Higgs Property Measurements

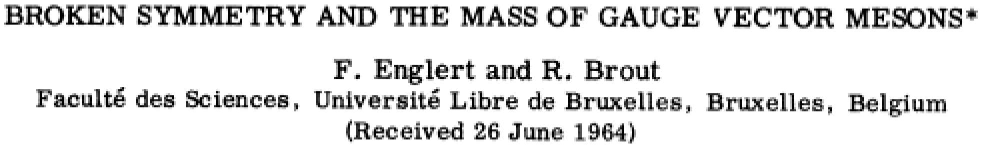
Introduction
Five main decay modes
Rate and Coupling
Mass and Width
Spin and CP
Rare processes
BSM implications
Future prospects

Jianming Qian
University of Michigan

Hadron Collider Physics Summer School
August 11-22, Fermilab

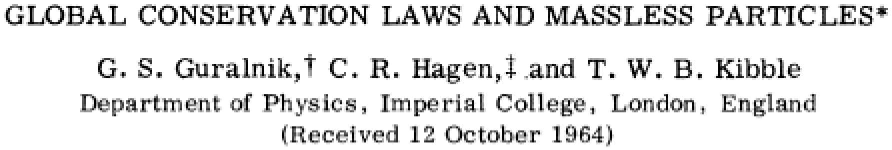
Historical Development

In 1964, three teams published proposals on how mass could arise in local gauge theories. They are now credited for the BEH mechanism and the Higgs boson.



BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

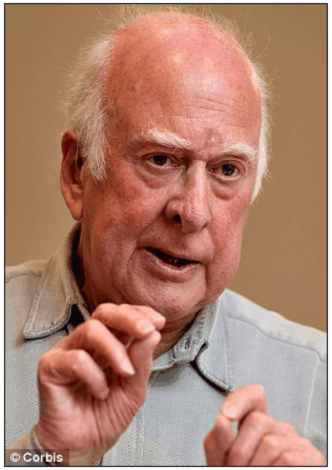
F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)



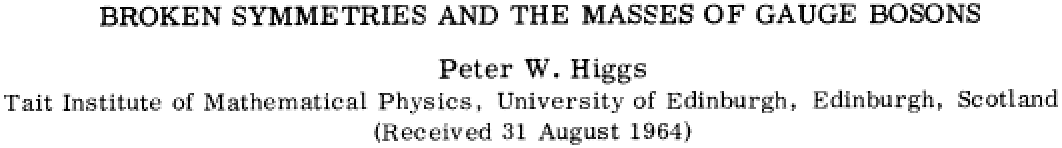
GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)

L to R: Kibble, Guralnik, Hagen, Englert, and Brout



Higgs

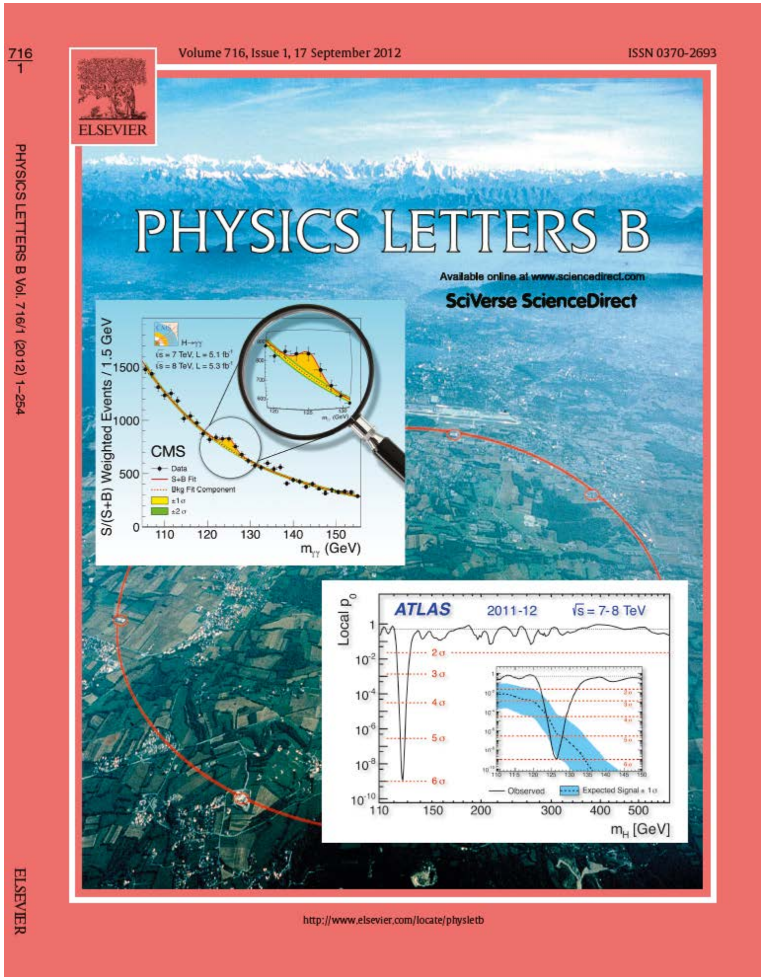


BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

2013 Nobel Prize!

The 2012 Discovery



716
1

PHYSICS LETTERS B Vol. 716/1 (2012) 1–254

ELSEVIER

Volume 716, Issue 1, 17 September 2012

ISSN 0370-2693

PHYSICS LETTERS B

Available online at www.sciencedirect.com

SciVerse ScienceDirect

http://www.elsevier.com/locate/physletb

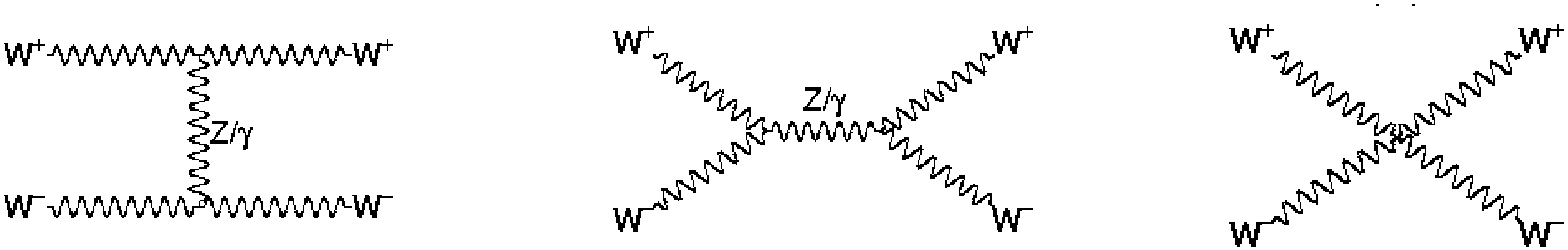
The question remains:

Is the new boson solely responsible for the electroweak symmetry breaking?

Two parallel approaches:

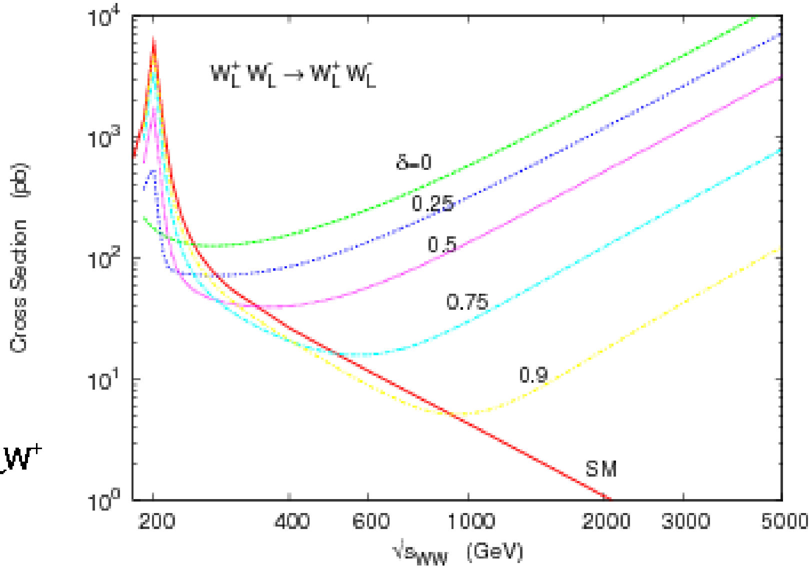
1. precise property measurements;
2. direct searches of exotic decays as well as additional Higgs bosons.

WW Scattering

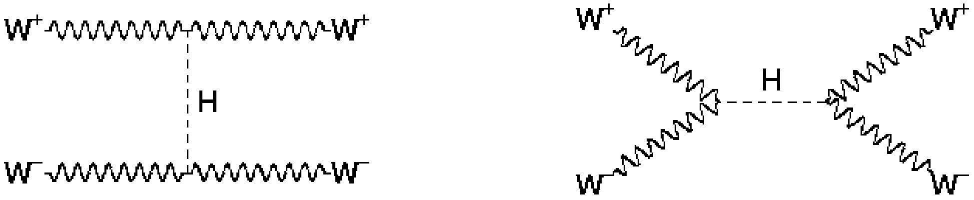


Without the Higgs boson, the cross section for these scattering diagrams divergences at high energy

$$\sigma \sim \frac{s}{M_W^2} \quad \text{as} \quad s \rightarrow \infty$$



Cheung, Chiang & Yuan, arXiv:0803.2661

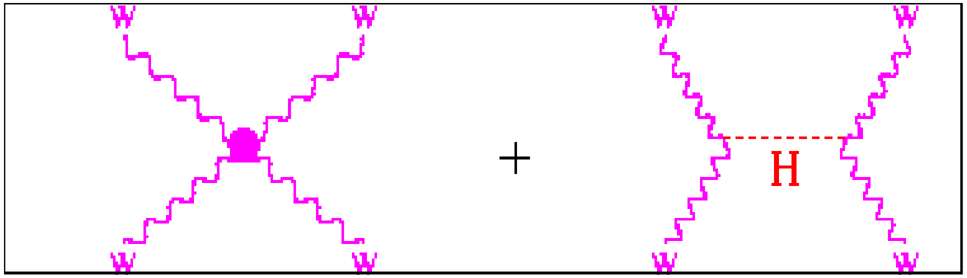


The additional Higgs diagrams cancel these residual divergences

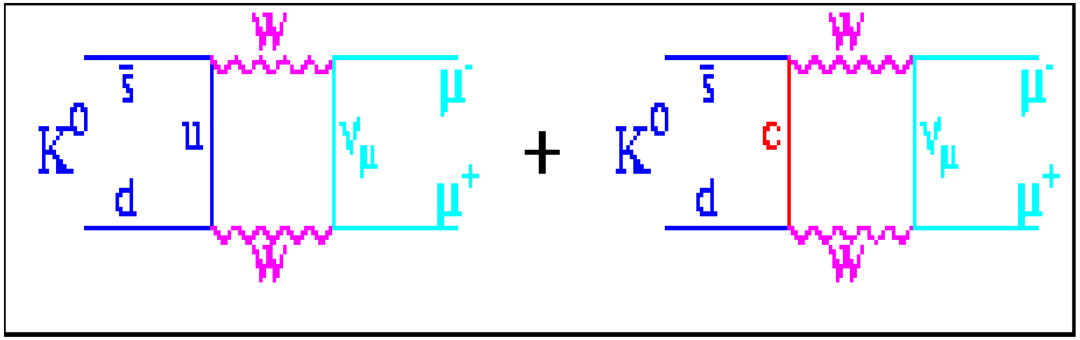
$$\sigma \rightarrow 0 \quad \text{as} \quad s \rightarrow \infty$$

Historical Precedents

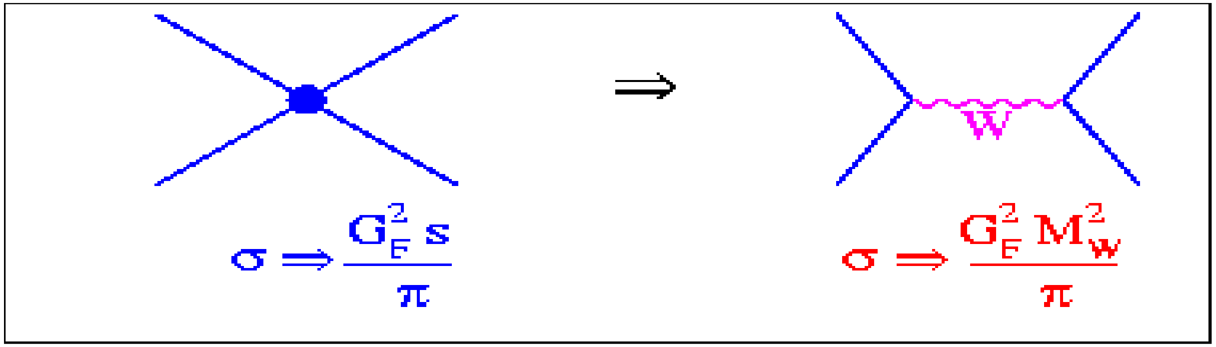
Higgs boson is also needed to make $\sigma\left(W_L^+W_L^- \rightarrow W_L^+W_L^-\right)$ finite



Charm quark was first postulated to explain the small observed $K^0 \rightarrow \mu\mu$ decay branching ratio.

