H(126) @ LHC

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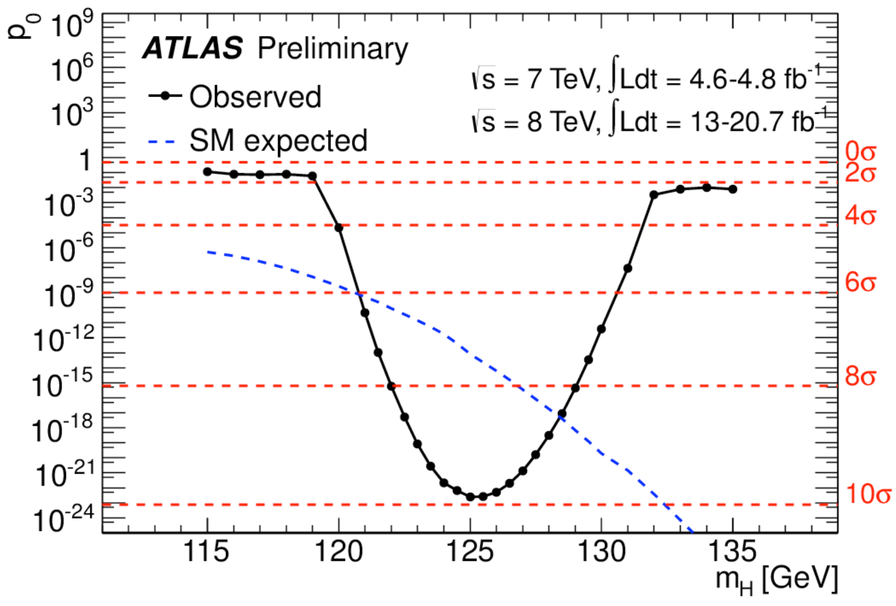
Outline:

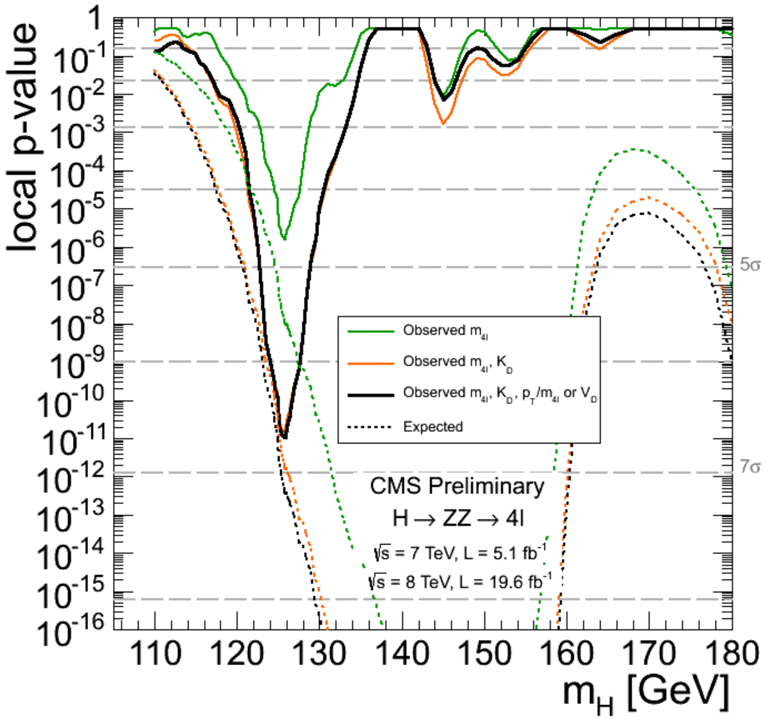
Introduction

Recent results on Higgs searches

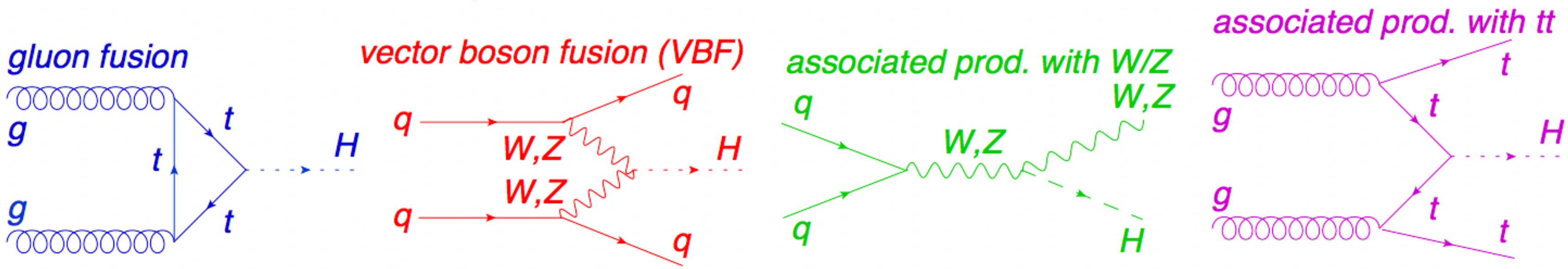
Recent results on Higgs properties

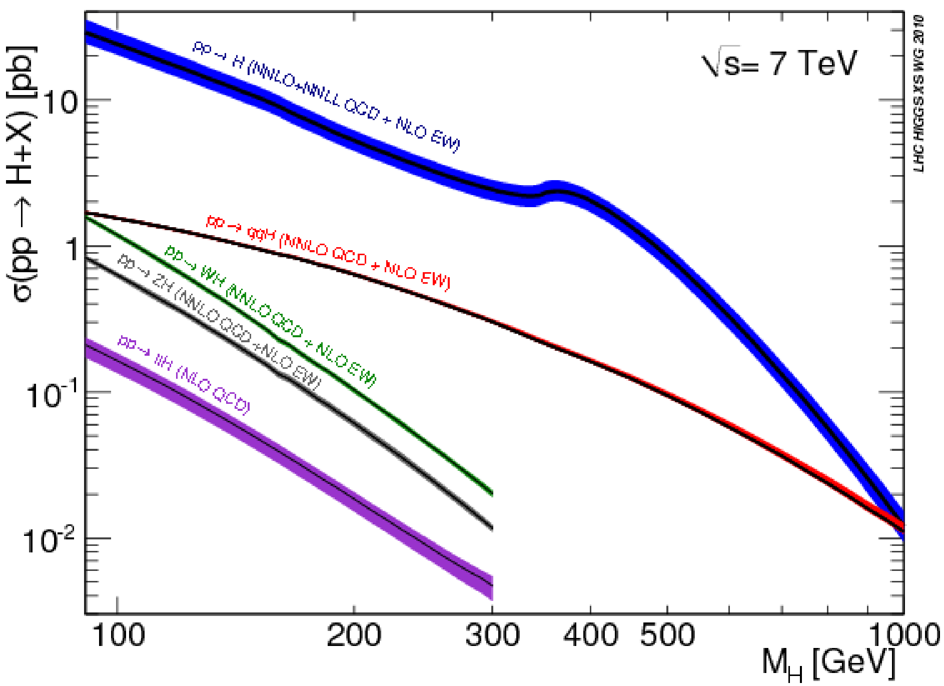
Prospects and Summary



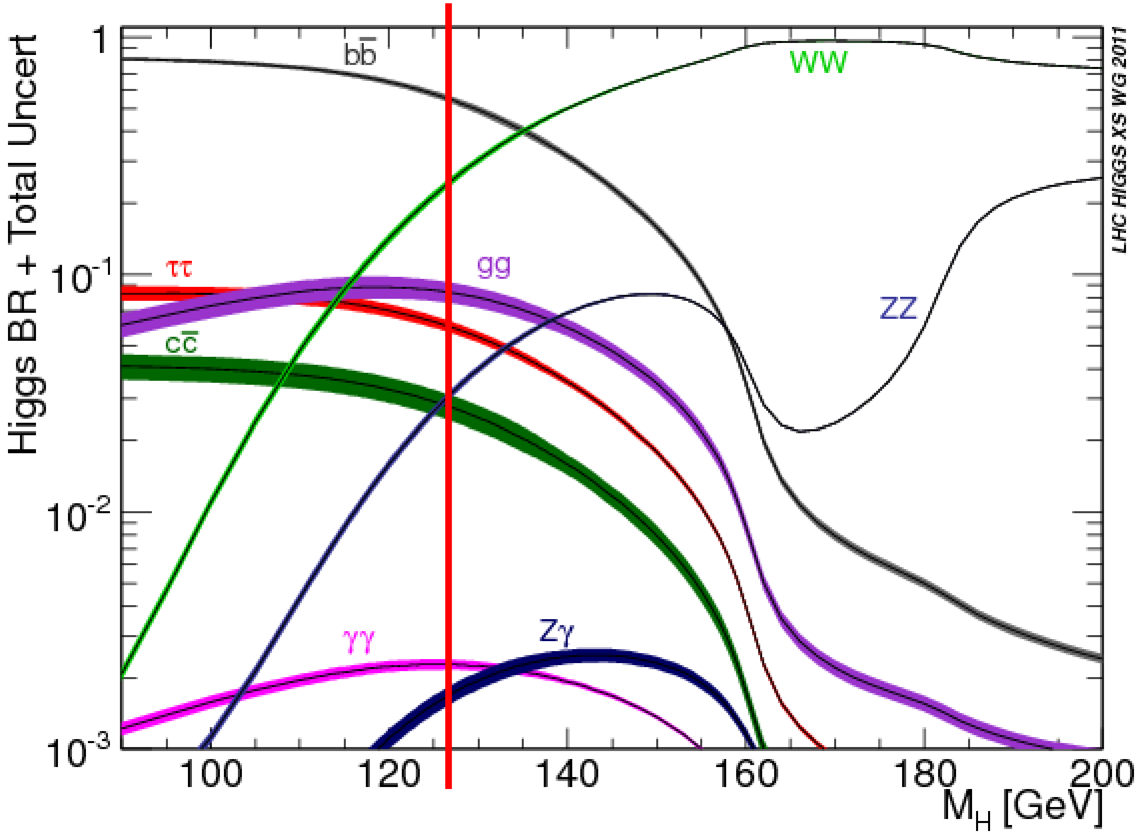


Production


gluon fusion
g
g
t
t
t
H
vector boson fusion (VBF)
q
q
W,Z
W,Z
q
q
H
associated prod. with W/Z
q
q
W,Z
W,Z
H
associated prod. with tt
g
g
t
t
t
t
H


√s= 7 TeV
LHC HIGGS XS WG 2010
pp → H (NNLO+NNLL QCD + NLO EW)
pp → qqH (NNLO QCD + NLO EW)
pp → WH (NNLO QCD + NLO EW)
pp → ZH (NNLO QCD +NLO EW)
pp → ttH (NLO QCD)
σ(pp → H+X) [pb]
10
1
10⁻¹
10⁻²
100
200
300
400
500
1000
M_H [GeV]

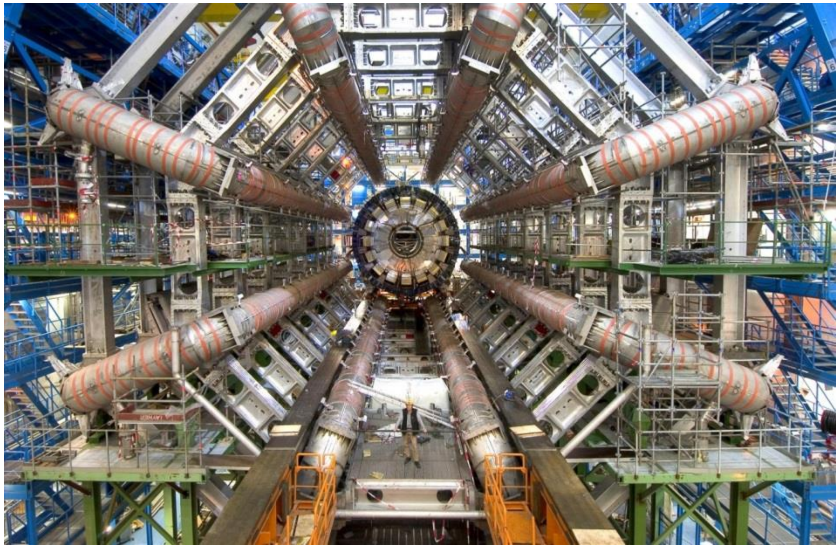
Decay

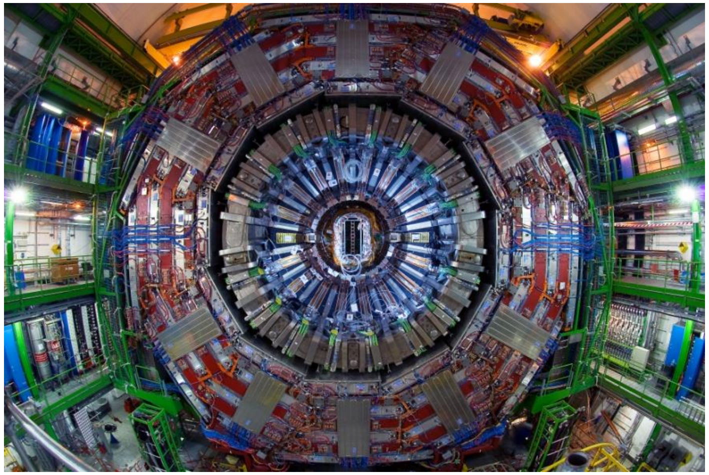


126 GeV a good place to be with many accessible channels

Combined measurements across many production and decay modes gives access to ratio's of couplings

LHC, CMS and ATLAS

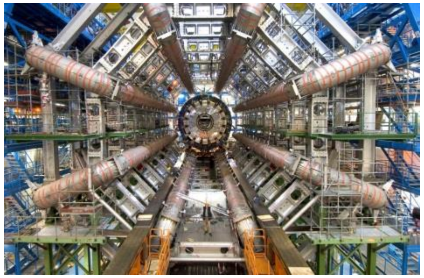




ATLAS and CMS:
  General purpose detectors

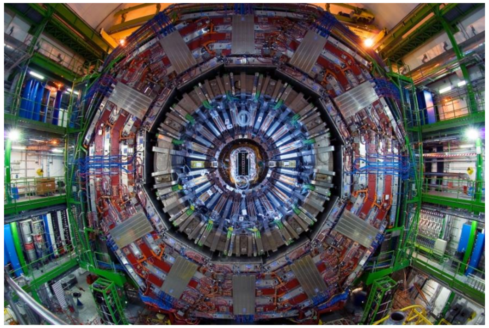
LHC:
  Proton-proton collider
   7TeV in 2011, 8TeV in 2012
   13TeV ? in 2015

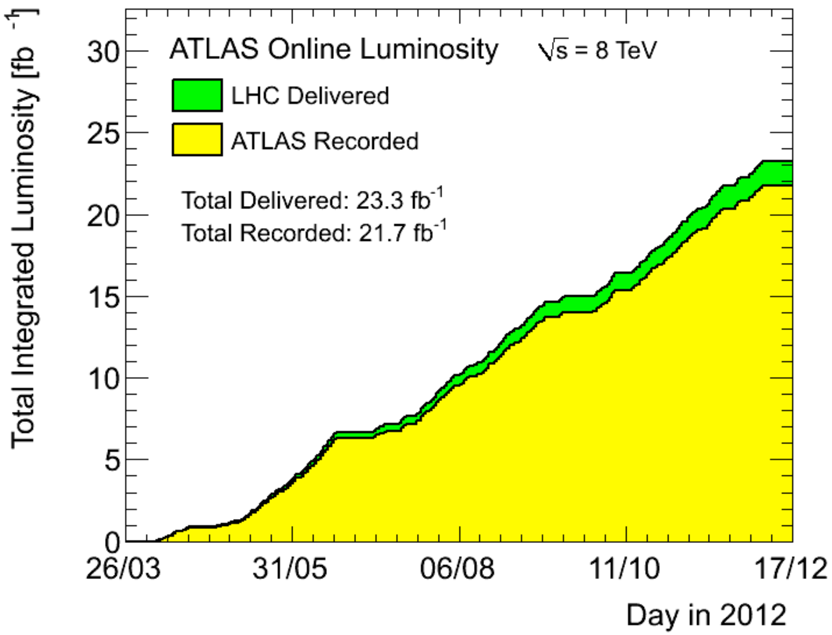
LHC, CMS and ATLAS

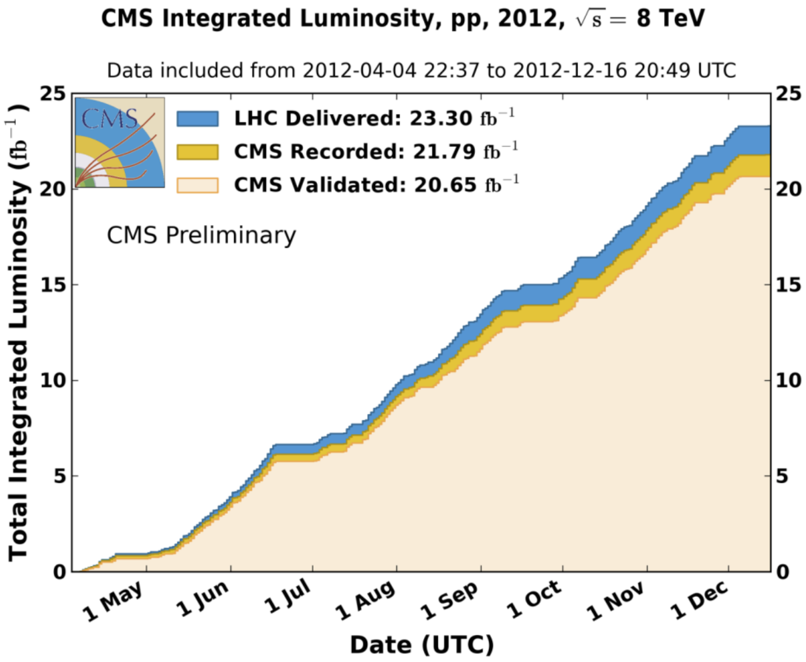


Excellent performance of accelerator and detectors

94% data taking efficiency







Introduction

Search channels largely defined by predicted production and decay in SM (+benchmark BSM) and expected ability to detect a signal above background

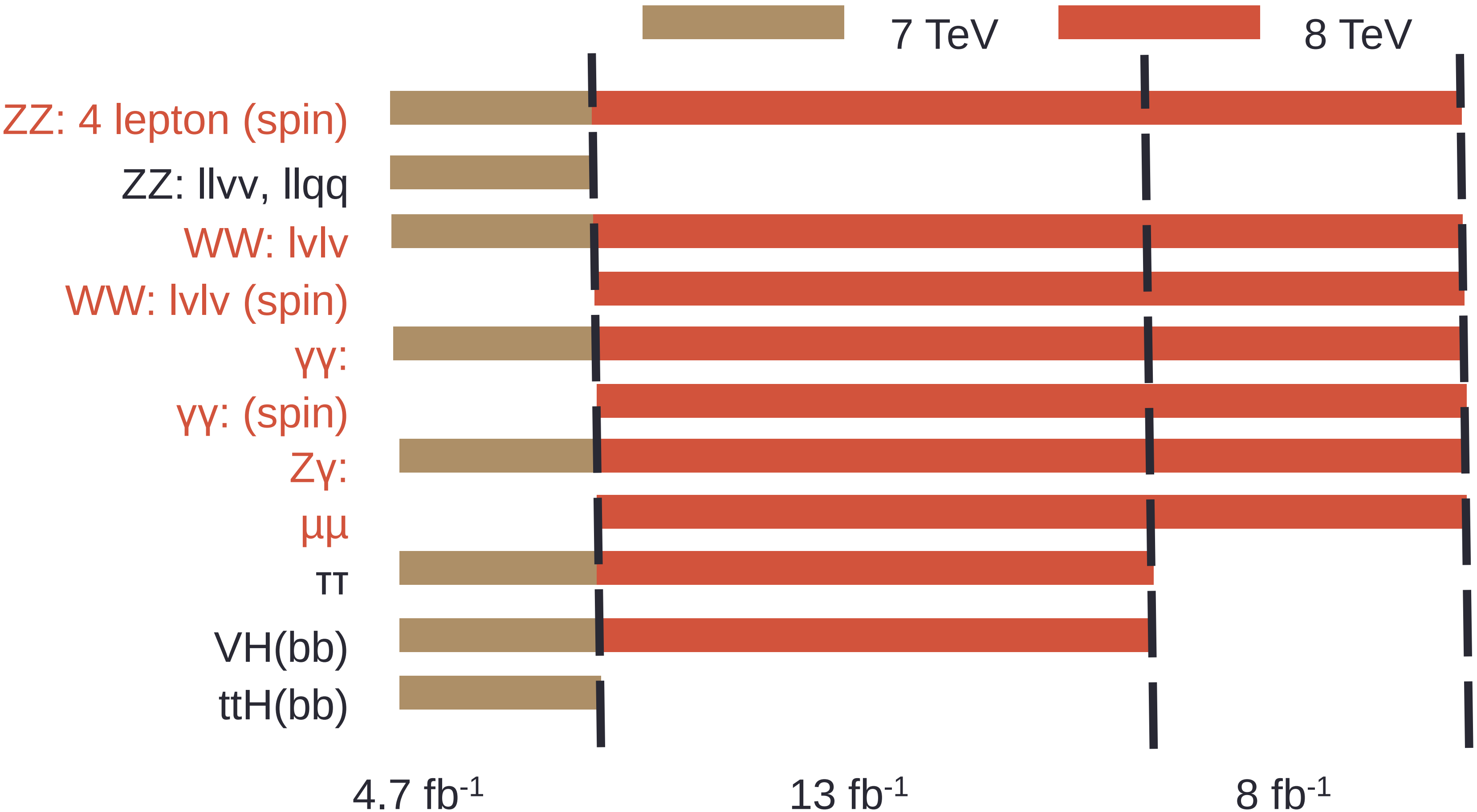
Original emphasis – many channels, maximise sensitivity to SM

Channel	ggF	VBF	VH	ttH	Spin	Mass
$\gamma\gamma$	✓	✓	✓	✓	✓	✓
$Z \rightarrow 4l$	✓	✓	✓		✓	✓
$WW \rightarrow l\upsilon l\upsilon$	✓	✓	✓		✓	
$Z\gamma$	✓					
$\tau\tau$	✓	✓	✓			
$\mu\mu$	✓					
bb			✓	✓		

Beyond discovery emphasise precise measurement and distinguish between different production modes by looking for extra signatures, leptons, jets, MET

Continue to search for additional Higgs bosons.

Data sets for SM Analyses



Updated at Winter Conferences this year

ATLAS-CONF-2013-013
CMS-PAS-HIG-13-002

Higgs to 4 leptons (ZZ)

Updated for winter conferences with full 25fb^{-1} data set

Golden channel – clear signature and low background

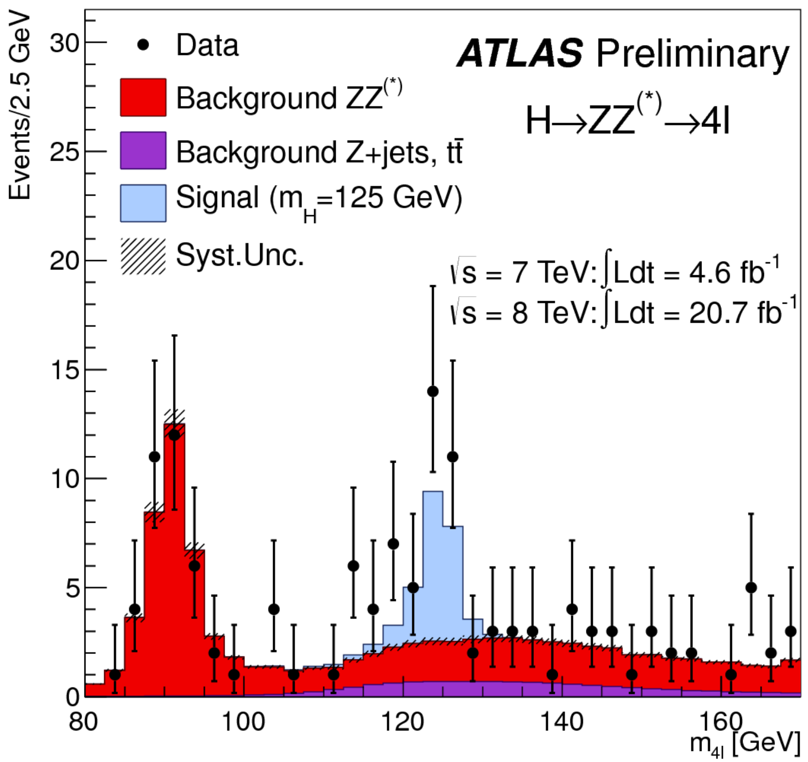
4 final states:
4e, 4μ, 2e2μ, 2μ2e, (+τ for CMS)

S/B ~ 1.4

Single and double lepton triggers

At least 2 pairs same flavour opposite sign isolated leptons

One tight, one loose Z mass constraint



Event categorizations:
- **VBF-like : jet tags (CMS+ATLAS)**
- **VH-like: extra lepton tag (ATLAS)**

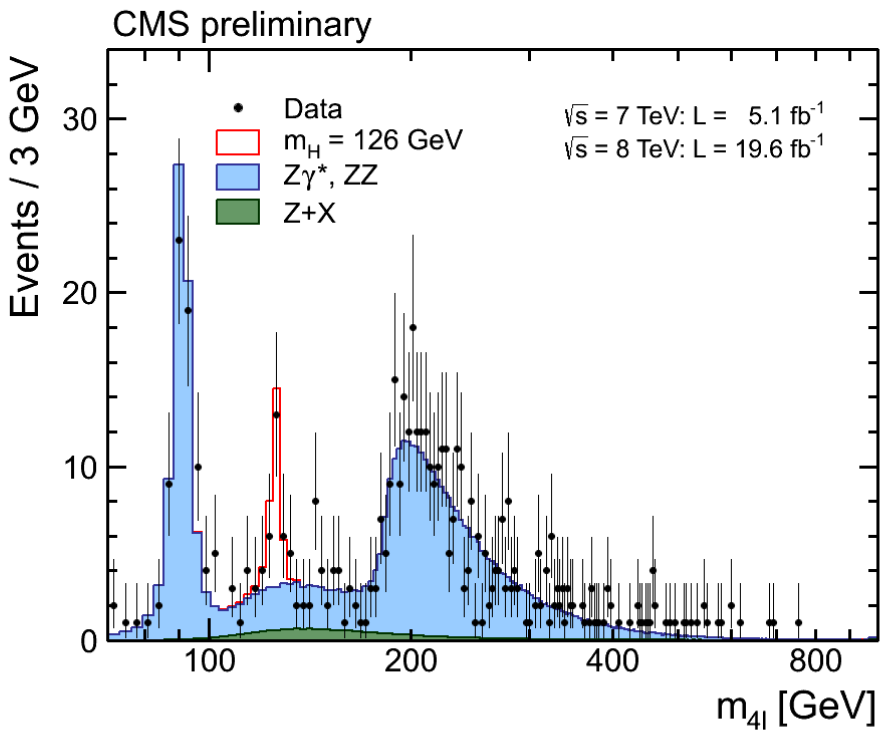
ATLAS-CONF-2013-013
CMS-PAS-HIG-13-002

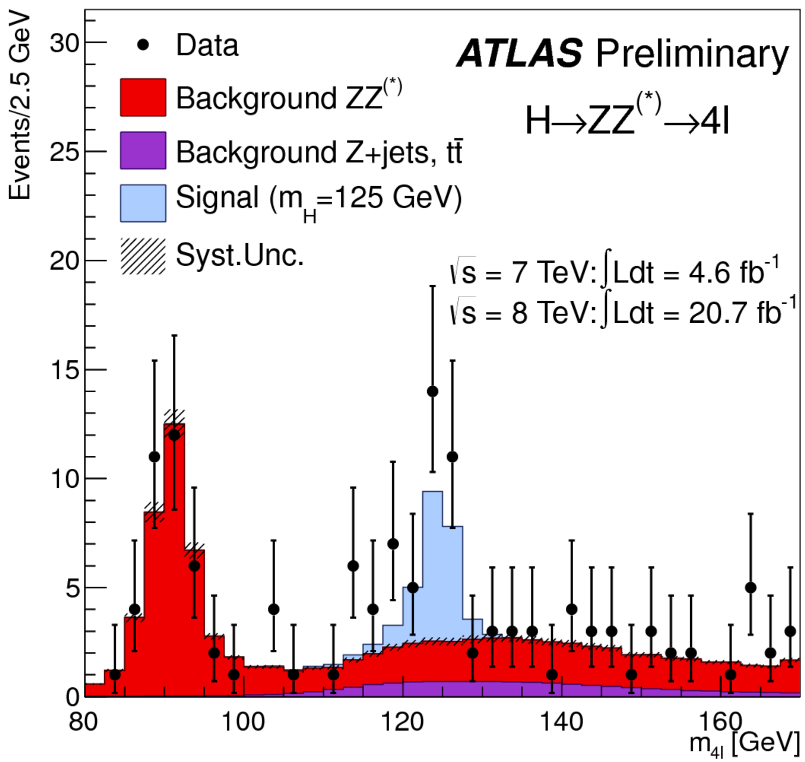
Higgs to 4 leptons (ZZ)

Extract signal from: 4-lepton mass (ATLAS), mass+MELA+other kinematics (CMS)

Main backgrounds:
SM ZZ* production (irreducible, from MC)
Top, Z+jets (reducible, data driven techniques)

S/B ~ 1.4





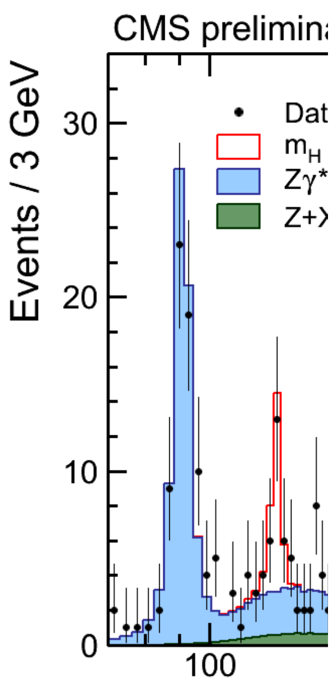
ATLAS-CONF-2013-013
CMS-PAS-HIG-13-002

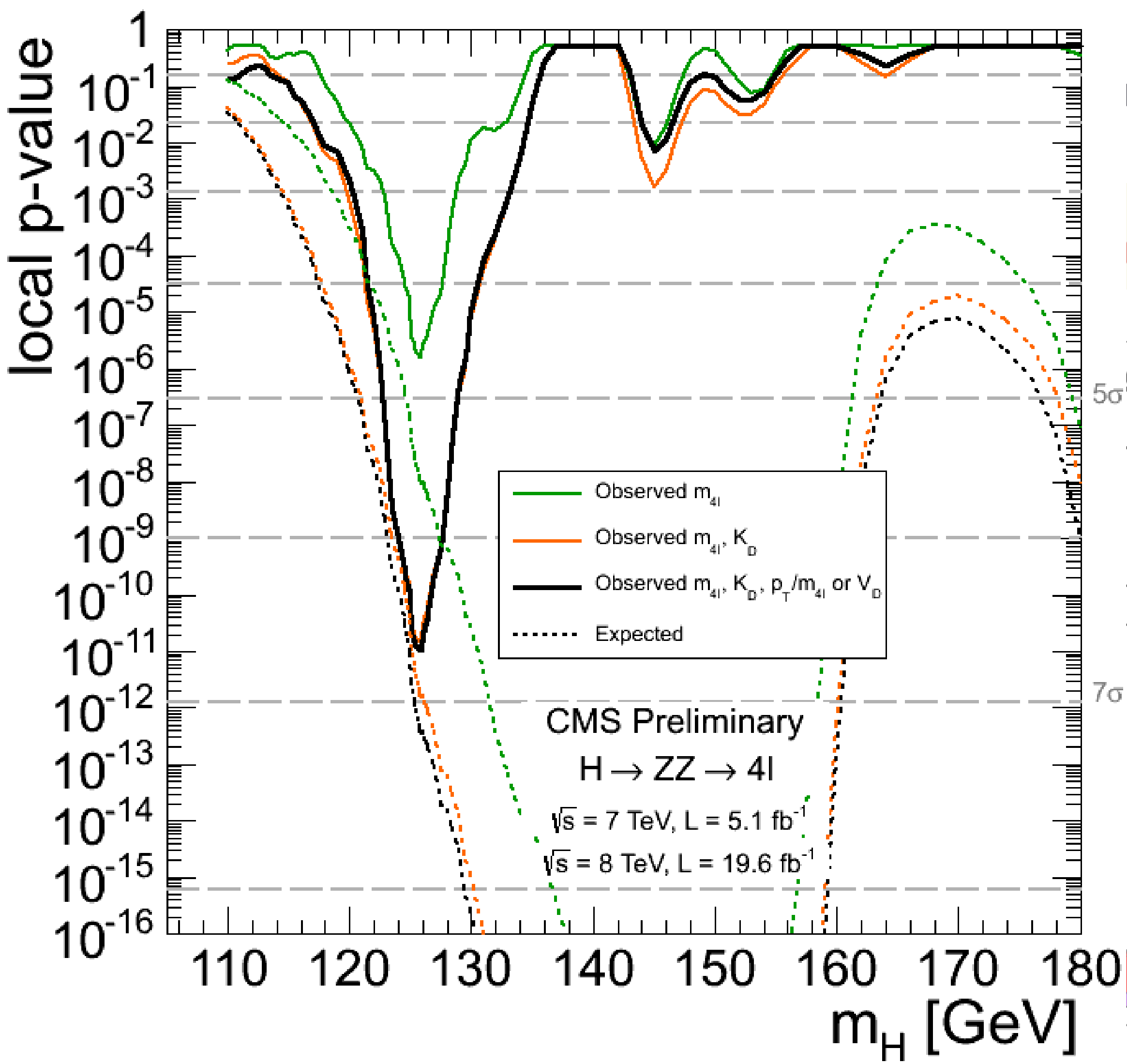
Higgs to 4 leptons (ZZ)

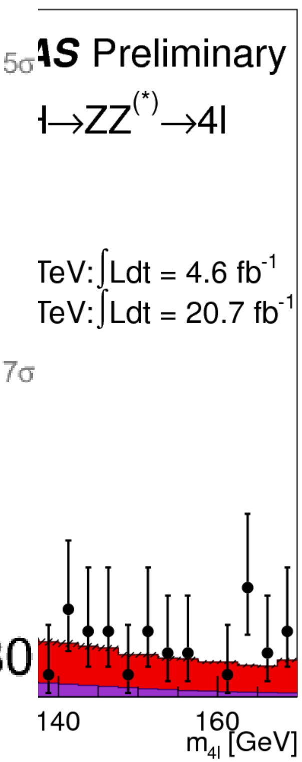
Extract signal fro … tics (CMS)

