The Higgs Particle Mass, Width and Couplings

Seminar 'Particle Physics at the LHC'

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Contents

We found a Higgs boson!

So... What now?

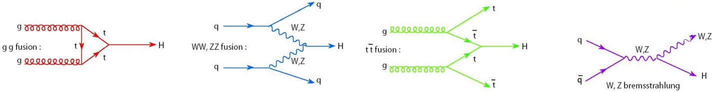
what we can measure

- mass
- spin
- CP
- width
- couplings

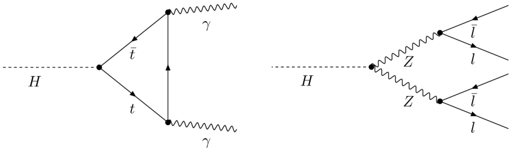
introduction

a short reminder about Higgs boson interactios

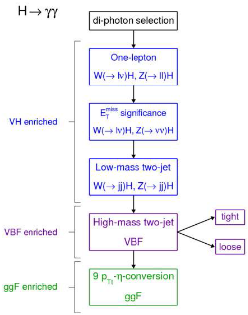
production

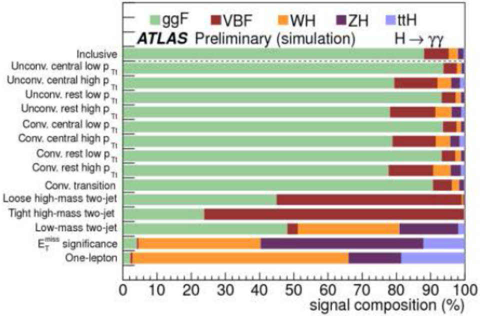


decay



How do we separate?





significant channels

Which Channels are suitable for the mass measurement?

- H→ $\gamma\gamma$
- H→Z→ 4ℓ

But why?

very good knowlegde of detector (e & γ)

- energy calibration (global & cell specific)
- behaviour of different layers
- material in front of the calorimeter

controlled with $>$ 7 million events
(Z$\rightarrow e^+e^-$, Z$\rightarrow \ell^+\ell^-\gamma$, $J/\psi \rightarrow e^+e^-$)

similar for μ, controlled with ~15million events
(Z$\rightarrow \mu^+\mu^-$, $J/\psi \rightarrow \mu^+\mu^-$)
separate for inner detector & muon spectrometer

H$\rightarrow \gamma\gamma$

this channel is good because

- very good mass resolution (2γ final state)
- smooth background can be determined from data

many many categories

We separate into 10 categories:

- converted γ vs. unconverted γ
  - different η regions
  - different p_{Tt} regions

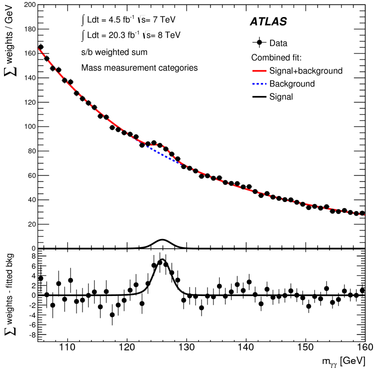
$$\text{note} : p_{Tt} = \left| \left(p_T^{\gamma_1} + p_T^{\gamma_2}\right) \times \frac{p_T^{\gamma_1} - p_T^{\gamma_2}}{\left|p_T^{\gamma_1} - p_T^{\gamma_2}\right|} \right|$$

$$= \text{projection orthogonal to thrust axis}$$

the categories

Category	n_{sig}	FWHM [GeV]	σ_{eff} [GeV]	b in $\pm\sigma_{eff90}$	s/b [%]	$s/\sqrt{b}$
			$\sqrt{s}$=8 TeV			
Inclusive	402.	3.69	1.67	10670	3.39	3.50
Unconv. central low p_{Tt}	59.3	3.13	1.35	801	6.66	1.88
Unconv. central high p_{Tt}	7.1	2.81	1.21	26.0	24.6	1.26
Unconv. rest low p_{Tt}	96.2	3.49	1.53	2624	3.30	1.69
Unconv. rest high p_{Tt}	10.4	3.11	1.36	93.9	9.95	0.96
Unconv. transition	26.0	4.24	1.86	910	2.57	0.78
Conv. central low p_{Tt}	37.2	3.47	1.52	589	5.69	1.38
Conv. central high p_{Tt}	4.5	3.07	1.35	20.9	19.4	0.88
Conv. rest low p_{Tt}	107.2	4.23	1.88	3834	2.52	1.56
Conv. rest high p_{Tt}	11.9	3.71	1.64	144.2	7.44	0.89
Conv. transition	42.1	5.31	2.41	1977	1.92	0.85
			$\sqrt{s}$=7 TeV			
Inclusive	73.9	3.38	1.54	1752	3.80	1.59
Unconv. central low p_{Tt}	10.8	2.89	1.24	128	7.55	0.85
Unconv. central high p_{Tt}	1.2	2.59	1.11	3.7	30.0	0.58
Unconv. rest low p_{Tt}	16.5	3.09	1.35	363	4.08	0.78
Unconv. rest high p_{Tt}	1.8	2.78	1.21	13.6	11.6	0.43
Unconv. transition	4.5	3.65	1.61	125	3.21	0.36
Conv. central low p_{Tt}	7.1	3.28	1.44	105	6.06	0.62
Conv. central high p_{Tt}	0.8	2.87	1.25	3.5	21.6	0.40
Conv. rest low p_{Tt}	21.0	3.93	1.75	695	2.72	0.72
Conv. rest high p_{Tt}	2.2	3.43	1.51	24.7	7.98	0.40
Conv. transition	8.1	4.81	2.23	365	2.00	0.38