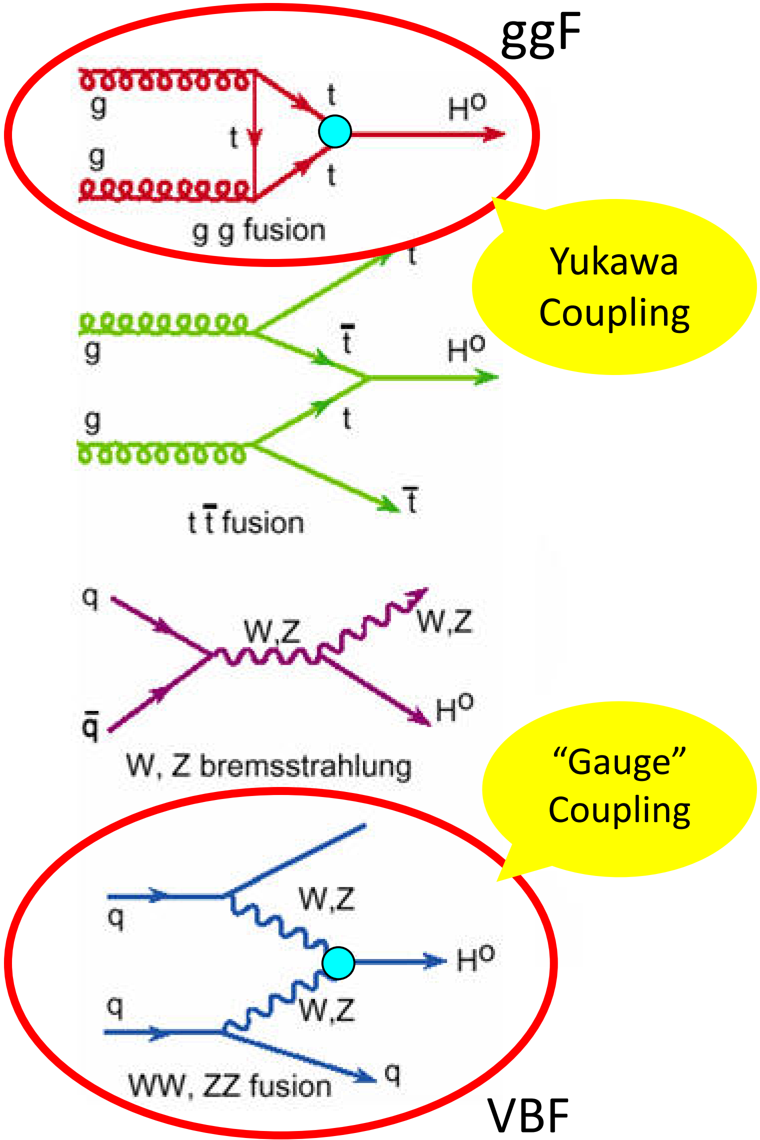


W boson is needed to make $\sigma\left(e\nu \rightarrow e\nu\right)$ finite

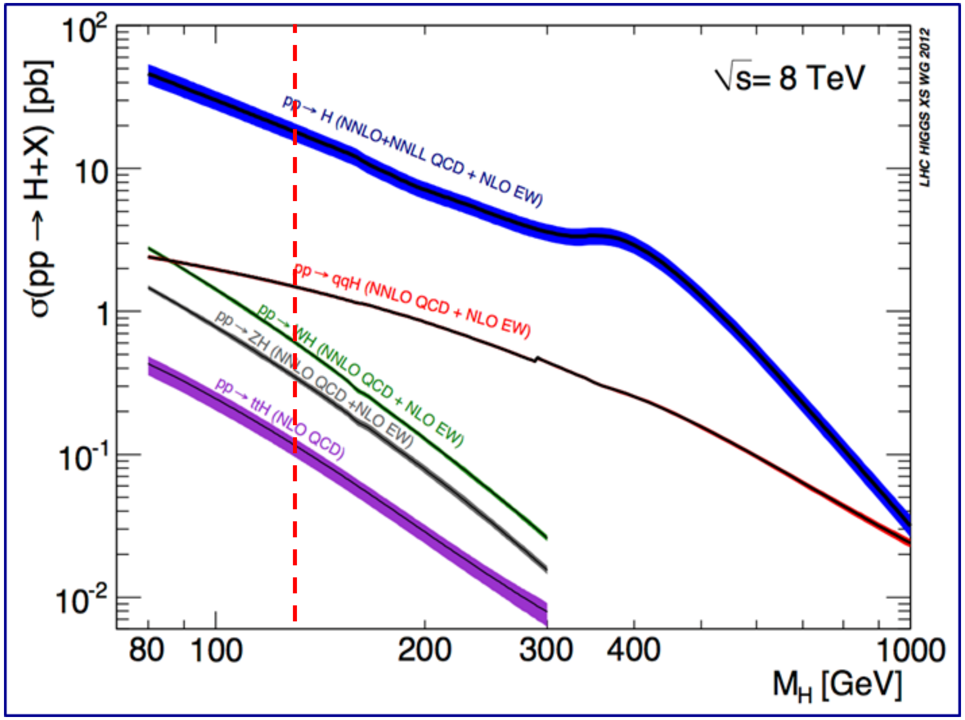


$$\sigma \Rightarrow \frac{G_F^2\, s}{\pi} \qquad \sigma \Rightarrow \frac{G_F^2\, M_W^2}{\pi}$$

Higgs Boson Production at LHC



gluon-gluon fusion gg→H and vector-boson fusion qq→qqH diagrams dominate



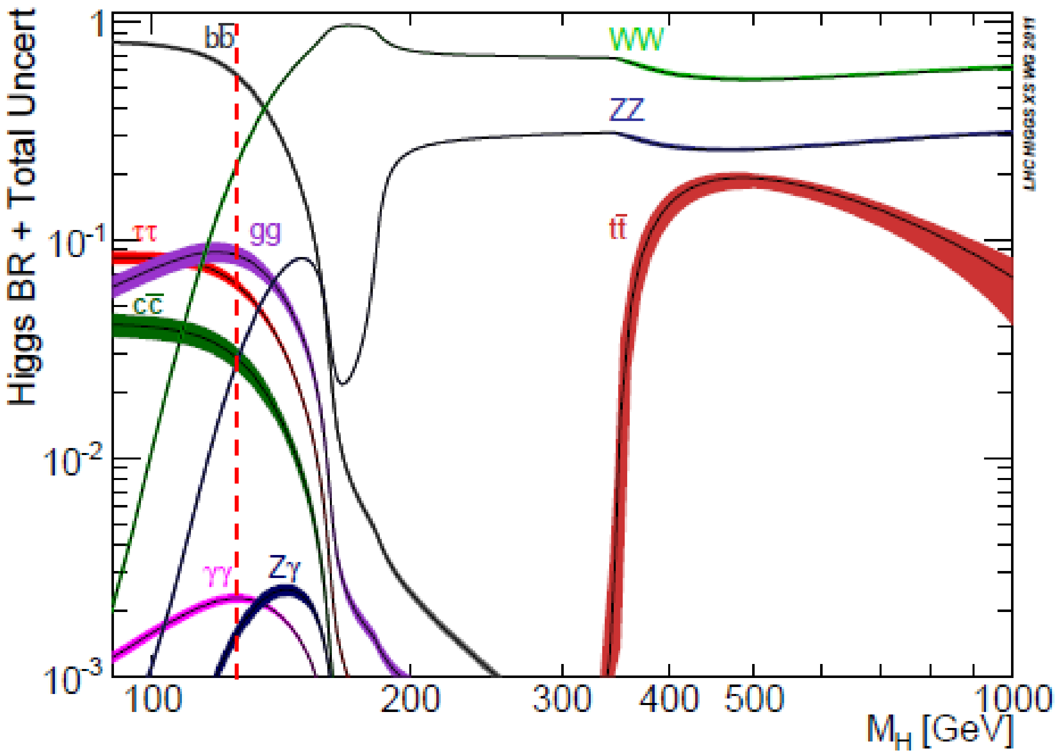
Production cross section for $m_H = 125$ GeV

Process	Tot	ggF	VBF	WH	ZH	$t\bar{t}H$
σ (pb)	22.3	19.5	1.6	0.70	0.39	0.13
σ/σ_{tot} (%)		87.4	7.2	3.1	1.7	0.6

Over 1,000,000 Higgs bosons produced at LHC so far !

Higgs Boson Decays

Around 125 GeV, many accessible decay modes, rapid changes in $H \to WW^*$ and $H \to ZZ^*$ decay BR.



Branching ratio @ 125 GeV	
$H \to b\bar{b}$	57.7%
$H \to WW^*$	21.5%
$H \to \tau\tau$	6.32%
$H \to ZZ^*$	2.64%
$H \to \gamma\gamma$	0.23%
$H \to Z\gamma$	0.15%
$H \to \mu\mu$	0.02%

Dominant decays:

$H \to b\bar{b}$ for $m_H < 130$ GeV,

$H \to WW^*$ for $m_H < 130$ GeV

for SM-like Higgs bosons.

Theory and MC Tool Box

Tremendous effort from the theory community, …

Cross section tools:

ggF:
- HIGLU (NNLO QCD+NLO EW)
- FeHiPro (NNLO QCD+NLO EW)
- HNNLO, HRes (NNLO+NNLL QCD)
- ggh@NNLO (NNLO QCD), …

VBF:
- VV2H (NLO QCD)
- VBFNLO (NLO QCD)
- HAWK (NLO QCD+EW)
- VBF@NNLO (NNLO QCD), …

VH:
- V2HV (NLO QCD)
- VH@NNLO (NNLO), …

ttH:
- HQQ (LO QCD), …

MC tools:

aMC@NL
POWHEG,
SHERPA,
HERWIG++,
MadGraph5, ….

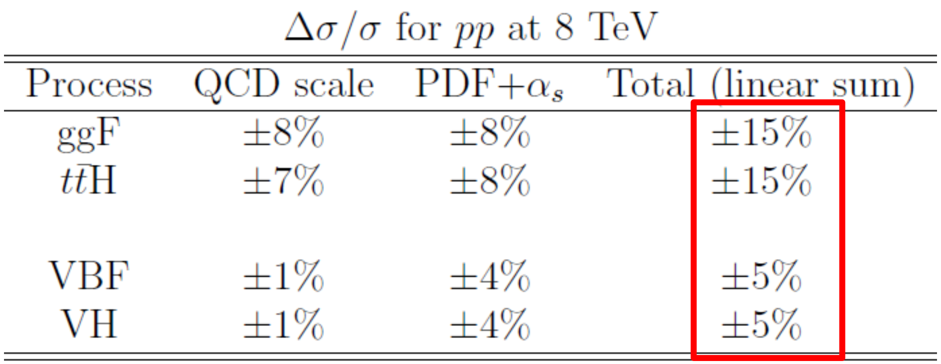
Higgs decays:
- HDECAY (NLO)
- Prophecy4f (NLO), …

Others
- HqT (NLO+NNLL)
- ResBos (NLO+NNLL)
- MINLO
- JetVHeto
- MELA/JHU,
- MEKD, …

+ general programs such as MCFM and many private codes…

LHC Higgs Cross Section Working Group

Theoretical Uncertainties



$\Delta\sigma/\sigma$ for pp at 8 TeV

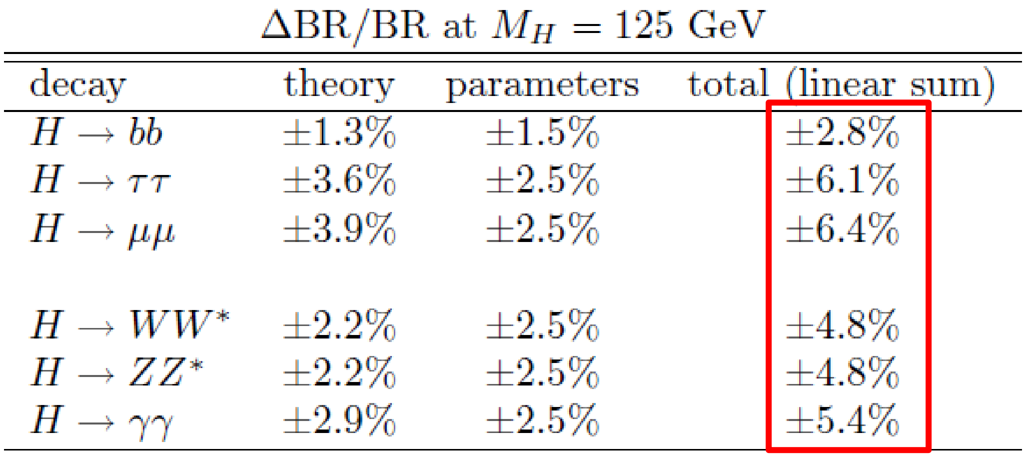
Process	QCD scale	PDF+α_s	Total (linear sum)
ggF	±8%	±8%	±15%
$t\bar{t}$H	±7%	±8%	±15%
VBF	±1%	±4%	±5%
VH	±1%	±4%	±5%

LHC cross section working group

The uncertainties in the ggF process are starting to limit the precision of the coupling measurements.

$\Gamma_{b\bar{b}} \approx 0.57\Gamma_H \Rightarrow \Delta m_b$ has a large impact on parametric uncertainties

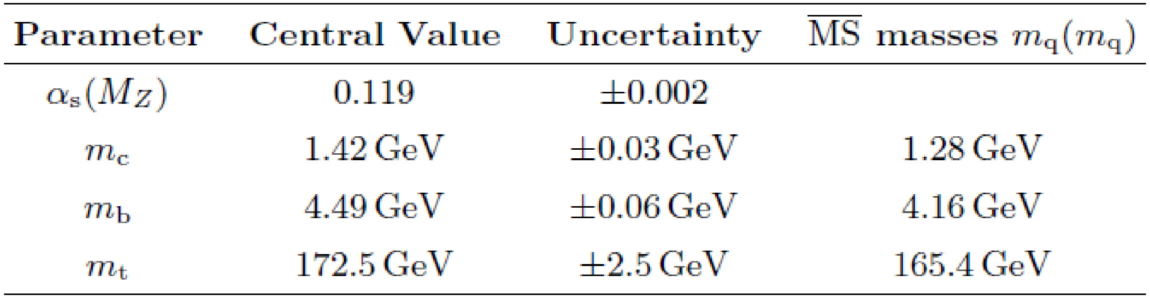
$$\frac{\Delta\Gamma_{bb}}{\Gamma_{bb}} \sim 2\frac{\Delta m_b}{m_b} \sim 2.6\%$$



ΔBR/BR at $M_H = 125$ GeV

decay	theory	parameters	total (linear sum)
$H \to bb$	±1.3%	±1.5%	±2.8%
$H \to \tau\tau$	±3.6%	±2.5%	±6.1%
$H \to \mu\mu$	±3.9%	±2.5%	±6.4%
$H \to WW^*$	±2.2%	±2.5%	±4.8%
$H \to ZZ^*$	±2.2%	±2.5%	±4.8%
$H \to \gamma\gamma$	±2.9%	±2.5%	±5.4%

A. Denner et al., arXiv:1107.5909

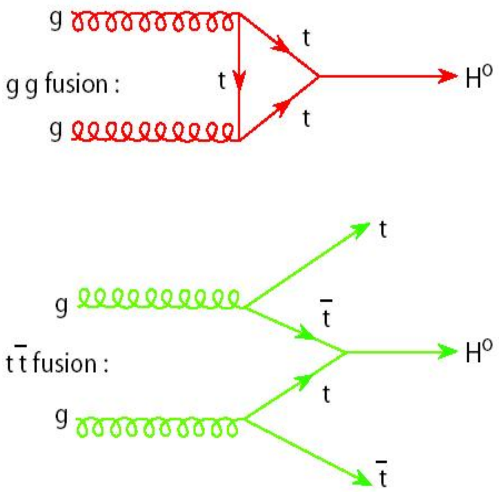


Parameter	Central Value	Uncertainty	$\overline{\text{MS}}$ masses $m_q(m_q)$
$\alpha_s(M_Z)$	0.119	±0.002	
m_c	1.42 GeV	±0.03 GeV	1.28 GeV
m_b	4.49 GeV	±0.06 GeV	4.16 GeV
m_t	172.5 GeV	±2.5 GeV	165.4 GeV

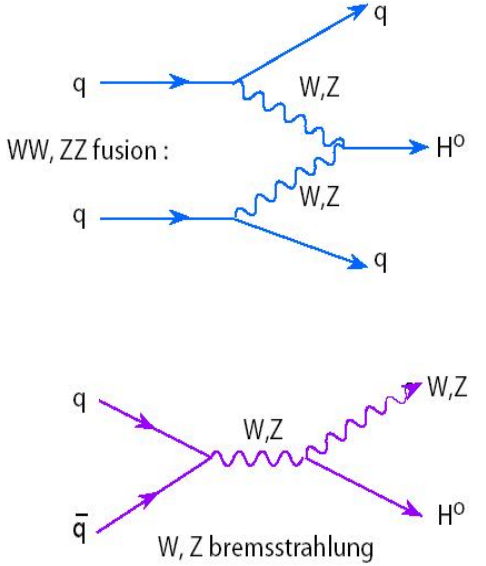
Conservative assumptions by the LHC Higgs cross section, usually 2-3x larger than PDG values.

Disentangle Production Processes – Why?

Production processes naturally fall into two groups



Strong Production
Fermion Coupling



Electroweak Production,
Vector Boson Coupling

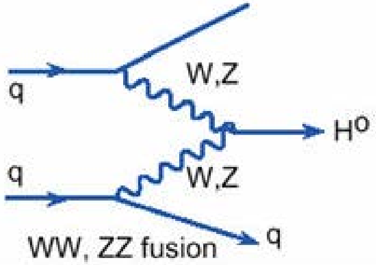
Higgs candidate events are selected from their decay signatures, independent of production.