Main b…
SM Z…
Top, Z…

/B ~ 1.4



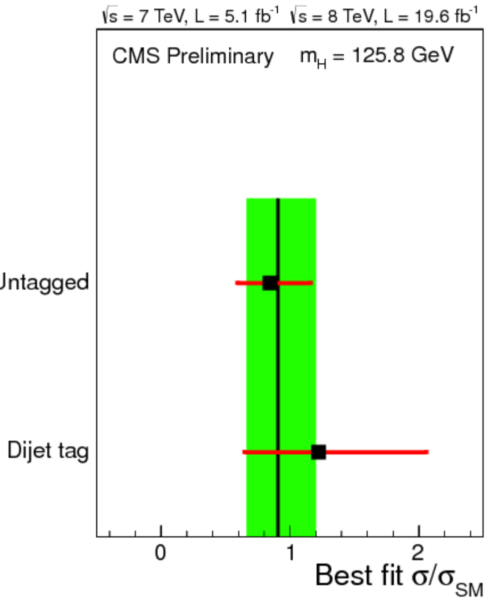


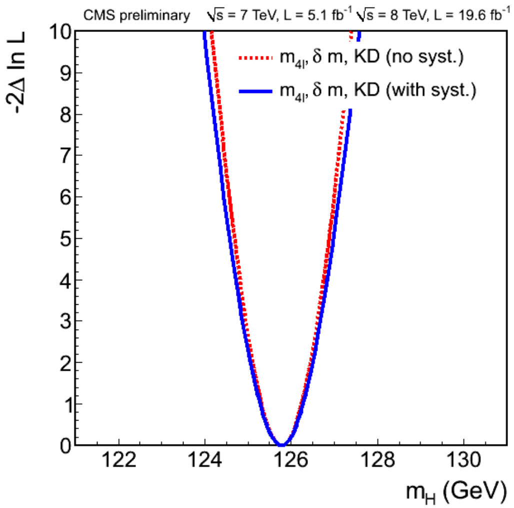


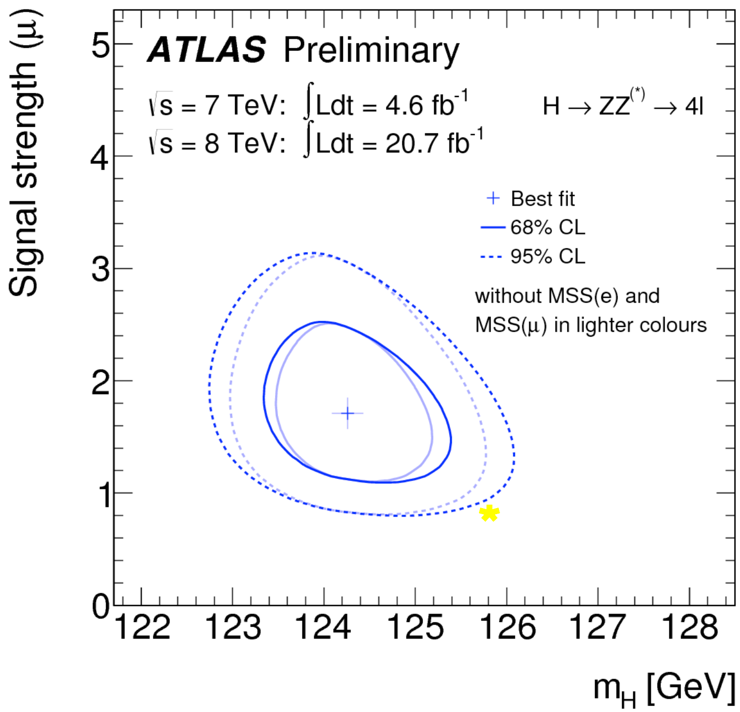
ATLAS-CONF-2013-013
CMS-PAS-HIG-13-002

Higgs to 4 leptons (ZZ)

ATLAS: 6.6σ (SM expectation 4.4σ)
CMS: 6.7σ (SM expectation 7.2σ)







$m_H = 125.8 \pm 0.5\ (\text{stat}) \pm 0.2\ (\text{syst})$ GeV

$\mu(125.8) = 0.91^{+0.3}_{-0.24}$

$m_H = 124.3 \pm 0.6\ (\text{stat}) \pm 0.4\ (\text{syst})$ GeV

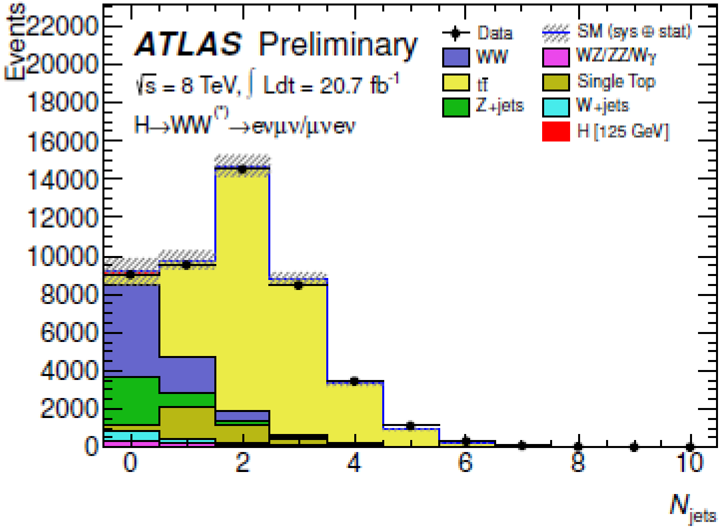
$\mu(124.3) = 1.7^{+0.5}_{-0.4}$

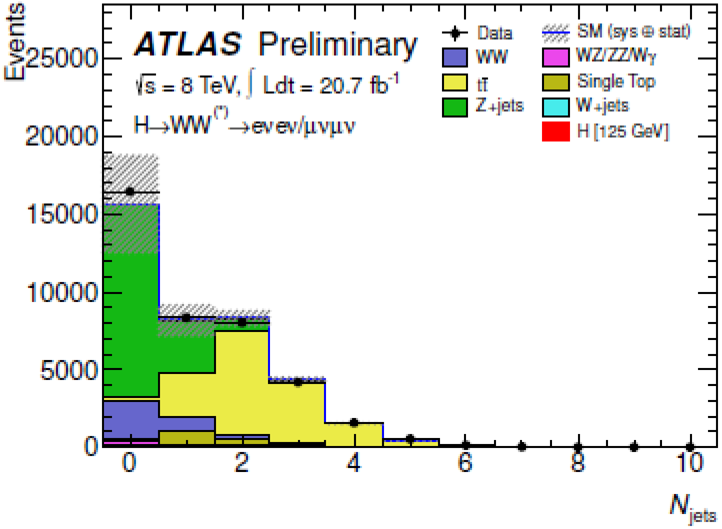
ATLAS-CONF-2013-030 CMS-PAS-HIG-13-003

Higgs to 2 leptons and 2 neutrinos (WW)

Select for 2 OS leptons (e or μ) + missing ET + VBF jet tagging for Njets>=2

Categorize according to lepton flavour, jet multiplicity and dilepton mass:
varying backgrounds, S/B and sensitivity to production modes



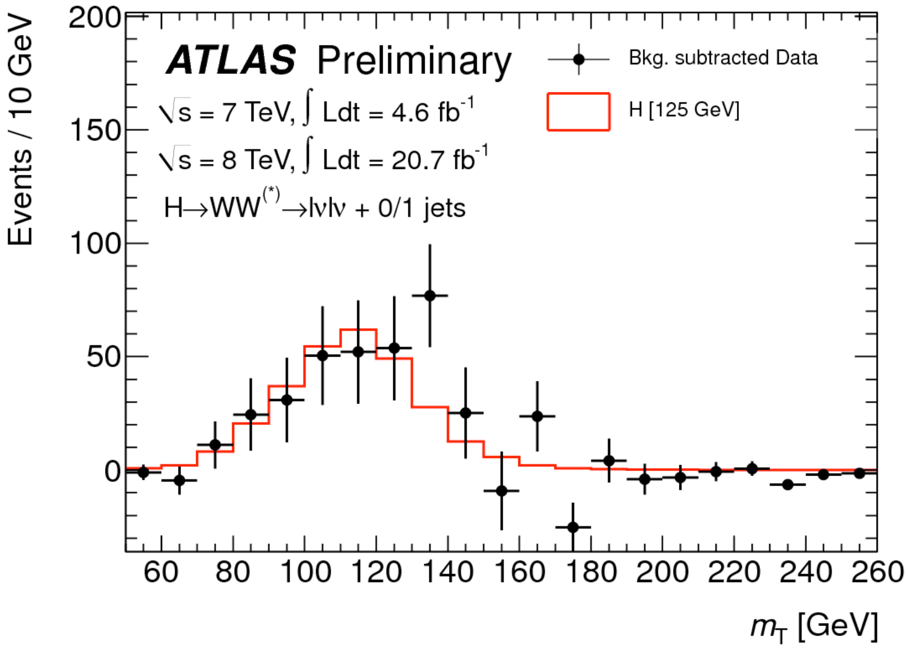


For Njets=0,1 ggF dominates production (CMS+ATLAS)
For Njets>=2, additional jet requirements mean VBF dominates (ATLAS)
(VH included in signal model but effectively negligible)

Dominant (WW, top, $\tau\tau$) backgrounds modelled with MC normalised in control regions

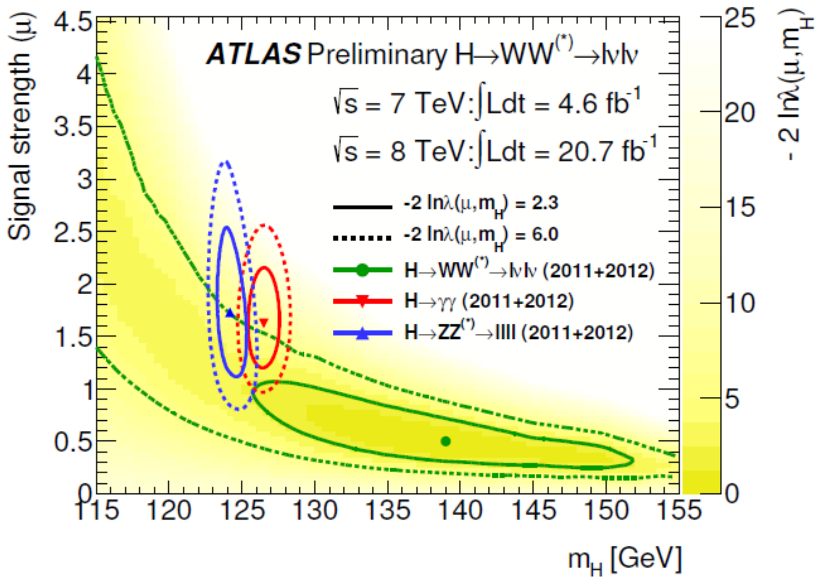
ATLAS-CONF-2013-030 CMS-PAS-HIG-13-003

Higgs to 2 leptons and 2 neutrinos (WW)



Highest significance at M_H=140, 4.1σ

Significance at M_H=125, 3.8σ



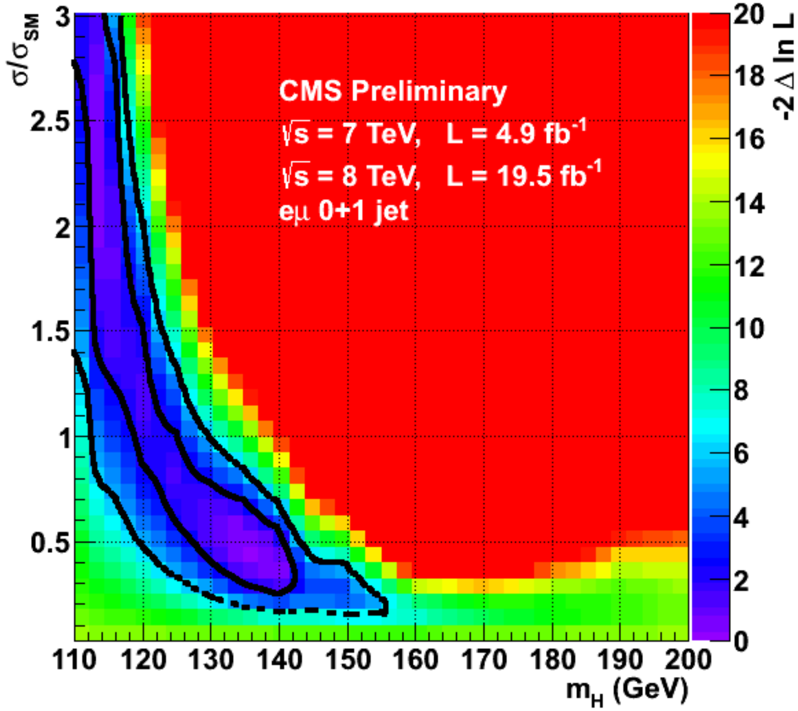
At M_H=125

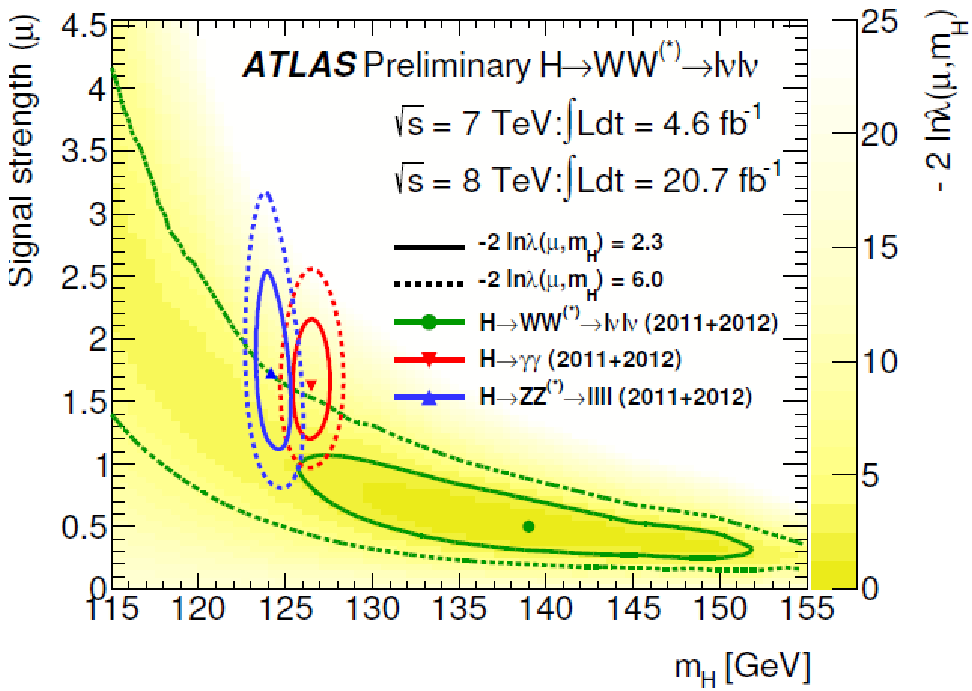
μ_{obs} = 1.01 ± 0.21(stat) ± 0.19 (theo) ± 0.12 (exp) + 0.04 (lumi)

Dominant theory uncertainties from WW background and signal yields

ATLAS-CONF-2013-030 CMS-PAS-HIG-13-003

Higgs to 2 leptons and 2 neutrinos (WW)





At M_H=125, 3.8σ (3.7exp)

μ_{obs} = 1.01 ± 0.21(stat) ± 0.19 (theo) ± 0.12 (exp) + 0.04 (lumi)

At M_H=125, 4.0σ (5.0exp)

μ_{obs} = 0.76 ± 0.13(stat) ± 0.16 (syst)

ATLAS-CONF-2013-030

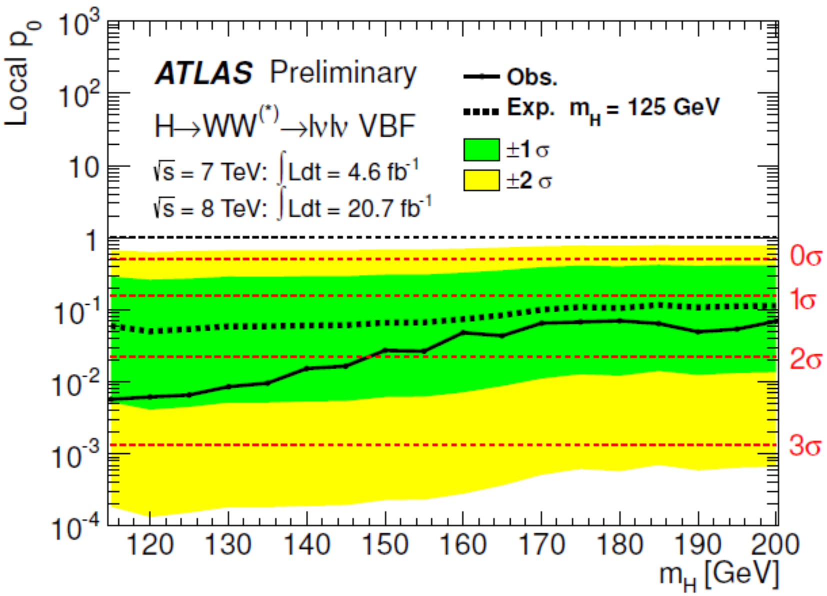
Higgs to 2 leptons and 2 neutrinos (WW)

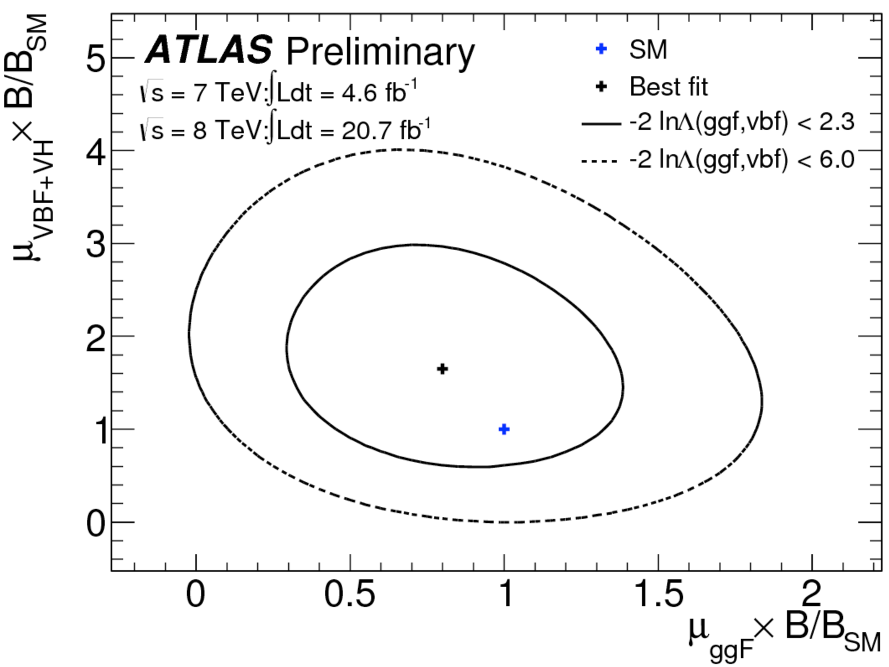
Fit for VBF, profiling ggF as background:

$\mu^{VBF}_{obs} = 1.66 \pm 0.67(stat) \pm 0.42\ (syst)$

Fit for ggF, profiling VBF as background:

$\mu^{ggF}_{obs} = 0.82 \pm 0.24(stat) \pm 0.28\ (syst)$





ATLAS-CONF-2013-012
CMS-PAS-13-001

Higgs to photons

Low BR but clean signature of isolated di-photons

Large diphoton backgrounds mitigated by excellent mass resolution ~1.8 GeV

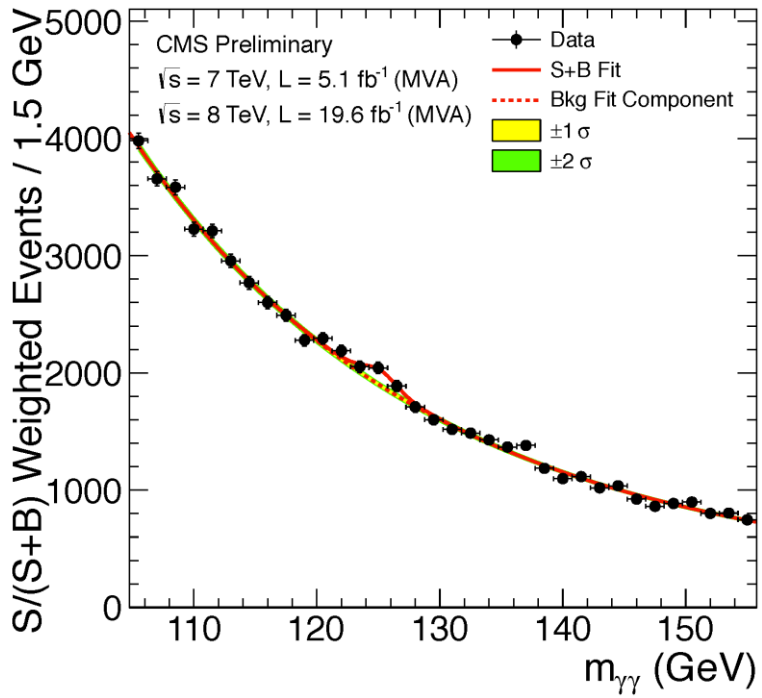
Select events with two high pT isolated photons

Categorize events for resolution, S/B and production mode

ATLAS: cut based categories

CMS: cut based + BDT based categories

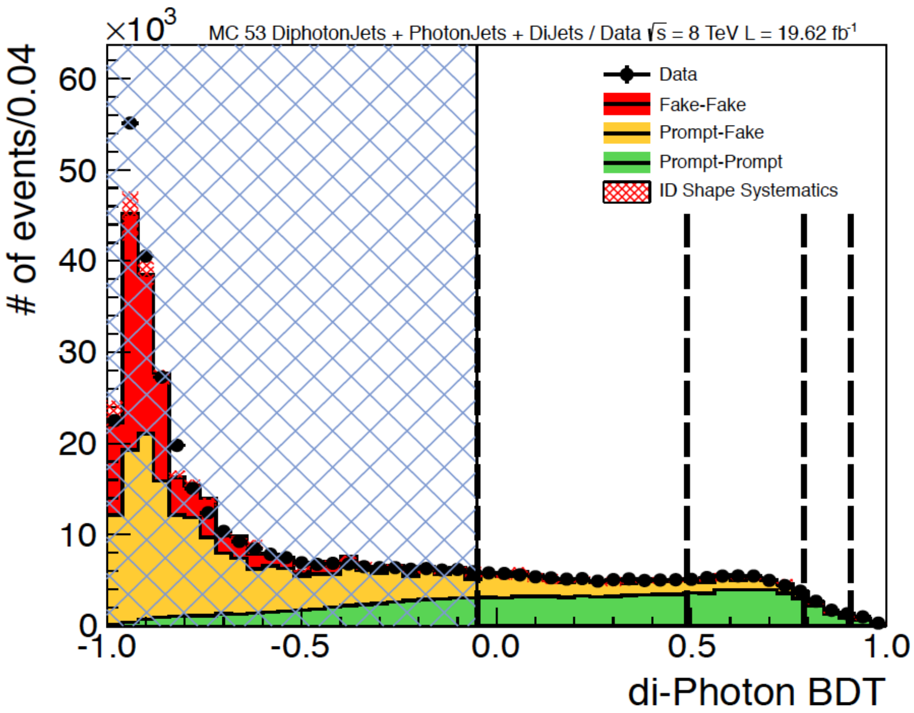
Signal extracted from fits to diphoton invariant mass

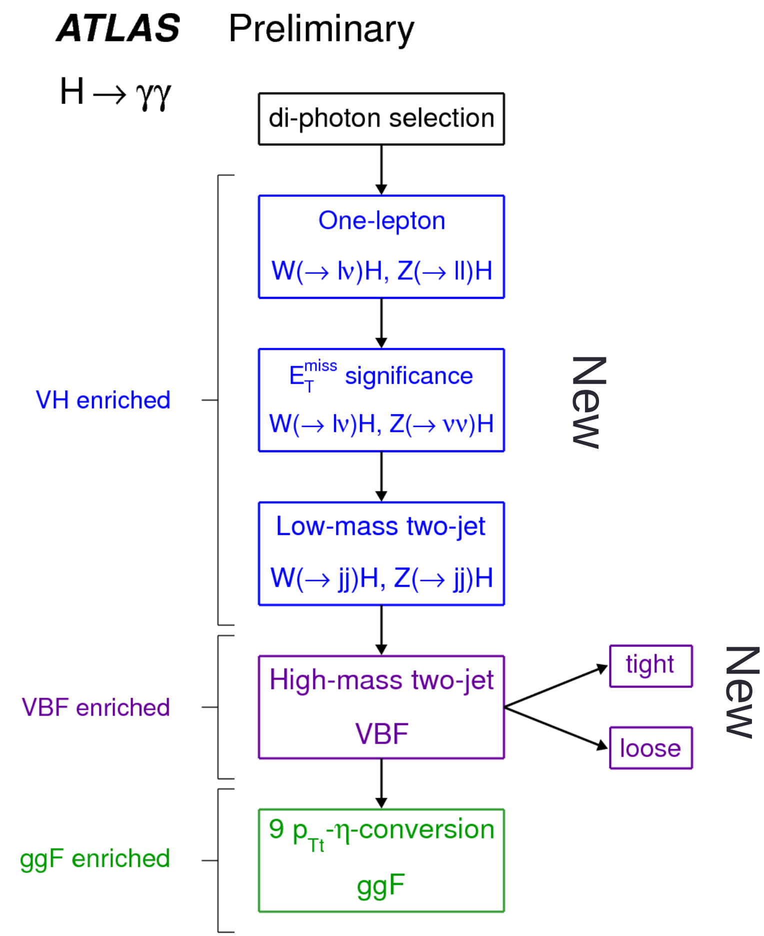


ATLAS-CONF-2013-012
CMS-PAS-13-001

Higgs to photons

Low BR but clean signature of isolated di-photons

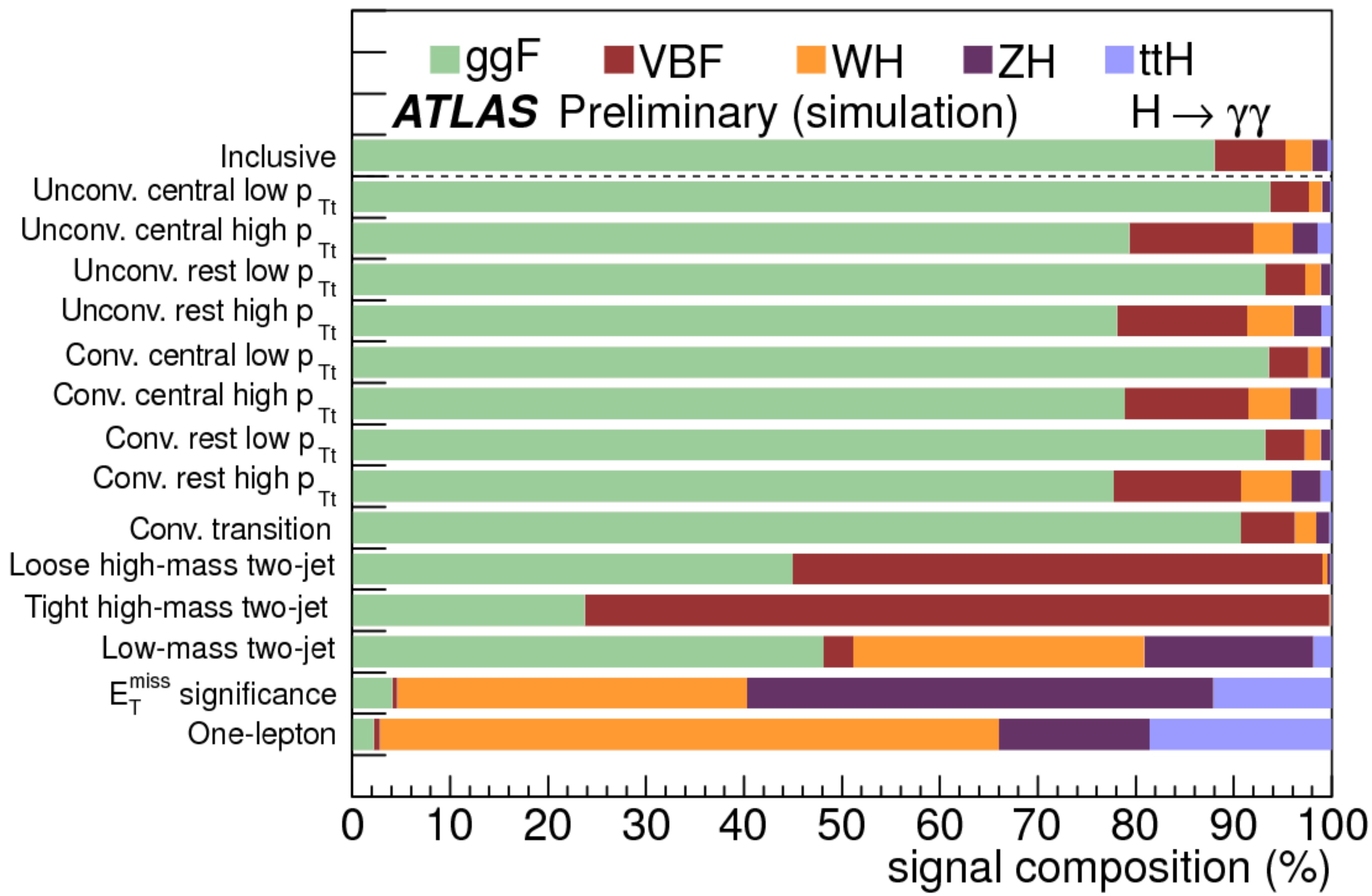




Plus lepton based and di-jet BDT based categories (CMS)

ATLAS-CONF-2013-012
CMS-PAS-13-001

Higgs to photons



ATLAS-CONF-2013-012
CMS-PAS-13-001

Higgs to photons

Expected signal and estimated background

Event classes		SM Higgs boson expected signal (m_H=125 GeV) Total	ggH	VBF	VH	ttH	σ_{eff} (GeV)	FWHM/2.35 (GeV)	Background $m_{\gamma\gamma}$ = 125 GeV (ev./GeV)
7 TeV 5.1 fb^{-1}	Untagged 0	3.2	61.4%	16.8%	18.7%	3.1%	1.21	1.14	3.3 ± 0.4
	Untagged 1	16.3	87.6%	6.2%	5.6%	0.5%	1.26	1.08	37.5 ± 1.3
	Untagged 2	21.5	91.3%	4.4%	3.9%	0.3%	1.59	1.32	74.8 ± 1.9
	Untagged 3	32.8	91.3%	4.4%	4.1%	0.2%	2.47	2.07	193.6 ± 3.0
	Dijet tag	2.9	26.8%	72.5%	0.6%	–	1.73	1.37	1.7 ± 0.2
8 TeV 19.6 fb^{-1}	Untagged 0	17.0	72.9%	11.6%	12.9%	2.6%	1.36	1.27	22.1 ± 0.5
	Untagged 1	37.8	83.5%	8.4%	7.1%	1.0%	1.50	1.39	94.3 ± 1.0
	Untagged 2	150.2	91.6%	4.5%	3.6%	0.4%	1.77	1.54	570.5 ± 2.6
	Untagged 3	159.9	92.5%	3.9%	3.3%	0.3%	2.61	2.14	1060.9 ± 3.5
	Dijet tight	9.2	20.7%	78.9%	0.3%	0.1%	1.79	1.50	3.4 ± 0.2
	Dijet loose	11.5	47.0%	50.9%	1.7%	0.5%	1.87	1.60	12.4 ± 0.4
	Muon tag	1.4	0.0%	0.2%	79.0%	20.8%	1.85	1.52	0.7 ± 0.1
	Electron tag	0.9	1.1%	0.4%	78.7%	19.8%	1.88	1.54	0.7 ± 0.1
	E_T^{miss} tag	1.7	22.0%	2.6%	63.7%	11.7%	1.79	1.64	1.8 ± 0.1

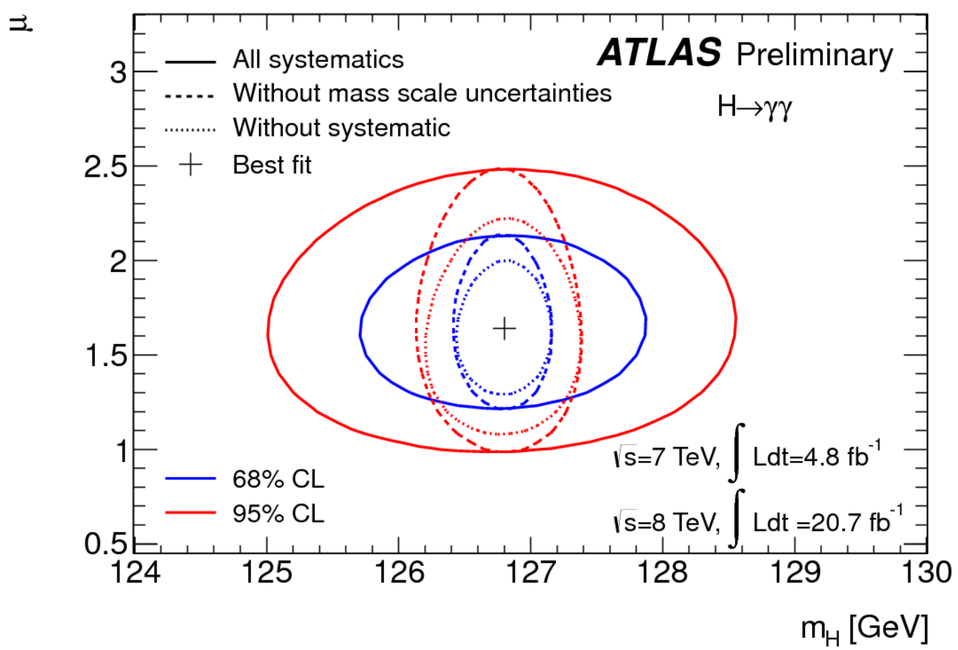
ATLAS-CONF-2013-012
CMS-PAS-13-001

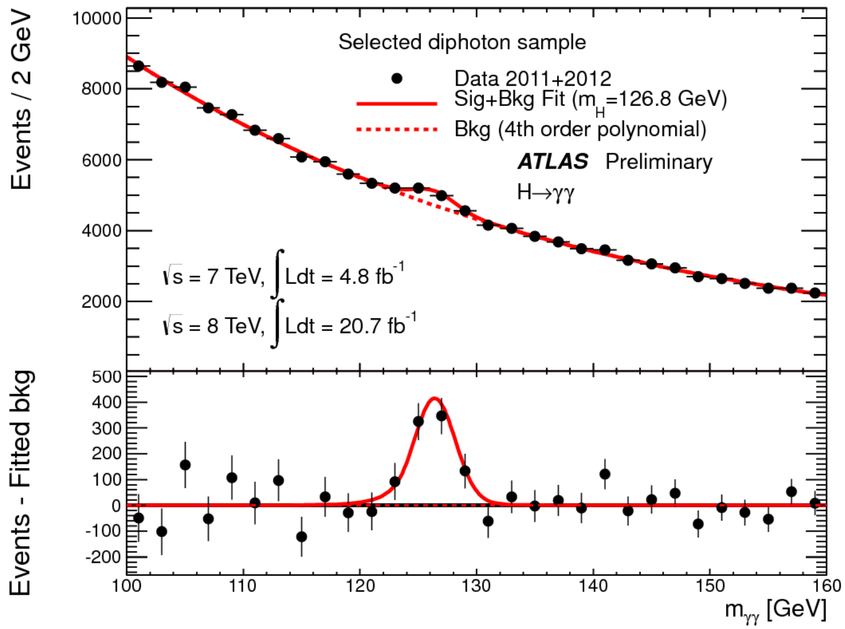
Higgs to photons

Observed significance 7.4σ (4.1σ exp.)