results



for illustration each channel is weighted with its signal to background ratio

systematics

of course we have systematics to account for

	Unconverted					Converted				
	Central		Rest		Trans.	Central		Rest		Trans.
Class	low p_{Tt}	high p_{Tt}	low p_{Tt}	high p_{Tt}		low p_{Tt}	high p_{Tt}	low p_{Tt}	high p_{Tt}	
$Z \to e^+e^-$ calibration	0.02	0.03	0.04	0.04	0.11	0.02	0.02	0.05	0.05	0.11
LAr cell non-linearity	0.12	0.19	0.09	0.16	0.39	0.09	0.19	0.06	0.14	0.29
Layer calibration	0.13	0.16	0.11	0.13	0.13	0.07	0.10	0.05	0.07	0.07
ID material	0.06	0.06	0.08	0.08	0.10	0.05	0.05	0.06	0.06	0.06
Other material	0.07	0.08	0.14	0.15	0.35	0.04	0.04	0.07	0.08	0.20
Conversion reconstruction	0.02	0.02	0.03	0.03	0.05	0.03	0.02	0.05	0.04	0.06
Lateral shower shape	0.04	0.04	0.07	0.07	0.06	0.09	0.09	0.18	0.19	0.16
Background modeling	0.10	0.06	0.05	0.11	0.16	0.13	0.06	0.14	0.18	0.20
Vertex measurement					0.03					
Total	0.23	0.28	0.24	0.30	0.59	0.21	0.25	0.27	0.33	0.47

relative uncertainties in %

relults, again

the ATLAS collaboration measures

$$m_H = 125.98 \pm 0.42(\text{stat}) \pm 0.28(\text{syst})\text{GeV}$$

and a signal strength
= cross section normalized to SM expectation

$$\mu = 1.29 \pm 0.30$$

this channel is good because

- good signal to background ratio
- clean final state → good mass resolution

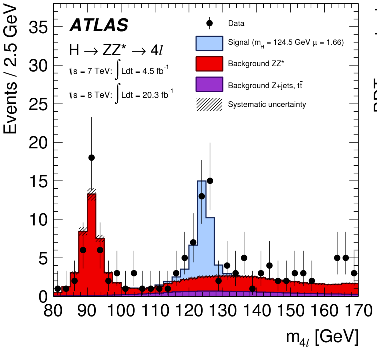
the categories

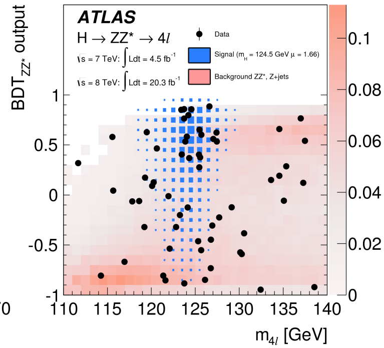
here the analysis is split into different final states

- 4μ
- $2e2\mu$
- $2\mu2e$
- $4e$

BDT for better signal/background separation

BDT input variables: p_T, η, $D_{ZZ^{(*)}} = \log \frac{|\mathcal{M}_{\text{sig}}|^2}{|\mathcal{M}_{\text{ZZ}}|^2}$