But need to disentangle the production processes using the production signatures for property measurements.

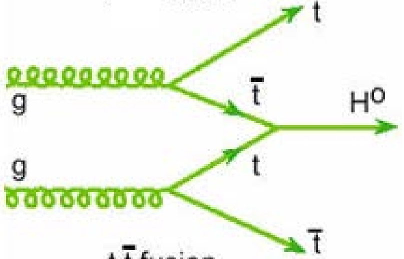
Disentangle Production Processes – How?

From other activities in candidate events…

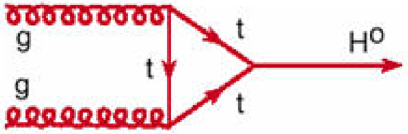
W, Z bremsstrahlung



WW, ZZ fusion



t t̄ fusion



g g fusion

VH

Tagged by W/Z decay signatures:

leptons, missing ET or low-mass dijets from W or Z decays

VBF

Two high pT jets with high-mass and large pseudorapidity separation

ttH

Tagged by top decay signatures:

leptons, missing ET, multijets or b-tagged jets

ggF

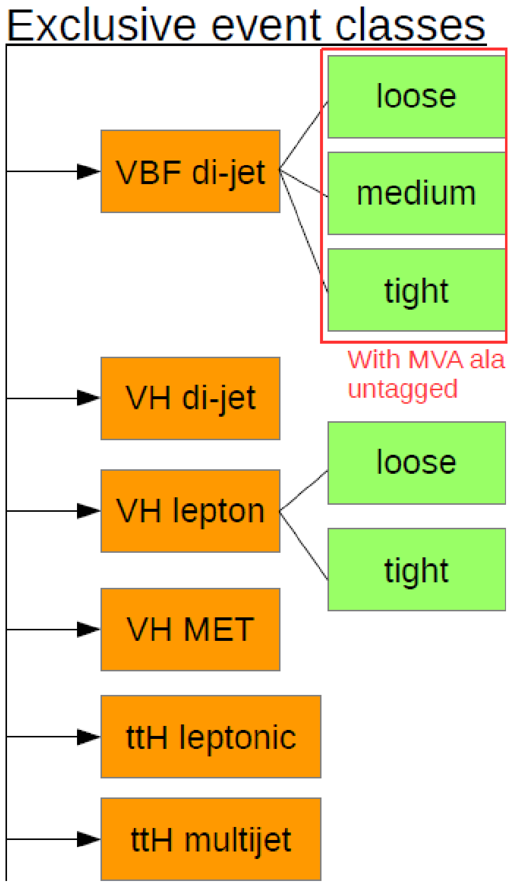
Untagged: the rest

separate into 0, 1 or 2 jets

Analysis Categorization

Categorized analysis to improve S/B and to separate different production processes…

Tagged categories
of CMS H→γγ

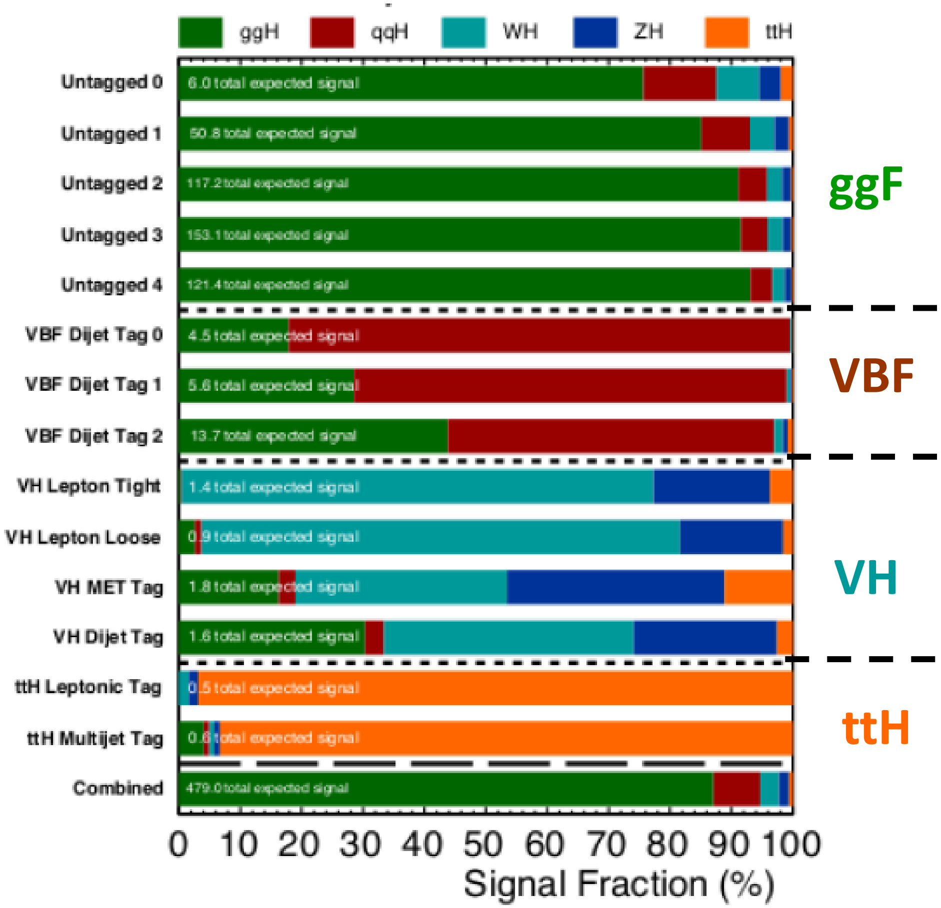


Exclusive event classes

- VBF di-jet
  - loose
  - medium
  - tight
- VH di-jet
- VH lepton
  - loose
  - tight
- VH MET
- ttH leptonic
- ttH multijet

With MVA ala untagged

Signal compositions



Signal Strength

The measured rate relative to the SM prediction

$$\boxed{\text{Signal strength: } \mu = \frac{\sigma \times BR}{(\sigma \times BR)_{SM}}}$$

The quantify has a strong Higgs mass dependence due to the normalization to the SM prediction.

It's meaning depends on the context. It is quoted
- inclusively, or for
- specific decay final state;
- specific production process

Statistical Procedure

Construct likelihood from Poisson probabilities with parameter of interest (signal strength μ in this case):

$$L(\text{data} \mid \mu, \theta) = \text{Poisson}\left(\text{data} \mid \mu \cdot s(\theta) + b(\theta)\right) \times p\left(\tilde{\theta} \mid \theta\right)$$

μ: signal strength; θ: 'nuisance' parameters (efficiencies...)

Hypothesized value of μ is tested with a test statistic:

$$q_\mu = -2\ln\Lambda(\mu) = -2\ln\left[\frac{L\left(\mu, \hat{\hat{\theta}}(\mu)\right)}{L\left(\hat{\mu}, \hat{\theta}\right)}\right]$$

Systematic uncertainties are included as nuisance parameters constrained by chosen pdfs (Gaussian, log-normal, …)

Combination amounts to taking product of likelihoods from different channels: $L(\text{data} \mid \mu, \theta) = \Pi_i \, L_i\left(\text{data}_i \mid \mu, \theta_i\right)$

H→γγ Analysis

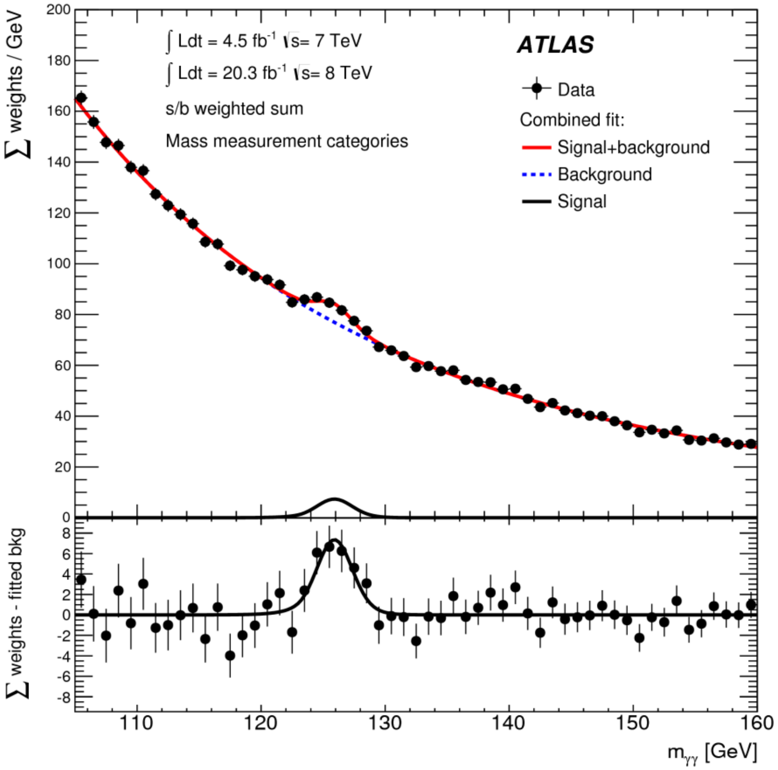
$\sigma(H)\times BR(H\rightarrow\gamma\gamma)\sim$ 51 fb @ 125 GeV

Simple topology: narrow diphoton resonance over a continuum background;

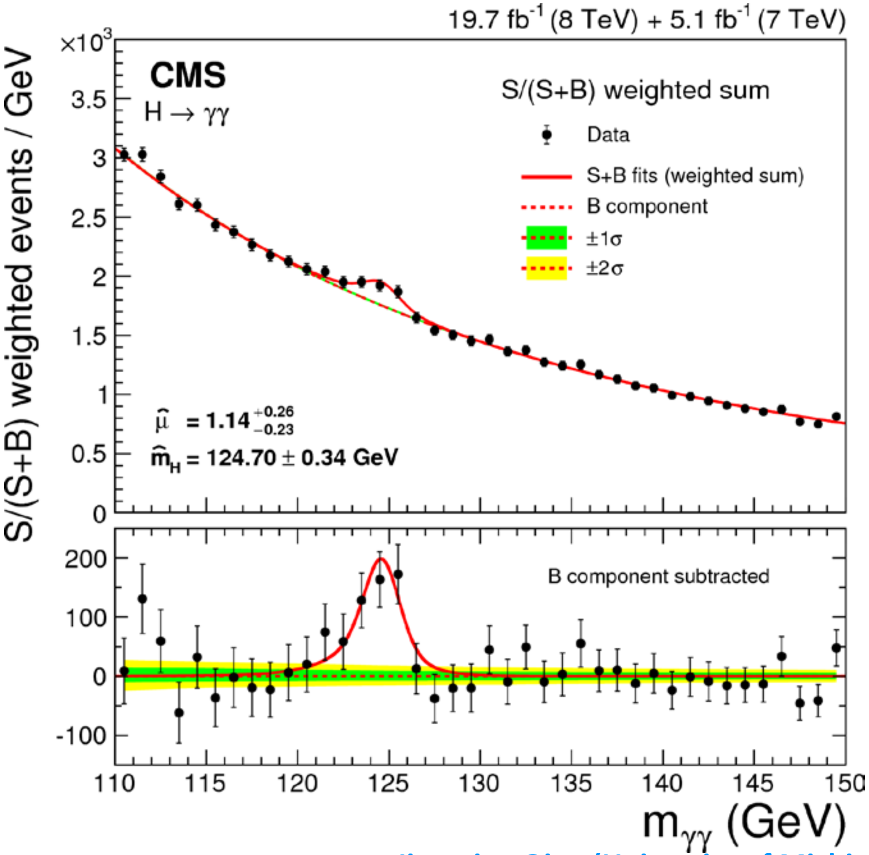
- determine background from data side-band;
- mass resolution is the key;
- typical efficiency ~ 40%

	ATLAS	CMS
Peak mass	126.0 GeV	124.7 GeV
Significance (expected)	5.2σ (4.6σ)	5.7σ (5.2σ)
Signal strength	1.29 ± 0.30	$1.14^{+0.26}_{-0.23}$

arXiv:1406.3827 (ATLAS)



arXiv:14070558 (CMS)

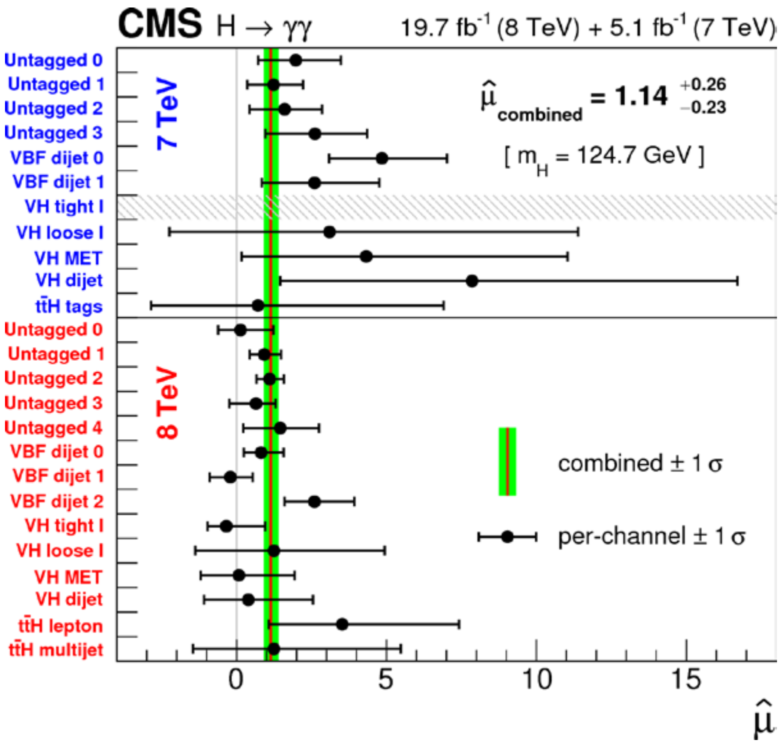


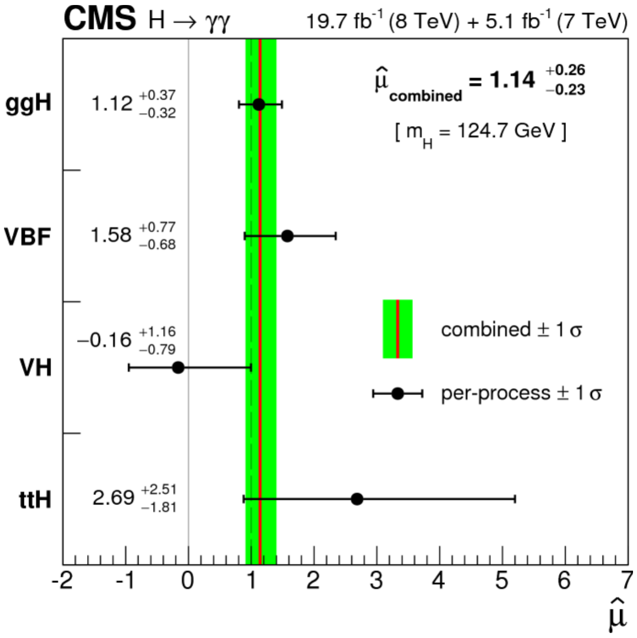
H→γγ: Categories

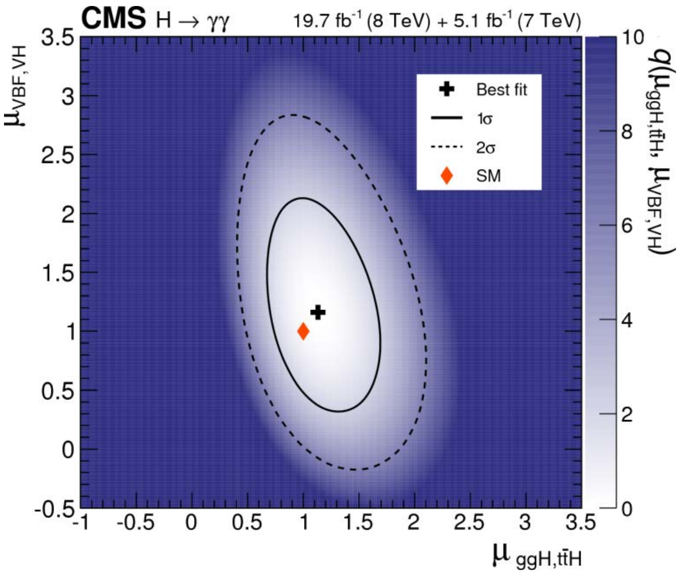
arXiv:14070558 (CMS)