$\mu = 1.65 \pm 0.24(\text{stat}) \pm 0.22(\text{syst})$

Consistent with SM at 2.3σ





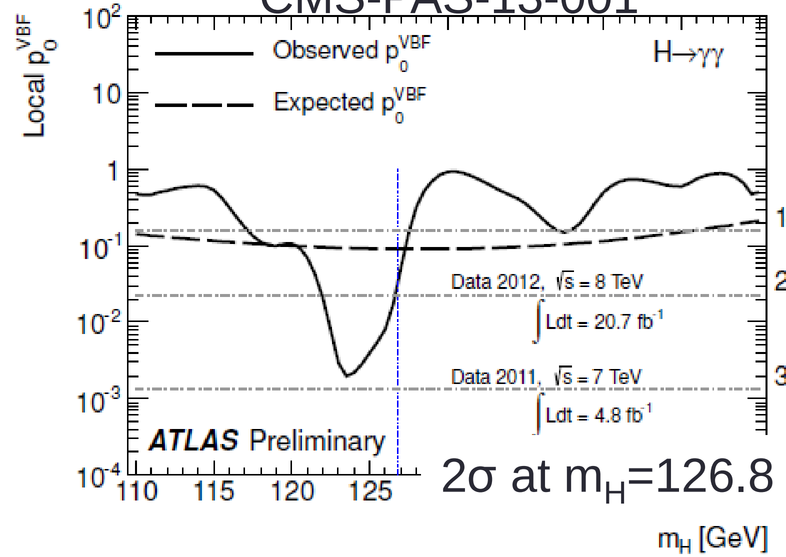
$m_H = 126.8 \pm 0.2(\text{stat}) \pm 0.7(\text{syst})$ GeV

Fit prefers mass 1.8σ narrower than nominal. Better than a perfectly uniform calorimeter. Probably due to background fluctuation. 10% lower yield if no fit of resolution.

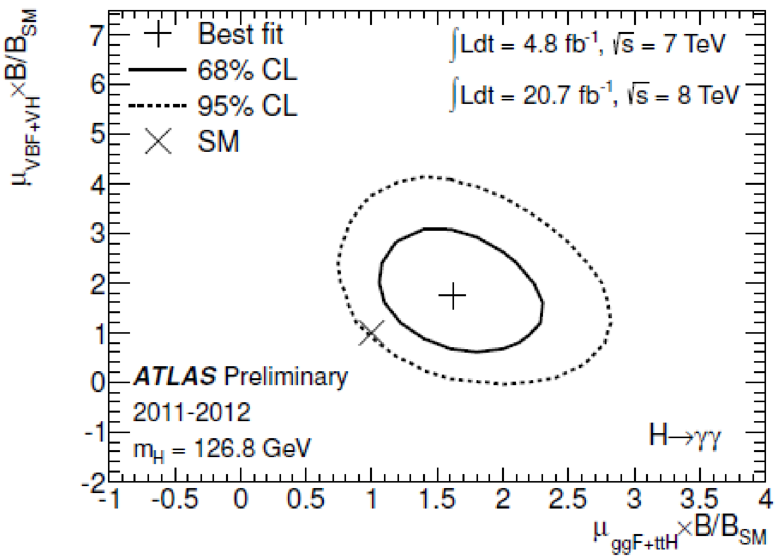
ATLAS-CONF-2013-012
CMS-PAS-13-001

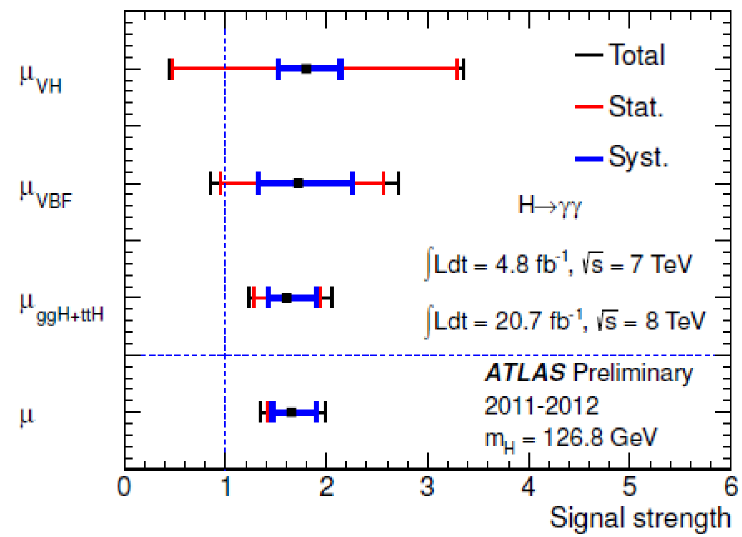
Higgs to photons

Exploit VBF categories to extract signal strength assuming ggF is background



2σ at m_H=126.8 GeV



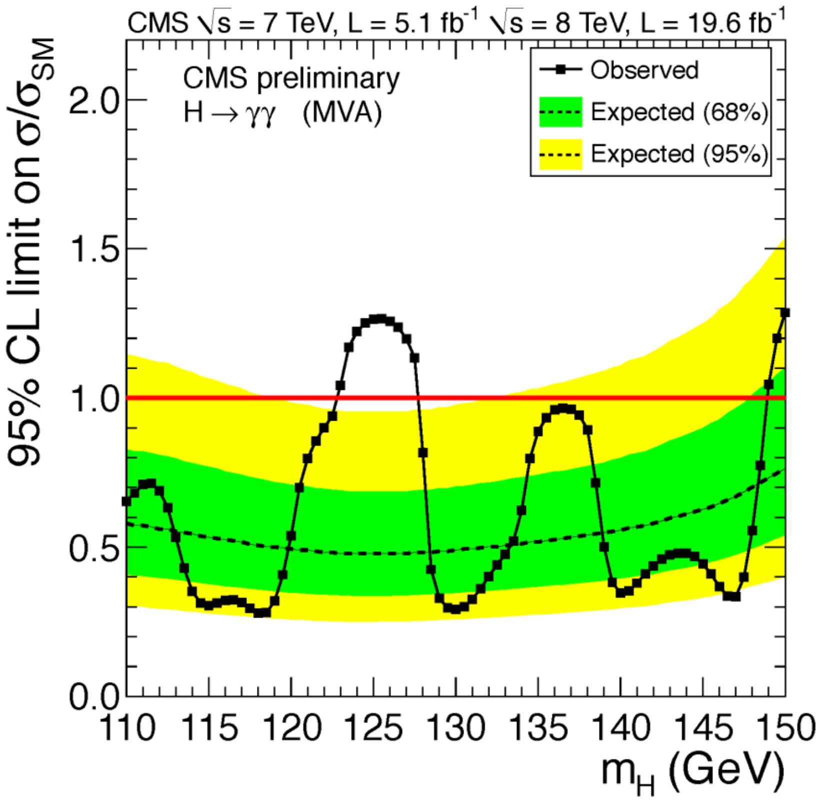


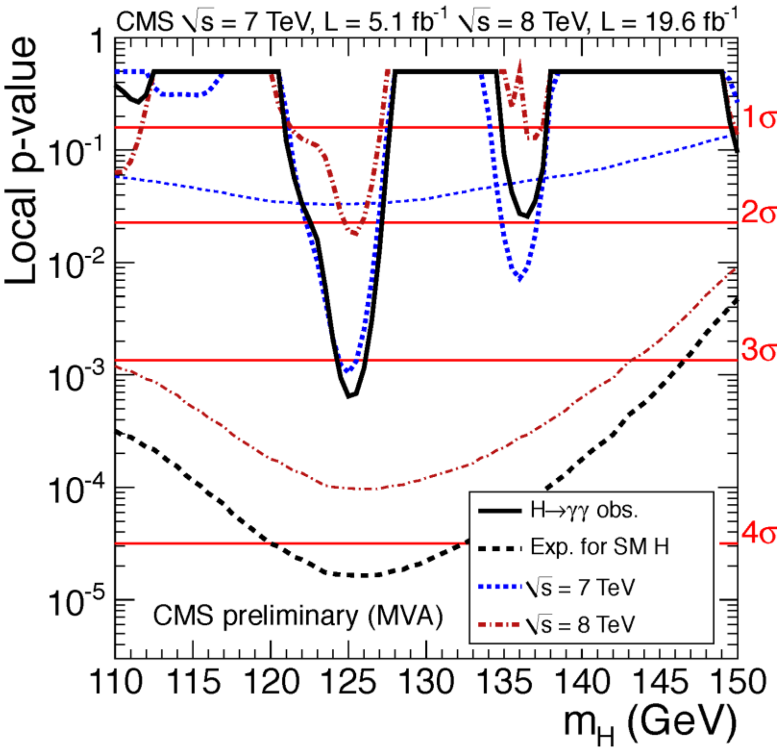
Fiducial cross section: 8TeV data:
$|\eta| < 2.37$, $p_T\gamma > 40/30$ GeV

σ_{fid} x BR = 56.2 ± 12.5 fb [±10.5(stat) ± 6.5(syst) ± 2.0(lumi)]

ATLAS-CONF-2013-012
CMS-PAS-13-001

Higgs to photons



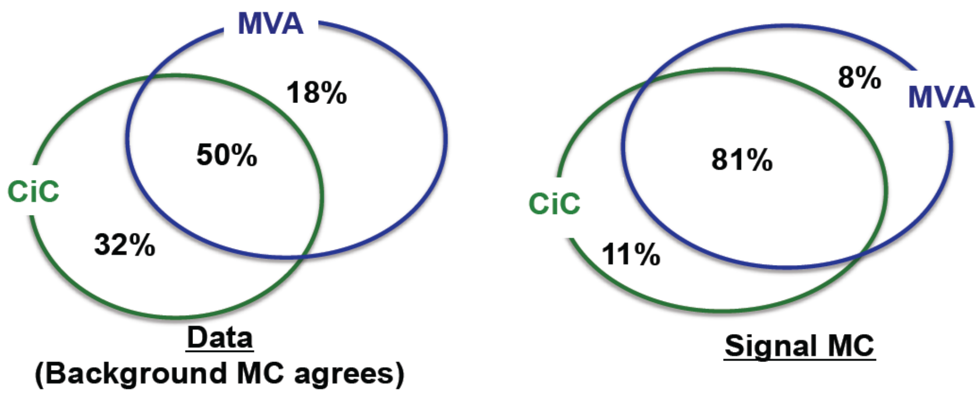


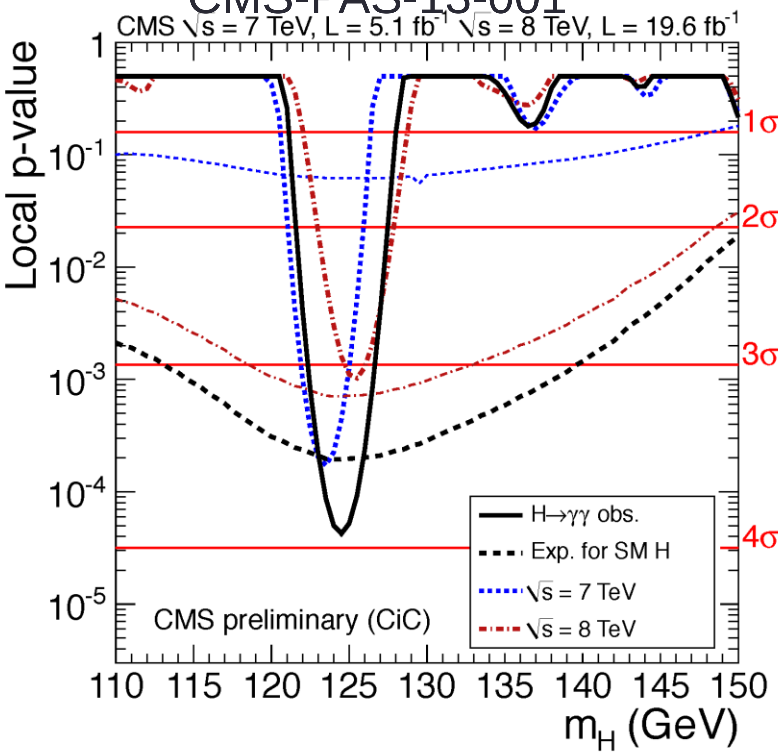
Excess 3.2σ (4.2 exp)

Alternate analysis finds: 3.9σ (3.5 exp)

ATLAS-CONF-2013-012
CMS-PAS-13-001

Higgs to photons





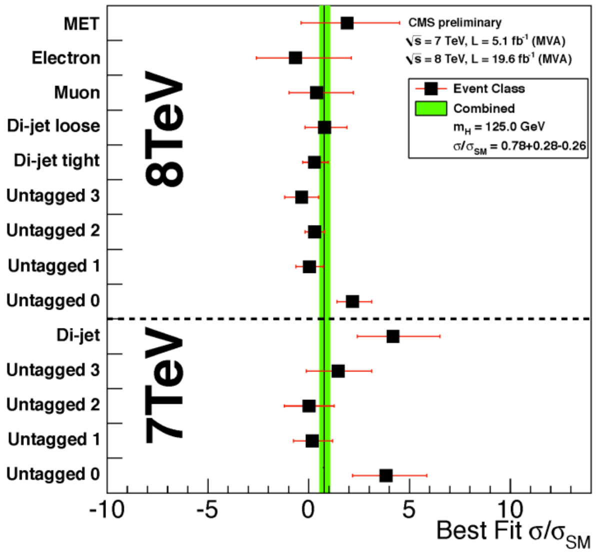
Strong correlation between analysis
~0.75 compatible at 1.5 sigma level

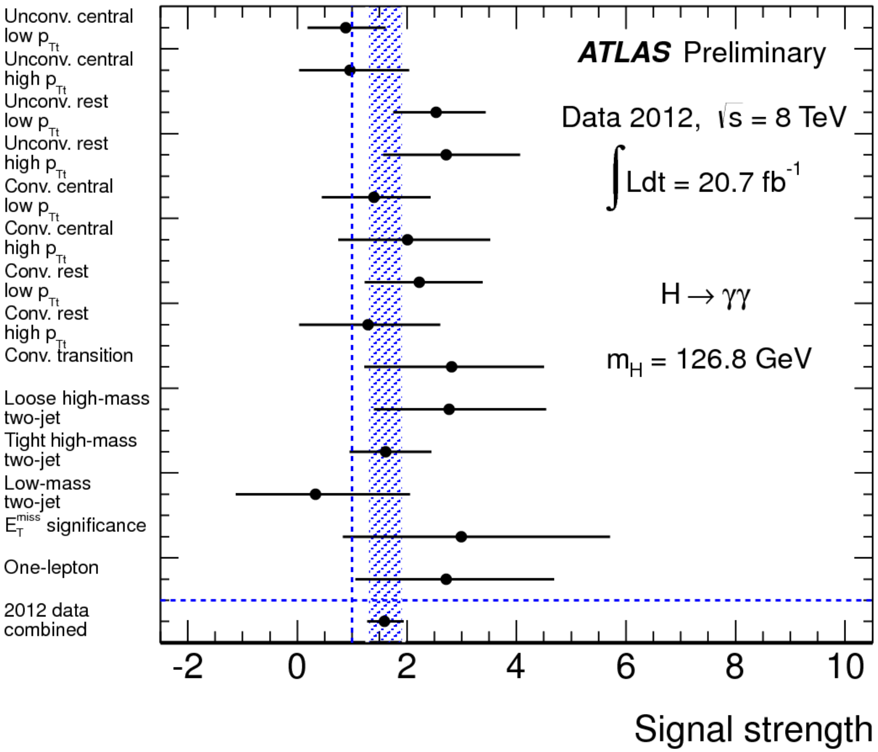
Excess 3.2σ (4.2 exp)

Alternate analysis finds: 3.9σ (3.5 exp)

ATLAS-CONF-2013-012
CMS-PAS-13-001

Higgs to photons





μ = 0.78 ± 0.28

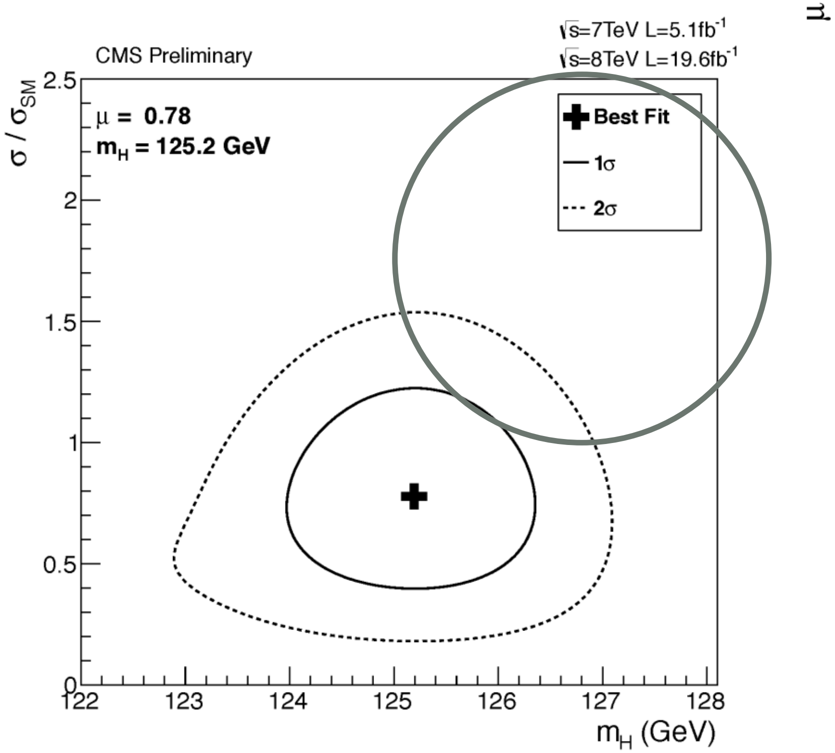
μ = 1.65 ± 0.24(stat) ± 0.22(syst)

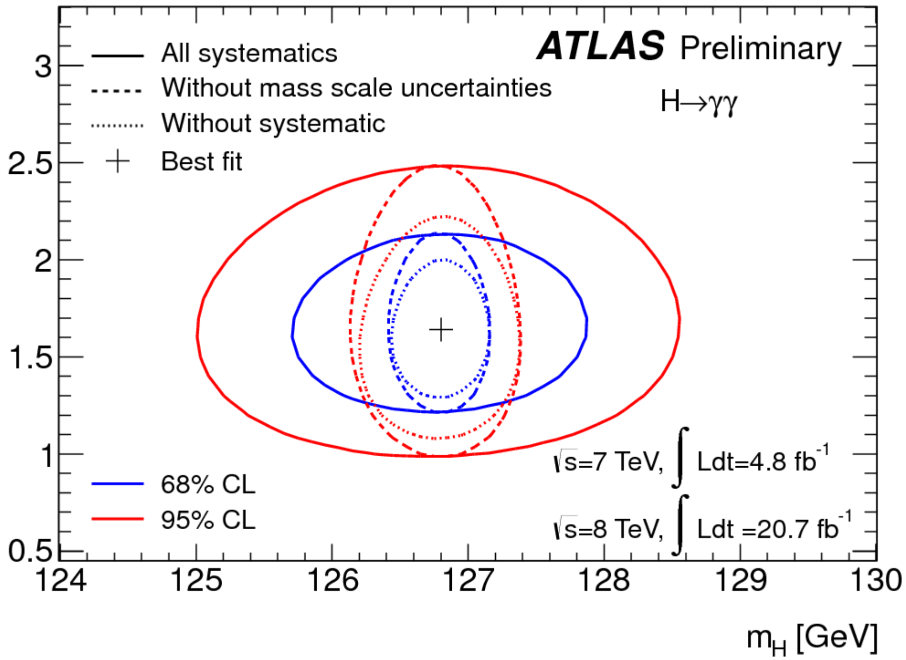
	MVA analysis (at m_H=125 GeV)	cut-based analysis (at m_H=124.5 GeV)
7 TeV	$1.69^{+0.65}_{-0.59}$	$2.27^{+0.80}_{-0.74}$
8 TeV	$0.55^{+0.29}_{-0.27}$	$0.93^{+0.34}_{-0.32}$
7 + 8 TeV	$0.78^{+0.28}_{-0.26}$	$1.11^{+0.32}_{-0.30}$

Clear tension between these results
More data needed to resolve

ATLAS-CONF-2013-012
CMS-PAS-13-001

Higgs to photons





m_H =126.8 ± 0.2(stat) ± 0.7(syst) GeV

m_H =125.4 ± 0.5(stat) ± 0.6(syst) GeV

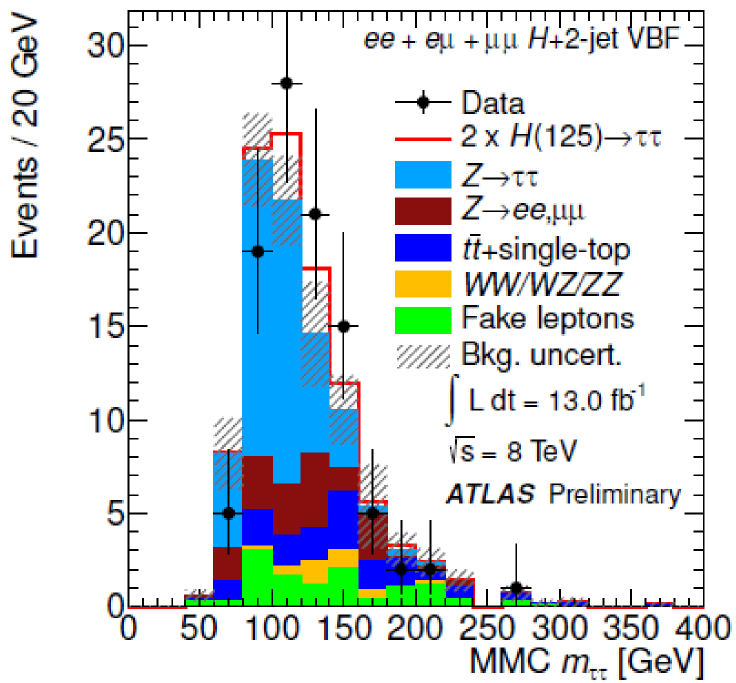
ATLAS-CONF-2012-160
CMS-PAS-HIG-13-004

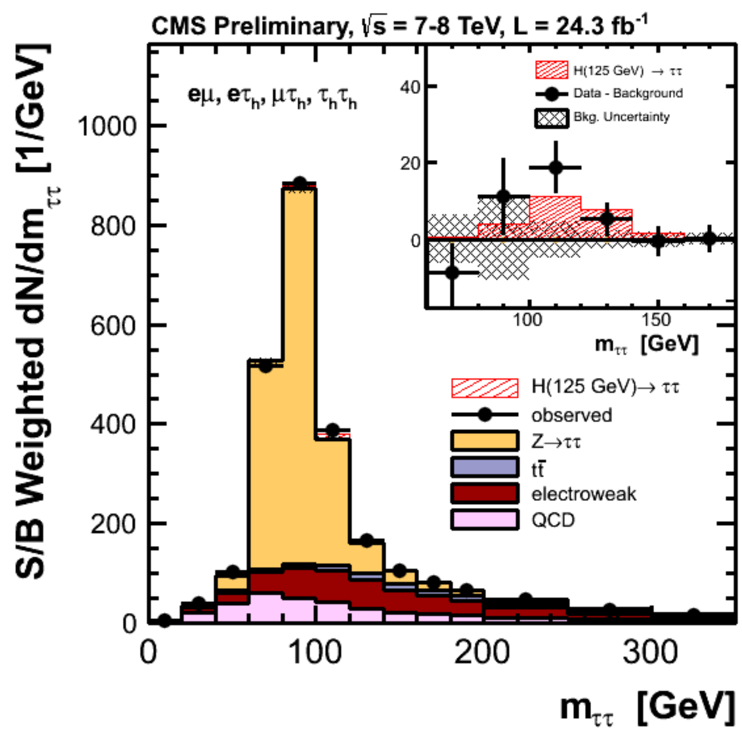
Higgs to taus

Select events with two opposite sign tau candidates – 0,1 or 2 leptonic decays

Categorize according to lepton and jet multiplicities and event kinematics
enhances S/B and sensitivity to ggF, VH and VBF production modes

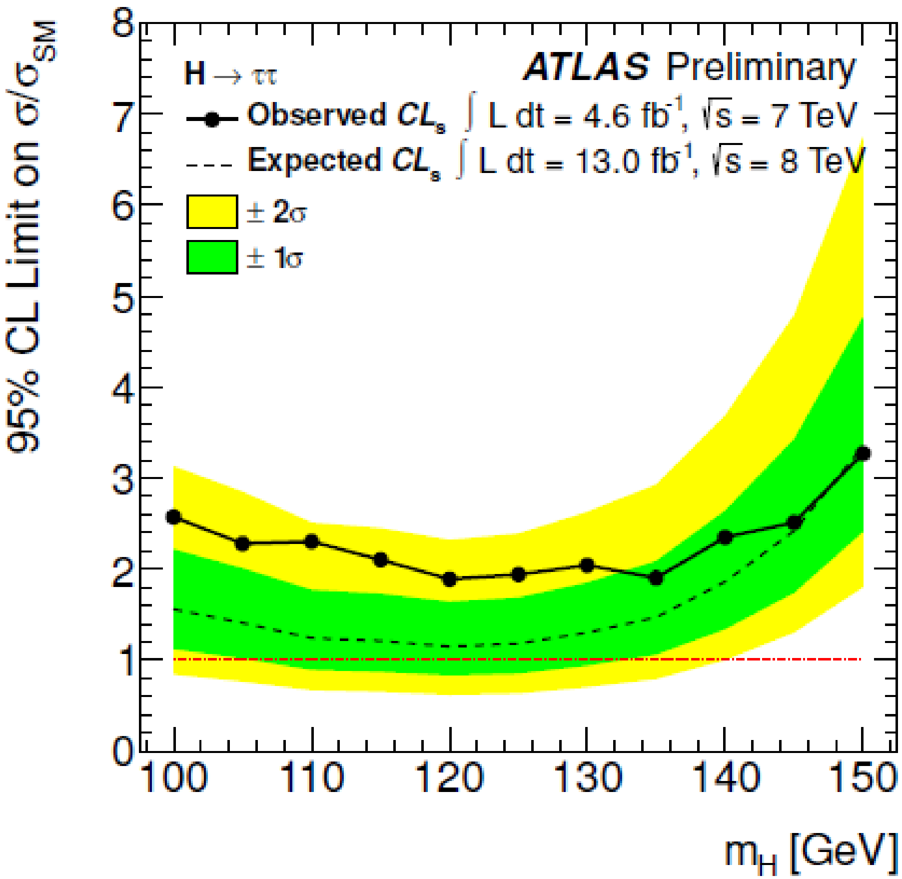
Dominant background $Z/\gamma^* \to \tau\tau$, model enhanced from data using μμ events

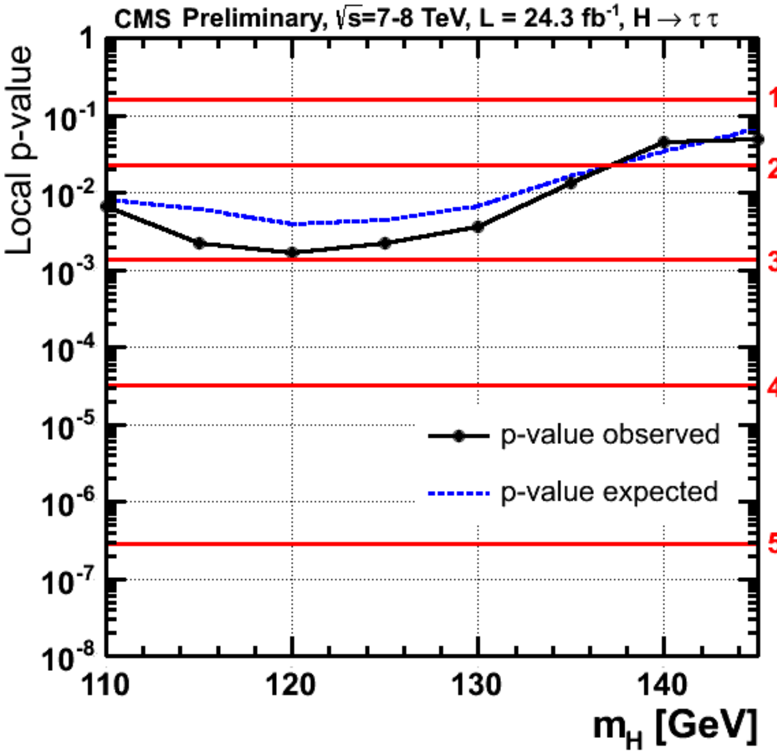




ATLAS-CONF-2012-160
CMS-PAS-HIG-13-004

Higgs to taus



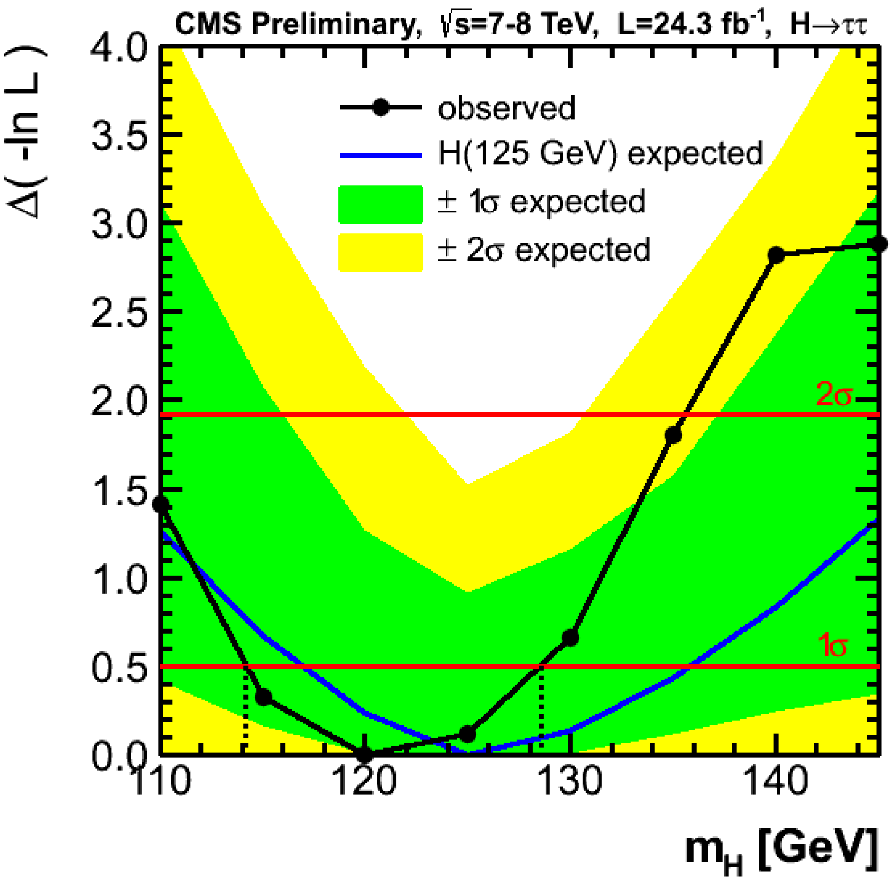


CMS see excess: **2.9σ (2.6exp)**

Not quite sensitive to SM yet at ATLAS
Small but not significant excess

ATLAS-CONF-2012-160
CMS-PAS-HIG-13-004

Higgs to taus



Poor resolution but not completely mass blind

$M = 120^{+9}_{-7}$ GeV

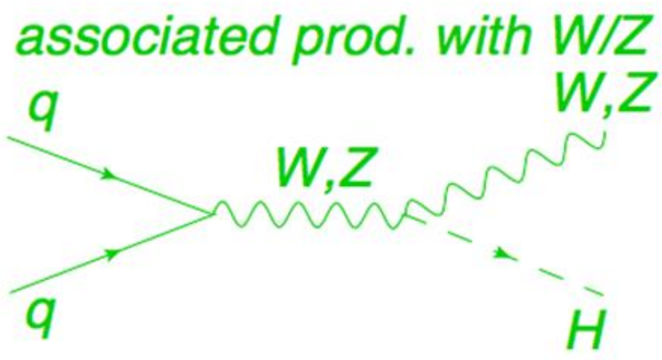
CMS see excess: **2.9σ (2.6exp)**

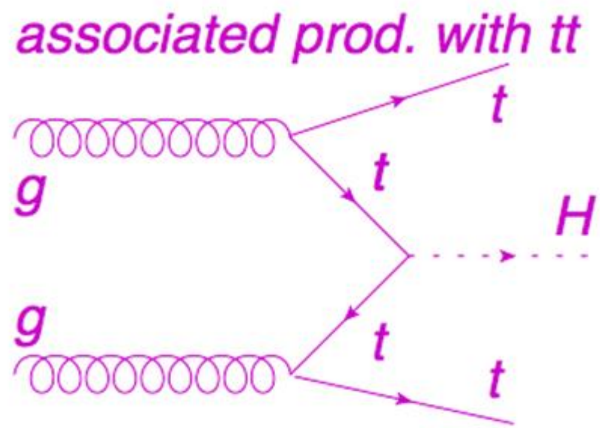
ATLAS-CONF-2012-161

Higgs to b quarks

Dominant BR at low mass for SM
Backgrounds make inclusive search very difficult

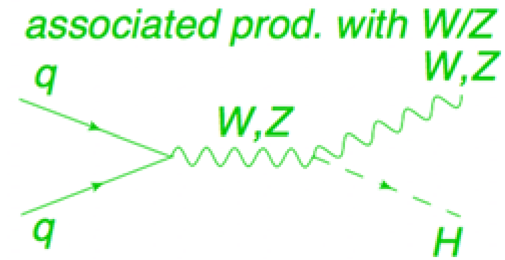
Extra signatures in VH and ttH modes make possible





ATLAS-CONF-2012-161
CMS-PAS-HIG-13-012

Higgs to b quarks (VH)

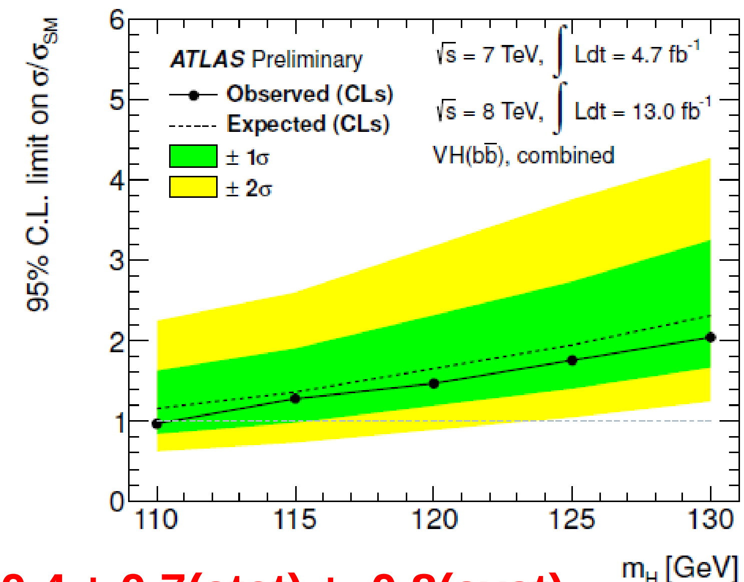


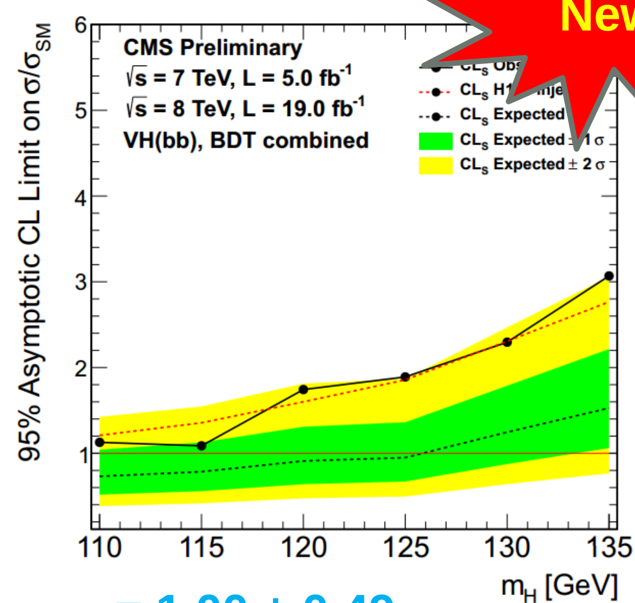
Categorization: by lepton content, V boost, b-tagging quality and missing ET

Signal extraction: m_{bb} (ATLAS) and MVA shape (CMS)

Most backgrounds from MC + data normalisation using control regions, Multi-jet data-driven and WZ and ZZ from simulation

New!