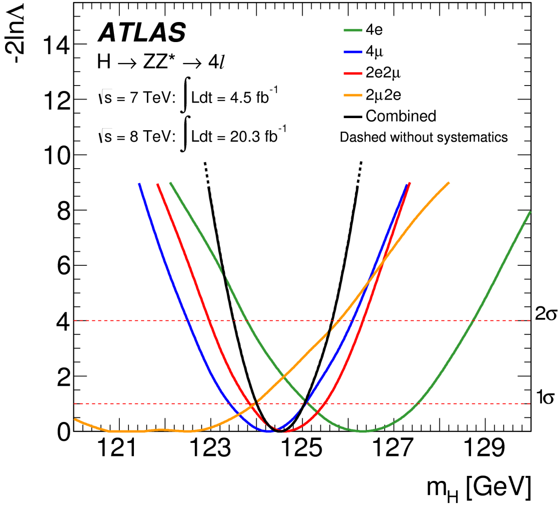




number of events, theory and measurement

Final state	Signal full mass range	Signal	ZZ^*	Z + jets, $t\bar{t}$	s/b	Expected	Observed
			$\sqrt{s}$ = 7 TeV	4.5fb^{-1}			
4μ	1.00 ± 0.10	0.91 ± 0.09	0.46 ± 0.02	0.10 ± 0.04	1.7	1.47 ± 0.10	2
$2e2\mu$	0.66 ± 0.06	0.58 ± 0.06	0.32 ± 0.02	0.09 ± 0.03	1.5	0.99 ± 0.07	2
$2\mu2e$	0.50 ± 0.05	0.44 ± 0.04	0.21 ± 0.01	0.36 ± 0.08	0.8	1.01 ± 0.09	1
$4e$	0.46 ± 0.05	0.39 ± 0.04	0.19 ± 0.01	0.40 ± 0.09	0.7	0.98 ± 0.10	1
Total	2.62 ± 0.26	2.32 ± 0.23	1.17 ± 0.06	0.96 ± 0.18	1.1	4.45 ± 0.30	6
			$\sqrt{s}$ = 8 TeV	20.3fb^{-1}			
4μ	5.80 ± 0.57	5.28 ± 0.52	2.36 ± 0.12	0.69 ± 0.13	1.7	8.33 ± 0.6	12
$2e2\mu$	3.92 ± 0.39	3.45 ± 0.34	1.67 ± 0.08	0.60 ± 0.10	1.5	5.72 ± 0.37	7
$2\mu2e$	3.06 ± 0.31	2.71 ± 0.28	1.17 ± 0.07	0.36 ± 0.08	1.8	4.23 ± 0.30	5
$4e$	2.79 ± 0.29	2.38 ± 0.25	1.03 ± 0.07	0.35 ± 0.07	1.7	3.77 ± 0.27	7
Total	15.6 ± 1.6	13.8 ± 1.4	6.24 ± 0.34	2.00 ± 0.28	1.7	22.1 ± 1.5	31
			$\sqrt{s}$ = 7 TeV and $\sqrt{s}$ = 8 TeV				
4μ	6.80 ± 0.67	6.20 ± 0.61	2.82 ± 0.14	0.79 ± 0.13	1.7	9.81 ± 0.64	14
$2e2\mu$	4.58 ± 0.45	4.04 ± 0.40	1.99 ± 0.10	0.69 ± 0.11	1.5	6.72 ± 0.42	9
$2\mu2e$	3.56 ± 0.36	3.15 ± 0.32	1.38 ± 0.08	0.72 ± 0.12	1.5	5.24 ± 0.35	6
$4e$	3.25 ± 0.34	2.77 ± 0.29	1.22 ± 0.08	0.76 ± 0.11	1.4	4.75 ± 0.32	8
Total	18.2 ± 1.8	16.2 ± 1.6	7.41 ± 0.40	2.95 ± 0.33	1.6	26.5 ± 1.7	37

likelihood ratios



H→ZZ* →4ℓ result

the ATLAS collaboration measures

$$m_H = 124.51 \pm 0.52(\text{stat}) \pm 0.06(\text{syst})\text{GeV}$$

and a signal strength

$$\mu = 1.66^{+0.45}_{-0.38}$$

combination

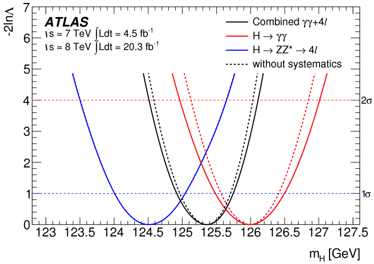
Can these be combined?

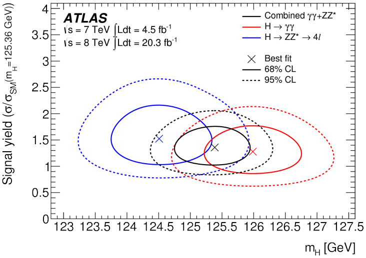
Yes they can!

$$\Delta m_H = 1.47 \pm 0.67(\text{stat}) \pm 0.28(\text{syst})\text{GeV}$$

$$\Rightarrow m_H = 125.36 \pm 0.37(\text{stat}) \pm 0.18(\text{syst})\text{GeV}$$

combination plots





systematics

Systematic	Uncertainty on m_H [MeV]
LAr syst on material before presampler (barrel)	70
LAr syst on material after presampler (barrel)	20
LAr cell non-linearity (layer 2)	60
LAr cell non-linearity (layer 1)	30
LAr layer calibration (barrel)	50
Lateral shower shape (conv)	50
Lateral shower shape (unconv)	40
Presampler energy scale (barrel)	20
ID material model ($\|\eta\| < 1.1$)	50
$H \to \gamma\gamma$ background model (unconv rest low p_{Tt})	40
$Z \to ee$ calibration	50
Primary vertex effect on mass scale	20
Muon momentum scale	10
Remaining systematic uncertainties	70
Total	180