14 categories to

- Discriminate among production processes
- Improve signal and background separation







Enabling the signal strength measurements for different processes:

Electroweak (Yukawa coupling)

vs strong ("Gauge" coupling) productions

$H\rightarrow\gamma\gamma$: m_H Measurement

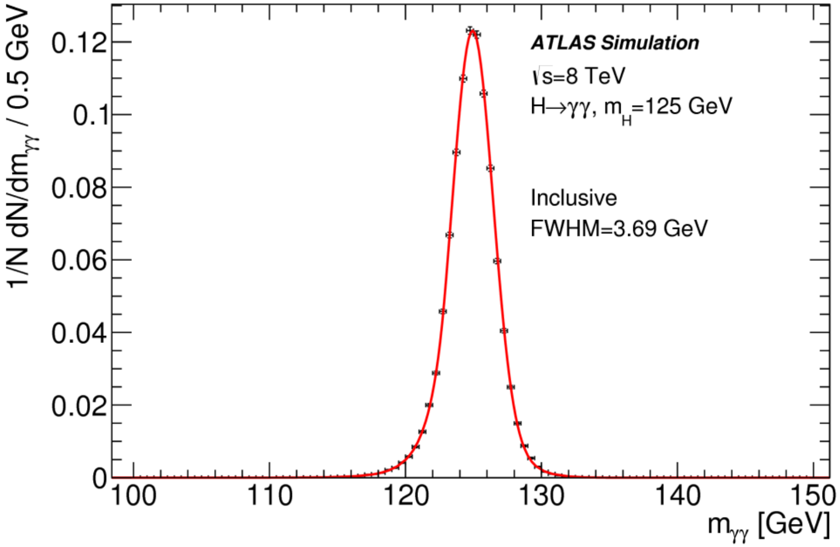
arXiv:14070558 (CMS)

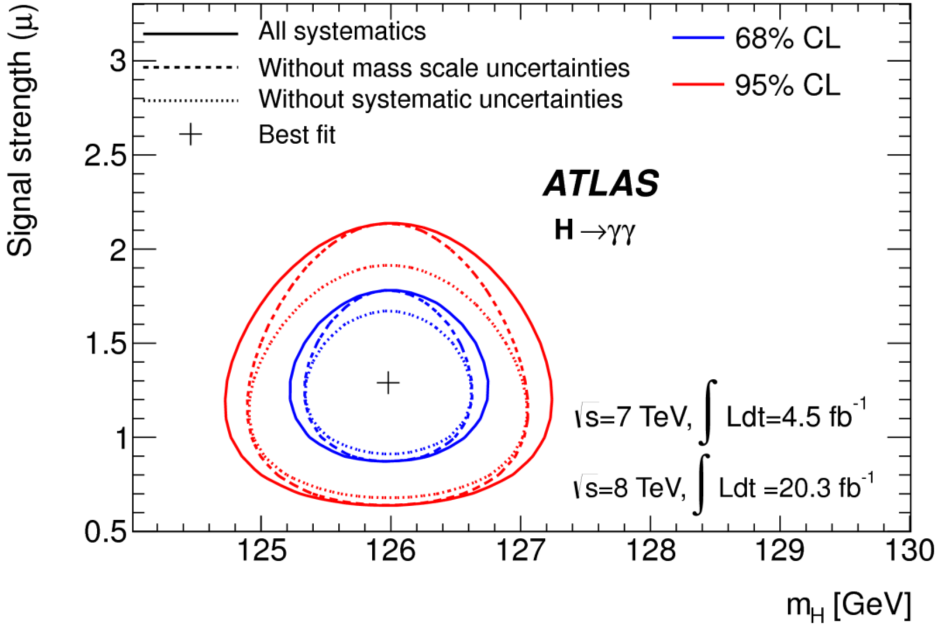
arXiv:1406.3827 (ATLAS)

Full $H\rightarrow\gamma\gamma$ decay reconstruction, excellent mass resultion $\sigma\sim1.5$ GeV

Systematic uncertainties dominated by those of photon energy calibration.

Largely independent of signal strength





ATLAS:

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

CMS:

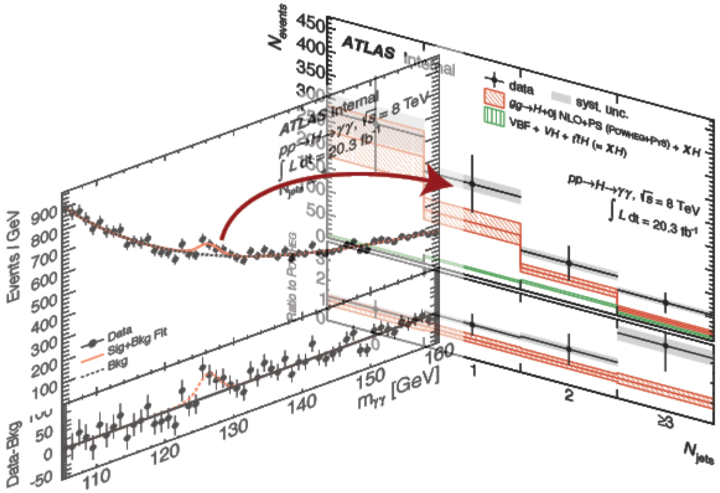
$$m_H = 124.70 \pm 0.31(\text{stat}) \pm 0.15(\text{syst})\ \text{GeV}$$

Note a 1.3 GeV ($\sim2\sigma$) difference between the two measurements

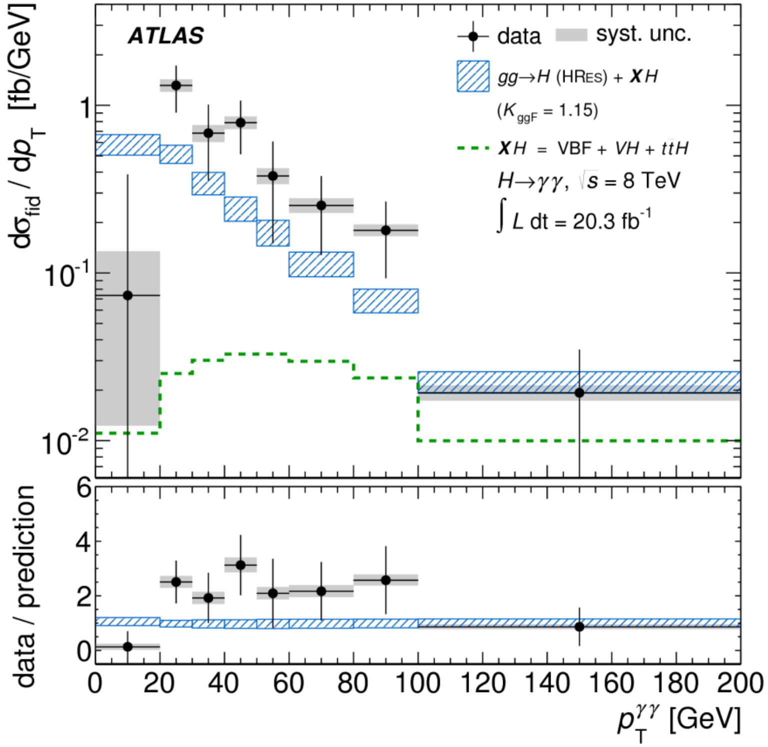
H→γγ: Differential Distributions

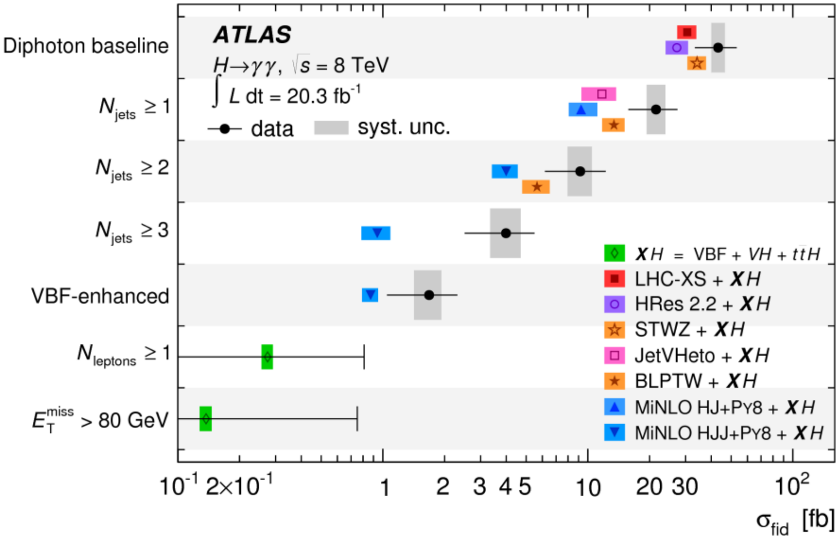
Study kinematics of candidate events:

- fit the mass distributions in bins of kinematic variables such as N_{jet} and $p_T^{\gamma\gamma}$,
- unfold to particle-level cross sections



arXiv:1407.4222 (ATLAS)





Reasonable agreements between data and the SM expectations, need to watch out a few distributions with more statistics….

$H \to ZZ^* \to 4\ell$ Analysis

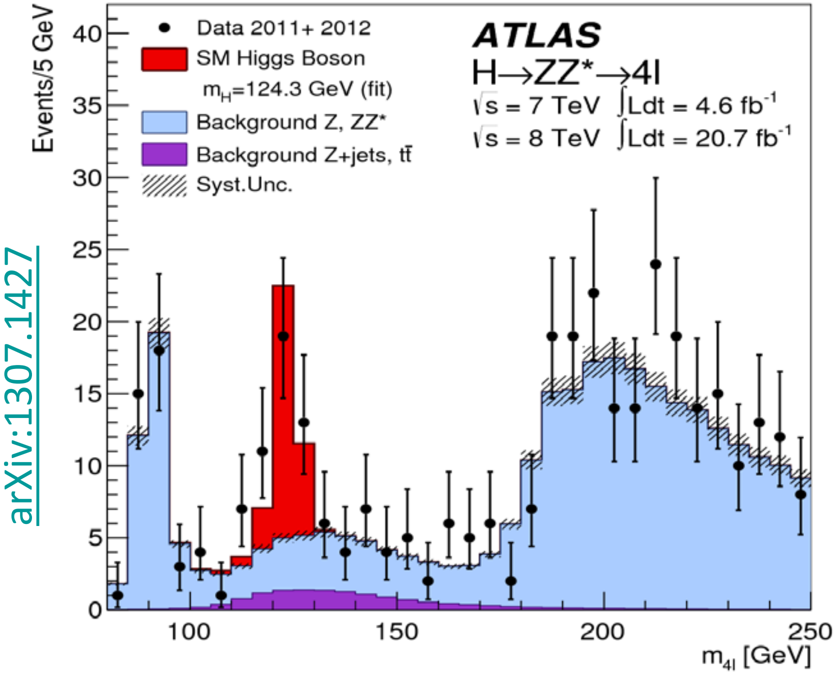
$$\boxed{\sigma(H)\times BR\left(H\to ZZ^*\to 4\ell\right)\sim 2.7\text{ fb @ 125 GeV}}$$

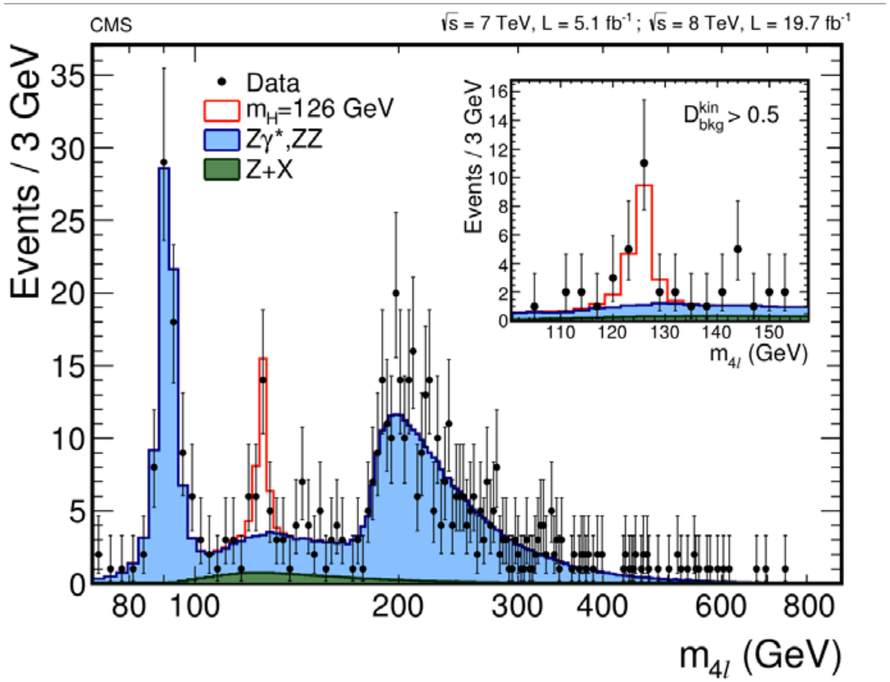
Clean signature, a narrow resonance
over small background mainly from irreducible SM ZZ contribution:

- statistics too low to have a smooth sideband;
- lepton efficiency and $m_{4\ell}$ resolution are keys;
- efficiency varies ~20% (4e) to ~40% (4μ).