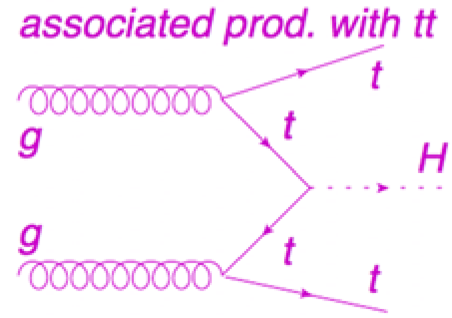


μ = -0.4 ± 0.7(stat) ± 0.8(syst)

μ = 1.00 ± 0.49

ATLAS-CONF-2012-35

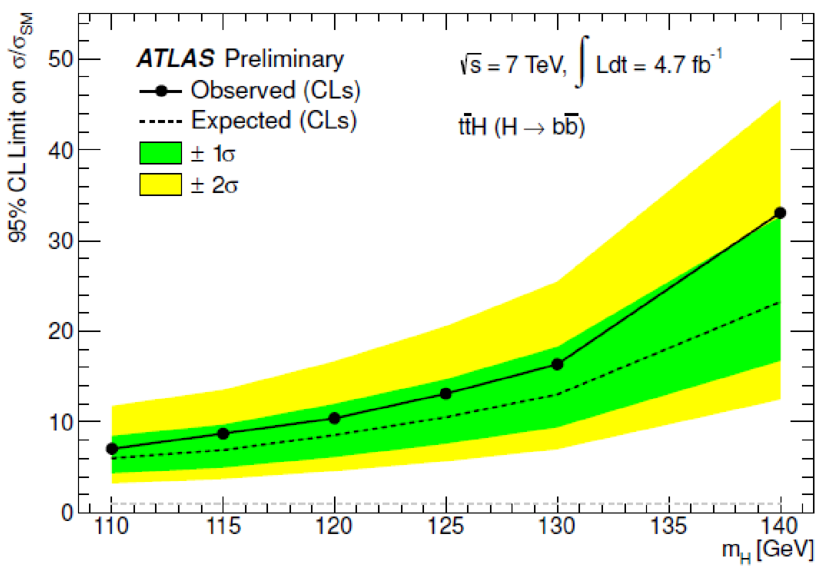
Higgs to b-quarks (ttH)

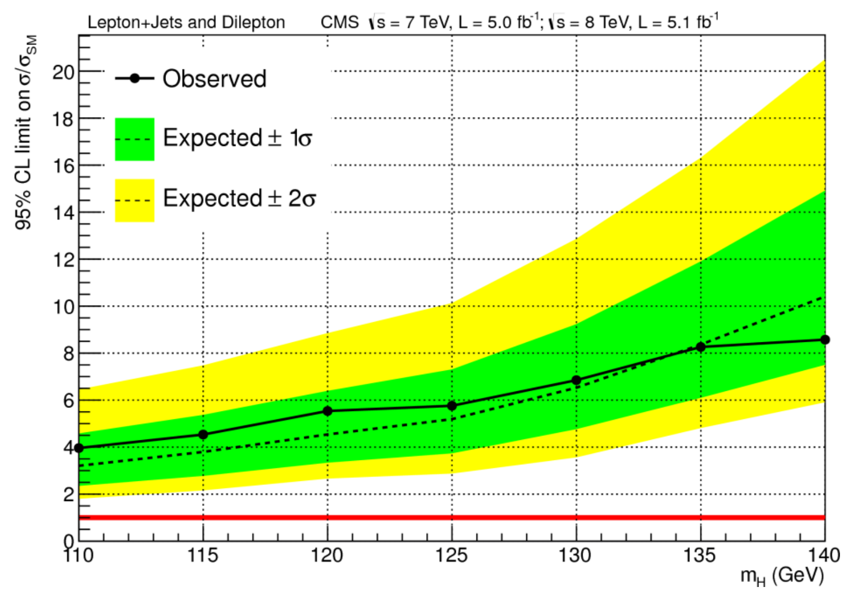


One semi-leptonic top-decay + many jets signature:
1 lepton + high missing ET + >=4 jets

Events categorized according to multiplicity of jets and b-tagged jets

ATLAS: mass/HT analysis, CMS: MVA shape analysis





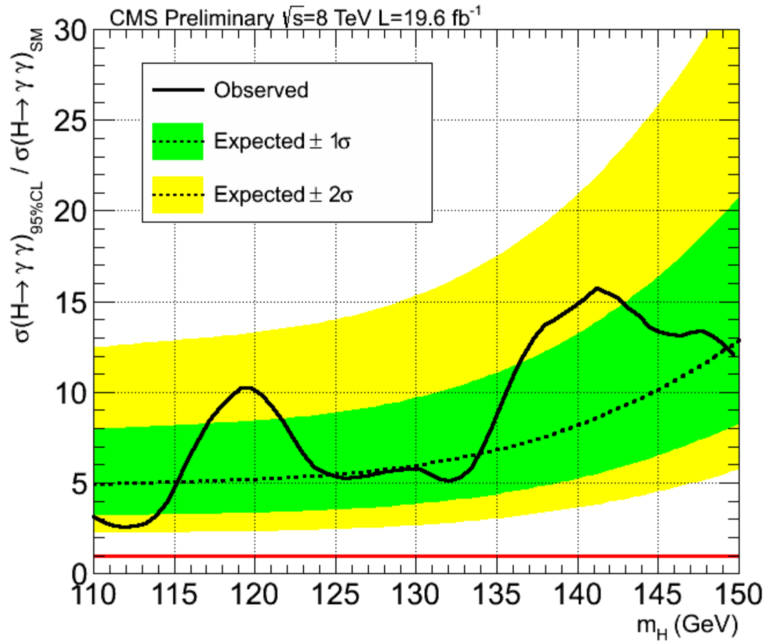
Some way away from SM sensitivity lots more data needed

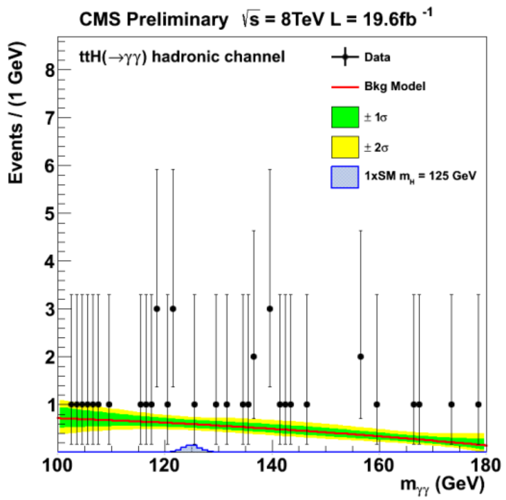
CMS-PAS-13-015

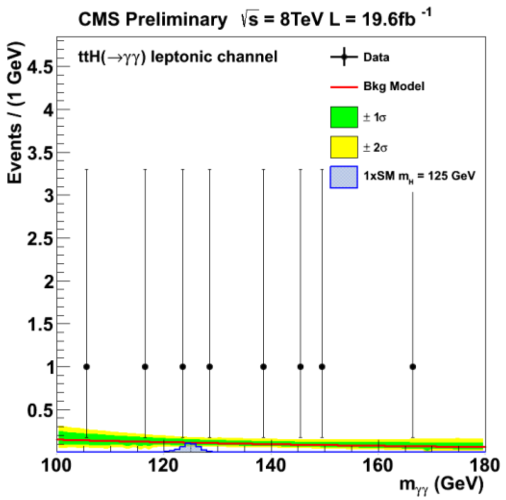
Higgs to photons (ttH)

Two approaches: leptonic and hadronic (top decays)

Process	Hadronic Channel	Leptonic Channel
$t\bar{t}H$	0.567 (87%)	0.429 (97%)
$gg \to H$	0.059 (9%)	0 (0%)
VBF H	0.006 (1%)	0 (0%)
WH/ZH	0.019 (3%)	0.013 (3%)
Total signal	0.65	0.44

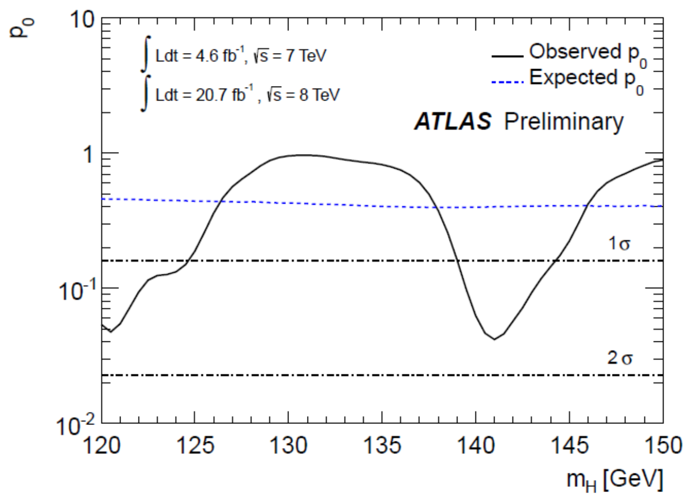






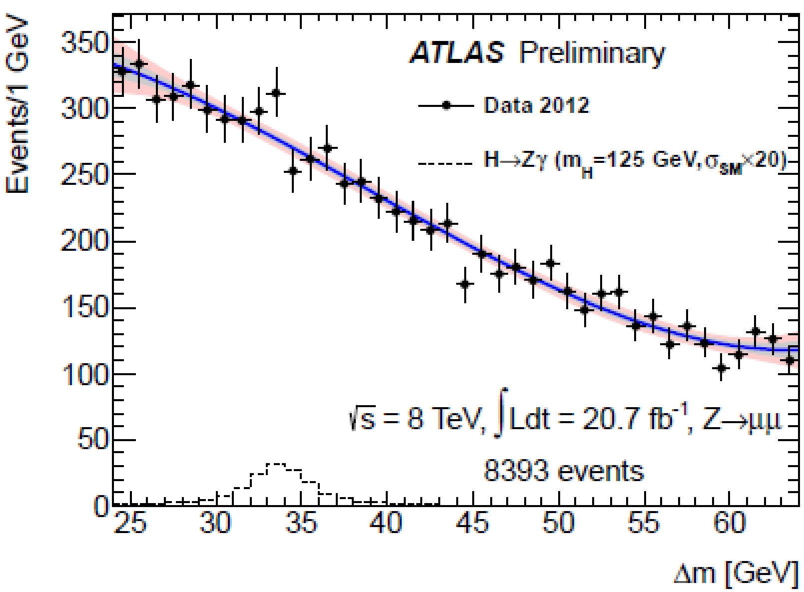
ATLAS-CONF-2013-009

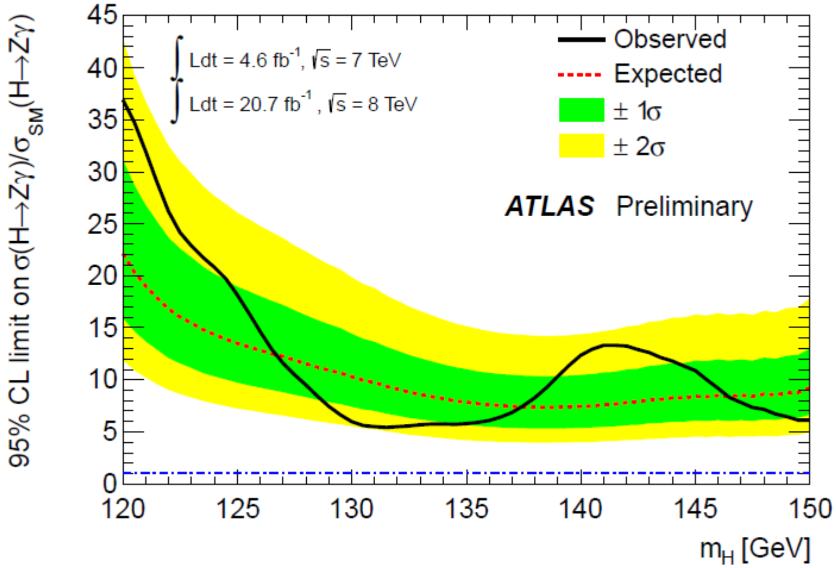
Higgs to Z + photon



Similar to diphoton channel
Loop production modes

Relative rate to diphoton interesting and sensitive to BSM



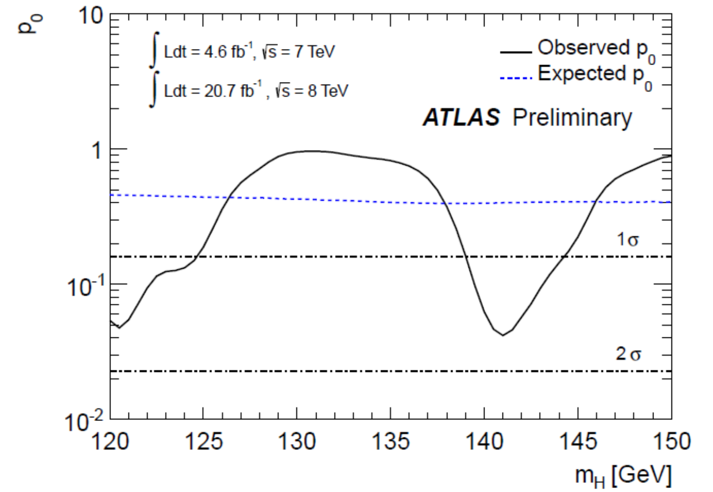


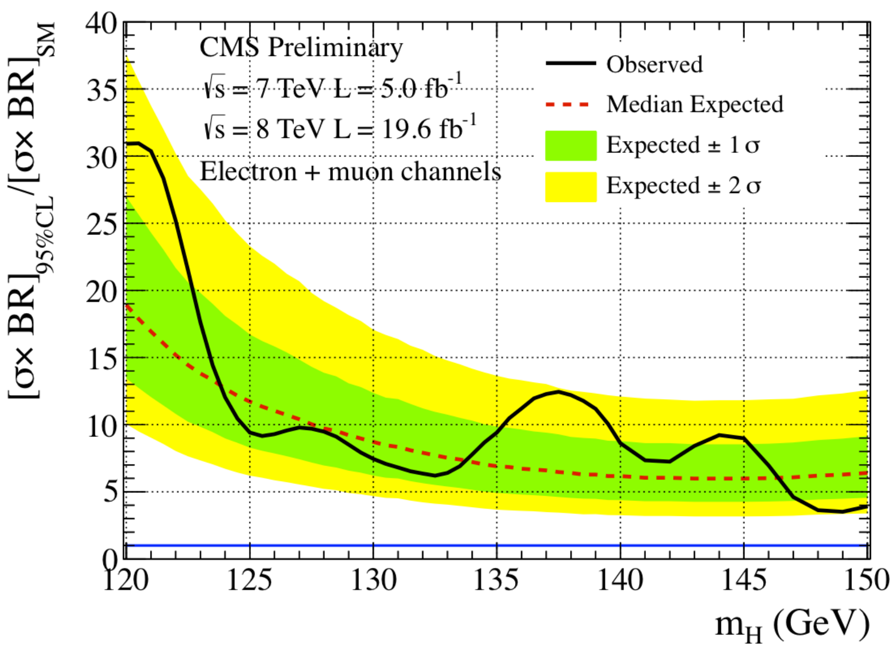
ATLAS-CONF-2013-009
CMS-PAS-HIG-13-006

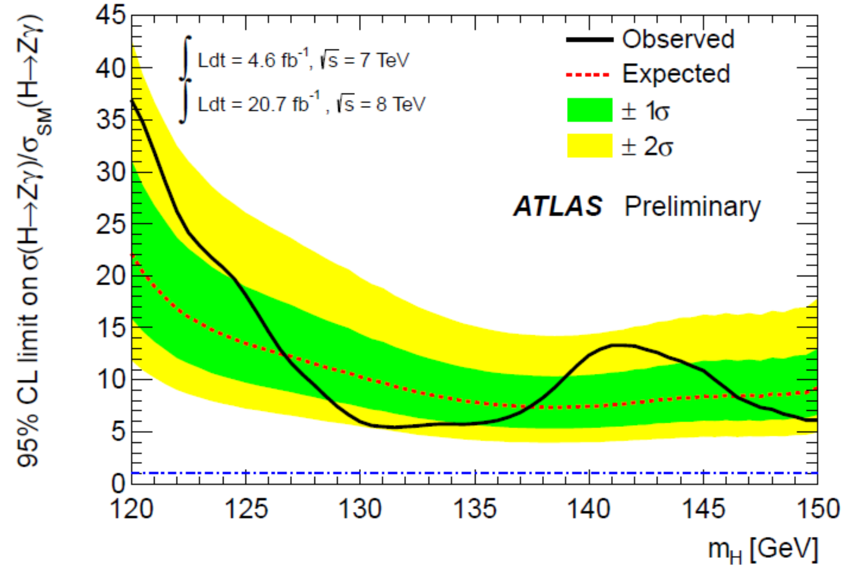
Higgs to Z + photon

Similar to diphoton channel
Loop production modes

Relative rate to diphoton interesting and sensitive to BSM







ATLAS-CONF-2013-010

Higgs to muons

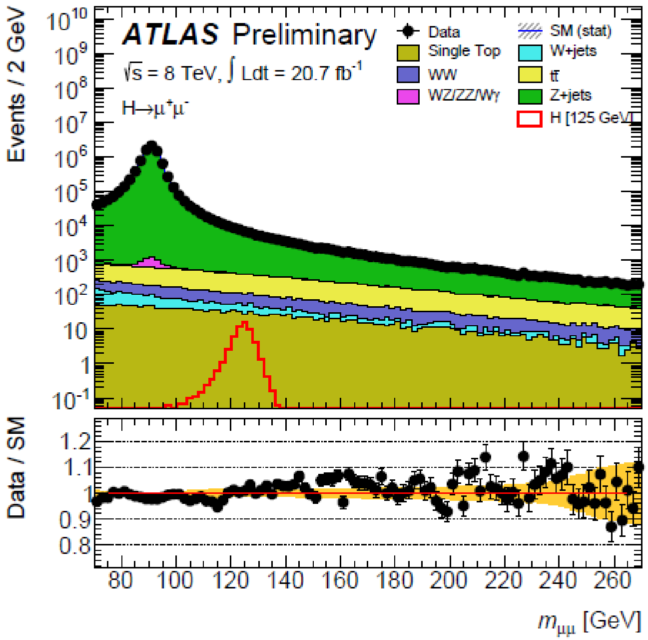
Probe Yukawa interactions for second generation fermions

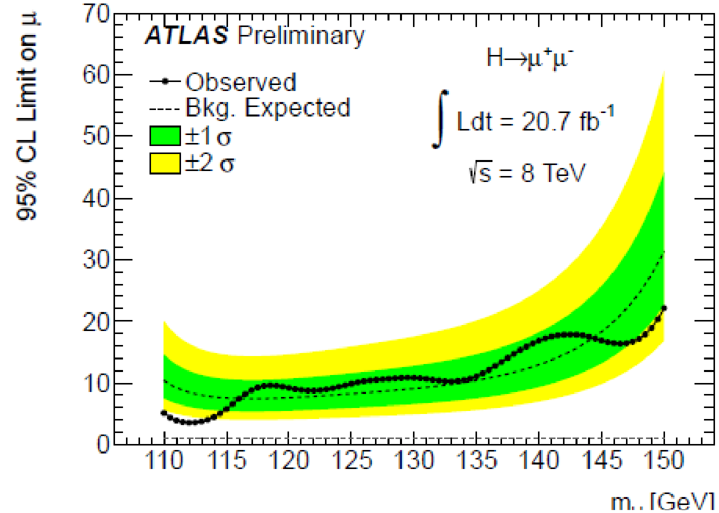
Select events with two OS isolated high pT muons

Huge Z/γ* background dominates

Extract signal from dimuon mass spectrum

Mass resolution ~2.3 GeV @ 125





No evidence for a signal at present
Not yet sensitive to SM rates

Higgs Mass

m_{4l} = 125.8 ± 0.5 (stat) ± 0.2 (syst) GeV

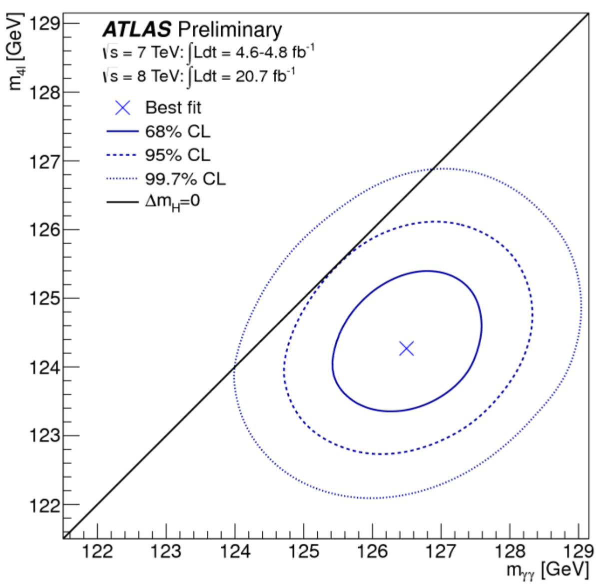
$m_{\gamma\gamma}$ =125.4 ± 0.5(stat) ± 0.6(syst) GeV

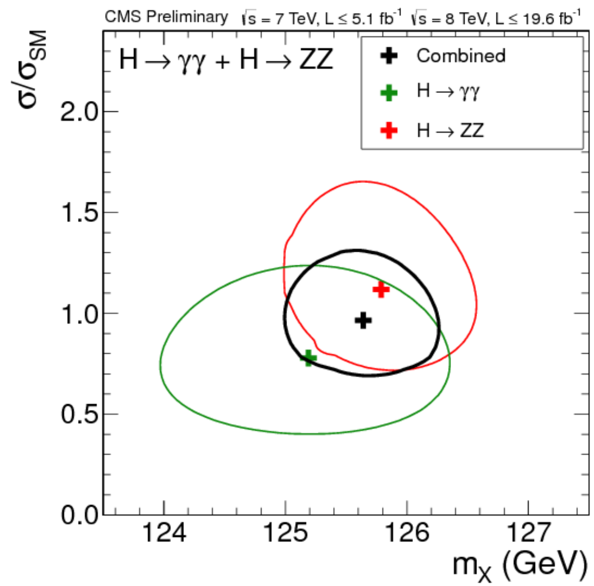
m_H=125.7±0.3 (stat) ± 0.3 (syst) GeV

m_{4l} = 124.3 ± 0.6 (stat) ± 0.4 (syst) GeV

$m_{\gamma\gamma}$ =126.8 ± 0.2(stat) ± 0.7(syst) GeV

m_H=125.5±0.2 (stat) $_{-0.6}^{+0.5}$ (syst) GeV





Energy scale systematics dominant for ZZ, electron-photon and energy scale extrapolation dominant for γγ

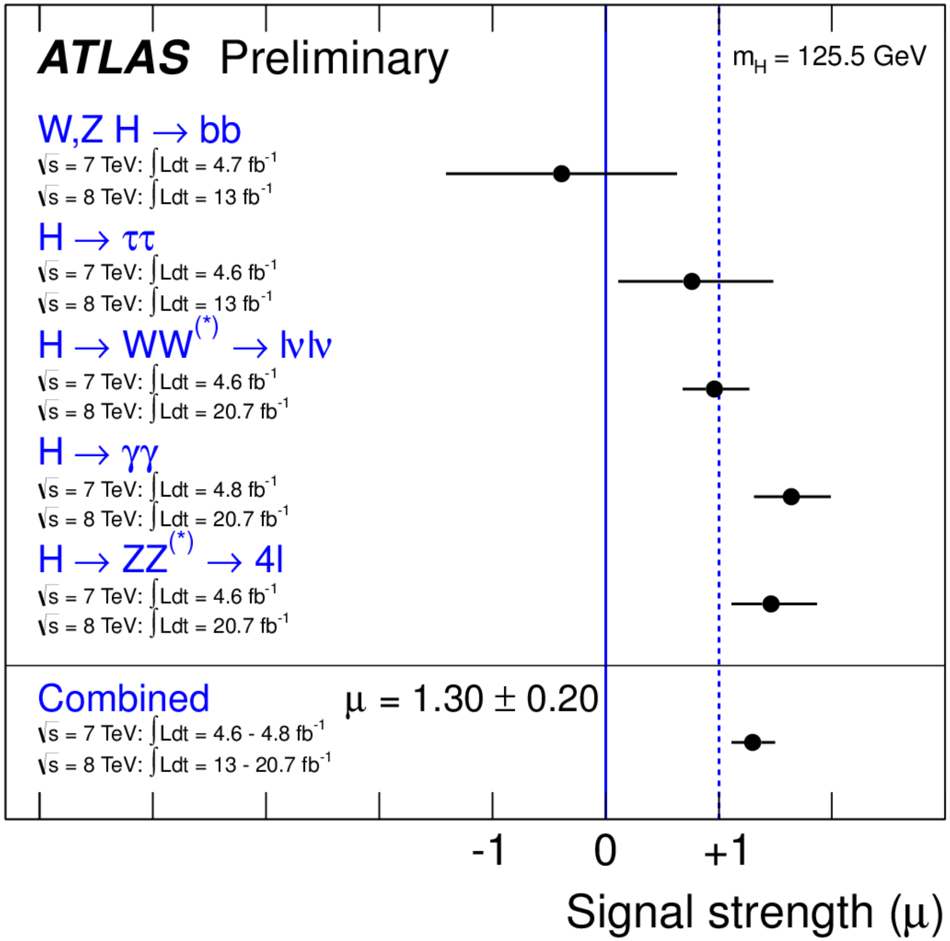
$\Delta m_H = m_{\gamma\gamma} - m_{4l} = 2.3_{-0.7}^{+0.6}$ (stat) ±0.6 (syst) GeV

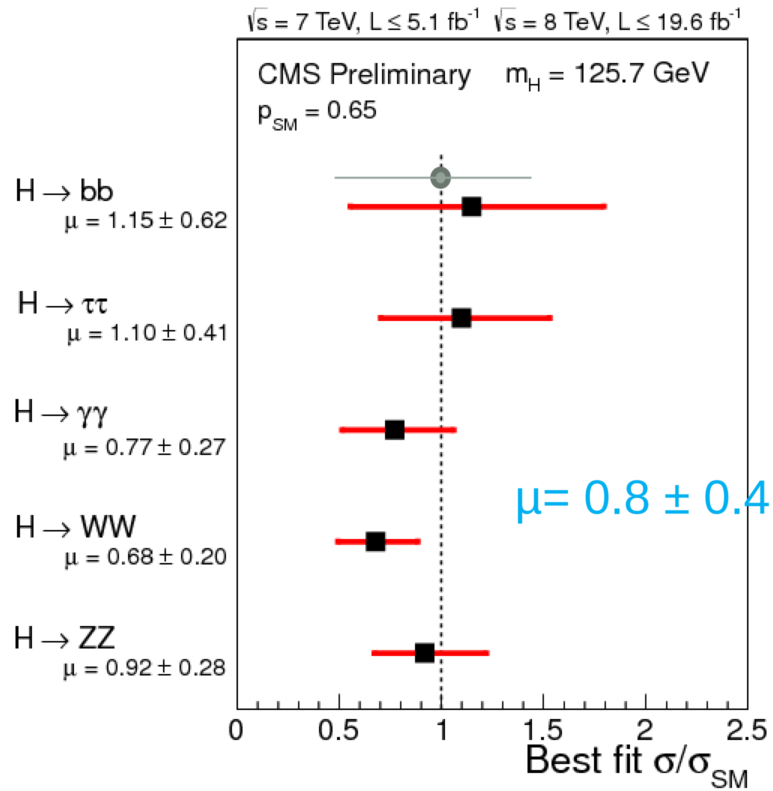
Consistent with $\Delta m_H = 0$ at 2.3σ level

Combined results compatible across experiments

Higgs Signal Strength

ATLAS-CONF-2013-14
ATLAS-CONF-2013-34
CMS-PAS-13-005

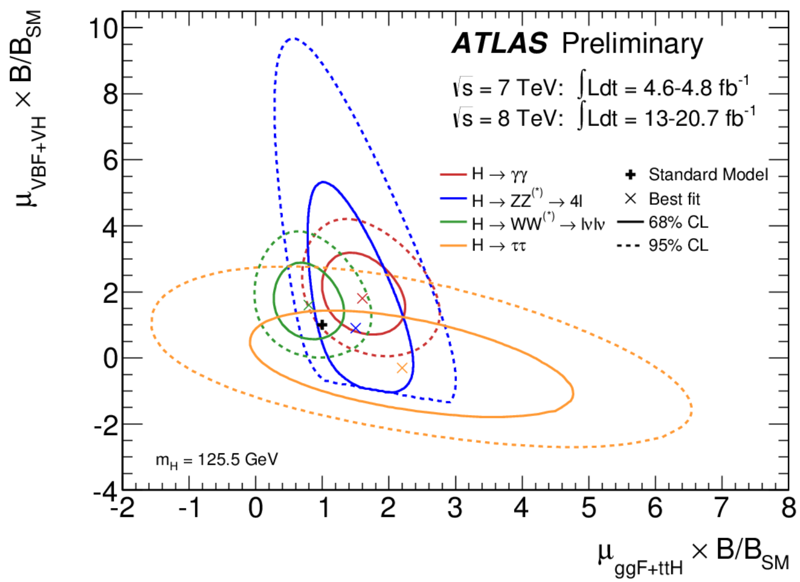


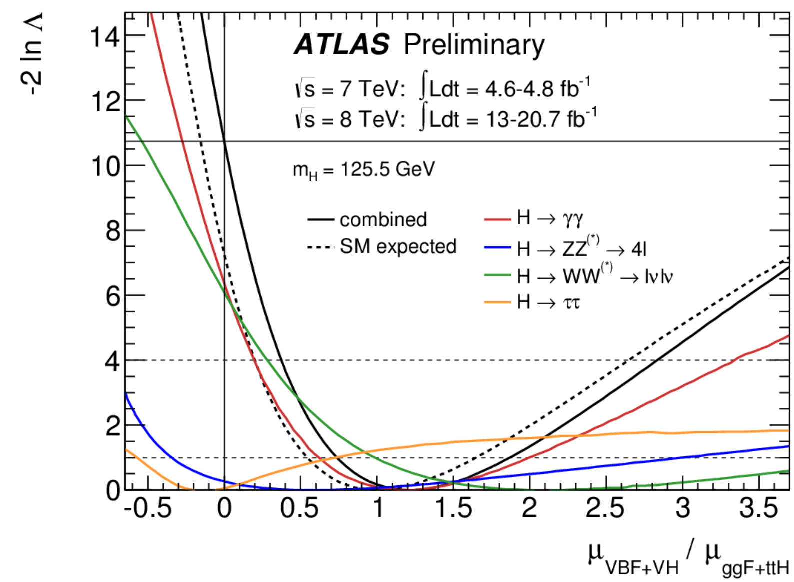


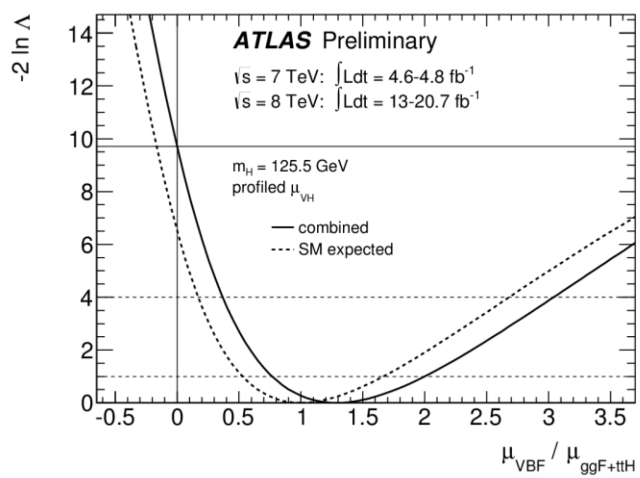
Consistent with the SM

Higgs Signal Strength

ATLAS-CONF-2013-14
ATLAS-CONF-2013-34
CMS-PAS-13-005







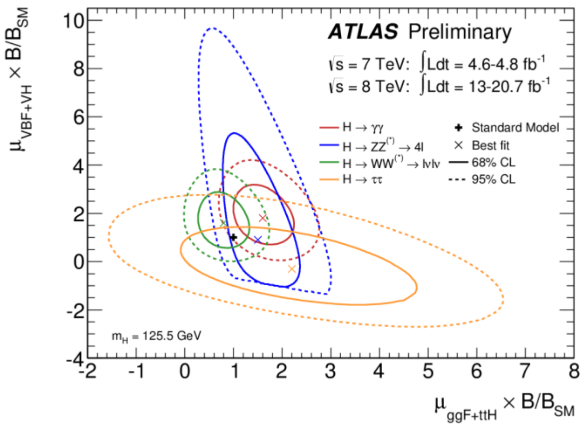
Model dependence in BR factored out in ratio allows for combination across channels