Theoretical prediction for the Higgs boson width:

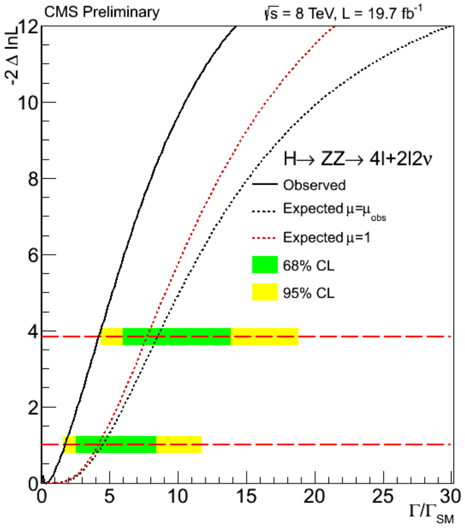
~4MeV

Experimental energy resolution:

~2GeV

but CMS did a thing

CMS and the Width of the Higgs Boson



What now?

measure relative contributions to the width

$\Downarrow$

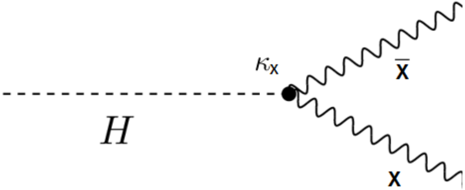
measurement of signal strengths and coupling strengths

the basics

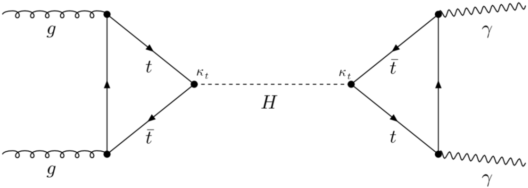
We have to make some basic assumptions:

- everything comes from the same single particle
- this particle is assumed to have zero decay width
- the particle is a CP-even scalar

modified couplings are introduced



one example



⇒ matrix element modified by κ_t^2

but: $W^{\pm}$ contribution ⇒ interference

$$\kappa_\gamma^2(\kappa_F \kappa_V) = 1.59\kappa_V^2 - 0.66\kappa_V\kappa_F + 0.07\kappa_F^2$$

SM only

SM contributions only

$$\kappa_V = \kappa_W = \kappa_Z$$

$$\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_g$$

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

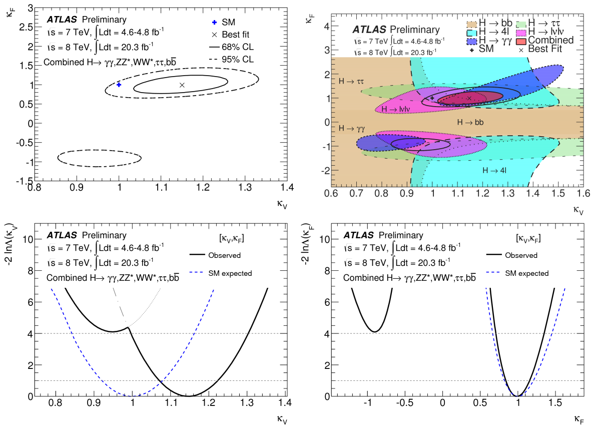
$$\sigma(qq' \to qq'H) \times BR(H \to \gamma\gamma) \sim \frac{\kappa_V^2 \kappa_\gamma^2(\kappa_F \kappa_V)}{0.75\kappa_F^2 + 0.25\kappa_V^2}$$

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

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

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

SM only results



$\kappa_F = 1.15 \pm 0.08$

$\kappa_V = 0.99^{+0.17}_{-0.15}$

free total width variable

no assumption on total width
hide total width in ratios as free parameter

$$\kappa_{VV} = \kappa_V \, {}^{\kappa_V}\!/_{\kappa_H}$$
$$\lambda_{FV} = {}^{\kappa_F}\!/_{\kappa_V}$$

$\Rightarrow$ only ratios measurable

free total width functionalities

$$\sigma(gg \to H) \times BR(H \to \gamma\gamma) \sim \lambda_{FV}^2 \kappa_{VV}^2 \kappa_\gamma^2(\lambda_{FV}, 1)$$