	ATLAS	CMS
Peak mass	124.3 GeV	125.6 GeV
Excess significance	6.6σ (4.4σ)	6.8σ (6.7σ)
Signal strength	$1.7 \pm 0.5 \pm 0.4$	0.93 ± 0.27

arXiv:1307.1427



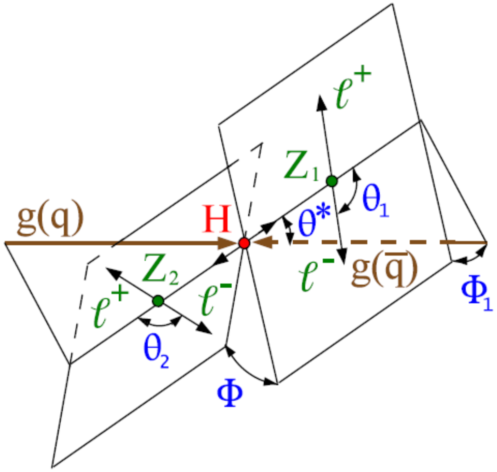


arXiv:1312.5353 (CMS)

$H\rightarrow ZZ^*\rightarrow 4\ell$: Kinematics Exploration

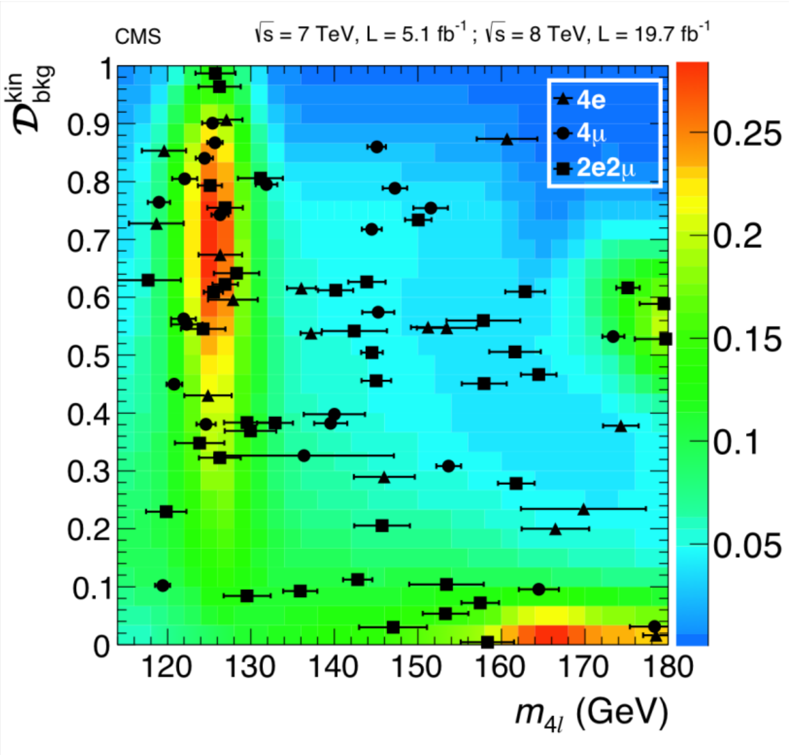
Compared with $H\rightarrow\gamma\gamma$, more complicated kinematics for 4ℓ final states $\Rightarrow$ advanced techniques can improve sensitivity significantly:

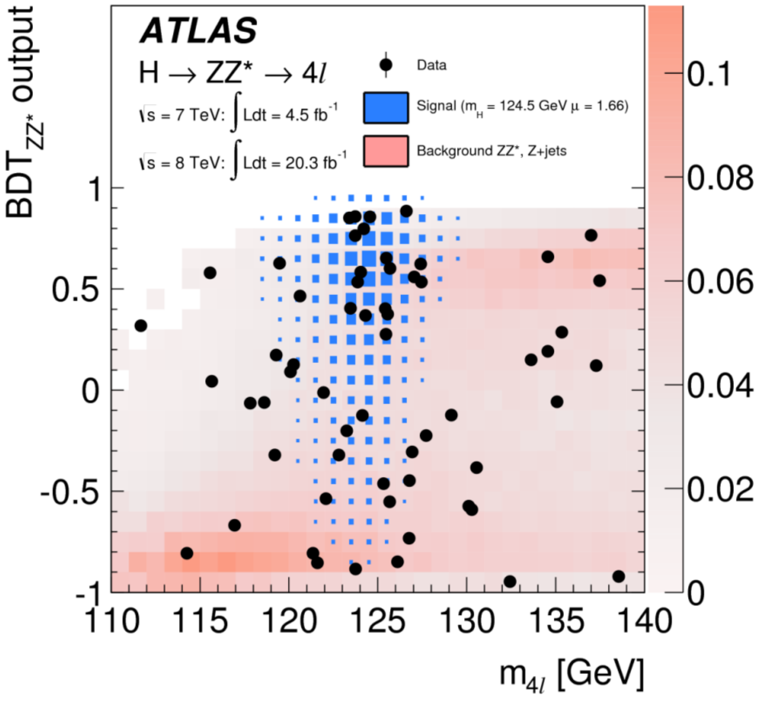
ATLAS: Boosted Decision Tree
CMS: Matrix-Element based discriminant



$$\mathcal{D}_{\rm bkg}^{\rm kin} = \frac{\mathcal{P}_{0^+}^{\rm kin}}{\mathcal{P}_{0^+}^{\rm kin}+\mathcal{P}_{\rm bkg}^{\rm kin}} = \left[1+\frac{\mathcal{P}_{\rm bkg}^{\rm kin}(m_{Z_1},m_{Z_2},\vec{\Omega}|m_{4\ell})}{\mathcal{P}_{0^+}^{\rm kin}(m_{Z_1},m_{Z_2},\vec{\Omega}|m_{4\ell})}\right]^{-1}$$

arXiv:1312.5353 (CMS)





arXiv:1406.3827 (ATLAS)

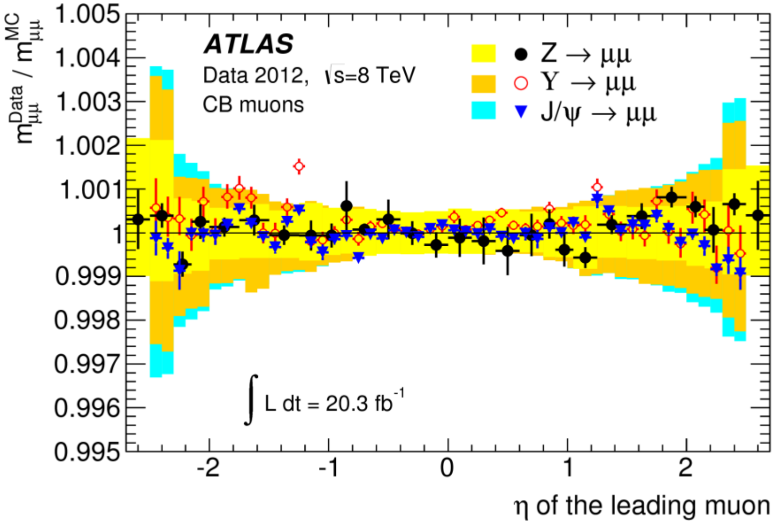
$H \to ZZ^* \to 4\ell$: m_H Measurement

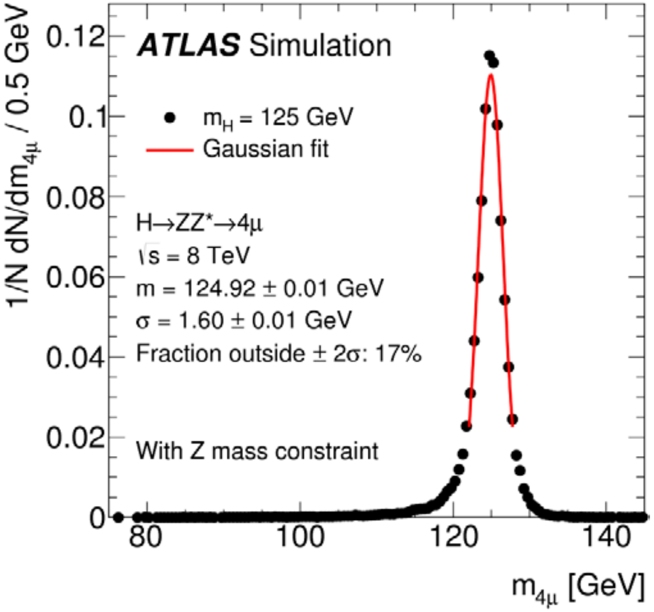
Full $H \to ZZ^* \to 4\ell$ reconstruction, excellent $m_{4\ell}$ mass resolution

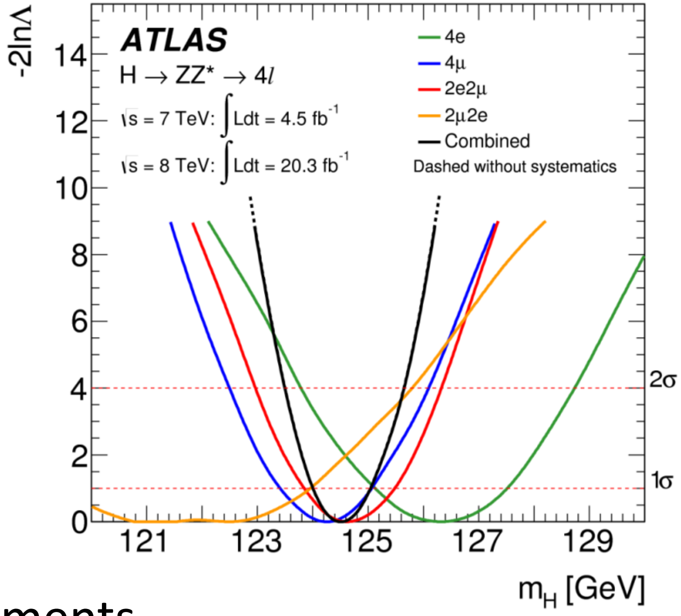
Energy/momentum calibration from data of "Standard candle" events

arXiv:1406.3827 (ATLAS)

arXiv:1312.5353 (CMS)







ATLAS:

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

CMS:

$$m_H = 125.6 \pm 0.4(\mathrm{stat}) \pm 0.2(\mathrm{syst})\ \mathrm{GeV}$$

Good agreements between the two measurements

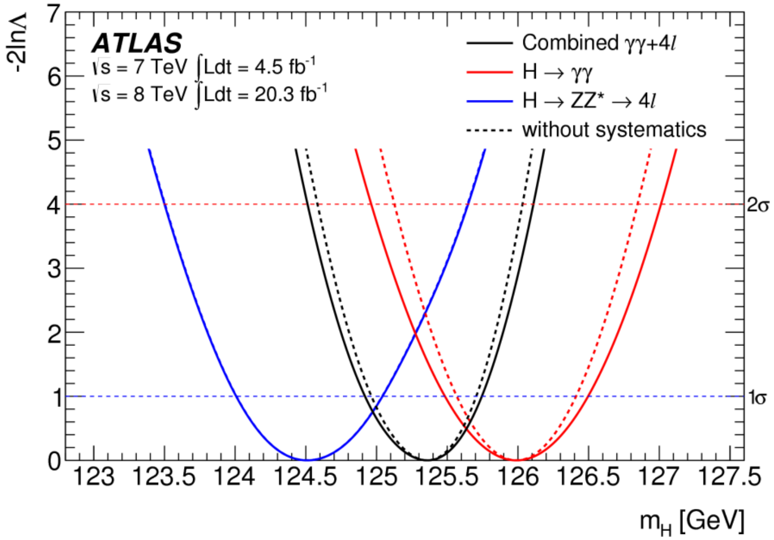
m_H Combination

ATLAS:

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

$$m_H^{4\ell} = 124.51 \pm 0.52\left(stat\right) \pm 0.06\left(syst\right)\ \text{GeV}$$

a $2.0\sigma\left(4.9\%\right)$ difference between $m_H^{\gamma\gamma}$ and $m_H^{4\ell}$, not unlikely, interesting to see what Run 2 entails...



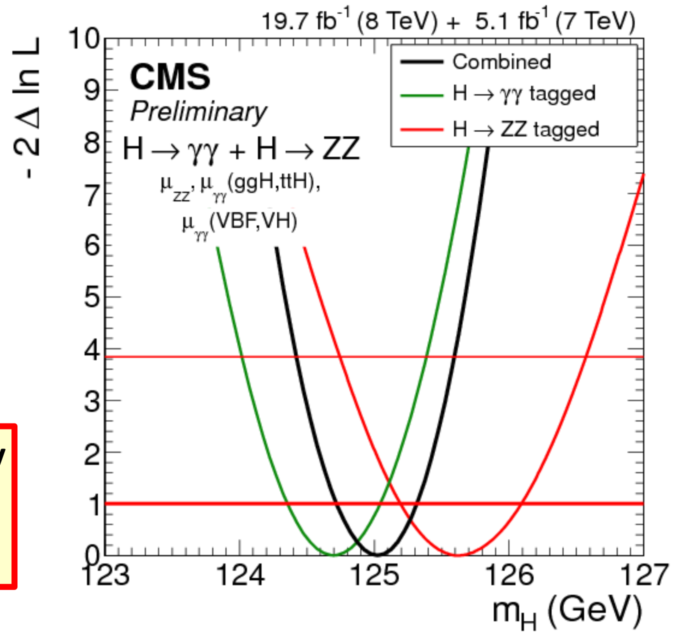
arXiv:1406.3827 (ATLAS)

CMS:

$$m_H^{\gamma\gamma} = 124.70 \pm 0.31\left(stat\right) \pm 0.15\left(syst\right)\ \text{GeV}$$

$$m_H^{4\ell} = 125.6 \pm 0.4\left(stat\right) \pm 0.2\left(syst\right)\ \text{GeV}$$

$\sim 1^{+}\sigma$ difference in the other direction



CMS-PAS-HIG-14-009

Combined:

$$m_H^{ATLAS} = 125.36 \pm 0.37\left(stat\right) \pm 0.18\left(syst\right)\ \text{GeV}$$

$$m_H^{CMS} = 125.03 \pm 0.27\left(stat\right) \pm 0.14\left(syst\right)\ \text{GeV}$$

$H\rightarrow WW^*\rightarrow \ell\nu\ell\nu$ Analysis

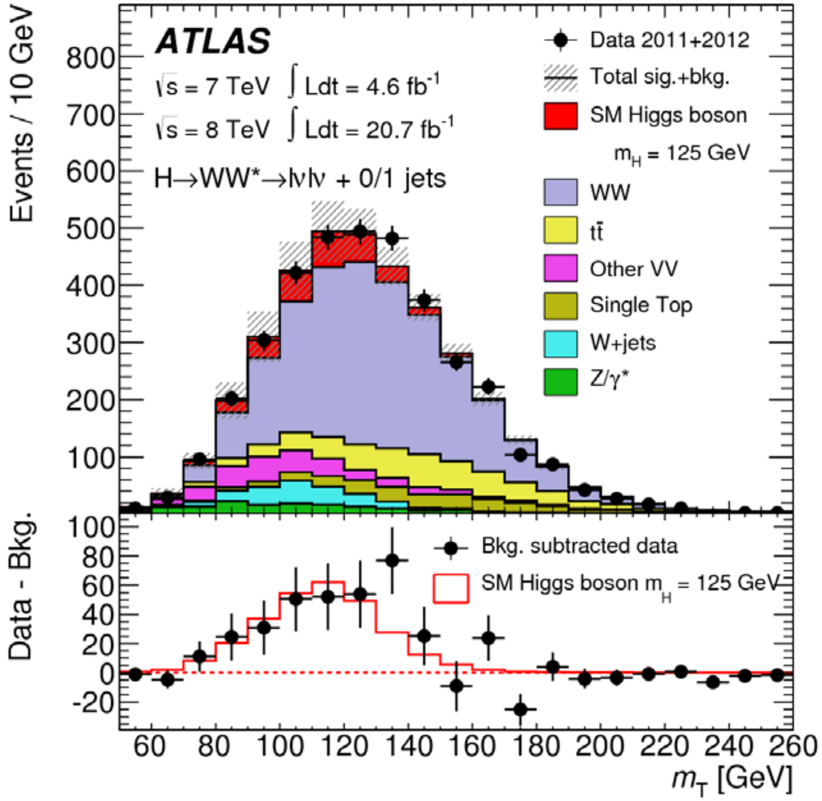
$$\boxed{\sigma(H)\times BR(H\rightarrow WW^*\rightarrow \ell\nu\ell'\nu)\sim 224 \text{ fb @ } 125 \text{ GeV}}$$

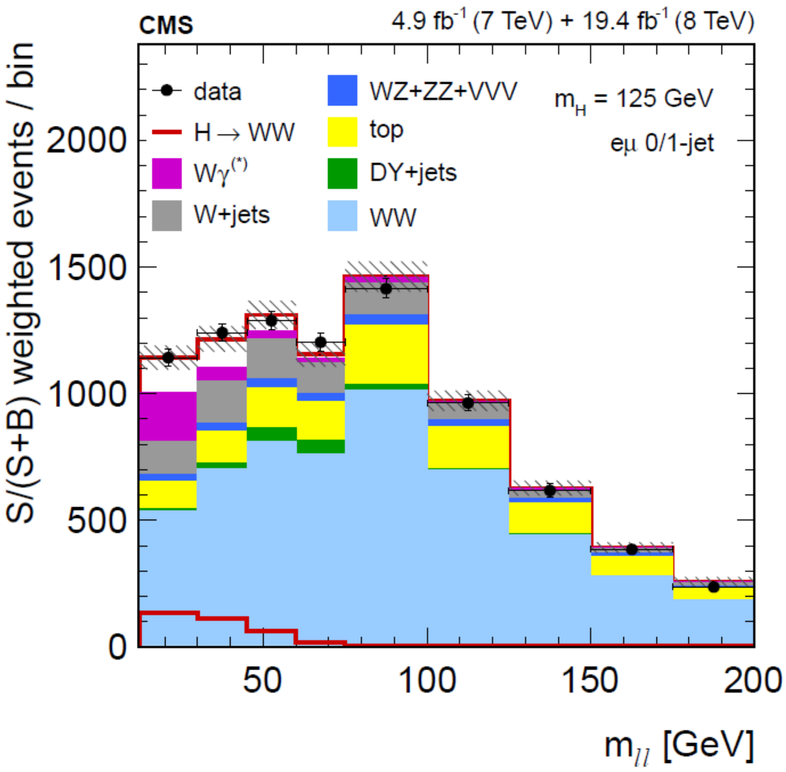
No full Higgs decay reconstruction, complicated background compositions.