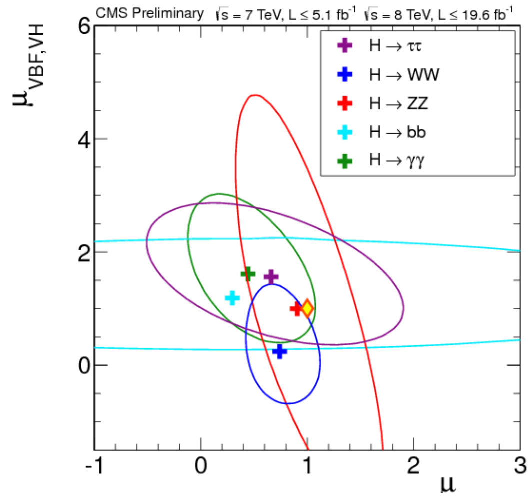
p-value for excluding VBF/ggF = 0
- 0.05% (fixing ratio VH/VBF)
- 0.09% (profiling ratio VH/VBF)

~ 3 sigmas

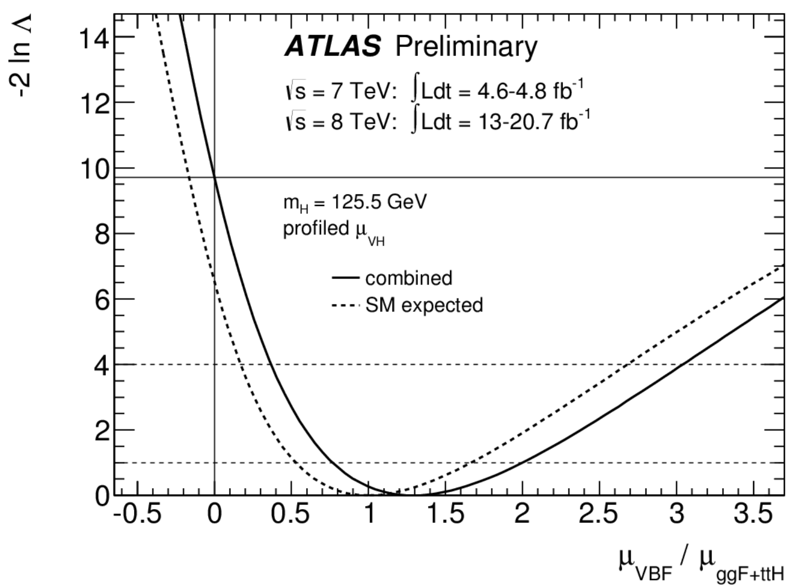
Higgs Signal Strength

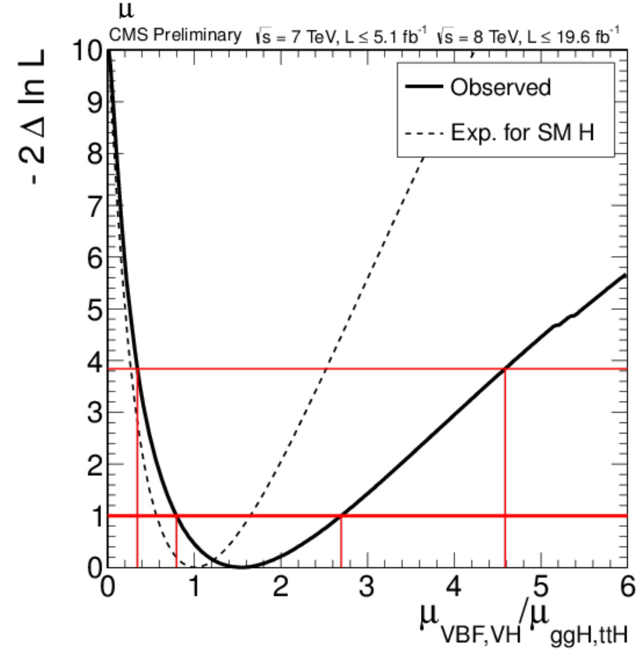
ATLAS-CONF-2013-14
ATLAS-CONF-2013-34
CMS-PAS-13-005





Compatible with the SM





Higgs fits

ATLAS-CONF-2013-14
ATLAS-CONF-2013-34
CMS-PAS-13-005

Largely use parameterisations from LHCHXSWG arXiv:1209.0040

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

Production modes

$$\frac{\sigma_{\mathrm{ggH}}}{\sigma^{\mathrm{SM}}_{\mathrm{ggH}}} = \begin{cases} \kappa^2_{\mathrm{g}}(\kappa_{\mathrm{b}}, \kappa_{\mathrm{t}}, m_{\mathrm{H}}) \\ \kappa^2_{\mathrm{g}} \end{cases}$$

$$\frac{\sigma_{\mathrm{VBF}}}{\sigma^{\mathrm{SM}}_{\mathrm{VBF}}} = \kappa^2_{\mathrm{VBF}}(\kappa_{\mathrm{W}}, \kappa_{\mathrm{Z}}, m_{\mathrm{H}})$$

$$\frac{\sigma_{\mathrm{WH}}}{\sigma^{\mathrm{SM}}_{\mathrm{WH}}} = \kappa^2_{\mathrm{W}}$$

$$\frac{\sigma_{\mathrm{ZH}}}{\sigma^{\mathrm{SM}}_{\mathrm{ZH}}} = \kappa^2_{\mathrm{Z}}$$

$$\frac{\sigma_{\mathrm{t\bar{t}H}}}{\sigma^{\mathrm{SM}}_{\mathrm{t\bar{t}H}}} = \kappa^2_{\mathrm{t}}$$

Assume all signals near 126 come from a single resonance of zero width, with SM-like coupling structure

Total width = sum of all decays widths (+ invisible)

Decay modes

$$\frac{\Gamma_{\mathrm{WW}^{(*)}}}{\Gamma^{\mathrm{SM}}_{\mathrm{WW}^{(*)}}} = \kappa^2_{\mathrm{W}}$$

$$\frac{\Gamma_{\mathrm{ZZ}^{(*)}}}{\Gamma^{\mathrm{SM}}_{\mathrm{ZZ}^{(*)}}} = \kappa^2_{\mathrm{Z}}$$

$$\frac{\Gamma_{\mathrm{b\bar{b}}}}{\Gamma^{\mathrm{SM}}_{\mathrm{b\bar{b}}}} = \kappa^2_{\mathrm{b}}$$

$$\frac{\Gamma_{\tau^-\tau^+}}{\Gamma^{\mathrm{SM}}_{\tau^-\tau^+}} = \kappa^2_{\tau}$$

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma^{\mathrm{SM}}_{\gamma\gamma}} = \begin{cases} \kappa^2_{\gamma}(\kappa_{\mathrm{b}}, \kappa_{\mathrm{t}}, \kappa_{\tau}, \kappa_{\mathrm{W}}, m_{\mathrm{H}}) \\ \kappa^2_{\gamma} \end{cases}$$

$$\frac{\Gamma_{\mathrm{Z}\gamma}}{\Gamma^{\mathrm{SM}}_{\mathrm{Z}\gamma}} = \begin{cases} \kappa^2_{(\mathrm{Z}\gamma)}(\kappa_{\mathrm{b}}, \kappa_{\mathrm{t}}, \kappa_{\tau}, \kappa_{\mathrm{W}}, m_{\mathrm{H}}) \\ \kappa^2_{(\mathrm{Z}\gamma)} \end{cases}$$

Higgs fits

ATLAS-CONF-2013-14
ATLAS-CONF-2013-34
CMS-PAS-13-005

Largely use parameterisations from LHCHXSWG arXiv:1209.0040

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

Production modes

$$\frac{\sigma_{\mathrm{ggH}}}{\sigma_{\mathrm{ggH}}^{\mathrm{SM}}} = \begin{cases} \kappa_g^2(\kappa_b, \kappa_t, m_{\mathrm{H}}) \\ \kappa_g^2 \end{cases}$$

$$\frac{\sigma_{\mathrm{VBF}}}{\sigma_{\mathrm{VBF}}^{\mathrm{SM}}} = \kappa_{\mathrm{VBF}}^2(\kappa_W, \kappa_Z, m_{\mathrm{H}})$$

$$\frac{\sigma_{\mathrm{WH}}}{\sigma_{\mathrm{WH}}^{\mathrm{SM}}} = \kappa_W^2$$

$$\frac{\sigma_{\mathrm{ZH}}}{\sigma_{\mathrm{ZH}}^{\mathrm{SM}}} = \kappa_Z^2$$

$$\frac{\sigma_{t\bar{t}\mathrm{H}}}{\sigma_{t\bar{t}\mathrm{H}}^{\mathrm{SM}}} = \kappa_t^2$$

Assume all signals near 126 come from a single resonance of zero width, with SM-like coupling structure

Total width = sum of all decays widths (+ invisible)

Decay modes

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

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

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

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

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

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

Loops can be resolved into constituent contributions assuming SM or left as free parameter -> BSM

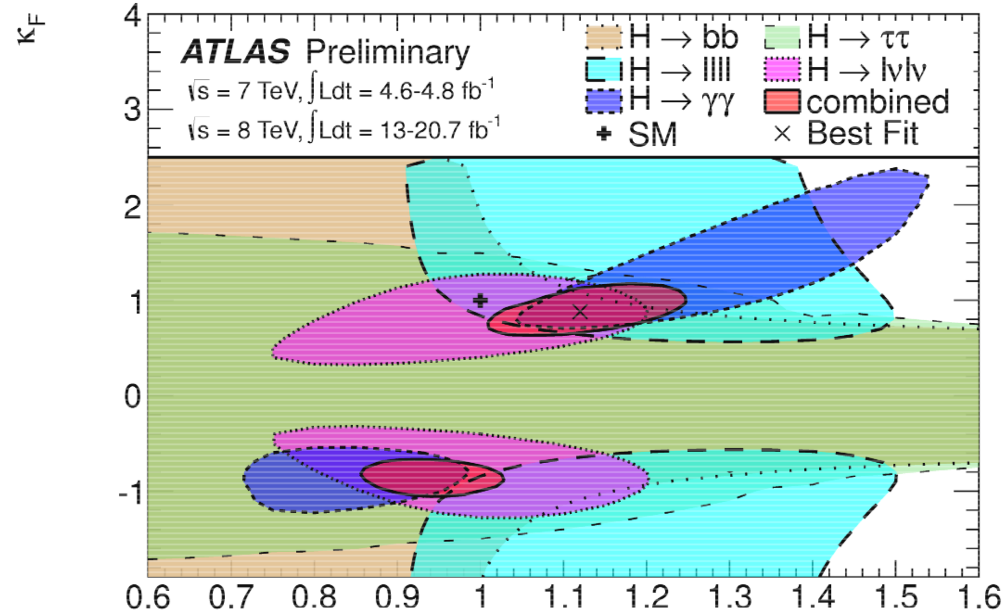
Higgs fits

ATLAS-CONF-2013-14
ATLAS-CONF-2013-34
CMS-PAS-13-005

2 parameter model

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

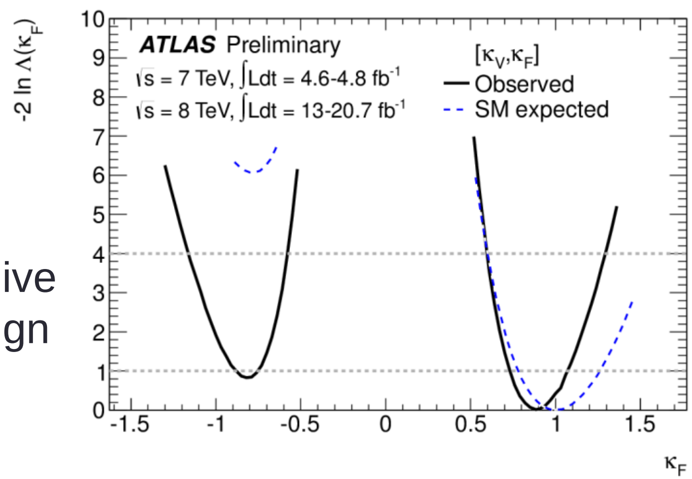
$$\kappa_F \in [-0.88, -0.75] \cup [0.73, 1.07]$$
$$\kappa_V \in [0.91, 0.97] \cup [1.05, 1.21] \quad .$$

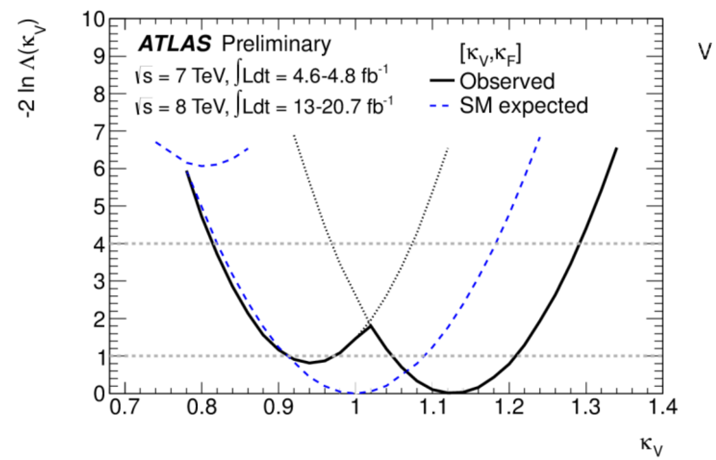


Compatible with the SM

$$\Gamma_{\gamma\gamma} \backsim |\alpha\kappa_F + \beta\kappa_V|^2$$

photon loop could give access to relative sign



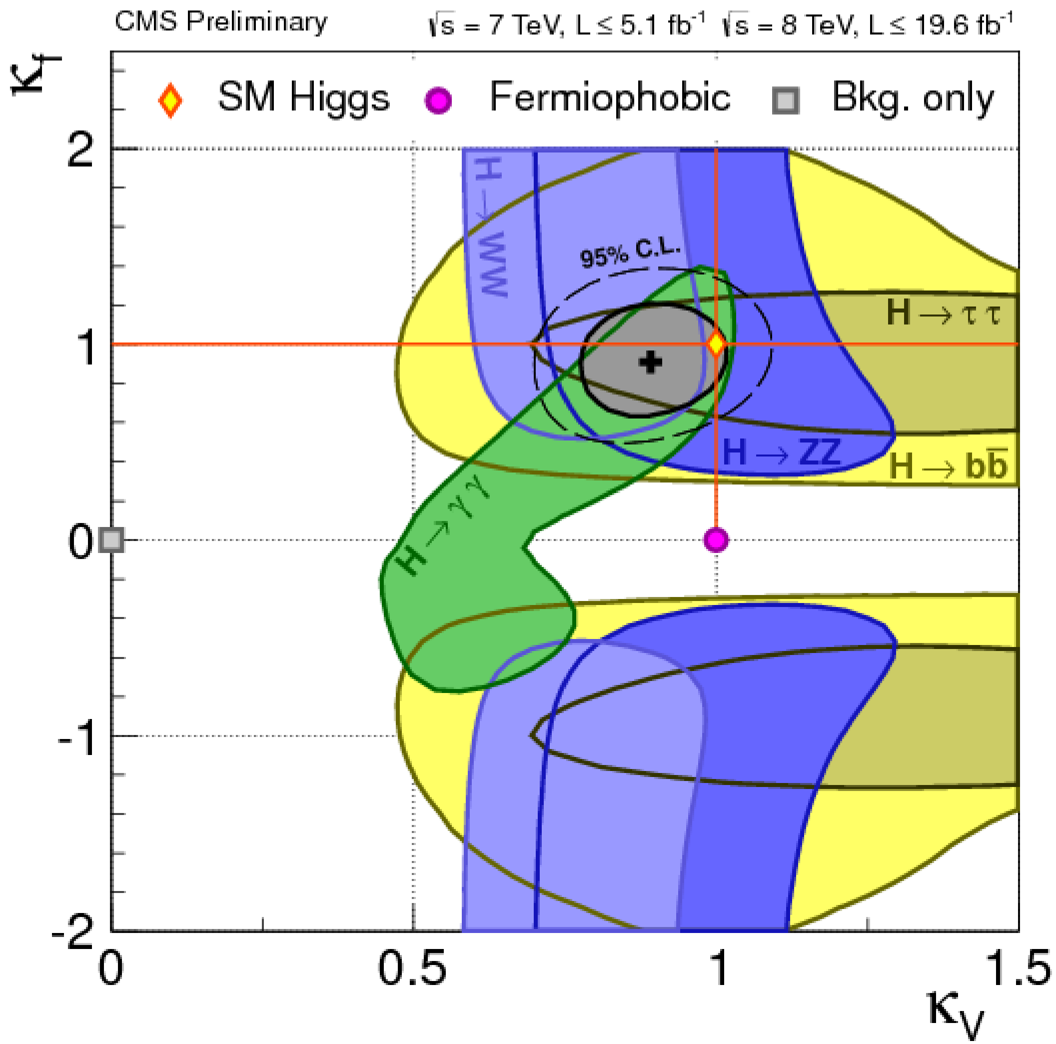


Higgs fits

ATLAS-CONF-2013-14
ATLAS-CONF-2013-34
CMS-PAS-13-005

2 parameter model

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



Compatible with the SM

$$\Gamma_{\gamma\gamma} \backsim |\alpha\kappa_F + \beta\kappa_V|^2$$

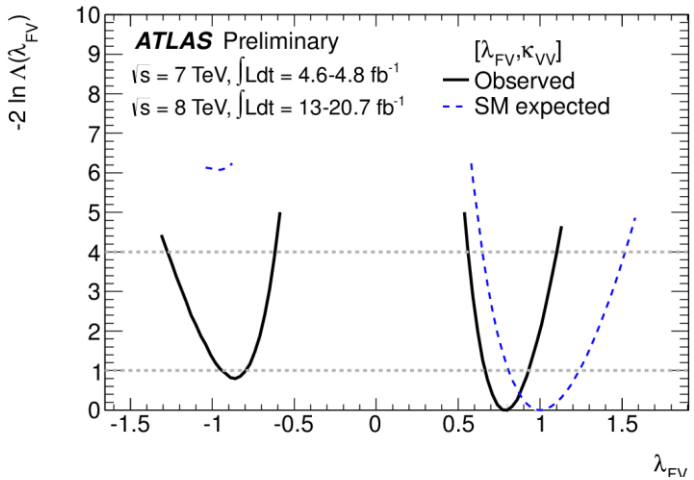
photon loop could give access to relative sign

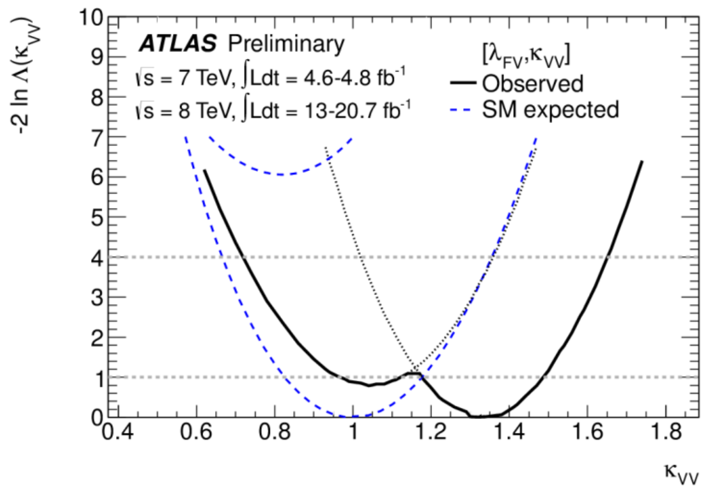
Higgs fits

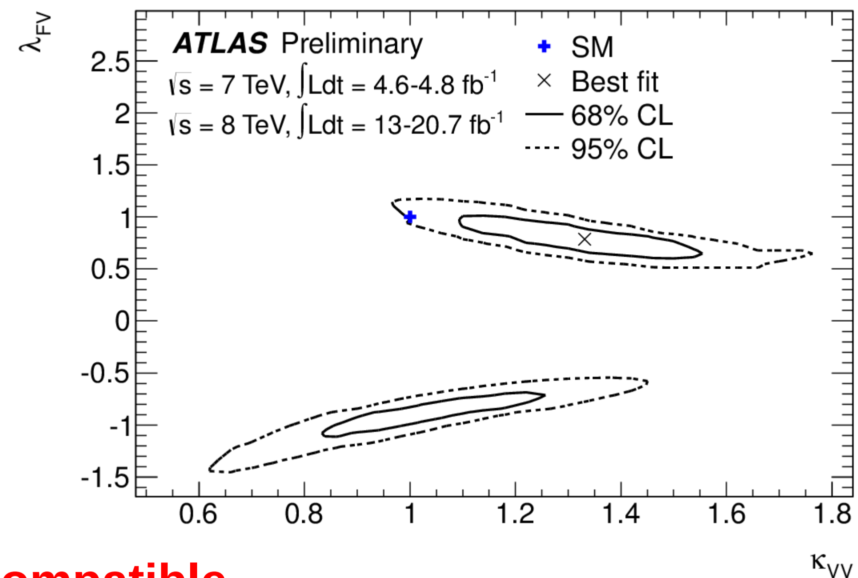
ATLAS-CONF-2013-14
ATLAS-CONF-2013-34
CMS-PAS-13-005

2 parameter model but no assumption on the total width

$$\lambda_{FV} = \kappa_F / \kappa_V$$
$$\kappa_{VV} = \kappa_V \cdot \kappa_V / \kappa_H$$







Compatible with the SM

$$\lambda_{FV} \in [-0.94, -0.80] \cup [0.67, 0.93]$$
$$\kappa_{VV} \in [0.96, 1.12] \cup [1.18, 1.49] \quad .$$

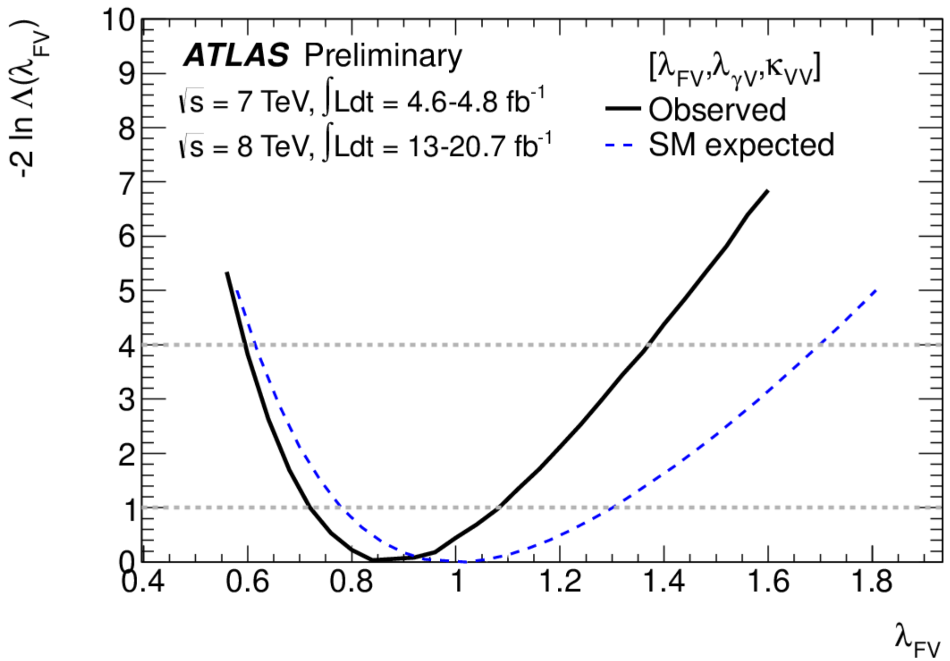
Higgs fits

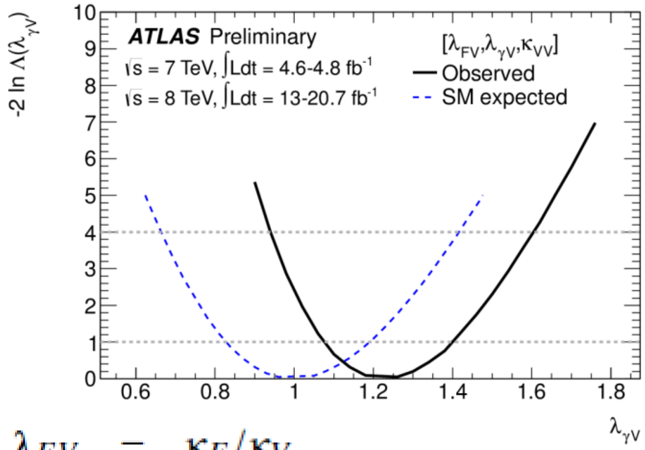
ATLAS-CONF-2013-14
ATLAS-CONF-2013-34
CMS-PAS-13-005

3 parameter model – don't resolve the photon loop

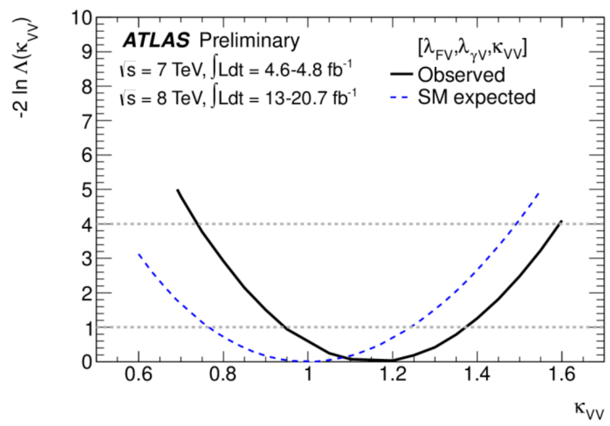
$$\lambda_{FV} = 0.85^{+0.23}_{-0.13}$$
$$\lambda_{\gamma V} = 1.22^{+0.18}_{-0.14}$$
$$\kappa_{VV} = 1.15 \pm 0.21$$

Compatible with the SM





$$\lambda_{FV} = \kappa_F / \kappa_V$$
$$\lambda_{\gamma V} = \kappa_\gamma / \kappa_V$$
$$\kappa_{VV} = \kappa_V \cdot \kappa_V / \kappa_H$$

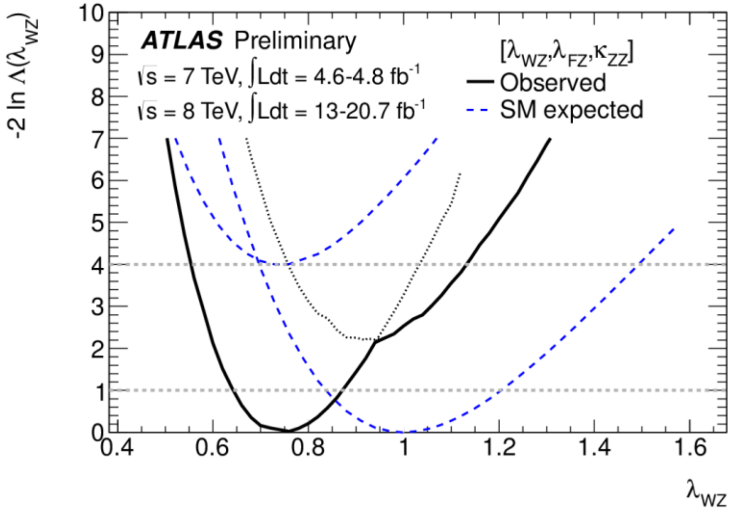


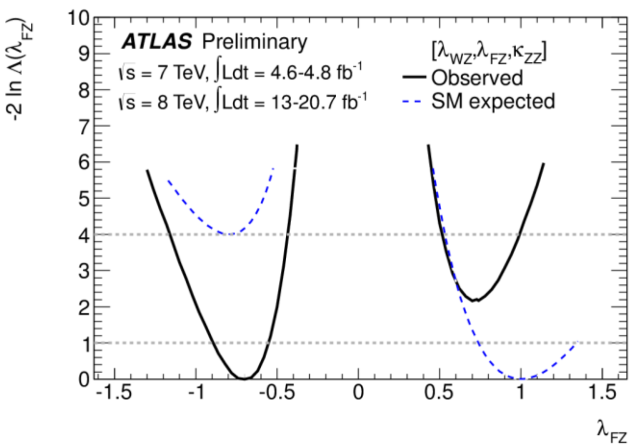
3D compatibility with SM 9%

Higgs fits

ATLAS-CONF-2013-14
ATLAS-CONF-2013-34
CMS-PAS-13-005

Custodial symmetry





$$\kappa_{ZZ} = \kappa_Z \cdot \kappa_Z / \kappa_H$$
$$\lambda_{WZ} = \kappa_W / \kappa_Z$$
$$\lambda_{FZ} = \kappa_F / \kappa_Z \quad .$$

Compatible with the SM

$$\lambda_{WZ} \in [0.64, 0.87]$$
$$\lambda_{FZ} \in [-0.89, -0.55]$$
$$\kappa_{ZZ} \in [1.20, 2.08]$$

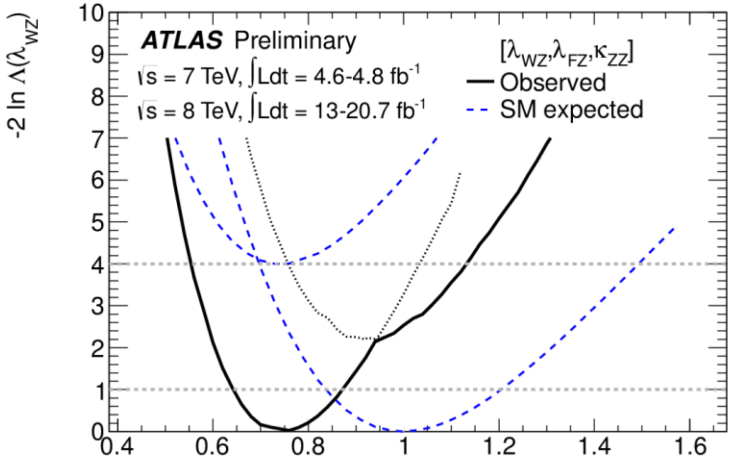
λ_{FZ} prefers non-physical region but not strongly compared with +ve quadrant minimum

3D SM compatibility 5%

Higgs fits

ATLAS-CONF-2013-14
ATLAS-CONF-2013-34
CMS-PAS-13-005

Custodial symmetry



3D SM compatibility 5%

$$\kappa_{ZZ} = \kappa_Z \cdot \kappa_Z / \kappa_H$$
$$\lambda_{WZ} = \kappa_W / \kappa_Z$$
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Compatible with the SM

$$\lambda_{WZ} \in [0.64, 0.87]$$
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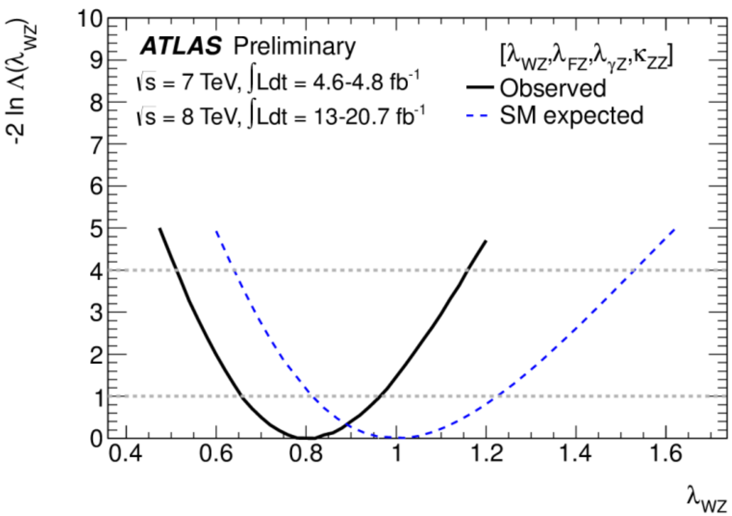


Decouple from diphoton rate

$$\kappa_{ZZ} = \kappa_Z \cdot \kappa_Z / \kappa_H$$
$$\lambda_{WZ} = \kappa_W / \kappa_Z$$
$$\lambda_{\gamma Z} = \kappa_\gamma / \kappa_Z$$
$$\lambda_{FZ} = \kappa_F / \kappa_Z \; .$$

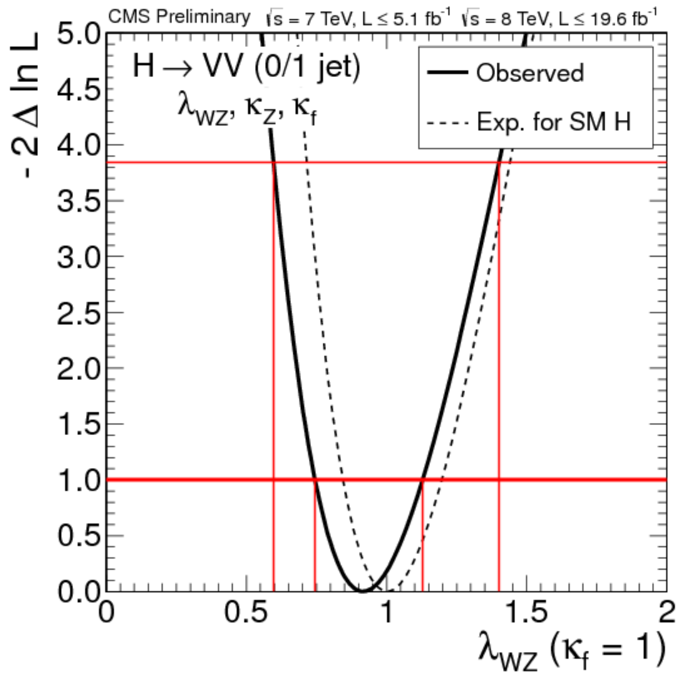
$$\lambda_{WZ} = 0.80 \pm 0.15$$
$$\lambda_{\gamma Z} = 1.10 \pm 0.18$$
$$\lambda_{FZ} = 0.74^{+0.21}_{-0.17}$$
$$\kappa_{ZZ} = 1.5^{+0.5}_{-0.4}$$