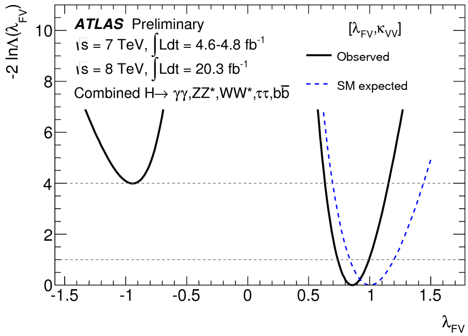
$$\sigma(qq' \to qq'H) \times BR(H \to \gamma\gamma) \sim \kappa_{VV}^2 \kappa_\gamma^2(\lambda_{FV}, 1)$$

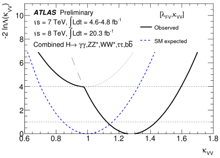
$$\sigma(gg \to H) \times BR(H \to ZZ^{(*)}, H \to WW^{(*)}) \sim \lambda_{FV}^2 \kappa_{VV}^2$$

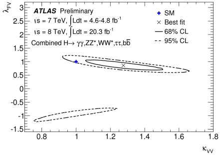
$$\sigma(qq' \to qq'H) \times BR(H \to ZZ^{(*)}, H \to WW^{(*)}) \sim \kappa_{VV}^2$$

$$\sigma(qq' \to qq'H, VH) \times BR(H \to \tau\tau, H \to b\bar{b}) \sim \kappa_{VV}^2 \lambda_{FV}^2$$

free total width relults







$$\lambda_{FV} = 0.86^{+0.14}_{-0.12}$$

$$\kappa_{VV} = 1.28^{+0.16}_{-0.15}$$

custodial symmetry

theory predicts same coupling scale factors for W & Z
$\Rightarrow$ we test it (again no assumption on total width):

$$\kappa_{ZZ} = \kappa_Z \kappa_Z / \kappa_H$$

$$\lambda_{WZ} = \kappa_W / \kappa_Z$$

$$\lambda_{FZ} = \kappa_F / \kappa_Z$$

$$\sigma(gg \to H) \times BR(H \to \gamma\gamma) \sim \lambda_{FZ}^2 \kappa_{ZZ}^2 \kappa_\gamma^2(\lambda_{FZ}, 1)$$

$$\sigma(qq' \to qq'H) \times BR(H \to \gamma\gamma) \sim \kappa_{VBF}^2(\lambda_{WZ}, 1) \kappa_{ZZ}^2 \kappa_\gamma^2(\lambda_{FZ}, 1)$$

$$\sigma(gg \to H) \times BR(H \to ZZ^{(*)}) \sim \lambda_{FZ}^2 \kappa_{ZZ}^2$$

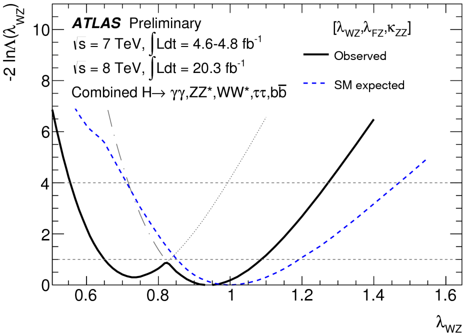
$$\sigma(qq' \to qq'H) \times BR(H \to ZZ^{(*)}) \sim \kappa_{VBF}^2(\lambda_{WZ}, 1) \kappa_{ZZ}^2$$

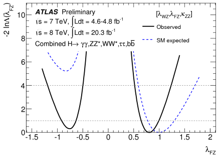
$$\sigma(gg \to H) \times BR(H \to WW^{(*)}) \sim \lambda_{FZ}^2 \kappa_{ZZ}^2 \lambda_{WZ}^2$$

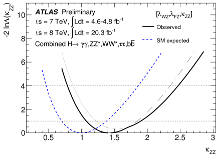
$$\sigma(qq' \to qq'H) \times BR(H \to WW^{(*)}) \sim \kappa_{VBF}^2(\lambda_{WZ}, 1) \kappa_{ZZ}^2 \lambda_{WZ}^2$$

$$\sigma(qq' \to qq'H, VH) \times BR(H \to \tau\tau, H \to b\bar{b}) \sim \kappa_{VBF}^2(\lambda_{WZ}, 1) \kappa_{ZZ}^2 \lambda_{FZ}^2$$

custodial symmetry results







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

$$\lambda_{FZ}\in[-0.91,-0.63]\cup[0.65,1.00]$$

$$\kappa_{ZZ}=1.41^{+0.49}_{-0.34}$$

SM loop contents

set everything to SM values

$\Rightarrow$ effective couplings at loops (for γ & g):

$$\sigma(gg\to H)\times BR(H\to\gamma\gamma)\sim\frac{\kappa_g^2\kappa_\gamma^2}{0.085\kappa_g^2+0.0023\kappa_\gamma^2+0.91}$$

