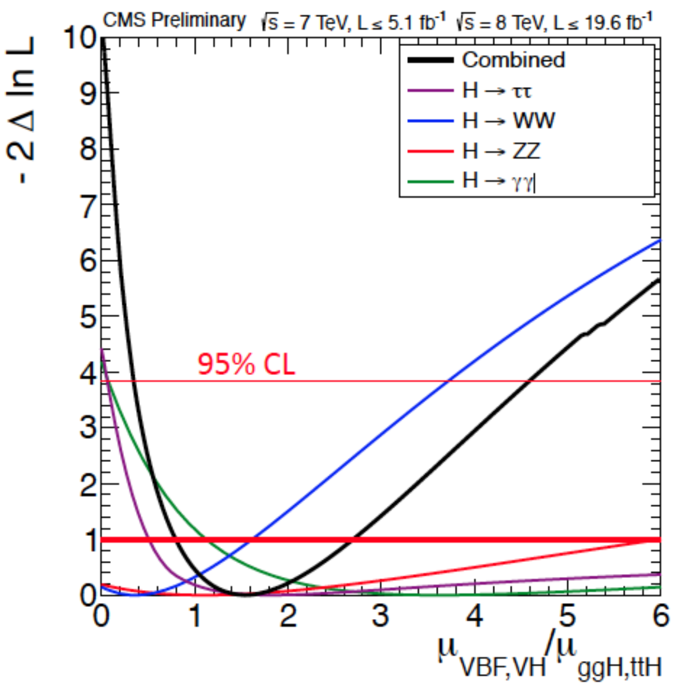


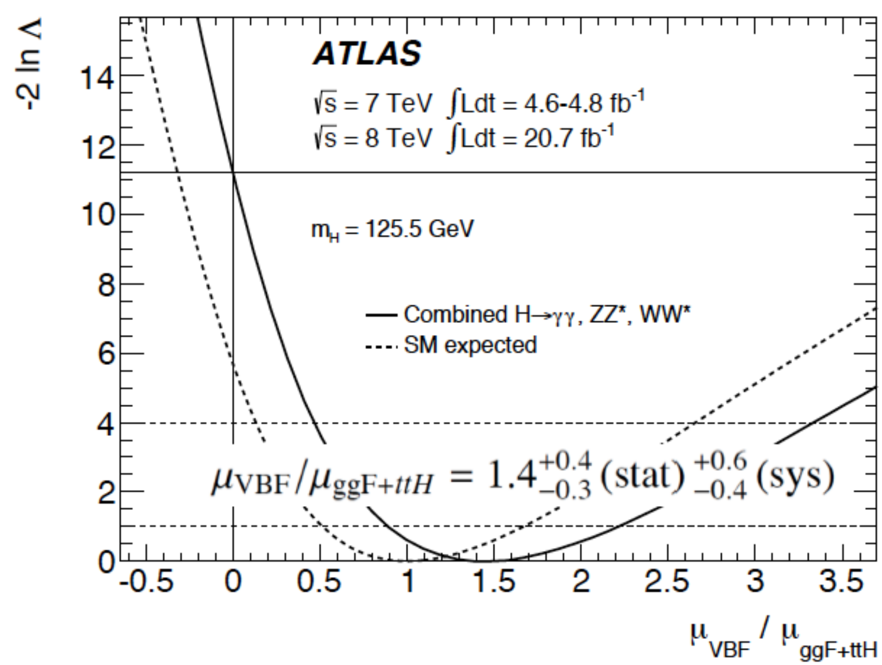
Fit to $\frac{\mu_{VBF+VH}}{\mu_{gg+ttH}}$ in different channels (BR's cancel)

CMS: Evidence for V-boson mediated production 3.2σ

ATLAS: Evidence for VBF production 3.3σ

V-mediated production compatible with SM





Higgs couplings to V and f

For a consistent measurement of Higgs boson couplings, production and decay modes cannot be treated independently.

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

Thus effective couplings

$$\kappa_V = \kappa_W = \kappa_Z$$
$$\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_g$$

are introduced which are assumed to modify SM observables. It is assumed: 1 resonance + Zero–Width Approx. + SM Lagrangian Tensor Structure ($J^P=0^+$)
As an example

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

$$\mu(ZH \to Zbb) = [\sigma_{ZH} \times BR(H \to bb)] / [\sigma_{ZH} \times BR(H \to bb)]_{SM} = (k_Z^2 \times k_b^2)/k_H^2$$

and $\kappa_\gamma^2(\kappa_F, \kappa_V) = 1.59 \cdot \kappa_V^2 - 0.66 \cdot \kappa_V \kappa_F + 0.07 \cdot \kappa_F^2$
is the first approximation SM functional dependence of the effective scale factor k_g on the scale factors k_F and k_V .

Higgs couplings - 2

If we take into account that 0.75 is the SM branching ratio to fermion and gluon final states and 0.25 the SM branching ratio into WW(*), ZZ(*) and for mH = 125.5 GeV the total Higgs width can be expressed as a function of the scale factors k_F and k_V as

$$\sigma(gg \to H) * \mathrm{BR}(H \to \gamma\gamma) \sim \frac{\kappa_F^2 \cdot \kappa_\gamma^2(\kappa_F, \kappa_V)}{0.75 \cdot \kappa_F^2 + 0.25 \cdot \kappa_V^2}$$

$$\sigma(qq' \to qq'H) * \mathrm{BR}(H \to \gamma\gamma) \sim \frac{\kappa_V^2 \cdot \kappa_\gamma^2(\kappa_F, \kappa_V)}{0.75 \cdot \kappa_F^2 + 0.25 \cdot \kappa_V^2}$$

$$\sigma(gg \to H) * \mathrm{BR}(H \to ZZ^{(*)}, H \to WW^{(*)}) \sim \frac{\kappa_F^2 \cdot \kappa_V^2}{0.75 \cdot \kappa_F^2 + 0.25 \cdot \kappa_V^2}$$

$$\sigma(qq' \to qq'H) * \mathrm{BR}(H \to ZZ^{(*)}, H \to WW^{(*)}) \sim \frac{\kappa_V^2 \cdot \kappa_V^2}{0.75 \cdot \kappa_F^2 + 0.25 \cdot \kappa_V^2}$$

$$\sigma(qq' \to qq'H, VH) * \mathrm{BR}(H \to \tau\tau, H \to b\bar{b}) \sim \frac{\kappa_V^2 \cdot \kappa_F^2}{0.75 \cdot \kappa_F^2 + 0.25 \cdot \kappa_V^2}$$