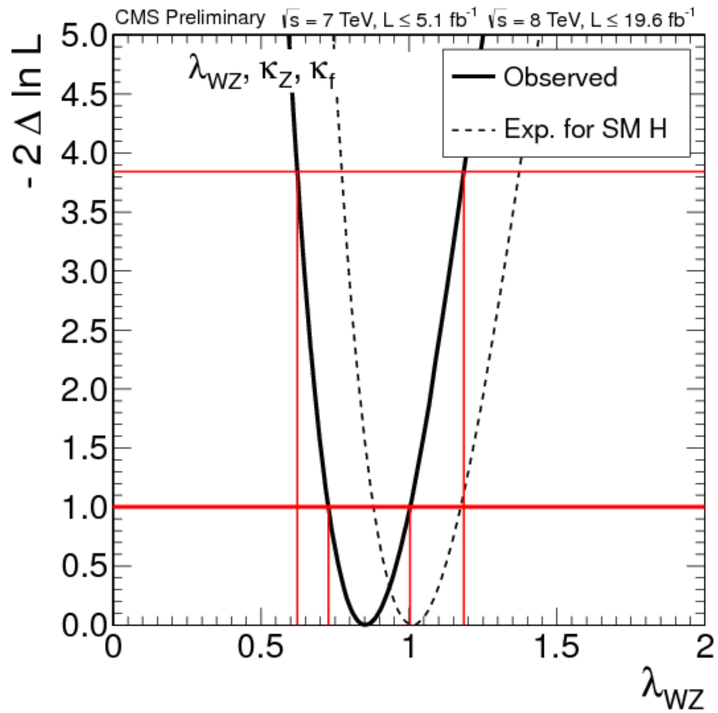
4D SM compatibility 9%

Higgs fits

ATLAS-CONF-2013-14
ATLAS-CONF-2013-34
CMS-PAS-13-005

Custodial symmetry





Using only WW and ZZ channels

Using all channels

Compatible with the SM

Higgs fits

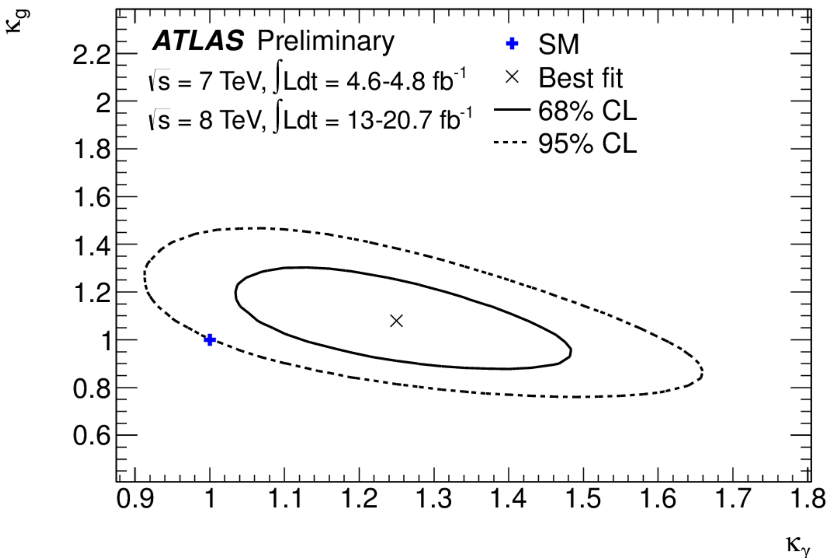
ATLAS-CONF-2013-14
ATLAS-CONF-2013-34
CMS-PAS-13-005

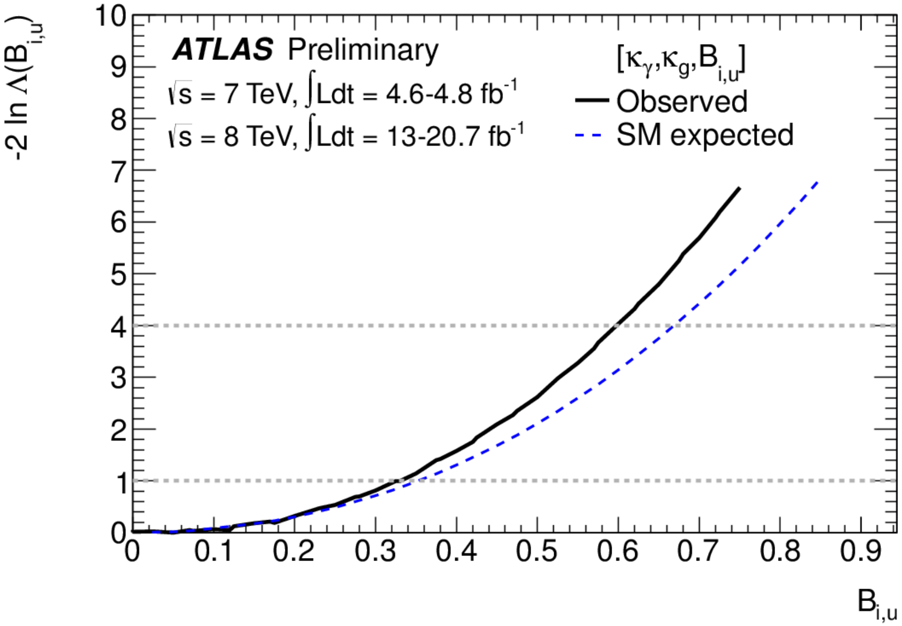
Probing the loops

Compatible with the SM

$$\kappa_g = 1.08 \pm 0.14$$
$$\kappa_\gamma = 1.23^{+0.16}_{-0.13}$$

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





2D SM compatibility 5%

3D SM compatibility 10%

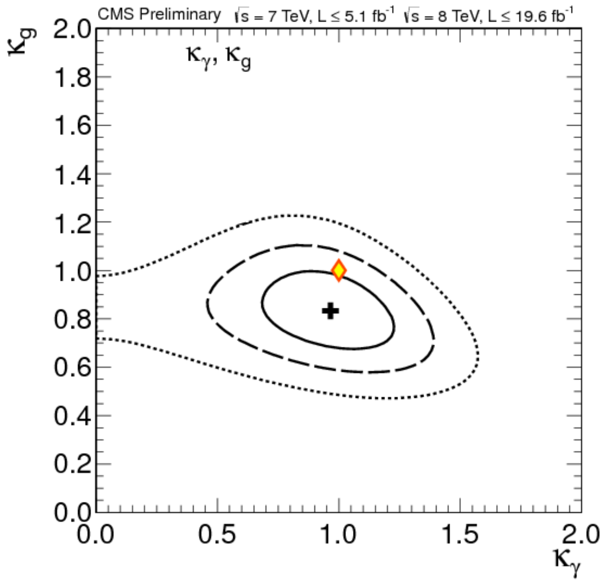
$$\kappa_g = 1.08^{+0.32}_{-0.14}$$
$$\kappa_\gamma = 1.24^{+0.16}_{-0.14}$$
$$BR_{inv.,undet.} < 0.33$$

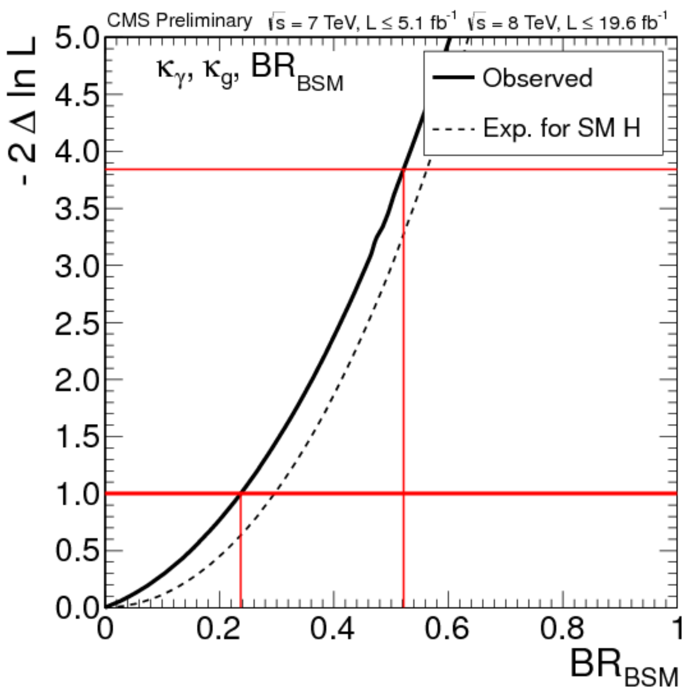
Higgs fits

ATLAS-CONF-2013-14
ATLAS-CONF-2013-34
CMS-PAS-13-005

Probing the loops

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



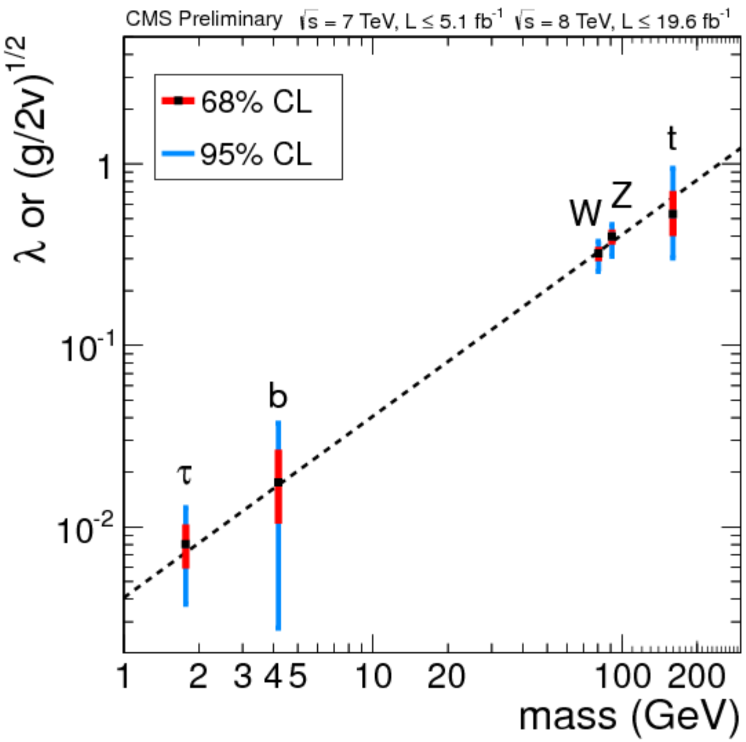


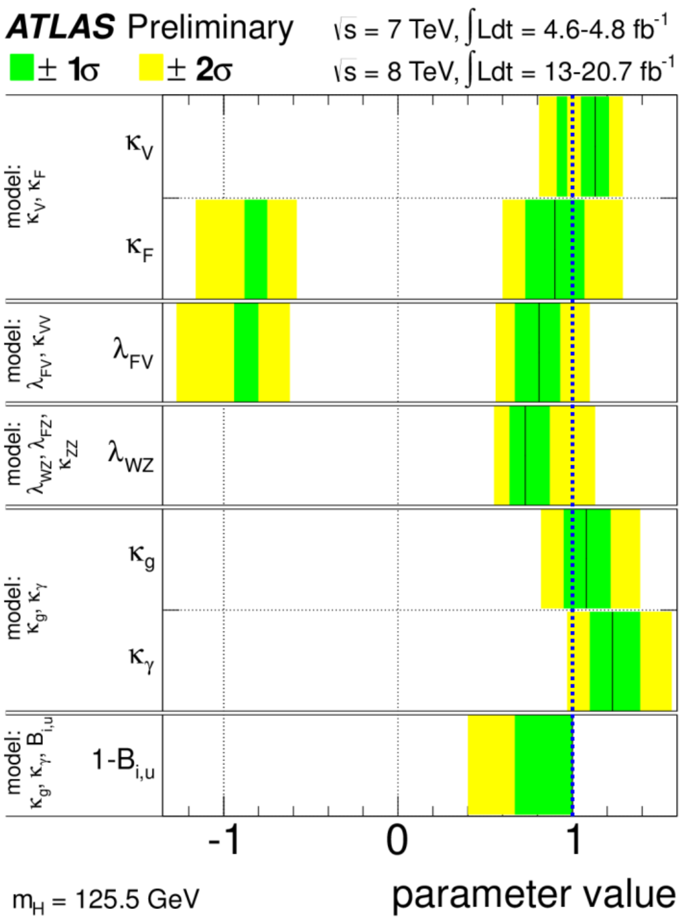
Compatible with the SM

BR(invis) < 0.52 @ 95% CL

Higgs fits

ATLAS-CONF-2013-14
ATLAS-CONF-2013-34
CMS-PAS-13-005





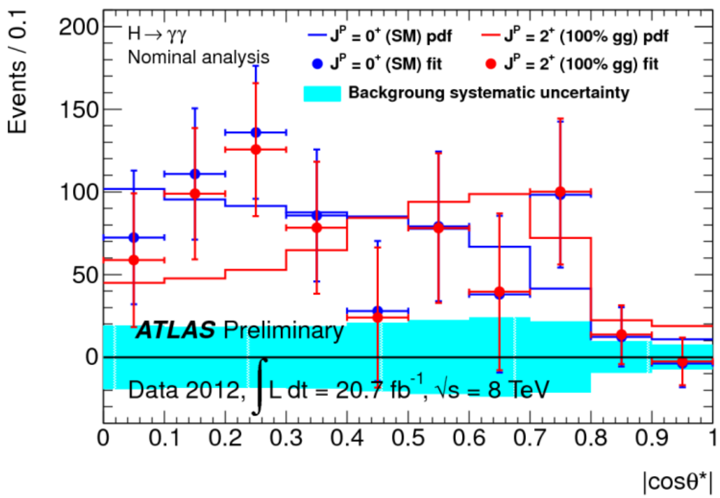
No significant deviation from the SM seen in any of the benchmark fits performed.

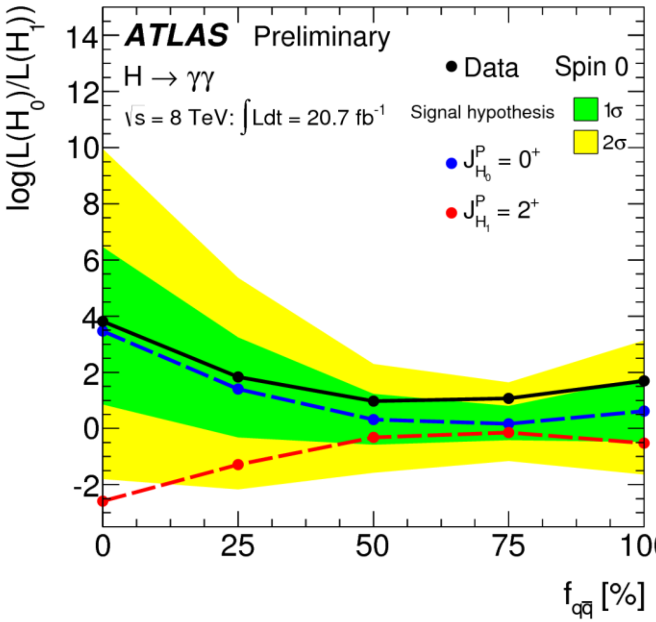
Compatible with the SM

Higgs Spin Studies

ATLAS-CONF-2013-029

Compare 0+ with 2+ "graviton" model with minimal couplings in diphotons





Fit 2D product PDF in $m_{\gamma\gamma}$ x cosθ*

$f_{q\bar{q}}$ (%)	Spin hypothesis	p-values (%)		$1 - CL_S(2^+)$ (%)
		expected	observed	
0	0^+	1.2	58.8	99.3
	2^+	0.5	0.3	
25	0^+	5.2	60.9	94.6
	2^+	3.9	2.1	
50	0^+	19.8	70.8	74
	2^+	18.7	7.6	
75	0^+	31.9	90.2	66
	2^+	30.5	3.3	
100	0^+	14.8	79.8	88
	2^+	13.5	2.5	

2+ disfavoured for ggF production

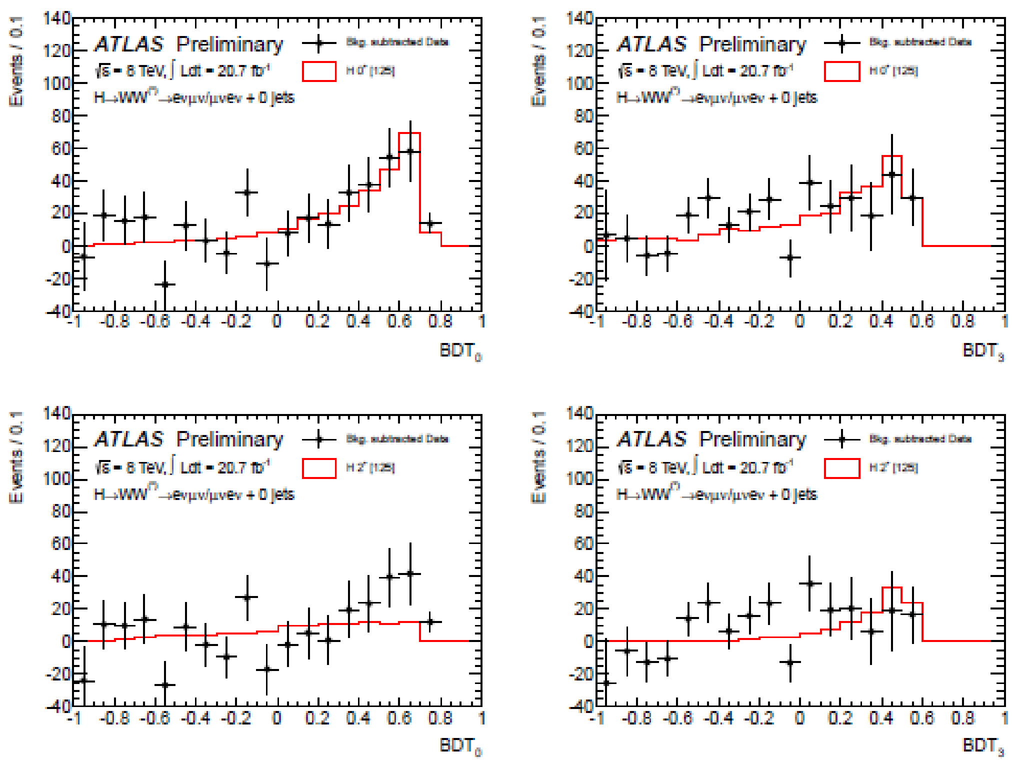
Higgs Spin Studies

ATLAS-CONF-2013-031

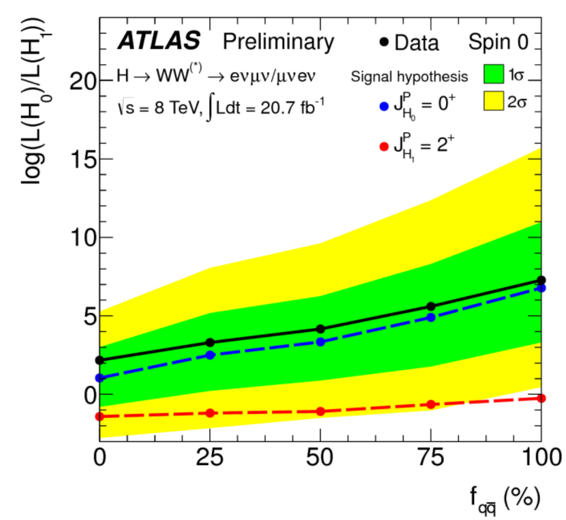
Compare 0+ with 2+ “graviton” model with minimal couplings in WW→llνν

Slightly different selection to rate analysis to remove spin dependent assumptions

Variable	Spin analysis	Rate analysis [5]
common $e\mu/\mu e$ lepton selection		
$E_{T,rel}^{miss}$	> 20 GeV	> 25 GeV
N_{jets}	0 jets	$0, 1, \geq 2$ jet selections
$p_T^{\ell\ell}$	> 20 GeV	> 30 GeV
$m_{\ell\ell}$	< 80 GeV	< 50 GeV
$\Delta\phi_{\ell\ell}$	< 2.8	< 1.8



BDTs trained to reject background versus each signal hypothesis



Data favour 0+ model

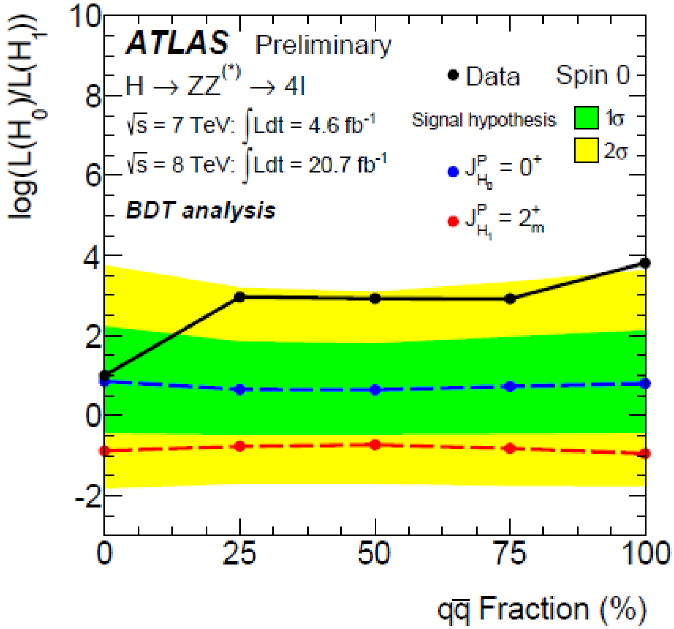
Higgs Spin Studies

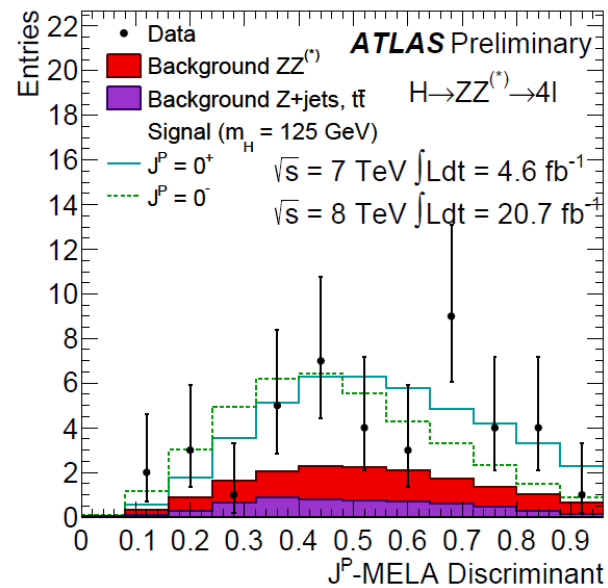
ATLAS-CONF-2013-013

Compare 0+ with variety of spin models in 4leptons

0- and 1+ excluded at >97.5%CL in favour of 0+

Data also favour 0+ versus 2+ with little variation versus qq fraction





2 approaches MELA and BDT

		BDT analysis				J^P-MELA analysis			
		tested J^P for an assumed 0^+		tested 0^+ for an assumed J^P	CL_S	tested J^P for an assumed 0^+		tested 0^+ for an assumed J^P	CL_S
		expected	observed	observed*		expected	observed	observed*	
0^-	p_0	0.0037	0.015	0.31	0.022	0.0011	0.0022	0.40	0.004
1^+	p_0	0.0016	0.001	0.55	0.002	0.0031	0.0028	0.51	0.006
1^-	p_0	0.0038	0.051	0.15	0.060	0.0010	0.027	0.11	0.031
2^+_m	p_0	0.092	0.079	0.53	0.168	0.064	0.11	0.38	0.182
2^-	p_0	0.0053	0.25	0.034	0.258	0.0032	0.11	0.08	0.116

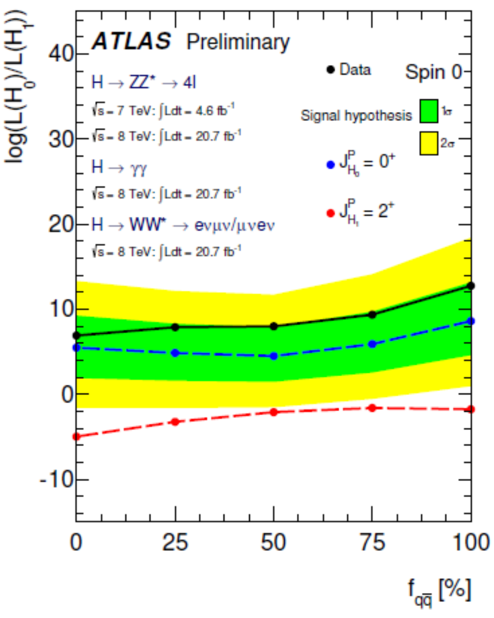
Higgs Spin Studies

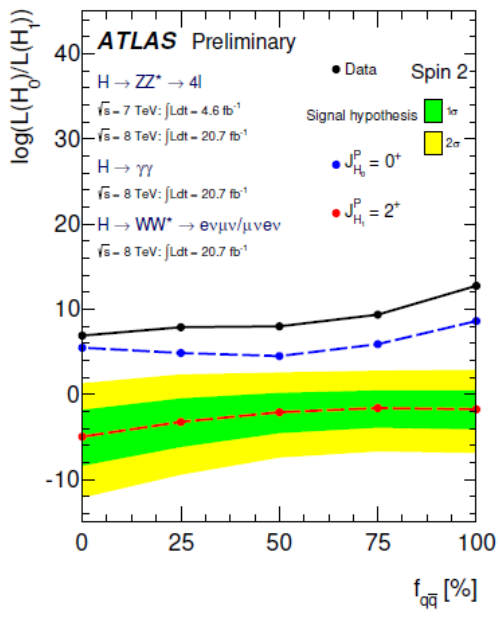
ATLAS-CONF-2013-040

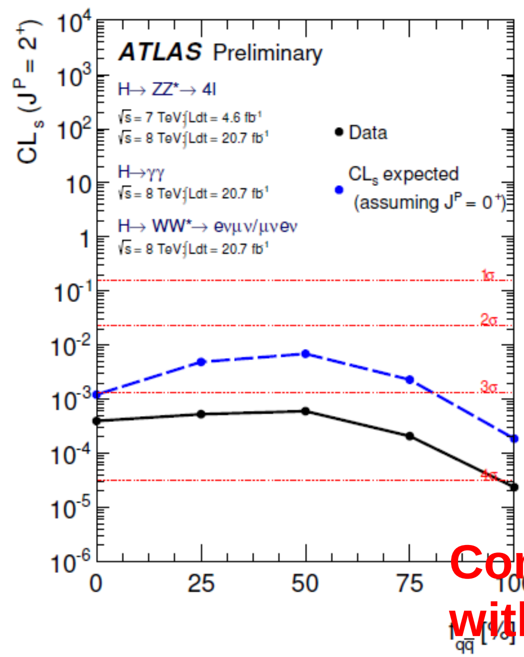
Combine all the 0+ versus 2+ studies

$f_{q\bar{q}}$	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%	$3.4 \cdot 10^{-3}$	$9.4 \cdot 10^{-5}$	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	$1.4 \cdot 10^{-4}$	$4.0 \cdot 10^{-4}$

2+ excluded at better than 99.9%CL versus 0+ for all qq fractions



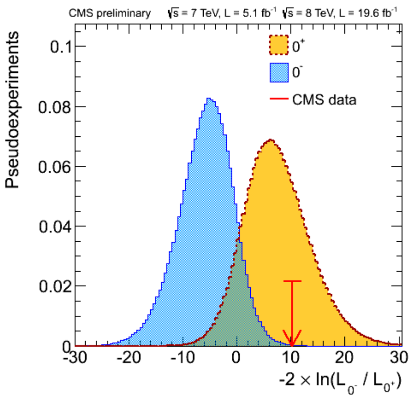




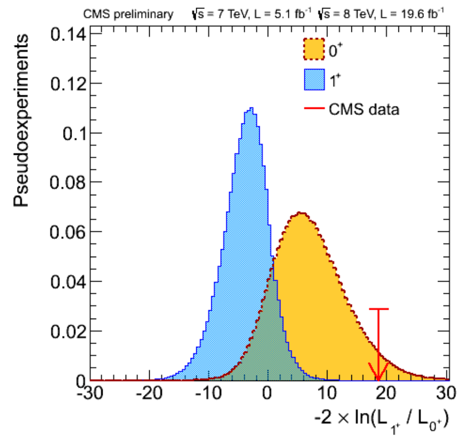
Compatible with the SM

Higgs Spin Studies

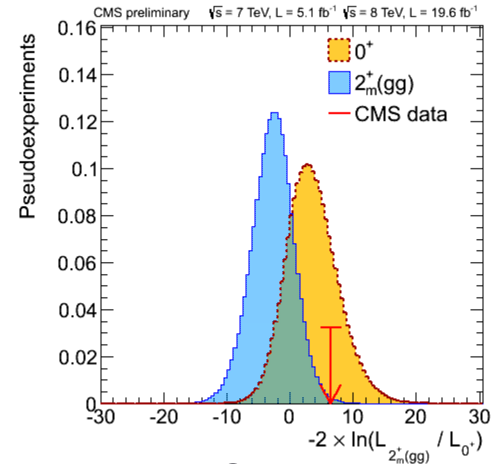
Compatible with the SM



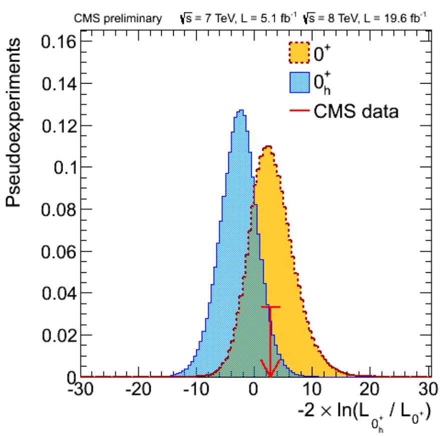
0^- vs H:
CLs = 0.0016



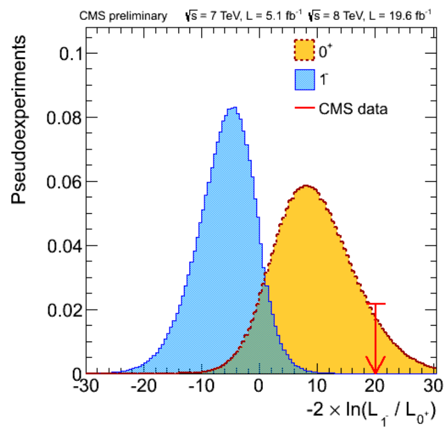
$qq \to 1^-$ vs H
CLs = 0.001



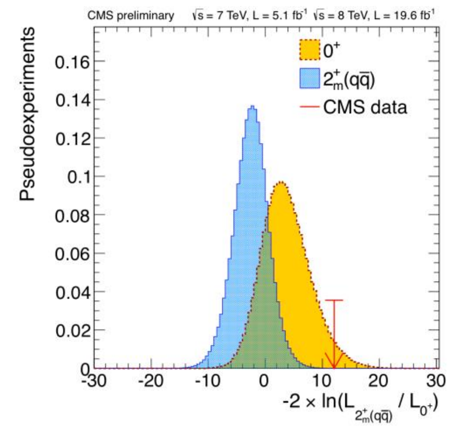
$gg \to 2^+_m$ vs H
CLs = 0.015



0^+_m vs H:
CLs = 0.081



$qq \to 1^+$ vs H
CLs = 0.001



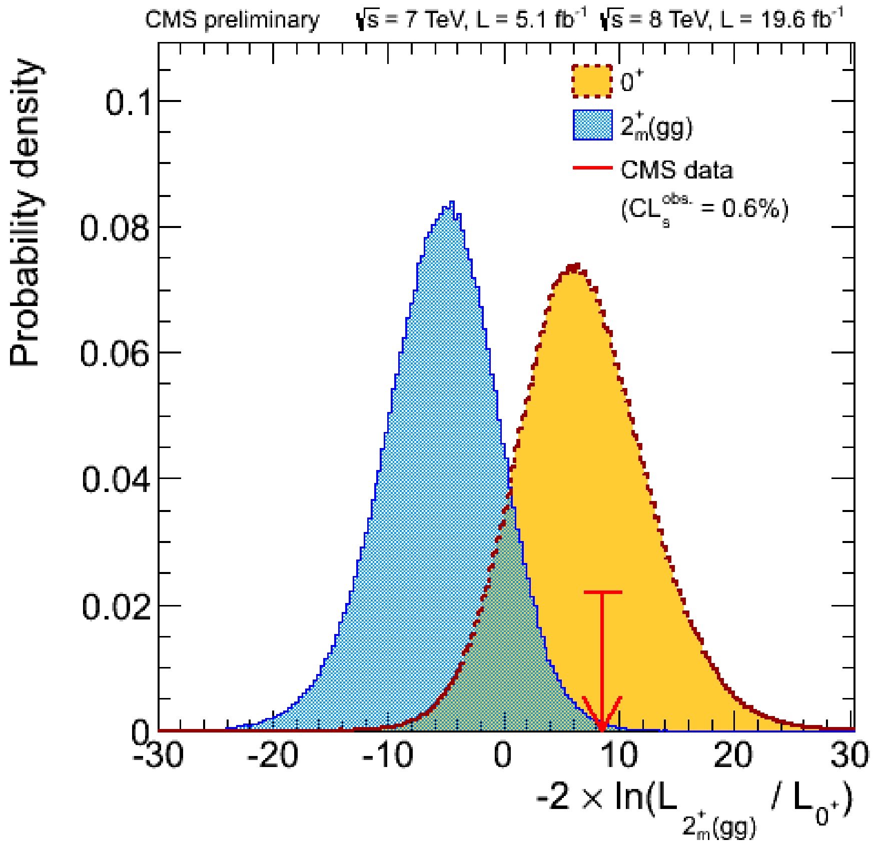
$qq \to 2^+_m$ vs H
CLs = 0.001

Higgs Spin Studies

WW+ZZ gg $\rightarrow 2^+_m$ versus SM H

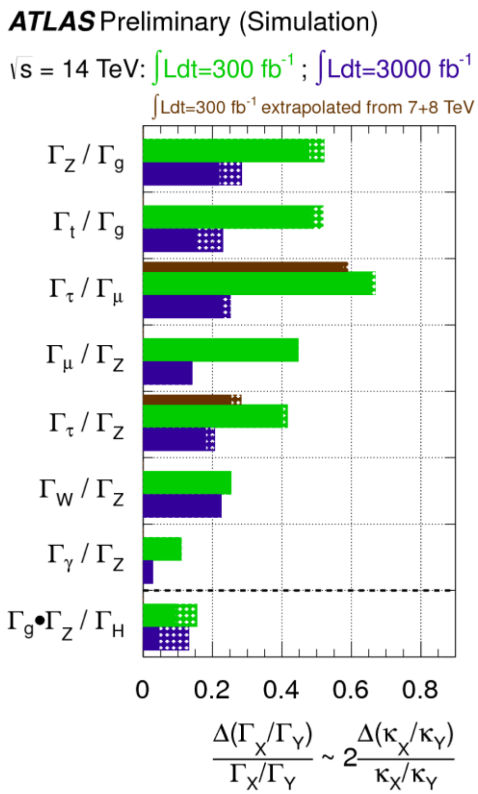
	Expected 1-CL_s	Observed 1-CL_s
ZZ	93.1%	98.6%
WW	91.9%	86.0%
Combination	98.8%	99.4%

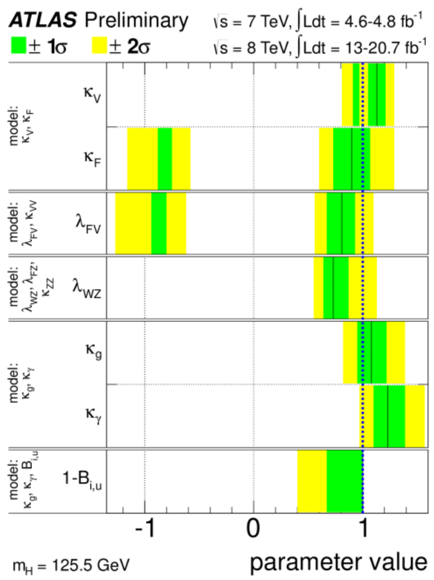
gg $\rightarrow 2^+_m$ excluded at 99% CL in combined result

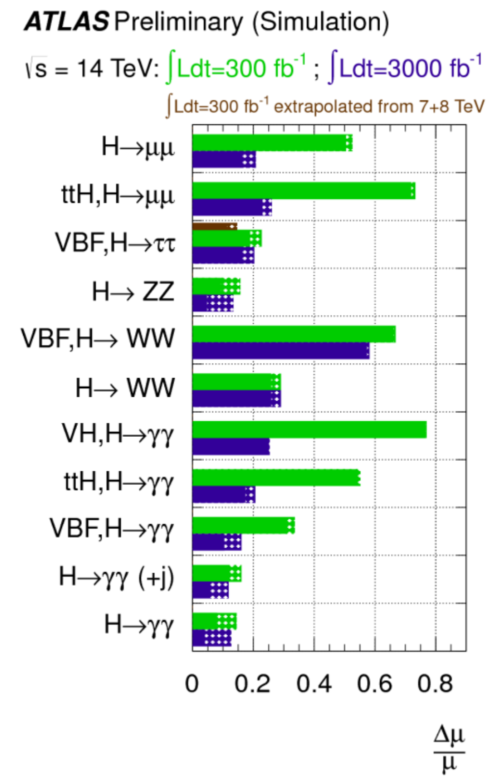


Summary and prospects

Huge programme of work searching for a measuring Higgs boson signals







Results so far are largely compatible with Standard Model

Prospects

Where to look next?