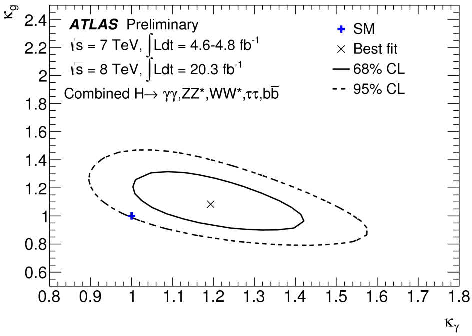
$$\sigma(qq'\to qq'H)\times BR(H\to\gamma\gamma)\sim\frac{\kappa_\gamma^2}{0.085\kappa_g^2+0.0023\kappa_\gamma^2+0.91}$$

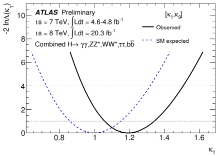
$$\sigma(gg\to H)\times BR(H\to ZZ^{(*)},H\to WW^{(*)})\sim\frac{\kappa_g^2}{0.085\kappa_g^2+0.0023\kappa_\gamma^2+0.91}$$

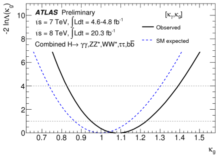
$$\sigma(qq'\to qq'H)\times BR(H\to ZZ^{(*)},H\to WW^{(*)})\sim\frac{1}{0.085\kappa_g^2+0.0023\kappa_\gamma^2+0.91}$$

$$\sigma(qq'\to qq'H,VH)\times BR(H\to\tau\tau,H\to b\bar{b})\sim\frac{1}{0.085\kappa_g^2+0.0023\kappa_\gamma^2+0.91}$$

SM loop contents results







$$\kappa_g = 1.08^{+0.15}_{-0.13}$$

$$\kappa_\gamma = 1.19^{+0.15}_{-0.12}$$

BSM loop contents

H→ invis ⇒ possible BSM decays

$$\Gamma_H = \frac{\kappa_H^2(\kappa_i)}{1 - BR_{\mathrm{inv,undet}}}\Gamma_H^{\mathrm{SM}}$$

$$\sigma(gg\to H)\times BR(H\to\gamma\gamma)\sim\frac{\kappa_g^2\kappa_\gamma^2}{0.085\kappa_g^2+0.0023\kappa_\gamma^2+0.91}(1-BR_{\mathrm{inv,undet}})$$

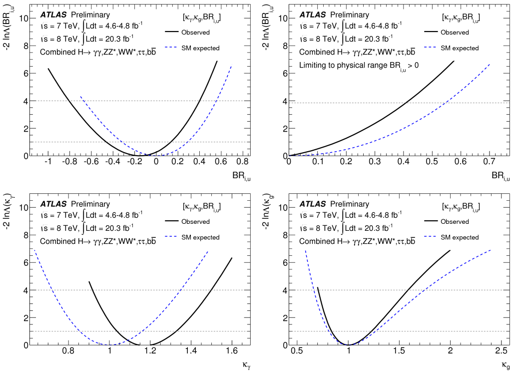
$$\sigma(qq'\to qq'H)\times BR(H\to\gamma\gamma)\sim\frac{\kappa_\gamma^2}{0.085\kappa_g^2+0.0023\kappa_\gamma^2+0.91}(1-BR_{\mathrm{inv,undet}})$$

$$\sigma(gg\to H)\times BR(H\to ZZ^{(*)},H\to WW^{(*)})\sim\frac{\kappa_g^2}{0.085\kappa_g^2+0.0023\kappa_\gamma^2+0.91}(1-BR_{\mathrm{inv,undet}})$$

$$\sigma(qq'\to qq'H)\times BR(H\to ZZ^{(*)},H\to WW^{(*)})\sim\frac{1}{0.085\kappa_g^2+0.0023\kappa_\gamma^2+0.91}(1-BR_{\mathrm{inv,undet}})$$

$$\sigma(qq'\to qq'H,VH)\times BR(H\to\tau\tau,H\to b\bar{b})\sim\frac{1}{0.085\kappa_g^2+0.0023\kappa_\gamma^2+0.91}(1-BR_{\mathrm{inv,undet}})$$

BSM loop contents results

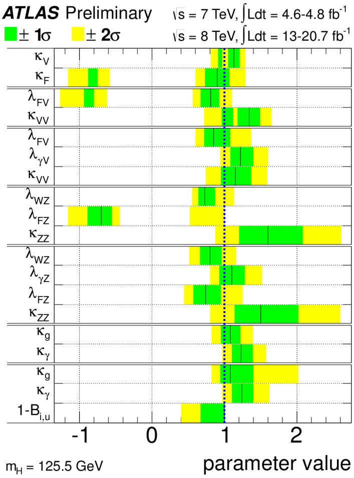


$$\kappa_g = 1.00^{+0.23}_{-0.16}$$

$$\kappa_\gamma = 0.94^{+0.16}_{-0.13}$$

$$BR_{\text{inv,undet}} = -0.16^{+0.29}_{-0.30}$$

In the end...