Excess over broad backgrounds:
  - precision background measurements;
  - “large” statistics.

	ATLAS	CMS
@ mass	125.5 GeV	125.6 GeV
Excess significance	3.8σ (3.8σ)	4.3σ (5.8σ)
Signal strength	$0.99^{+0.31}_{-0.28}$	$0.72^{+0.20}_{-0.18}$

arXiv:1307.1427 (ATLAS)





arXiv:1312.1129 (CMS)

H→WW*→$\ell\nu\ell\nu$: Jet Veto

ATLAS-CONF-2013-030

Background composition depends strongly on jet multiplicity ⇒ analysis is done in jet bin.

Most of the signal is in the 0-jet bin where the SM WW is the largest background.

Control region (CR) is used to normalize the WW background in the signal region (SR):

$$N^{SR}_{Data} = \left(\frac{N^{SR}}{N^{CR}}\right)_{MC} \times N^{CR}_{Data} = \left(\frac{N_{Data}}{N_{MC}}\right)_{CR} \times N^{SR}_{MC} = \boxed{R_{NF}} \times N^{SR}_{MC}$$

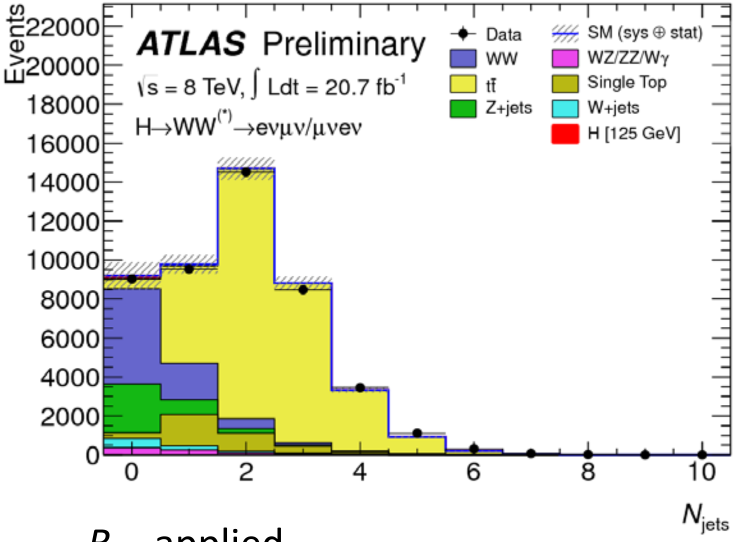
WW CR ($50 < m_{\ell\ell} < 100$ GeV)

Estimate	N_{obs}	N_{bkg}	N_{sig}
WW			
$N_{\text{jet}} = 0$	2224	1970 ± 17	31 ± 0.7
$N_{\text{jet}} = 1$	1897	1893 ± 17	1.9 ± 0.3

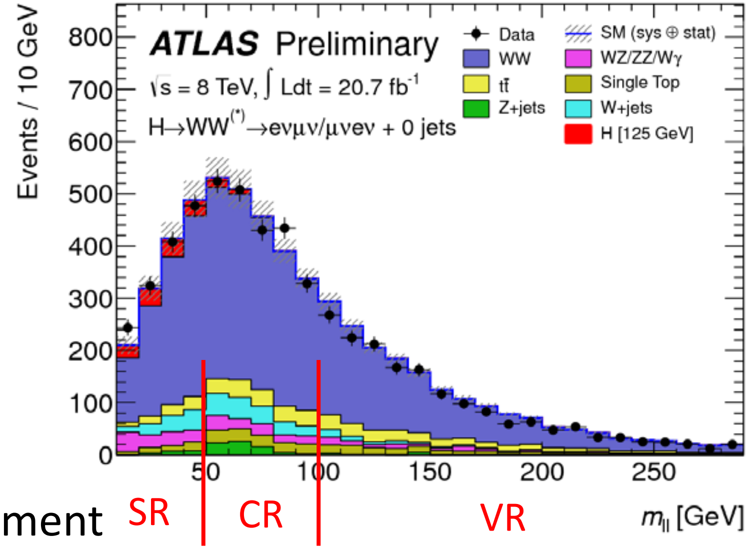
$$\Rightarrow R^{0\,jet}_{NF} \sim 1.12$$

Consistent with the SM WW cross section measurement which is ~15% higher than the prediction.

R_{NF} applied



R_{NF} applied



SR CR VR

(Validation Region)

H→WW*→$\ell\nu\ell\nu$: Mass Estimator

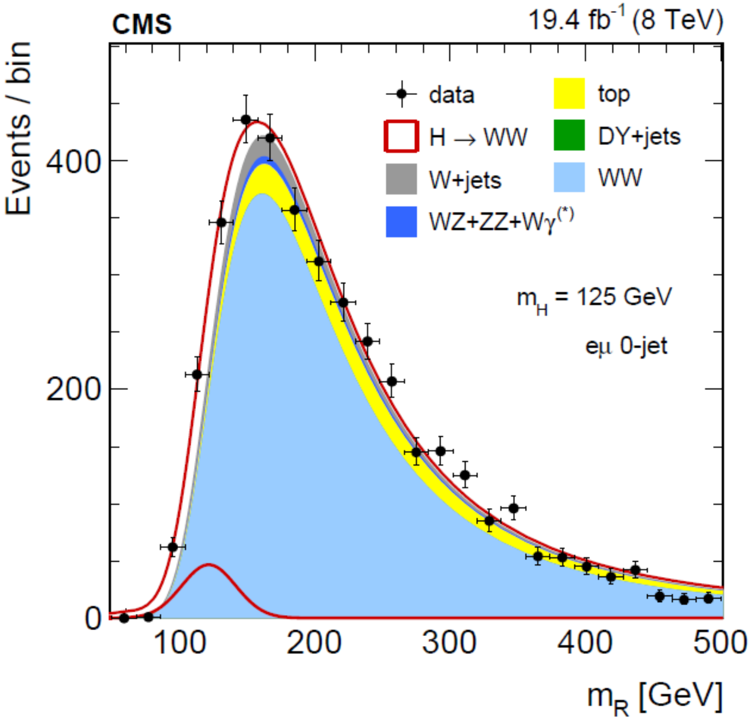
"Razor" frame: approximate Higgs rest frame through both longitudinal $\left[\beta_L = (p_z^{\ell_1} + p_z^{\ell_2})\big/(E_{\ell_1} + E_{\ell_2})\right]$ and transverse $\left[\vec{E}\!\!\!/_T\right]$ boosts

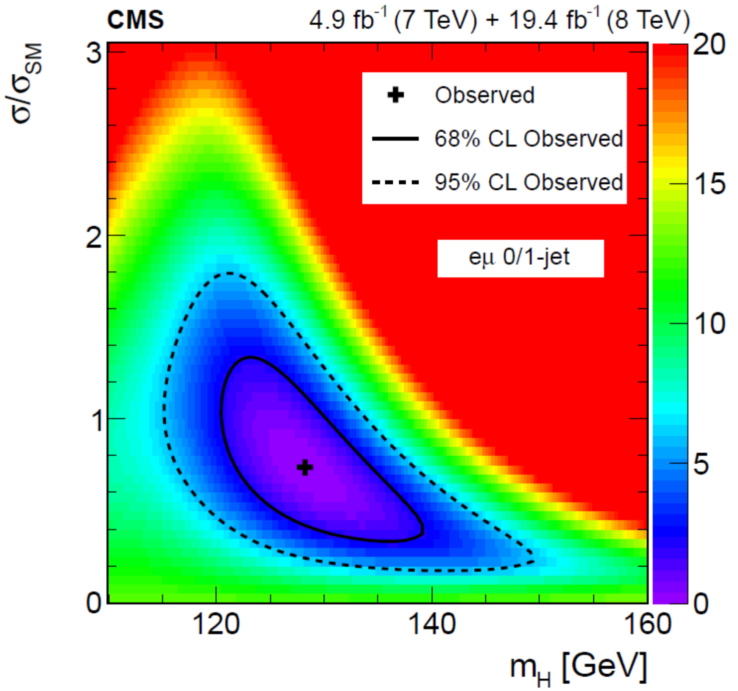
2D fit to Higgs mass estimator m_R and 2ℓ openning angle

$$m_R = \sqrt{\frac{1}{2}\left[m_{\ell\ell}^2 - \vec{E}_T^{\rm miss}\cdot\vec{p}_T^{\,\ell\ell} + \sqrt{(m_{\ell\ell}^2 + (p_T^{\ell\ell})^2)(m_{\ell\ell}^2 + (E_T^{\rm miss})^2)}\right]}$$

(~15% resolution at 125 GeV)

arXiv:1312.1129 (CMS)





$m_H = 125.5^{+3.6}_{-3.8}$ GeV assuming SM rate and $m_H = 128.2^{+6.6}_{-5.3}$ GeV floating the rate.

H→ττ Analysis

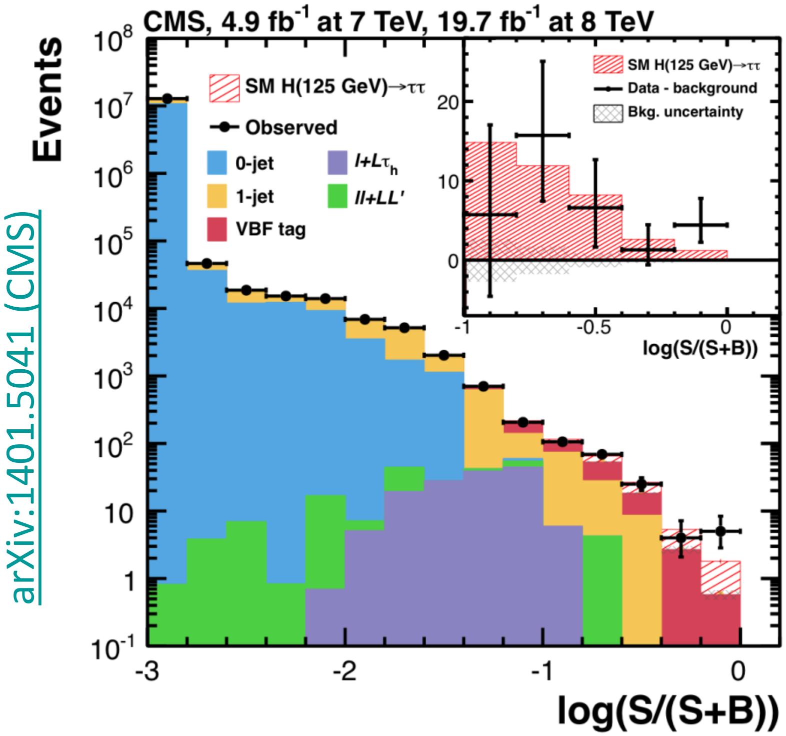
$$\boxed{\sigma(H)\times BR(H\to\tau\tau)\sim 1.4\text{ pb @ 125 GeV}}$$

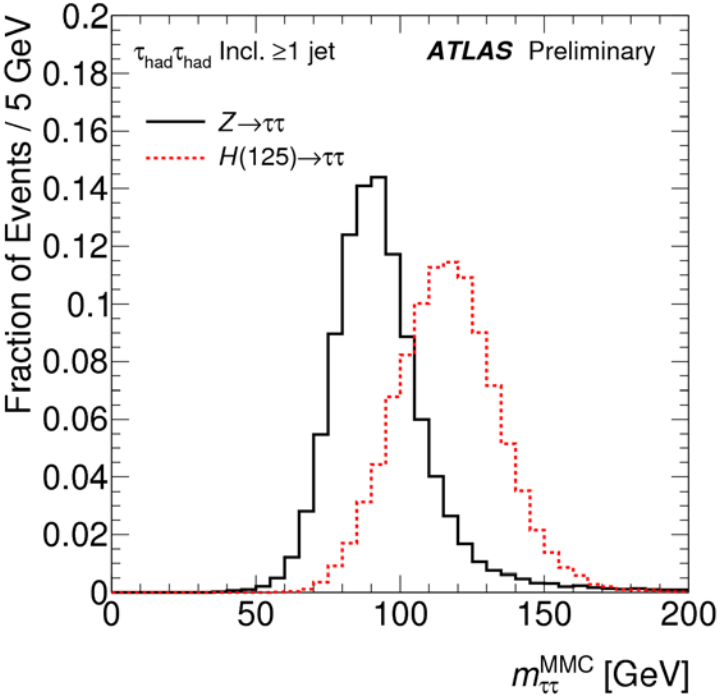
Large rate, but also large backgrounds, trigger and reconstruction are challenging.

Analyzed all three final states of the $\tau\tau$ decays:

- lep-lep channel: $H\to\tau\tau\to 2\ell+4\nu\ (12.4\%)$
- lep-had channel: $H\to\tau\tau\to \ell+\tau_{had}+3\nu\ (45.6\%)$
- had-had channel: $H\to\tau\tau\to 2\tau_{had}+2\nu\ (42\%)$

arXiv:1401.5041 (CMS)





ATLAS-CONF-2013-108

Reconstruct $\tau\tau$ mass using techniques such as the Missing Mass Calculator (MMC), typical $\tau\tau$ mass resolution $\sim$15%.

Two major categories: VBF and boosted ggF
Employing MVA after basic selection.