Continue to push SM searches
- Real challenges with pile-up and systematics

Global fits
- Everything SM like for now…

Look for additional Higgs bosons
- Existing searches with H(126) as background

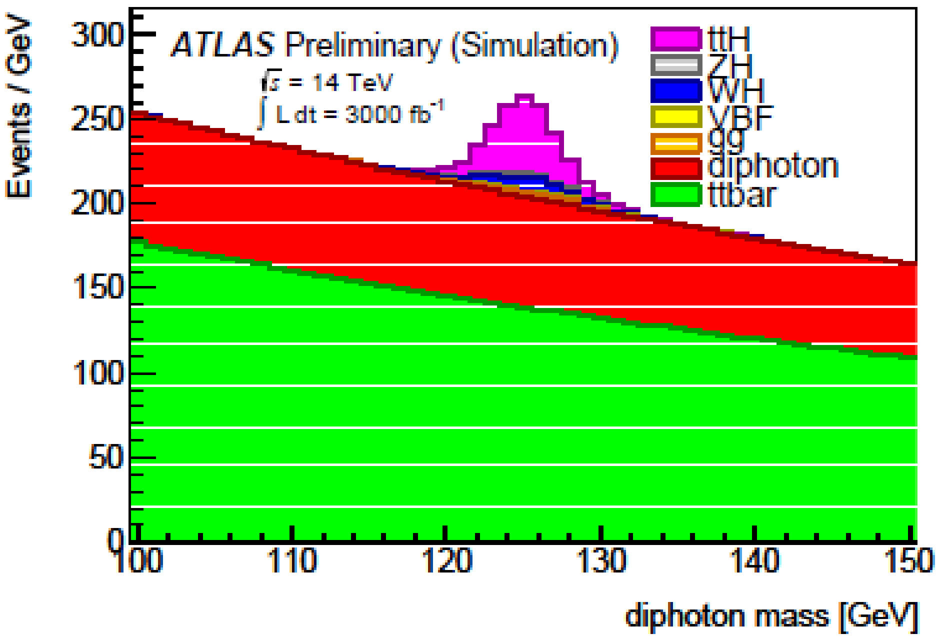
Traditional BSM searches – eg MSSM, Charged Higgs, etc
- Add H(126) as additional part of the signal

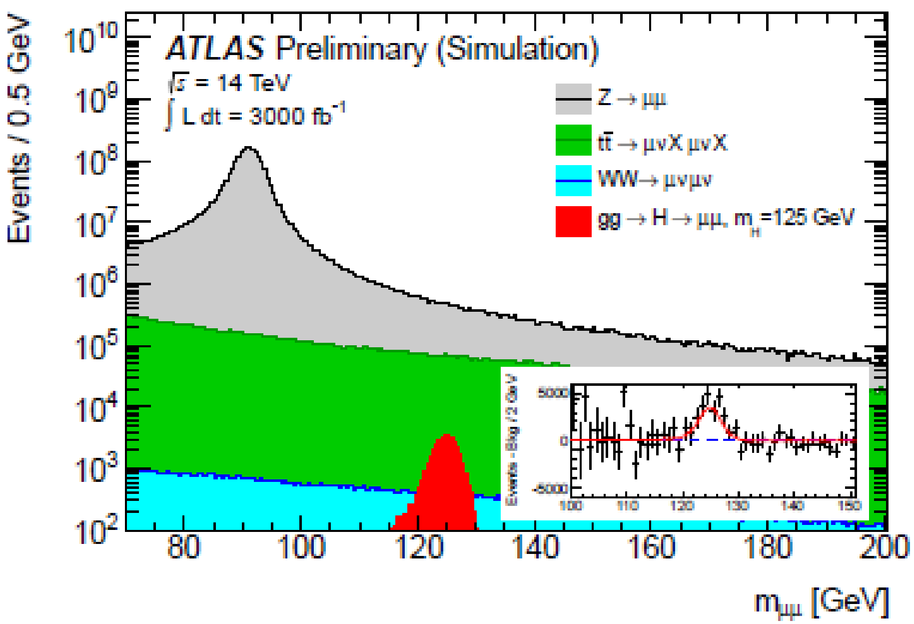
Open up new BSM searches:
- Generic 2HDM, decoupled or otherwise
- Higgs pair production : H+h, hh, H+H-, H+A, etc…

Summary and prospects

Higgs signal firmly established

But plenty of work still to do for the foreseeable future!





HIGGS TO 4 LEPTONS

Backup slides

Higgs to 4 leptons

Event yields

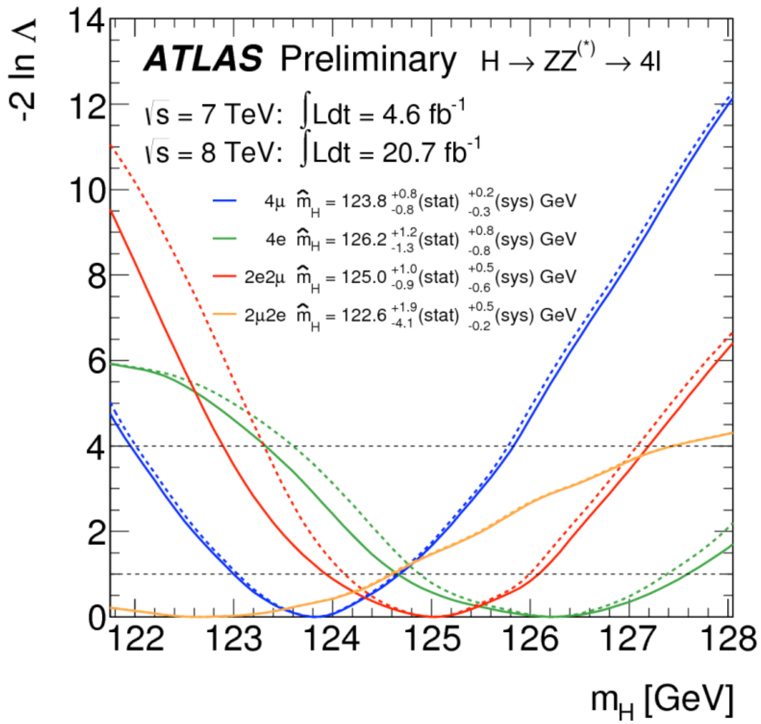
Table 7: The numbers of expected signal events for the m_H=125 GeV hypothesis and background events together with the numbers of observed events, in a window of ±5 GeV around 125 GeV for 20.7 fb^{-1} at $\sqrt{s}$ = 8 TeV and 4.6 fb^{-1} at $\sqrt{s}$ = 7 TeV as well as for their combination.

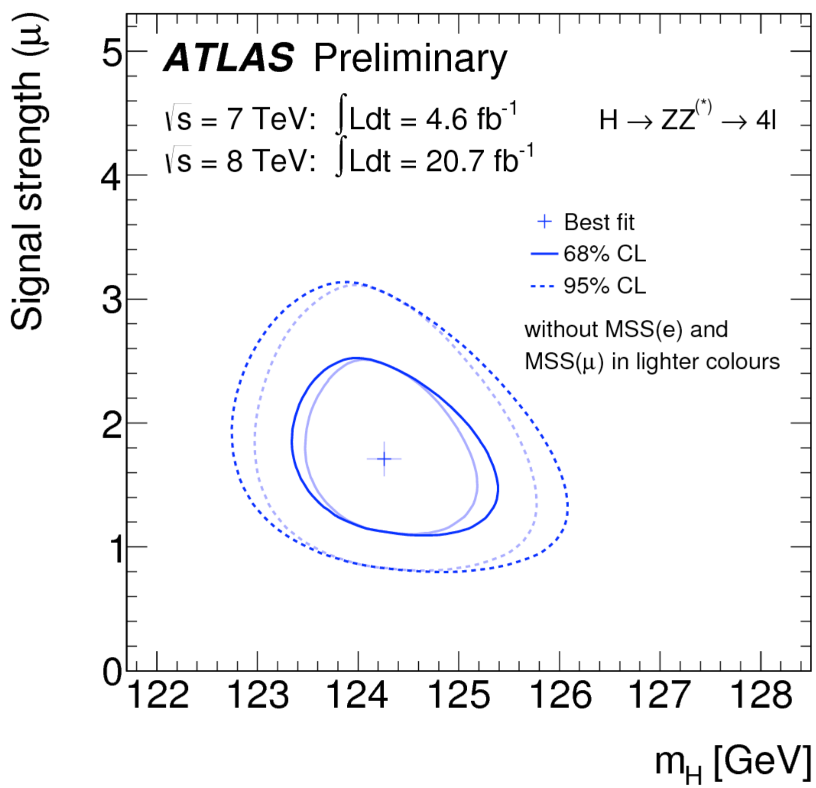
	total signal full mass range	signal	$ZZ^{(*)}$	Z + jets, $t\bar{t}$	S/B	expected	observed
			$\sqrt{s}$ = 8 TeV				
4μ	5.8 ± 0.7	5.3 ± 0.7	2.3 ± 0.1	0.50 ± 0.13	1.9	8.1 ± 0.9	11
$2\mu 2e$	3.0 ± 0.4	2.6 ± 0.4	1.2 ± 0.1	1.01 ± 0.21	1.2	4.8 ± 0.7	4
$2e2\mu$	4.0 ± 0.5	3.4 ± 0.4	1.7 ± 0.1	0.51 ± 0.16	1.5	5.6 ± 0.7	6
$4e$	2.9 ± 0.4	2.3 ± 0.3	1.0 ± 0.1	0.62 ± 0.16	1.4	3.9 ± 0.6	6
total	15.7 ± 2.0	13.7 ± 1.8	6.2 ± 0.4	2.62 ± 0.34	1.6	22.5 ± 2.9	27
			$\sqrt{s}$ = 7 TeV				
4μ	1.0 ± 0.1	0.97 ± 0.13	0.49 ± 0.02	0.05 ± 0.02	1.8	1.5 ± 0.2	2
$2\mu 2e$	0.4 ± 0.1	0.39 ± 0.05	0.21 ± 0.02	0.55 ± 0.12	0.5	1.2 ± 0.1	1
$2e2\mu$	0.7 ± 0.1	0.57 ± 0.08	0.33 ± 0.02	0.04 ± 0.01	1.5	0.9 ± 0.1	2
$4e$	0.4 ± 0.1	0.29 ± 0.04	0.15 ± 0.01	0.49 ± 0.12	0.5	0.9 ± 0.1	0
total	2.5 ± 0.4	2.2 ± 0.3	1.17 ± 0.07	1.12 ± 0.17	1.0	4.5 ± 0.5	5
			$\sqrt{s}$ = 8 TeV and $\sqrt{s}$ = 7 TeV				
4μ	6.8 ± 0.8	6.3 ± 0.8	2.8 ± 0.1	0.55 ± 0.15	1.9	9.6 ± 1.0	13
$2\mu 2e$	3.4 ± 0.5	3.0 ± 0.4	1.4 ± 0.1	1.56 ± 0.33	1.0	6.0 ± 0.8	5
$2e2\mu$	4.7 ± 0.6	4.0 ± 0.5	2.1 ± 0.1	0.55 ± 0.17	1.5	6.6 ± 0.8	8
$4e$	3.3 ± 0.5	2.6 ± 0.4	1.2 ± 0.1	1.11 ± 0.28	1.1	4.9 ± 0.8	6
total	18.2 ± 2.4	15.9 ± 2.1	7.4 ± 0.4	3.74 ± 0.93	1.4	27.1 ± 3.4	32

ATLAS-CONF-2013-013

Higgs to 4 leptons

Significance now **6.6σ** (SM expectation 4.4σ)





m_H = 124.3 ± 0.6 (stat) ± 0.4 (syst) GeV

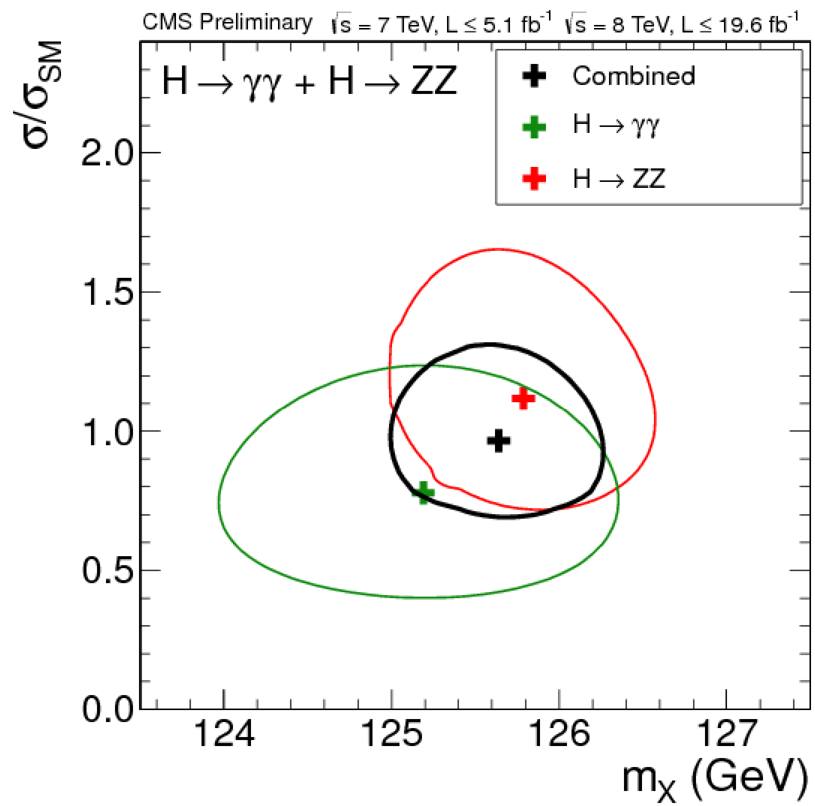
$\mu(124.3) = 1.7^{+0.5}_{-0.4}$

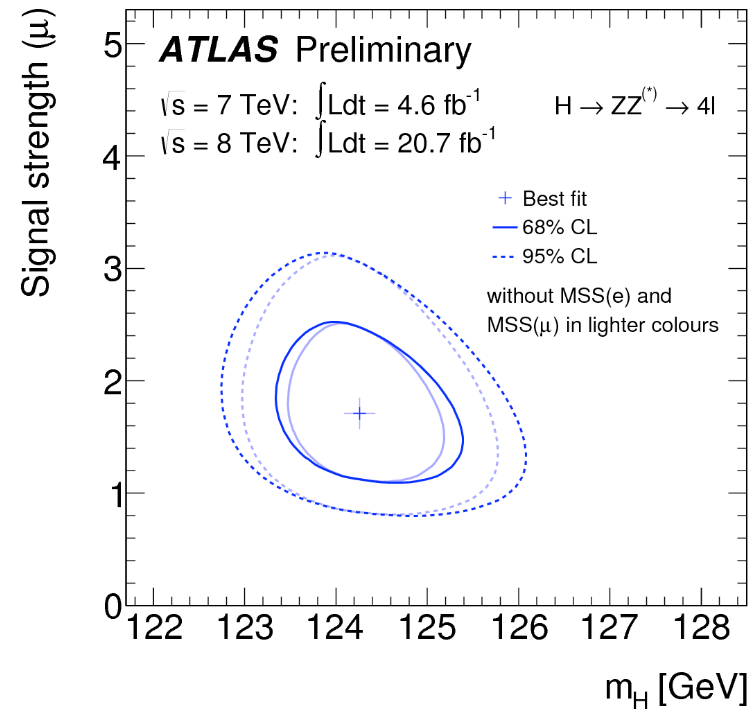
One VBF-tag event at 123.5 GeV, expect 0.4 from SM (in low mass region)

ATLAS-CONF-2013-013
CMS-PAS-HIG-13-002

Higgs to 4 leptons

ATLAS: **6.6σ** (SM expectation 4.4σ)
CMS: **6.7σ** (SM expectation 7.2σ)





m_H = 124.3 ± 0.6 (stat) ± 0.4 (syst) GeV

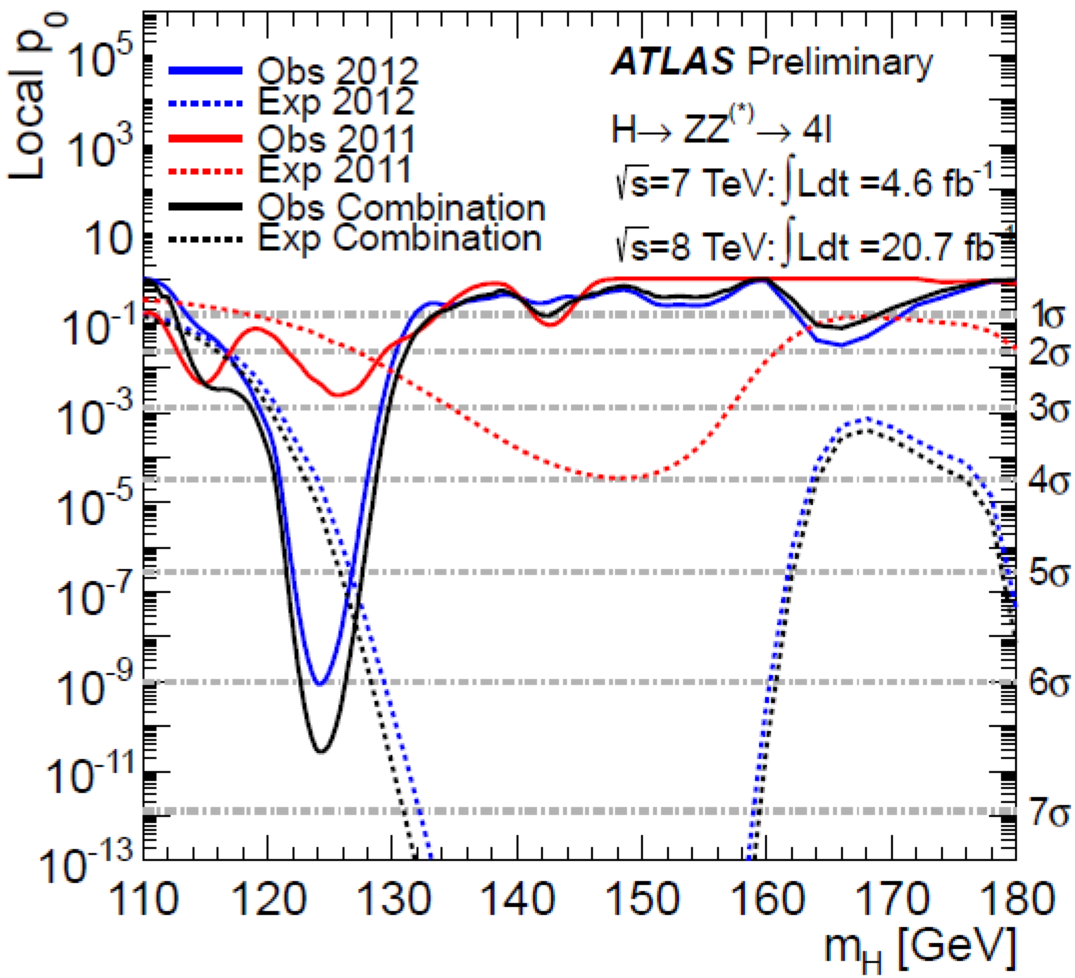
m_H = 125.8 ± 0.5 (stat) ± 0.2 (syst) GeV

$\mu(124.3) = 1.7^{+0.5}_{-0.4}$

$\mu(125.8) = 0.91^{+0.3}_{-0.24}$

Higgs to 4 leptons

P-values



Higgs to 4 leptons

Likelihood scan

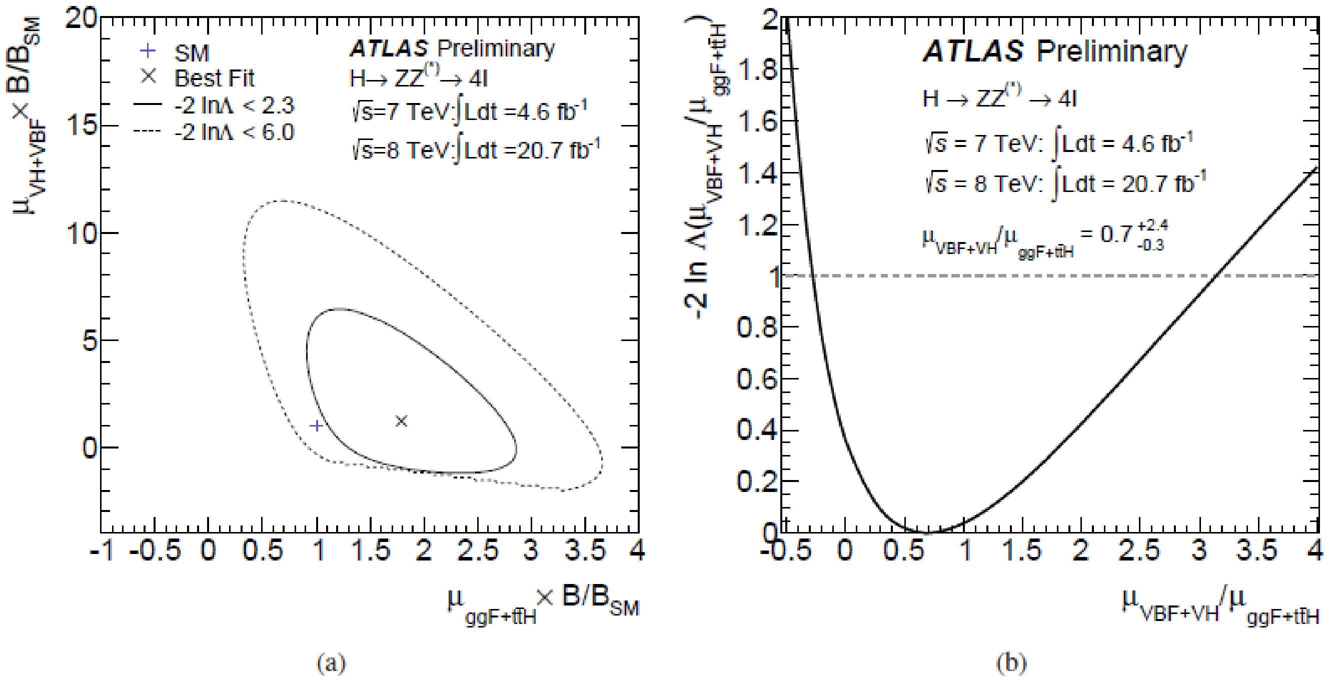


Figure 11: (a) Likelihood contours in the $(\mu_{ggF+t\bar{t}H}, \mu_{VBF+VH})$ plane including the branching ratio factor B/B_{SM}. The quantity $\mu_{ggF+t\bar{t}H}$ (μ_{VBF+VH}) is a common scale factor for the ggF and $t\bar{t}H$ (VBF and VH) production cross sections. Only the part of the plane where the expected numbers of signal events in each category is positive is considered. The best fit to the data (×) and $-2\ln\Lambda < 2.3$ (full) and 6.0 (dashed) contours are also indicated, as well as the SM expectation (+). (b) Results of a likelihood scan for $\mu_{VBF+VH}/\mu_{ggF+t\bar{t}H}$. The branching ratio factor B/B_{SM} cancels out in this ratio.

HIGGS TO 2 LEPTONS AND 2 NEUTRINOS

Backup slides

Higgs to 2 leptons and 2 neutrinos

MC Generators

Signal	MC generator	$\sigma \cdot \mathcal{B}$ (pb)
ggF	POWHEG [30]+PYTHIA8 [31]	0.44
VBF	POWHEG+PYTHIA8	0.035
VH	PYTHIA8	0.13

Background	MC generator	$\sigma \cdot \mathcal{B}$ (pb)
$q\bar{q}, gq \to WW$	POWHEG+PYTHIA6 [32]	5.7
$q\bar{q}, gq \to WW{+}2j$	Sherpa [33] with no $\mathcal{O}(\alpha_s)$ terms	0.039
$gg \to WW$	GG2WW 3.1.2 [34, 35]+HERWIG [36]	0.16
$t\bar{t}$	MC@NLO [37]+HERWIG	240
Single top: tW, tb	MC@NLO+HERWIG	28
Single top: tqb	AcerMC [38]+PYTHIA6	88
Z/γ^*, inclusive	ALPGEN+HERWIG	16000
$Z^{(*)} \to \ell\ell + 2j$	Sherpa processes up to $\mathcal{O}(\alpha_s)$	1.2
$Z^{(*)}Z^{(*)} \to 4\ell$	POWHEG+PYTHIA8	0.73
$WZ/W\gamma^*, m_{Z/\gamma^*}{>}7$	POWHEG+PYTHIA8	0.83
$W\gamma^*, m_{\gamma^*} \leq 7$	MadGraph [39–41]+PYTHIA6	11
$W\gamma$	ALPGEN+HERWIG	370

Higgs to 2 leptons and 2 neutrinos

Table 2: Selection listing for 8 TeV data. The criteria specific to $e\mu + \mu e$ and $ee + \mu\mu$ are noted as such; otherwise, they apply to both. Pre-selection applies to all N_{jet} modes. The rapidity gap is the y range spanned by the two leading jets. The $m_{\ell\ell}$ split is at 30 GeV. The modifications for the 7 TeV analysis are given in Section 6 and are not listed here. Energies, masses, and momenta are in units of GeV.

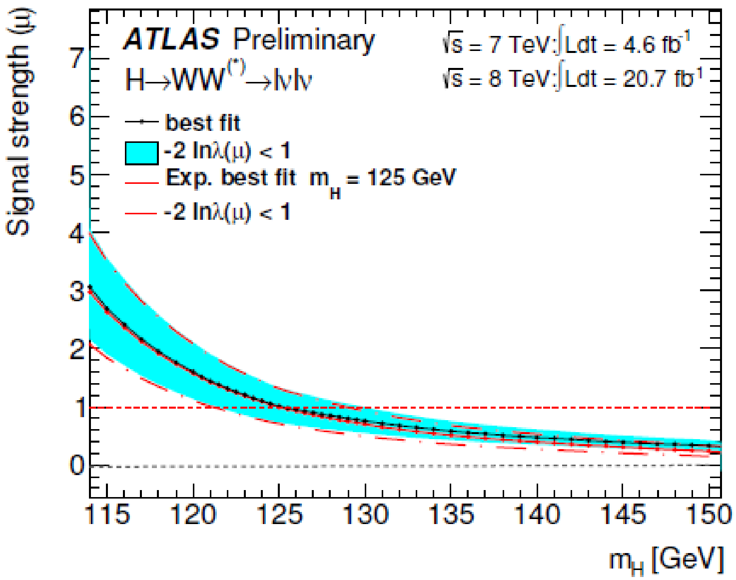
Category	$N_{\mathrm{jet}} = 0$	$N_{\mathrm{jet}} = 1$	$N_{\mathrm{jet}} \geq 2$
Pre-selection	Two isolated leptons ($\ell = e, \mu$) with opposite charge Leptons with $p_{\mathrm{T}}^{\mathrm{lead}} > 25$ and $p_{\mathrm{T}}^{\mathrm{sublead}} > 15$ $e\mu + \mu e$: $m_{\ell\ell} > 10$ $ee + \mu\mu$: $m_{\ell\ell} > 12$, $\lvert m_{\ell\ell} - m_Z \rvert > 15$		
Missing transverse momentum and hadronic recoil	$e\mu + \mu e$: $E_{\mathrm{T,rel}}^{\mathrm{miss}} > 25$ $ee + \mu\mu$: $E_{\mathrm{T,rel}}^{\mathrm{miss}} > 45$ $ee + \mu\mu$: $p_{\mathrm{T,rel}}^{\mathrm{miss}} > 45$ $ee + \mu\mu$: $f_{\mathrm{recoil}} < 0.05$	$e\mu + \mu e$: $E_{\mathrm{T,rel}}^{\mathrm{miss}} > 25$ $ee + \mu\mu$: $E_{\mathrm{T,rel}}^{\mathrm{miss}} > 45$ $ee + \mu\mu$: $p_{\mathrm{T,rel}}^{\mathrm{miss}} > 45$ $ee + \mu\mu$: $f_{\mathrm{recoil}} < 0.2$	$e\mu + \mu e$: $E_{\mathrm{T}}^{\mathrm{miss}} > 20$ $ee + \mu\mu$: $E_{\mathrm{T}}^{\mathrm{miss}} > 45$ $ee + \mu\mu$: $E_{\mathrm{T,STVF}}^{\mathrm{miss}} > 35$ -
General selection	- $\lvert \Delta\phi_{\ell\ell,MET} \rvert > \pi/2$ $p_{\mathrm{T}}^{\ell\ell} > 30$	$N_{b\text{-jet}} = 0$ - $e\mu + \mu e$: $Z/\gamma^* \to \tau\tau$ veto	$N_{b\text{-jet}} = 0$ $p_{\mathrm{T}}^{\mathrm{tot}} < 45$ $e\mu + \mu e$: $Z/\gamma^* \to \tau\tau$ veto
VBF topology	- - - -	- - - -	$m_{jj} > 500$ $\lvert \Delta y_{jj} \rvert > 2.8$ No jets ($p_{\mathrm{T}} > 20$) in rapidity gap Require both ℓ in rapidity gap
$H \to WW^{(*)} \to \ell\nu\ell\nu$ topology	$m_{\ell\ell} < 50$ $\lvert \Delta\phi_{\ell\ell} \rvert < 1.8$ $e\mu + \mu e$: split $m_{\ell\ell}$ Fit m_{T}	$m_{\ell\ell} < 50$ $\lvert \Delta\phi_{\ell\ell} \rvert < 1.8$ $e\mu + \mu e$: split $m_{\ell\ell}$ Fit m_{T}	$m_{\ell\ell} < 60$ $\lvert \Delta\phi_{\ell\ell} \rvert < 1.8$ - Fit m_{T}

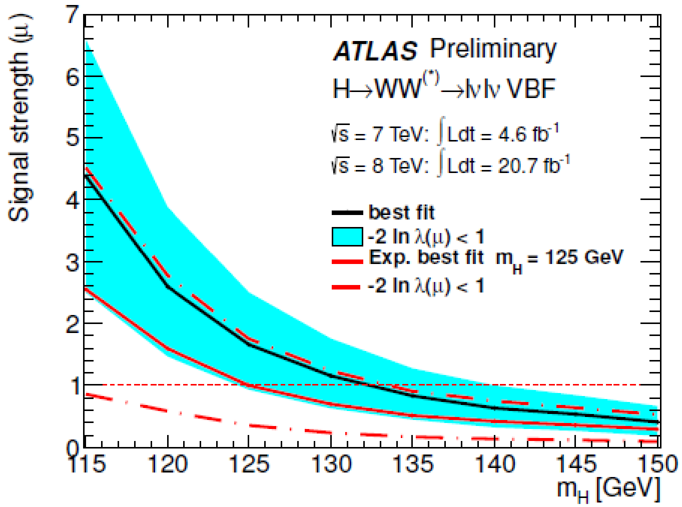
Higgs to 2 leptons and 2 neutrinos

Table 3: Background treatment listing. The estimation procedures for various background processes are given in four categories: normalised using a control region (CR); data-derived estimate (Data); normalised using the MC (MC); and normalised using the MC, but validated in a control region (MC + VR). The "$(e\mu+\mu e)$" terms denote that for the $ee+\mu\mu$ channel in the same $N_{\rm jet}$ mode, the $e\mu+\mu e$ region is used instead, for reasons of purity and/or statistics. The "(merged)" terms indicate that the fully combined $e\mu+\mu e+ee+\mu\mu$ control region is used for all channels.