ATLAS Preliminary
$\sqrt{s}$ = 7 TeV, $\int Ldt$ = 4.6-4.8 fb^{-1}
$\sqrt{s}$ = 8 TeV, $\int Ldt$ = 13-20.7 fb^{-1}
± 1σ
± 2σ
κ_V
κ_F
λ_{FV}
κ_{VV}
λ_{FV}
$\lambda_{\gamma V}$
κ_{VV}
λ_{WZ}
λ_{FZ}
κ_{ZZ}
λ_{WZ}
$\lambda_{\gamma Z}$
λ_{FZ}
κ_{ZZ}
κ_g
κ_γ
κ_g
κ_γ
$1\text{-}B_{i,u}$
-1
0
1
2
m_H = 125.5 GeV
parameter value

summary

- mass: $m_H = 125.36 \pm 0.41 \mathrm{GeV}$
- signal strength: $\mu = 1.30 \pm 0.20$
- all those couplings

$\Rightarrow$ SM validated within 2σ

The End?

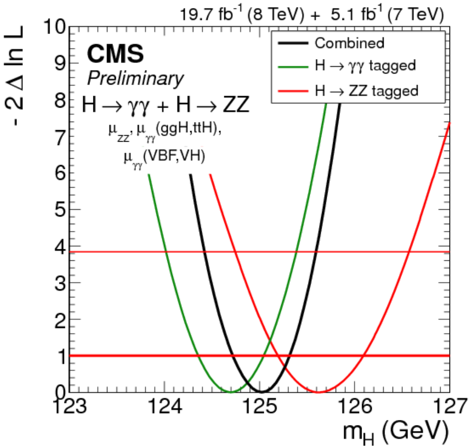
no end jet

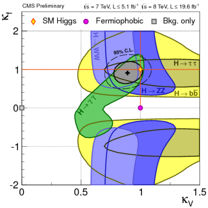
But wait there's more!

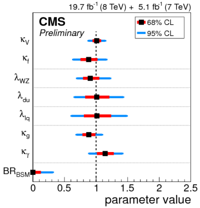
CMS has results, too

$$m_H = 125.03^{+0.26}_{-0.27}(\text{stat})^{+0.13}_{-0.15}(\text{syst})$$

CMS coupling







[1] ATLAS Collaboration, *Measurement of the Higgs boson mass from the H→ $\gamma\gamma$ and H→ZZ$^{(*)}4\ell$ channels with the ATLAS detector using 25 fb^{-1} of pp collision data*, arXiv:1406.3827v1, 15. Jun 2014

[2] ATLAS Collaboration, *Combined coupling measurement of the Higgs-like boson with the ATLAS detector using up to 25 fb^{-1} of proton-proton collision data*, ATLAS-CONF-2013-034, 13. Mar 2013

[3] ATLAS Collaboration, *Updated coupling measurement of the Higgs-like boson with the ATLAS detector using up to 25 fb^{-1} of proton-proton collision data*, ATLAS-CONF-2014-009, 20. Mar 2014

references II

[4] ATLAS Collaboration, *Measurement of Higgs boson production and couplings in diboson final states with the ATLAS detector at the LHC*, Physics Letters B 726 (2013) 88-119, Aug 2013

[5] CMS Collaboration, *Measurement of the properties of the new boson with a mass near 125 GeV*, CMS PAS HIG-13-005, 17. Apr 2013

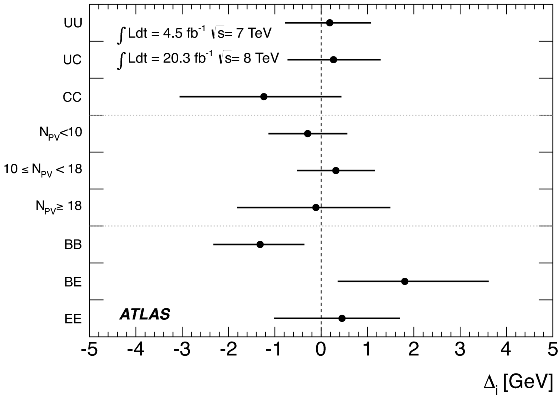
[6] CMS Collaboration, *Constraints on the Higgs boson width from off-shell production and decay of Z-boson pairs*, arXiv:1405.3455v1, 14. May 2014

Thanks for your attention!