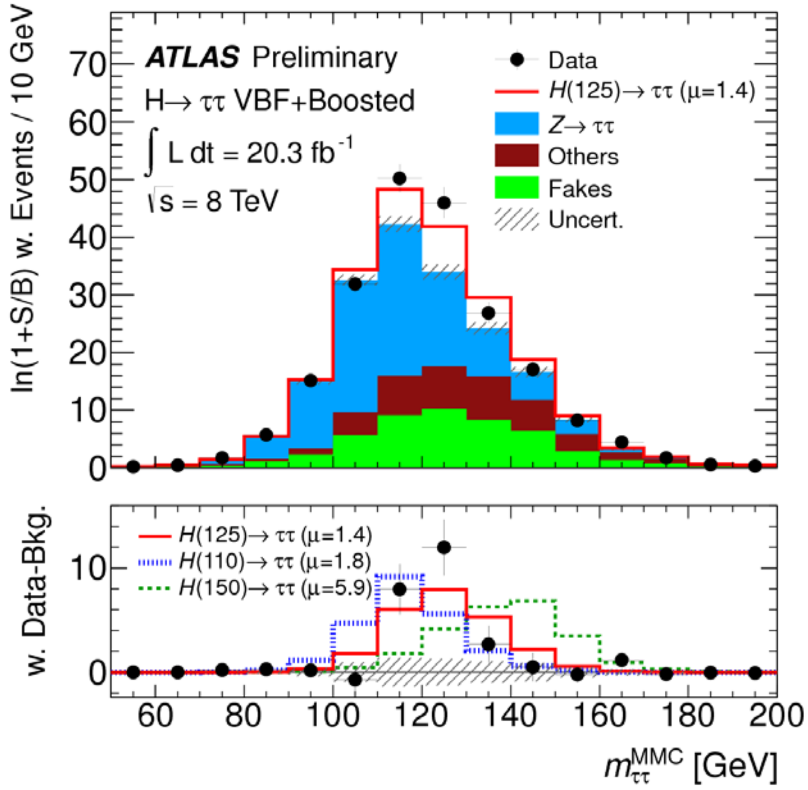
H→ττ Analysis

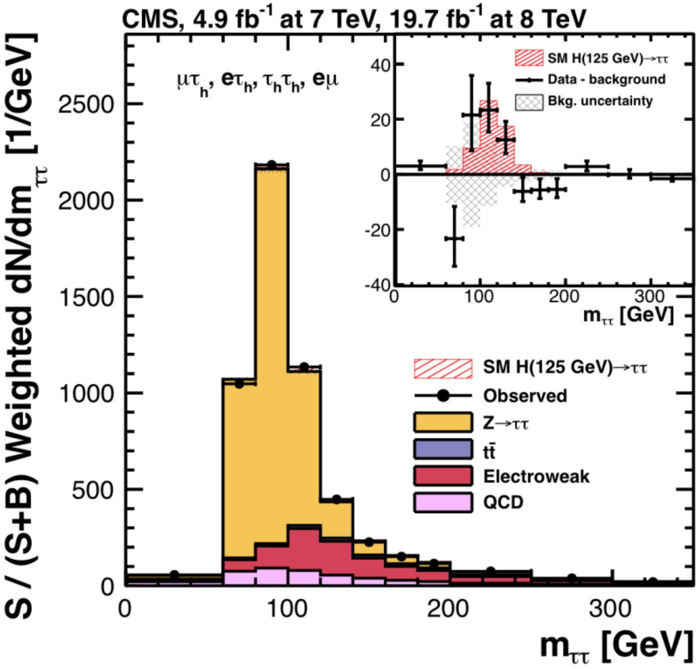
$Z \rightarrow \tau\tau$ dominates the background

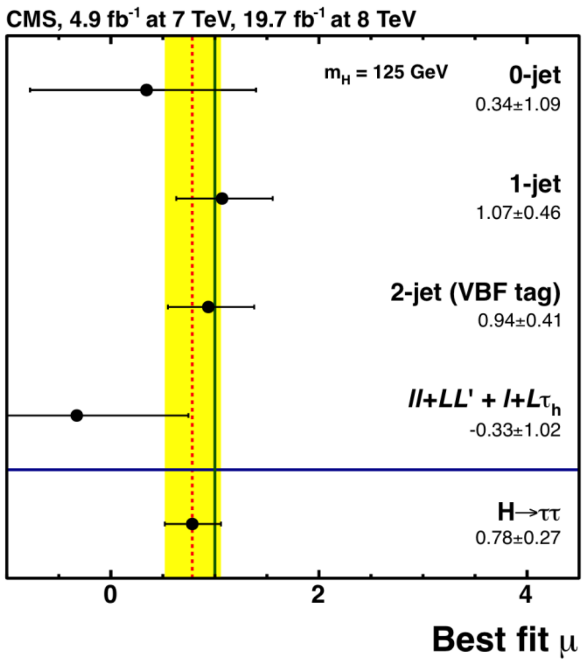
$\ell + \tau_{had}$ dominates the sensitivity

	ATLAS	CMS
@ mass	125 GeV	125 GeV
Significance	4.1σ (3.2σ)	3.4σ (3.6σ)
Signal strength	$1.4^{+0.5}_{-0.4}$	0.78 ± 0.27

ATLAS-CONF-2013-108







arXiv:1401.5041 (CMS)

VH with H→bb

$\sigma(VH)\times BR(H\to b\bar{b}) \sim 0.57$ pb @ 125 GeV

$H \to b\bar{b}$ has an even higher rate ($\times 10$) than $H \to \tau\tau$, but with no leptons, photons, nor missing ET from the Higgs decays, has to rely on associated objects such as V $(W$ or Z$)$ in the VH production.

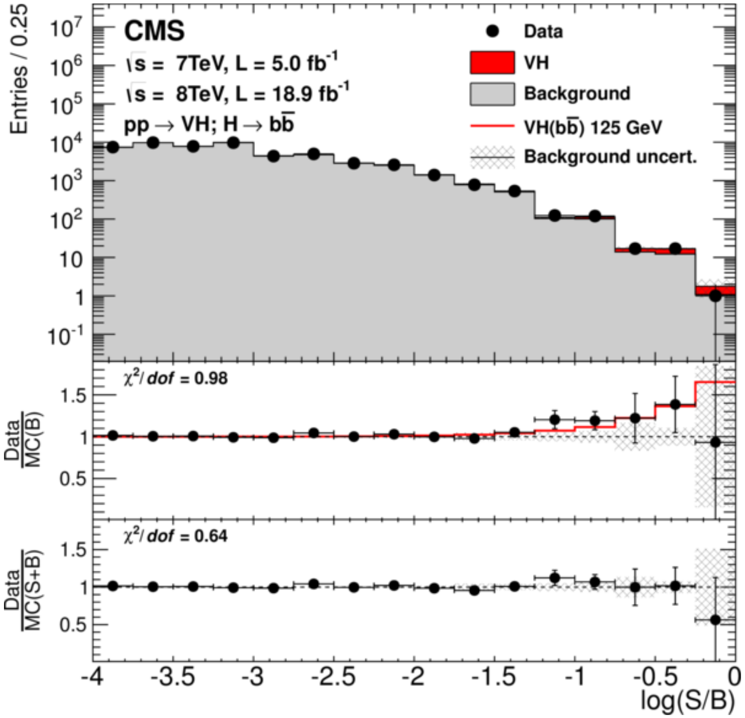
W, Z bremsstrahlung

Three distinct final states considered:

0-lepton: $\nu\nu b\bar{b}$ (ZH);
1-lepton: $\ell\nu b\bar{b}$ (WH);
2-leptons: $\ell\ell b\bar{b}$ (ZH)

While ATLAS relies on the cut-based analysis, CMS applies advanced techniques extensively in its analysis:

- Separate BDTs for each signal final state;
- Separate BDT for each major background source

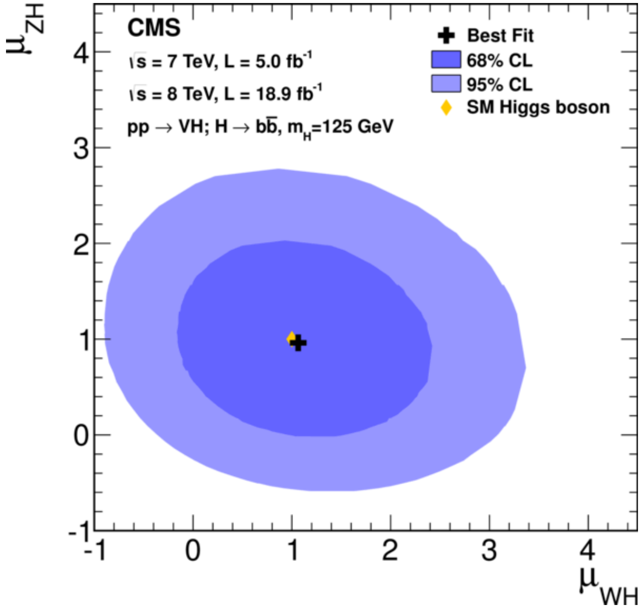


arXiv:1310.3687 (CMS)

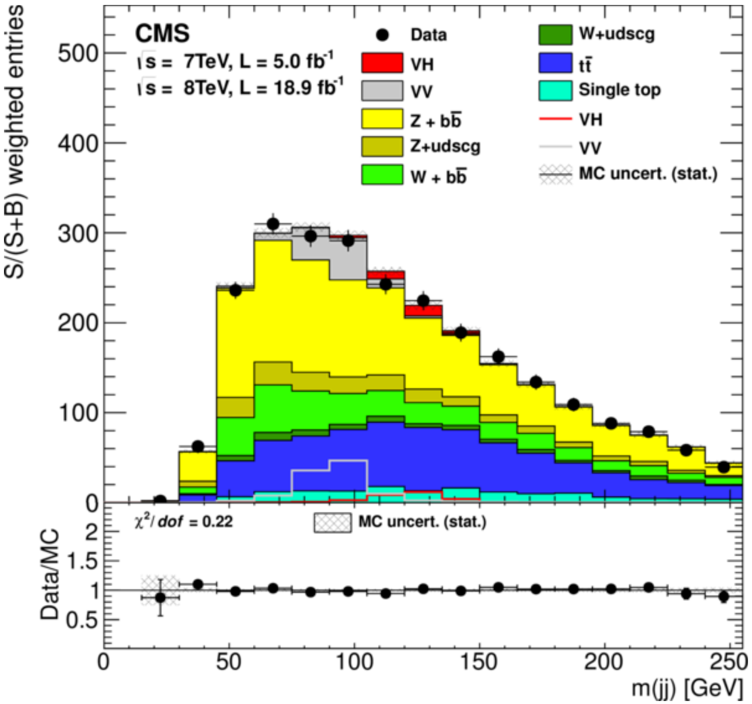
	ATLAS	CMS
@ mass	125 GeV	125 GeV
Significance	$p_0 = 0.36$ (0.05)	2.1σ (2.1σ)
Signal strength	$0.2 \pm 0.5(\text{stat}) \pm 0.4(\text{syst})$	1.0 ± 0.5

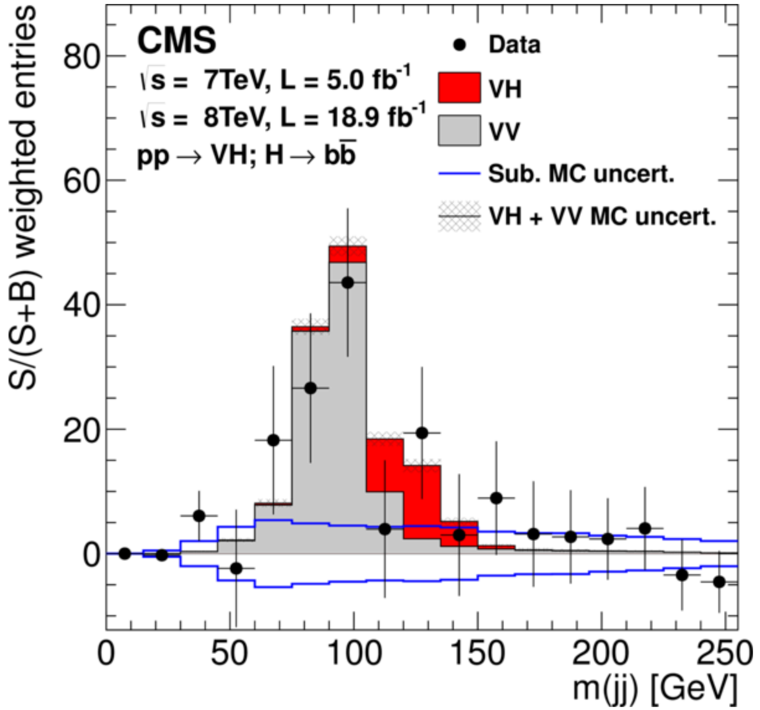
VH with H→bb

- Full H→bb reconstruction, but poor mass resolution (10-15%),
- b-tagging critical to reduce V+light-jet backgrounds,
- Large V+bb continuum backgrounds,
- VZ with Z→bb offers validation,
- Similar sensitivities from WH and ZH

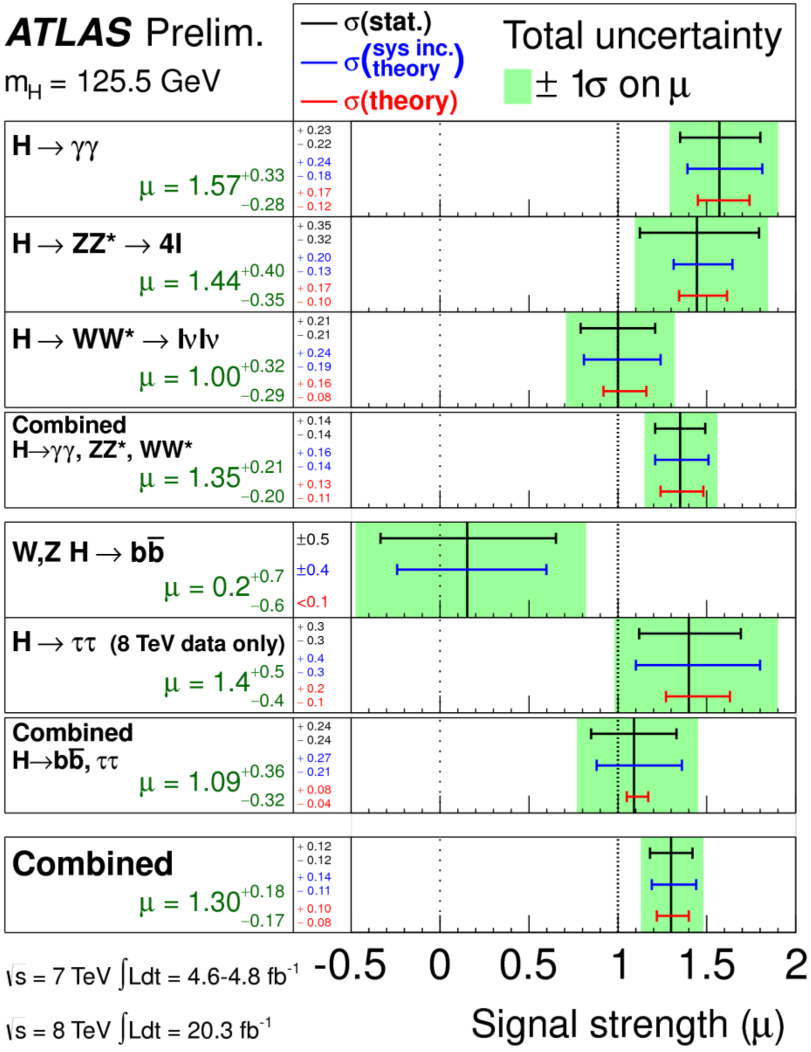


arXiv:1310.3687 (CMS)