Channel	WW	Top	$Z/\gamma^* \to \tau\tau$	$Z/\gamma^* \to \ell\ell$	W+jets	VV
$N_{\rm jet}=0$						
$e\mu+\mu e$	CR	CR	CR	MC	Data	MC + VR
$ee+\mu\mu$	CR $(e\mu+\mu e)$	CR $(e\mu+\mu e)$	CR $(e\mu+\mu e)$	Data	Data	MC + VR
$N_{\rm jet}=1$						
$e\mu+\mu e$	CR	CR	CR	MC	Data	MC + VR
$ee+\mu\mu$	CR $(e\mu+\mu e)$	CR $(e\mu+\mu e)$	CR $(e\mu+\mu e)$	Data	Data	MC + VR
$N_{\rm jet}\geq 2$						
$e\mu+\mu e$	MC	CR (merged)	CR	MC	Data	MC
$ee+\mu\mu$	MC	CR (merged)	CR $(e\mu+\mu e)$	Data	Data	MC

Higgs to 2 leptons and 2 neutrinos





VBF

Higgs to 2 leptons and 2 neutrinos

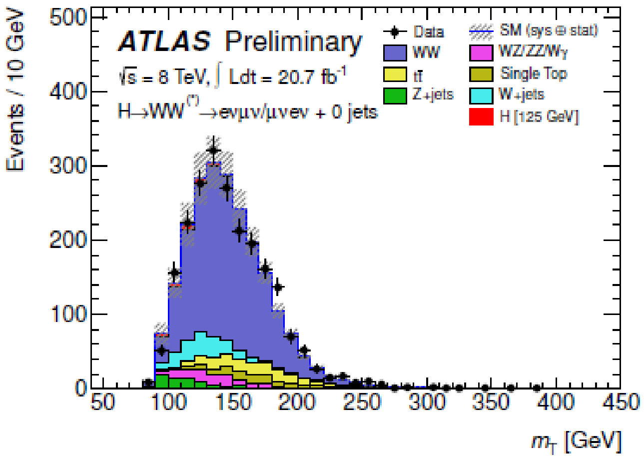
Table 13: Leading uncertainties on the signal strength μ for the combined 7 and 8 TeV analysis.

Category	Source	Uncertainty, up (%)	Uncertainty, down (%)
Statistical	Observed data	+21	−21
Theoretical	Signal yield ($\sigma \cdot \mathcal{B}$)	+12	−9
Theoretical	WW normalisation	+12	−12
Experimental	Objects and DY estimation	+9	−8
Theoretical	Signal acceptance	+9	−7
Experimental	MC statistics	+7	−7
Experimental	W+jets fake factor	+5	−5
Theoretical	Backgrounds, excluding WW	+5	−4
Luminosity	Integrated luminosity	+4	−4
Total		+32	−29

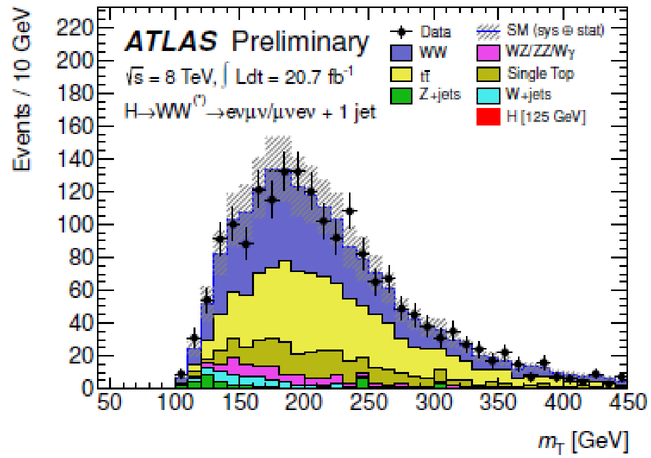
ATLAS-CONF-2013-030 CMS-PAS-HIG-13-003

Higgs to 2 leptons and 2 neutrinos (WW)

Dominant (WW, top, ττ) backgrounds modelled with MC normalised in control regions



(a) m_T for $N_{jet} = 0$

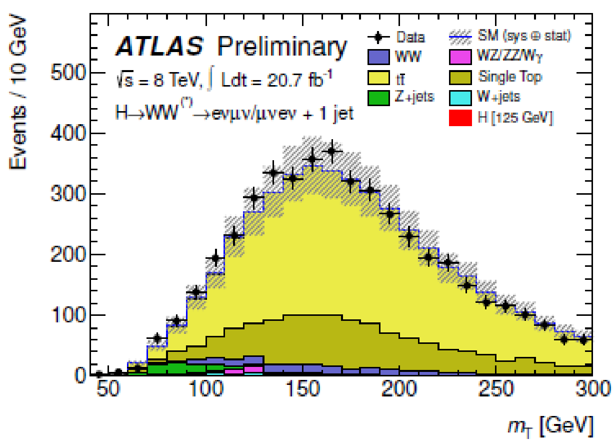


(b) m_T for $N_{jet} = 1$

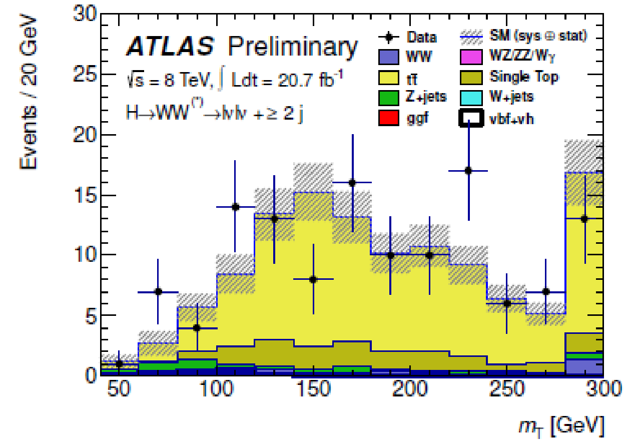
W+jets from data driven method

Z/γ* backgrounds suppressed with cuts on MET, m_{ll}, and recoil

From MC for OF
Data driven for SF



(a) $N_{jet} = 1$



(b) $N_{jet} \geq 2$

HIGGS TO PHOTONS

Backup slides

ATLAS-CONF-2013-012

Higgs to photons

$\sqrt{s}$	8 TeV						
Category	N_D	N_S	$gg \to H$ [%]	VBF [%]	WH [%]	ZH [%]	ttH [%]
Unconv. central, low p_{Tt}	10900	51.8	93.7	4.0	1.4	0.8	0.2
Unconv. central, high p_{Tt}	553	7.9	79.3	12.6	4.1	2.5	1.4
Unconv. rest, low p_{Tt}	41236	107.9	93.2	4.0	1.6	1.0	0.1
Unconv. rest, high p_{Tt}	2558	16.0	78.1	13.3	4.7	2.8	1.1
Conv. central, low p_{Tt}	7109	33.1	93.6	4.0	1.3	0.9	0.2
Conv. central, high p_{Tt}	363	5.1	78.9	12.6	4.3	2.7	1.5
Conv. rest, low p_{Tt}	38156	97.8	93.2	4.1	1.6	1.0	0.1
Conv. rest, high p_{Tt}	2360	14.4	77.7	13.0	5.2	3.0	1.1
Conv. transition	14864	40.1	90.7	5.5	2.2	1.3	0.2
Loose high-mass two-jet	276	5.3	45.0	54.1	0.5	0.3	0.1
Tight high-mass two-jet	136	8.1	23.8	76.0	0.1	0.1	0.0
Low-mass two-jet	210	3.3	48.1	3.0	29.7	17.2	1.9
$E_{\mathrm{T}}^{\mathrm{miss}}$ significance	49	1.3	4.1	0.5	35.7	47.6	12.1
One-lepton	123	2.9	2.2	0.6	63.2	15.4	18.6
All categories (inclusive)	118893	395.0	88.0	7.3	2.7	1.5	0.5

ATLAS-CONF-2013-012

Higgs to photons

Table 2: Signal mass resolution (σ_{CB}), number of observed events, number of expected signal events (N_S), number of expected background events (N_B) and signal to background ratio (N_S/N_B) in a mass window around $m_H = 126.5$ GeV containing 90% of the expected signal for each of the 14 categories of the 8 TeV data analysis. The numbers of background events are obtained from the background + signal fit to the $m_{\gamma\gamma}$ data distribution.

$\sqrt{s}$	8 TeV				
Category	σ_{CB}(GeV)	Observed	N_S	N_B	N_S/N_B
Unconv. central, low p_{Tt}	1.50	911	46.6	881	0.05
Unconv. central, high p_{Tt}	1.40	49	7.1	44	0.16
Unconv. rest, low p_{Tt}	1.74	4611	97.1	4347	0.02
Unconv. rest, high p_{Tt}	1.69	292	14.4	247	0.06
Conv. central, low p_{Tt}	1.68	722	29.8	687	0.04
Conv. central, high p_{Tt}	1.54	39	4.6	31	0.15
Conv. rest, low p_{Tt}	2.01	4865	88.0	4657	0.02
Conv. rest, high p_{Tt}	1.87	276	12.9	266	0.05
Conv. transition	2.52	2554	36.1	2499	0.01
Loose High-mass two-jet	1.71	40	4.8	28	0.17
Tight High-mass two-jet	1.64	24	7.3	13	0.57
Low-mass two-jet	1.62	21	3.0	21	0.14
$E_{\mathrm{T}}^{\mathrm{miss}}$ significance	1.74	8	1.1	4	0.24
One-lepton	1.75	19	2.6	12	0.20
Inclusive	1.77	14025	355.5	13280	0.03

ATLAS-CONF-2013-012

Higgs to photons

Table 3: Cross sections for the Standard Model Higgs boson production with m_H = 126.5 GeV at $\sqrt{s}$ = 8 TeV [57, 58]. The branching ratio to the two photons decay mode is $2.28 \cdot 10^{-3}$ at m_H = 126.5 GeV. Gluon fusion and vector boson fusion cross sections are computed in the complex pole scheme at NNLL+NNLO QCD and NLO EW [58]. Associated production cross section are computed with zero-width-approximation at NNLO QCD and NLO EW. The ttH process cross section is computed with zero-width-approximation at NLO QCD. QCD scale (±Scale) and the PDF+α_s uncertainties are treated as non-correlated [68].

Process	Cross section (pb)	+Scale %	-Scale %	+(PDF+α_s)%	-(PDF+α_s)%
ggF	19.07	+7.2	-7.8	+7.5	-6.9
VBF	1.56	+0.2	-0.2	+2.6	-2.7
WH	0.67	+0.2	-0.6	+3.5	-3.5
ZH	0.38	+1.6	-1.5	+3.6	-3.6
ttH	0.13	+3.8	-9.3	+7.8	-7.8

ATLAS-CONF-2013-012

Higgs to photons

Table 4: Systematic uncertainty on the number of fitted signal events due to the background model for the $\sqrt{s}$ = 7 TeV (10 categories) and $\sqrt{s}$ = 8 TeV (14 categories) analyses. Three different background models are used depending on the category; an exponential function, a fourth order polynomial and the exponential of a second order polynomial.

Category	Parametrisation	Uncertainty [N_{evt}]	
		$\sqrt{s}$ = 7 TeV	$\sqrt{s}$ = 8 TeV
Inclusive	4th order pol.	7.3	12.0
Unconverted central, low p_{Tt}	Exp. of 2nd order pol.	2.1	4.6
Unconverted central, high p_{Tt}	Exponential	0.2	0.8
Unconverted rest, low p_{Tt}	4th order pol.	2.2	11.4
Unconverted rest, high p_{Tt}	Exponential	0.5	2.0
Converted central, low p_{Tt}	Exp. of 2nd order pol.	1.6	2.4
Converted central, high p_{Tt}	Exponential	0.3	0.8
Converted rest, low p_{Tt}	4th order pol.	4.6	8.0
Converted rest, high p_{Tt}	Exponential	0.5	1.1
Converted transition	Exp. of 2nd order pol.	3.2	9.1
Loose high-mass two-jet	Exponential	0.4	1.1
Tight high-mass two-jet	Exponential	-	0.3
Low-mass two-jet	Exponential	-	0.6
E_T^{miss} significance	Exponential	-	0.1
One-lepton	Exponential	-	0.3

ATLAS-CONF-2013-012

Higgs to photons

Table 5: Summary of the impact of systematic uncertainties on the signal yields for the analysis of the 8 TeV data.

Systematic uncertainties	Value(%)			Constraint
Luminosity	±3.6			
Trigger	±0.5			
Photon Identification	±2.4			Log-normal
Isolation	±1.0			
Photon Energy Scale	±0.25			
Branching ratio	±5.9% – ±2.1% (m_H = 110 - 150 GeV)			Asymmetric Log-normal
Scale	ggF: $^{+7.2}_{-7.8}$ ZH: $^{+1.6}_{-1.5}$	VBF: $^{+0.2}_{-0.2}$ ttH: $^{+3.8}_{-9.3}$	WH: $^{+0.2}_{-0.6}$	Asymmetric Log-normal
PDF+α_s	ggF: $^{+7.5}_{-6.9}$ ZH: ±3.6	VBF: $^{+2.6}_{-2.7}$ ttH: ±7.8	WH: ±3.5	Asymmetric Log-normal
Theory cross section on ggF	Tight high-mass two-jet: ±48 Loose high-mass two-jet: ±28 Low-mass two-jet: ±30			Log-normal

ATLAS-CONF-2013-012

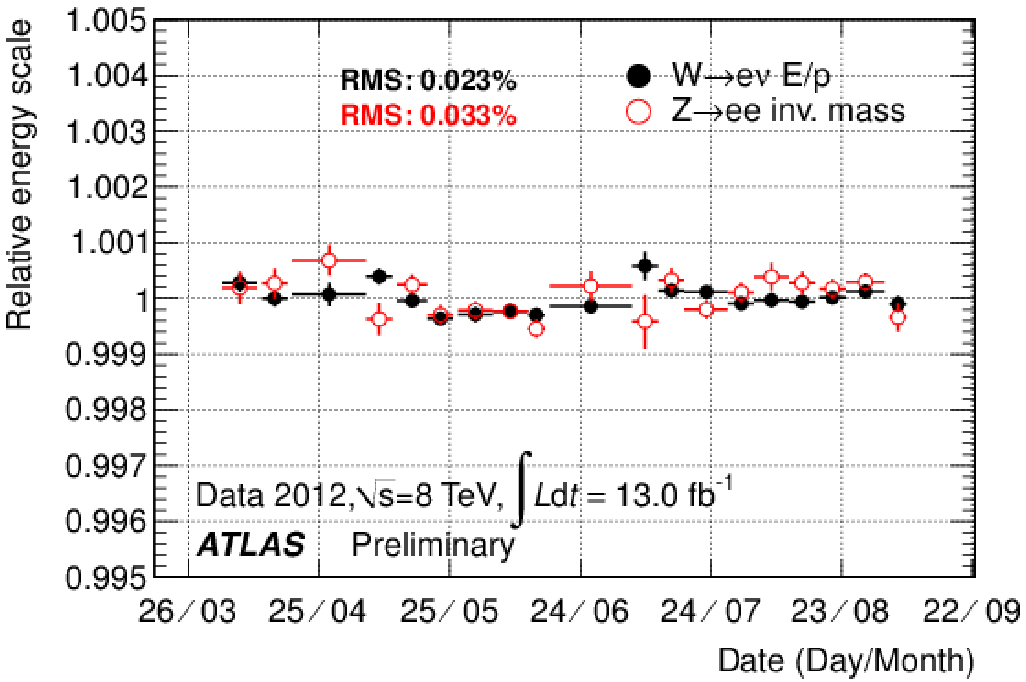
Higgs to photons

Energy scale key to mass measurement
Important when combining many categories

Derived from tuned MC +
dielectron and Zγ data

Calorimeter response stable at 0.1% level wrt. time/pile-up

Overall scale uncertainty ~0.6%
Driven by material modelling
and errors on in-situ calibration



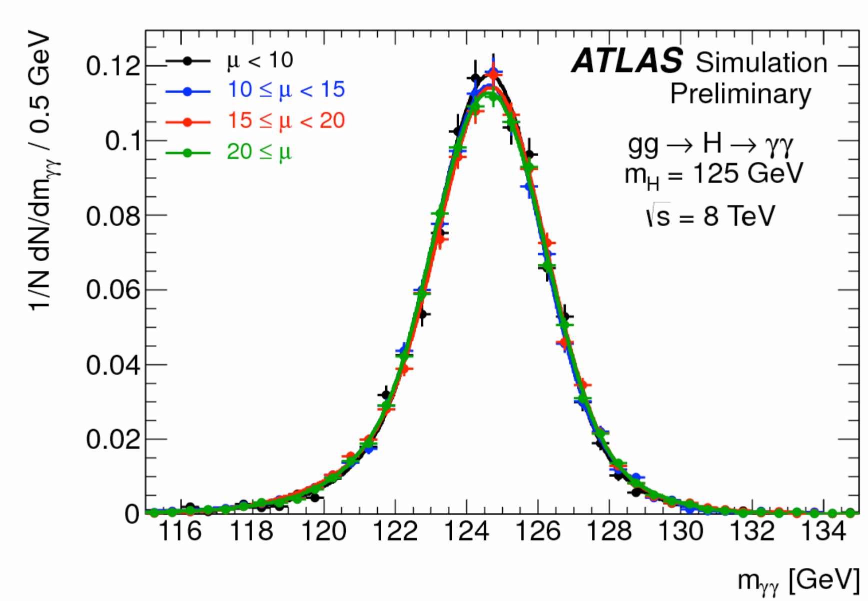
ATLAS-CONF-2013-012

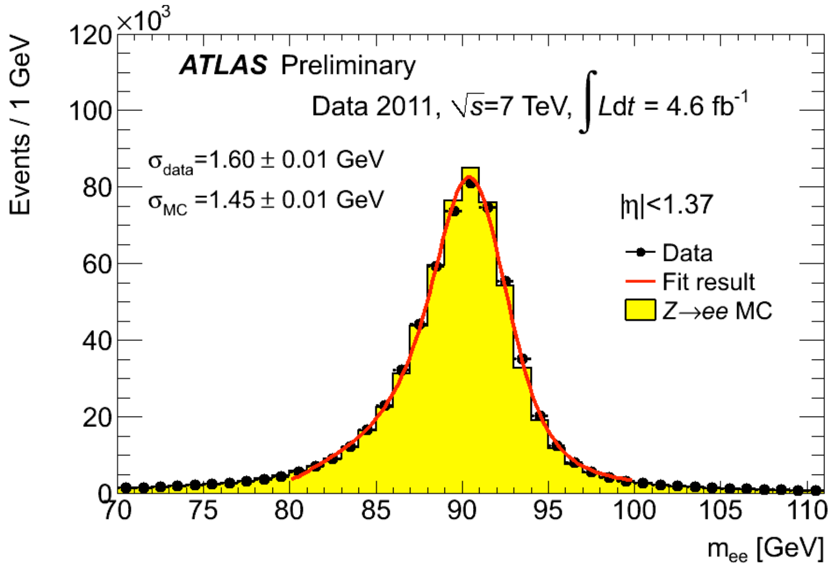
Higgs to photons

Mass resolution critical to sensitivity

Photon energy resolution
Vertex identification
- photon pointing

Additional constant-term smearing in MC derived from Z studies with electrons:
1% central, 1.5-2.5% forward





Uncertainty on photon resolution 14-23%

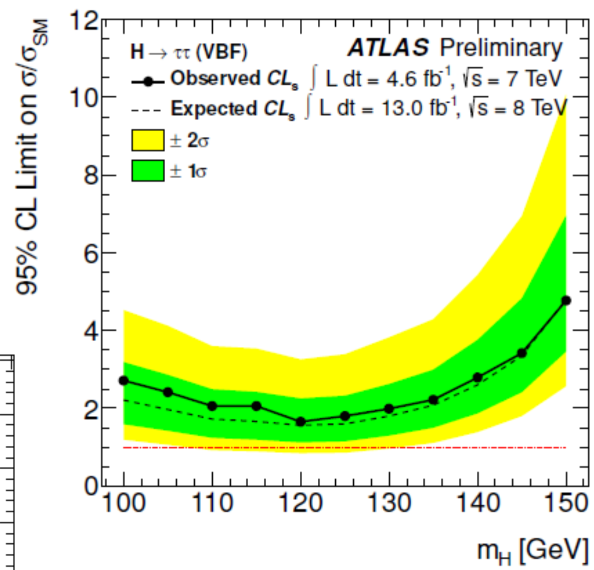
HIGGS TO TAUS

Backup slides

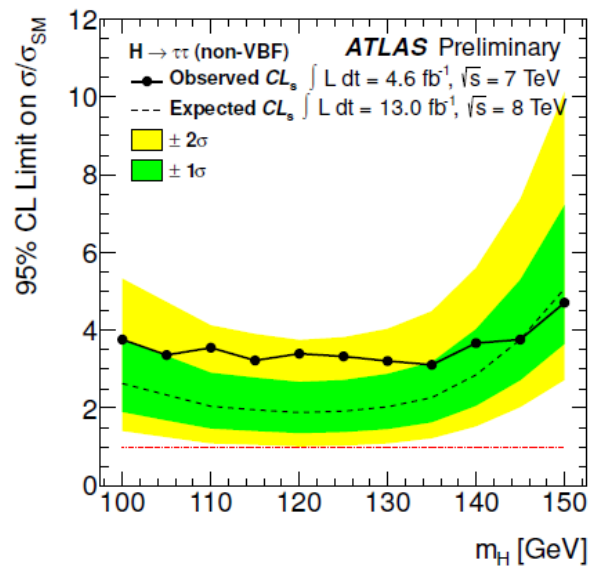
ATLAS-CONF-2012-160

Higgs to taus

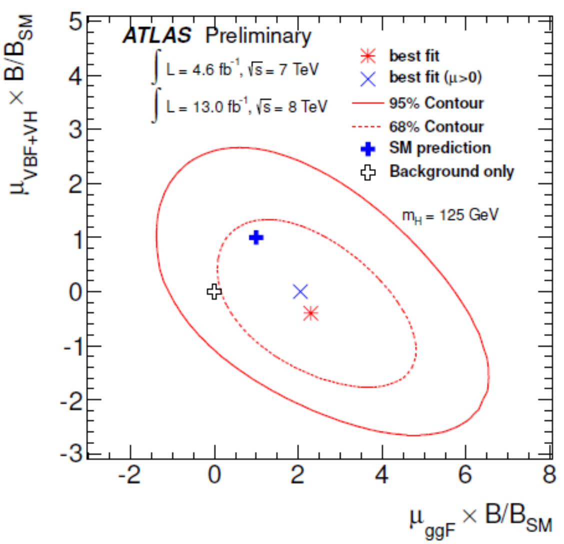
VBF versus non-VBF



(a) VBF categories



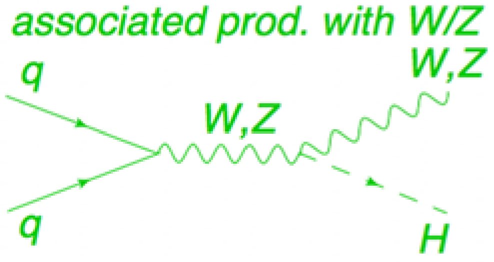
(b) Non-VBF categories

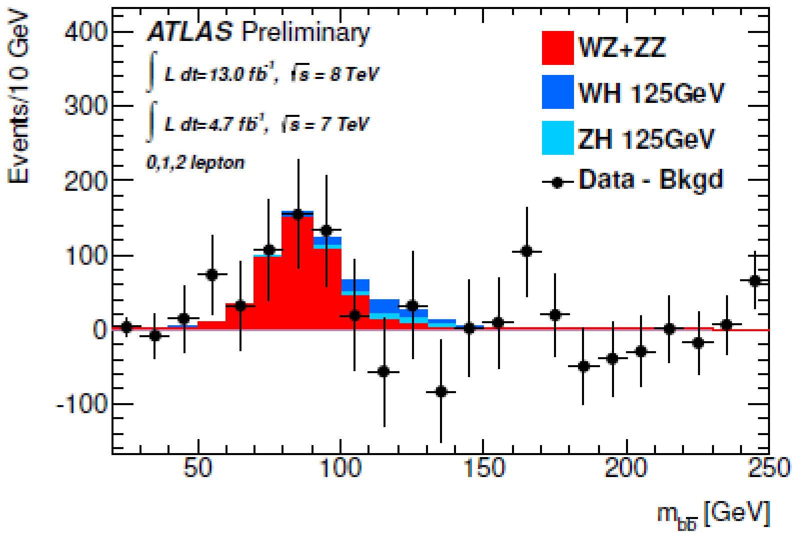


No evidence for a signal as yet – though some small excess of events
Compatible with SM so far…

ATLAS-CONF-2012-161

Higgs to b quarks



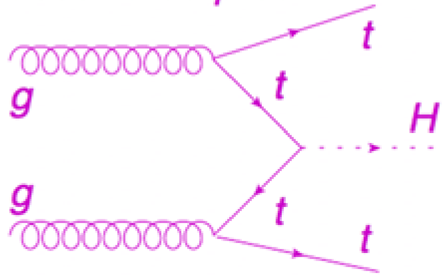


Cross check – search for diboson signal
Observed with ~4σ

ATLAS-CONF-2012-35

Higgs to b-quarks

associated prod. with tt

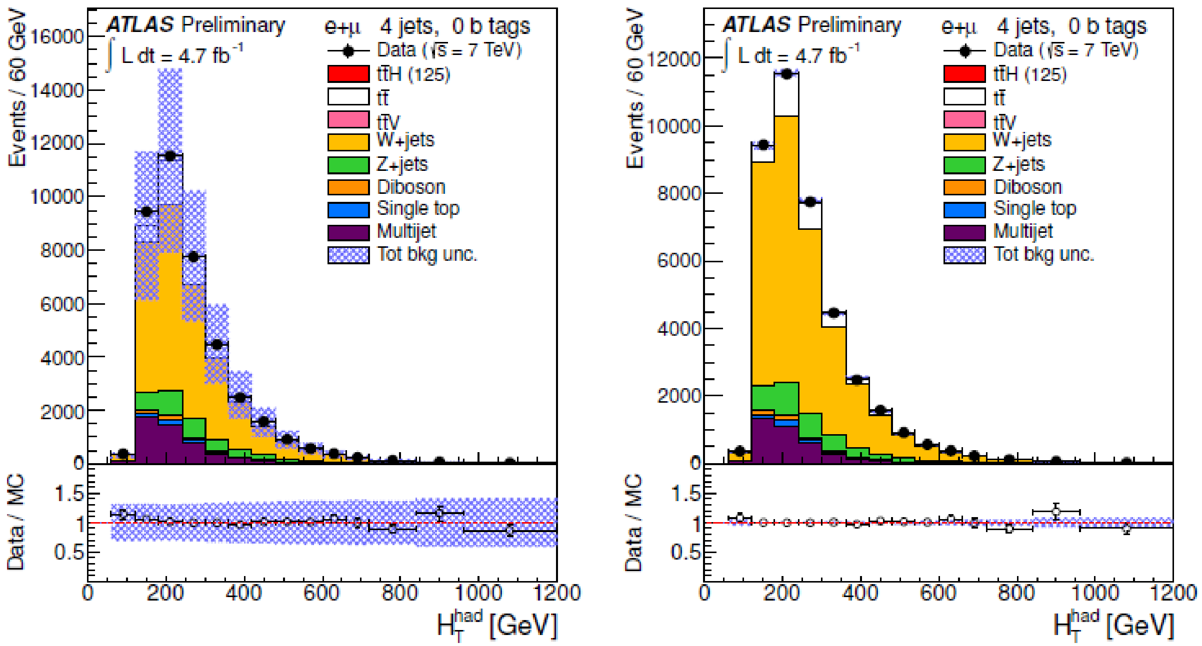


One semi-leptonic top-decay + many jets signature:

1 lepton + high missing ET + >=4 jets

Events categorized according to multiplicity of jets and b-tagged jets

Pre-Fit Post-Fit



Background dominated categories provide strong constraints on uncertainties

Table 4: A summary of the size of the components of the systematic uncertainty on the total estimated background after all cuts for the three channels of the $\sqrt{s} = 8$ TeV analysis. The uncertainties are shown as a percentage and grouped together into broad categories and are averaged over all p_T^V bins in each category. The total error is worked out by adding the individual components together in quadrature in each p_T^V bin and then averaging.

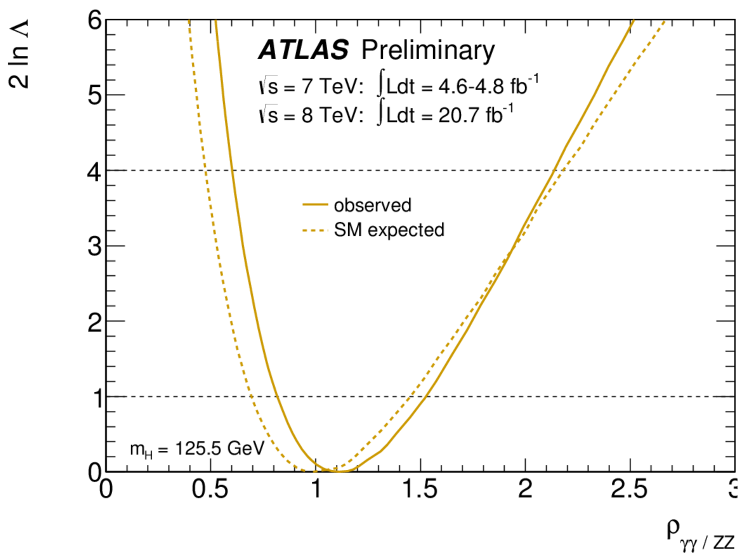
Uncertainty [%]	0 lepton	1 lepton	2 leptons
b-tagging	6.5	6.0	6.9
c-tagging	7.3	6.4	3.6
light tagging	2.1	2.2	2.8
Jet/Pile-up/E_T^{miss}	20	7.0	5.4
Lepton	0.0	2.1	1.8
Top modelling	2.7	4.1	0.5
W modelling	1.8	5.4	0.0
Z modelling	2.8	0.1	4.7
Diboson	0.8	0.3	0.5
Multijet	0.6	2.6	0.0
Luminosity	3.6	3.6	3.6
Statistical	8.3	3.6	6.6
Total	25	15	14

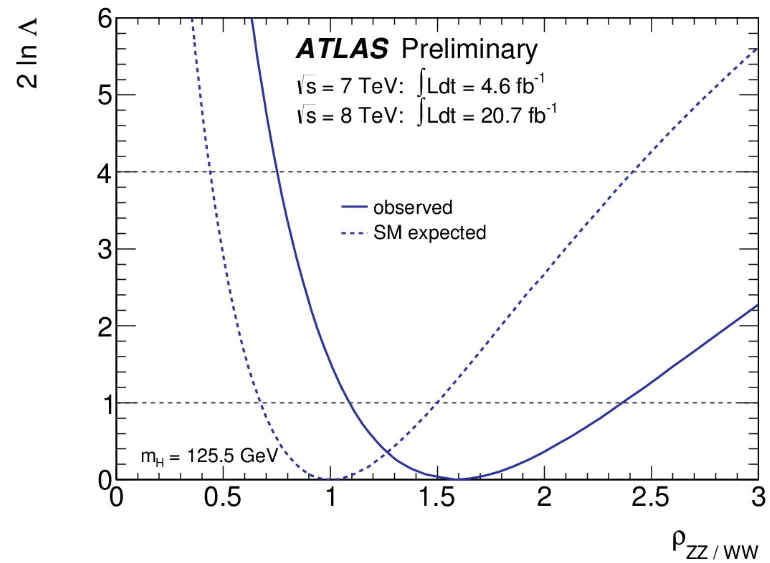
Table 5: A summary of the size of the components of the systematic uncertainty on the signal with $m_H = 125$ GeV for the three channels of the $\sqrt{s} = 8$ TeV analysis. The dominant signal is shown for the 1 lepton and 2 lepton channels, while for the 0 lepton channel both ZH and WH signals are listed. The uncertainties are shown as a percentage, grouped together into broad categories and are calculated by summing in quadrature within each p_T^V bin and then averaging over all p_T^V bins in a channel.

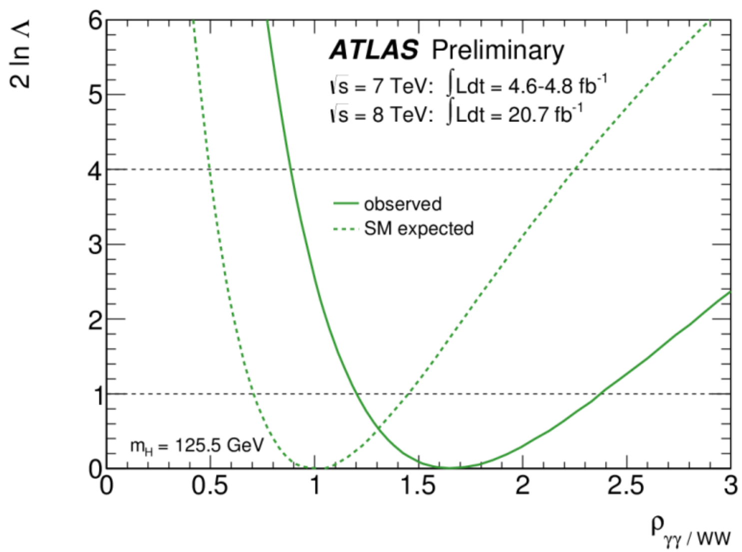
Uncertainty [%]	0 lepton		1 lepton	2 leptons
	ZH	WH	WH	ZH
b-tagging	8.9	9.0	8.8	8.6
Jet/Pile-up/E_T^{miss}	19	25	6.7	4.2
Lepton	0.0	0.0	2.1	1.8
$H \to bb$ BR	3.3	3.3	3.3	3.3
VH p_T-dependence	5.3	8.1	7.6	5.0
VH theory PDF	3.5	3.5	3.5	3.5
VH theory scale	1.6	0.4	0.4	1.6
Statistical	4.9	18	4.1	2.6
Luminosity	3.6	3.6	3.6	3.6
Total	24	34	16	13

Higgs Signal Strength

ATLAS-CONF-2013-14
ATLAS-CONF-2013-34







Ratios for same production mode but different final states

$$\rho_{\gamma\gamma/ZZ} = 1.1^{+0.4}_{-0.3}$$

$$\rho_{\gamma\gamma/WW} = 1.7^{+0.7}_{-0.5}$$

$$\rho_{ZZ/WW} = 1.6^{+0.8}_{-0.5}$$

In agreement with SM