Questions? Remarks?

backup

differences

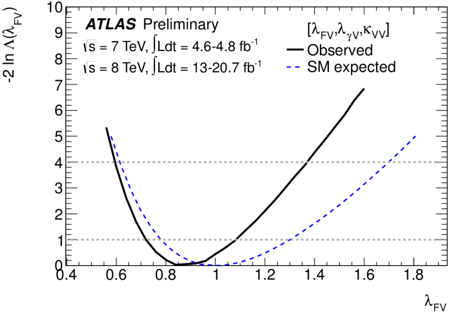


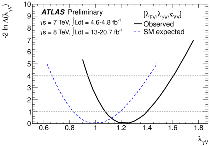
free loop content

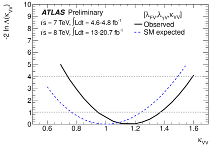
allow BSM loop contents
⇒ loose the sign information and get

$$\lambda_{FV} = \kappa_F / \kappa_V$$
$$\lambda_{\gamma V} = \kappa_\gamma / \kappa_V$$
$$\kappa_{VV} = \kappa_V \kappa_V / \kappa_H$$
$$\sigma(gg \to H) \times BR(H \to \gamma\gamma) \sim \lambda_{FV}^2 \kappa_{VV}^2 \lambda_{\gamma V}^2$$
$$\sigma(qq' \to qq'H) \times BR(H \to \gamma\gamma) \sim \kappa_{VV}^2 \lambda_{\gamma V}^2$$
$$\sigma(gg \to H) \times BR(H \to ZZ^{(*)}, H \to WW^{(*)}) \sim \lambda_{FV}^2 \kappa_{VV}^2$$
$$\sigma(qq' \to qq'H) \times BR(H \to ZZ^{(*)}, H \to WW^{(*)}) \sim \kappa_{VV}^2$$
$$\sigma(qq' \to qq'H, VH) \times BR(H \to \tau\tau, H \to b\bar{b}) \sim \kappa_{VV}^2 \lambda_{FV}^2$$

free loop contents result







$$\lambda_{FV}=0.85^{+0.23}_{-0.13}$$

$$\lambda_{\gamma V}=1.22^{+0.18}_{-0.14}$$

$$\kappa_{VV}=1.15\pm0.21$$

custodial symmetry BSM

testing custodial symmetry again, with free loop content:

$$\kappa_{ZZ}=\kappa_Z \kappa_Z/\kappa_H$$

$$\lambda_{WZ}=\kappa_W/\kappa_Z$$

$$\lambda_{\gamma Z}=\kappa_\gamma/\kappa_Z$$

$$\lambda_{FZ}=\kappa_F/\kappa_Z$$

$$\sigma(gg\to H)\times BR(H\to\gamma\gamma)\sim\lambda_{FZ}^2\kappa_{ZZ}^2\lambda_{\gamma Z}^2$$

$$\sigma(qq'\to qq'H)\times BR(H\to\gamma\gamma)\sim\kappa_{VBF}^2(\lambda_{WZ},1)\kappa_{ZZ}^2\lambda_{\gamma Z}^2$$

$$\sigma(gg\to H)\times BR(H\to ZZ^{(*)})\sim\lambda_{FZ}^2\kappa_{ZZ}^2$$

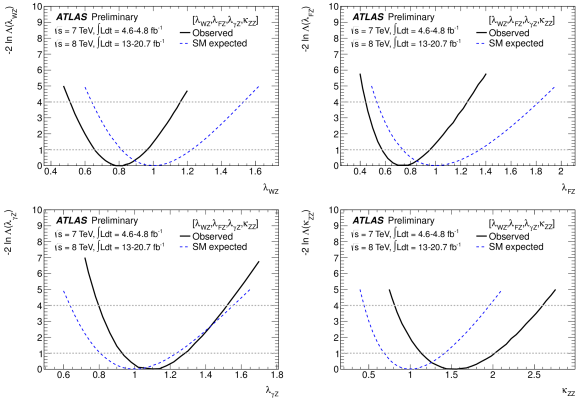
$$\sigma(qq'\to qq'H)\times BR(H\to ZZ^{(*)})\sim\kappa_{VBF}^2(\lambda_{WZ},1)\kappa_{ZZ}^2$$

$$\sigma(gg\to H)\times BR(H\to WW^{(*)})\sim\lambda_{FZ}^2\kappa_{ZZ}^2\lambda_{WZ}^2$$

$$\sigma(qq'\to qq'H)\times BR(H\to WW^{(*)})\sim\kappa_{VBF}^2(\lambda_{WZ},1)\kappa_{ZZ}^2\lambda_{WZ}^2$$

$$\sigma(qq'\to qq'H,VH)\times BR(H\to\tau\tau,H\to b\bar{b})\sim\kappa_{VBF}^2(\lambda_{WZ},1)\kappa_{ZZ}^2\lambda_{FZ}^2$$

custodial symmetry BSM results



$$\lambda_{WZ} = 0.80 \pm 0.15 \qquad \lambda_{FZ} = 0.74^{+0.21}_{-0.17}$$

$$\lambda_{\gamma Z} = 1.10 \pm 0.18 \qquad \kappa_{ZZ} = 1.5^{+0.5}_{-0.4}$$