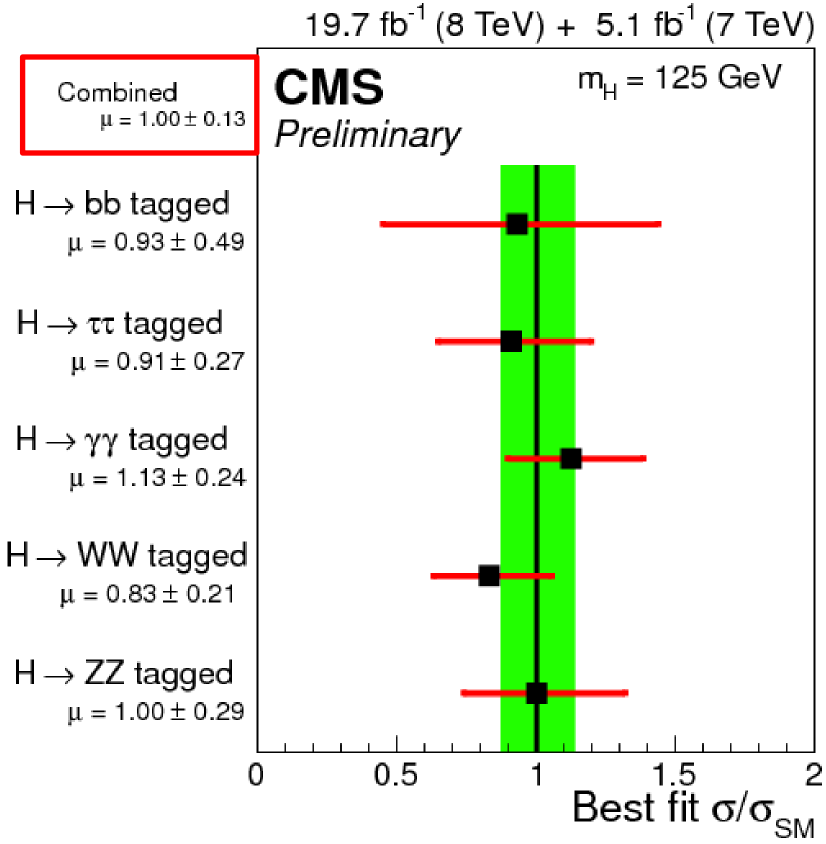


Summary of Rate Measurements



ATLAS-CONF-2013-034

(Note that not all entries are up-to-date)



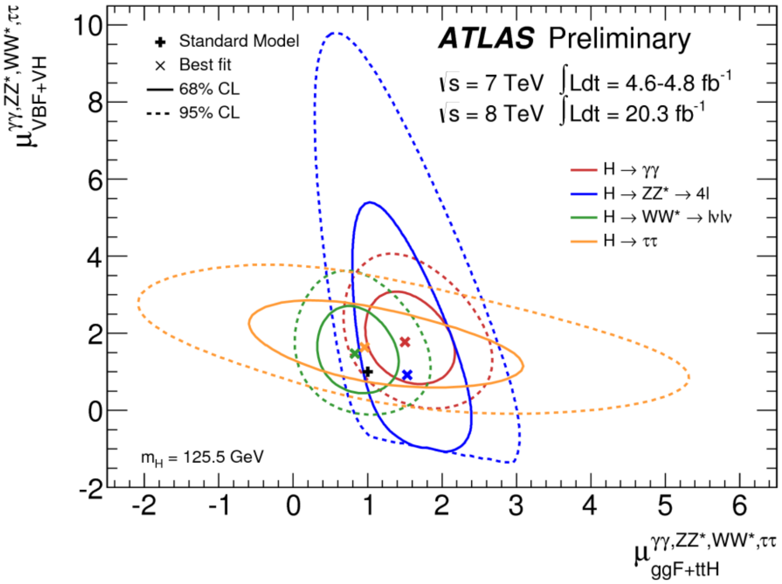
CMS-PAS-HIG-14-009

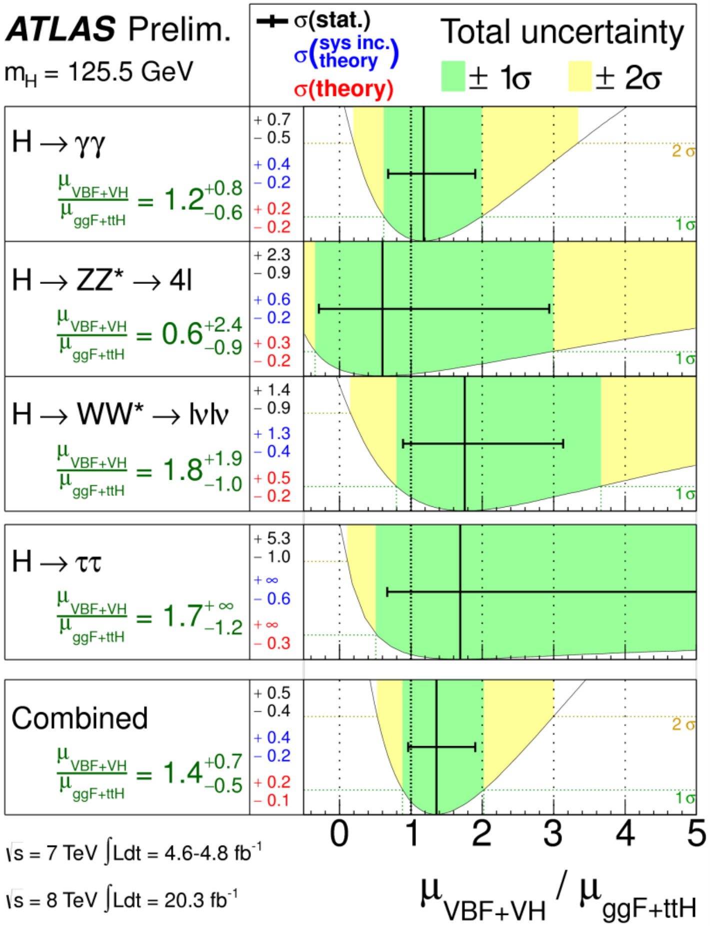
The measured rates are consistent with the SM expectations within their precisions.

Probing the Production…

ATLAS-CONF-2013-034

Strong vs electroweak
(fermion vs vector boson)





The ratio $\frac{\mu_{VBF+VH}}{\mu_{ggF+ttH}}$ probes production only
(BRs cancel out for each final state)

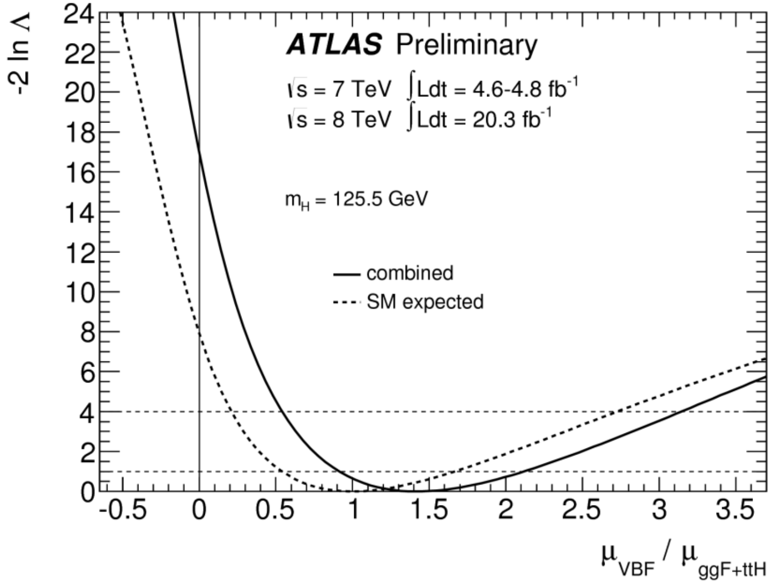
The combination is independent of potential new physics in different decay final states.

Evidences for non-ggF Productions

ATLAS-CONF-2013-034

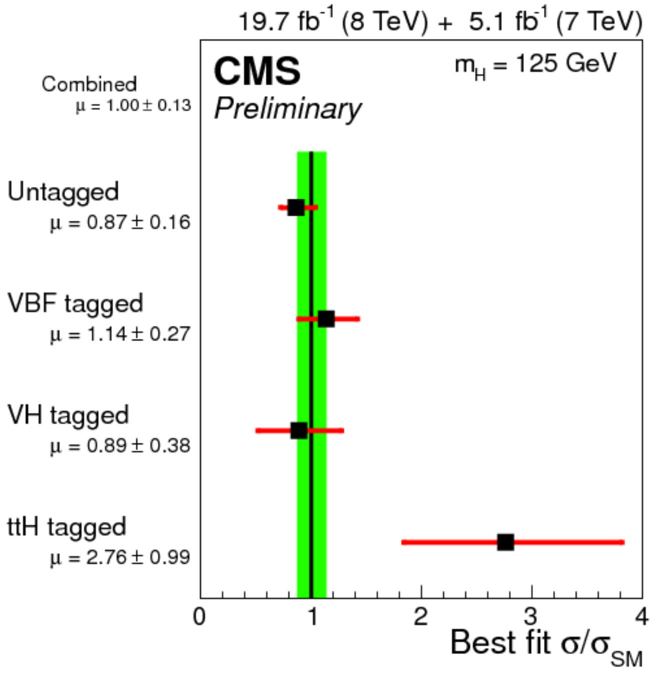
The signal strength of the VBF process can contribution from VH ⇒ little effect from the profiling:

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



A 4.1σ evidence for the VBF production.

CMS-PAS-HIG-14-009

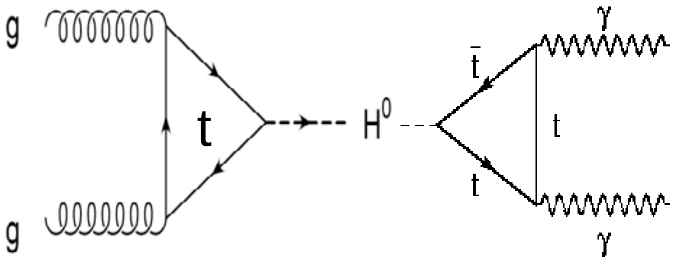


CMS extracted the signal strengths of the four processes from the tagged analyses

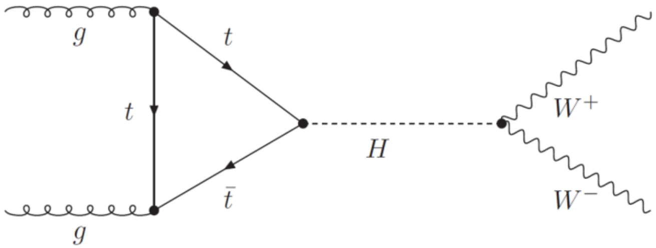
Parameter	Best-fit result (68% CL)
μ_{ggH}	$0.85^{+0.19}_{-0.17}$
μ_{VBF}	$1.15^{+0.37}_{-0.35}$
μ_{VH}	$1.00^{+0.40}_{-0.40}$
$\mu_{\mathrm{t\bar{t}H}}$	$2.93^{+1.04}_{-0.97}$

Beyond Signal Strengths

Signal strength mixes different production processes, production and decay, tree- and loop-level Higgs couplings. Consequently it could obscure potential new physics.



same couplings, but a mixture of production and decay



a mixture of fermion and vector boson couplings

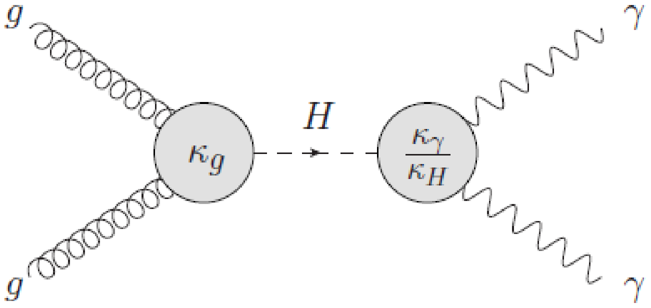
Higgs couplings to fermions and vector bosons are at the heart of all these. Potential deviations from SM can be studied from these couplings.

Using scale parameters $\boxed{\kappa}$ $\left(\text{SM: } \kappa = 1\right)$ to parametrized the deviations:

$$g_{Hff} = \frac{\sqrt{2}m_f}{\upsilon}, \qquad g_{HVV} = \frac{2m_V^2}{\upsilon} \quad \Rightarrow \quad g_{Hff} = \boxed{\kappa_f} \cdot \frac{\sqrt{2}m_f}{\upsilon}, \quad g_{HVV} = \boxed{\kappa_V} \cdot \frac{2m_V^2}{\upsilon}$$

Rate Modifications

Example:
$gg \rightarrow H \rightarrow \gamma\gamma$



$$(\sigma \cdot BR)(gg \rightarrow H \rightarrow \gamma\gamma) = \left[\sigma(gg \rightarrow H) \cdot BR(H \rightarrow \gamma\gamma)\right]_{SM} \times \boxed{\frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}}$$

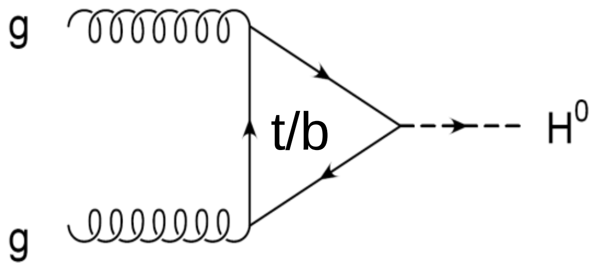
κ_H^2 is the scale factor to the total Higgs decay width

$$\kappa_H^2 = \sum_x \kappa_x^2 \cdot BR(H \rightarrow xx) \xrightarrow{\text{No BSM decays}} \kappa_H^2 = \sum_x \kappa_x^2 \cdot BR_{SM}(H \rightarrow xx)$$

$$\xrightarrow{\text{With BSM decays}} \kappa_H^2 = \sum \kappa_x^2 \cdot \frac{BR_{SM}(H \rightarrow xx)}{1 - BR_{BSM}}$$

κ's can then be extracted from fits to the measured rates. Theoretical cross section and branching ratio uncertainties are absorbed into the uncertainties of κ's.

Decomposing Loops…



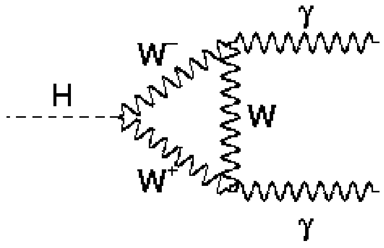
In SM, the $gg \rightarrow H$ cross section can be broken into three pieces: $\sigma_{SM} = \sigma_{tt} + \sigma_{bb} + \sigma_{tb}$

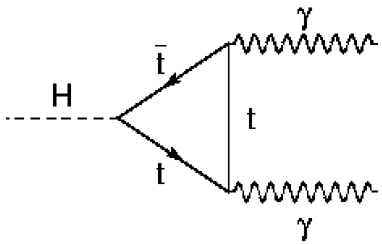
With coupling modifications, the cross section becomes $\Rightarrow \sigma = \kappa_t^2 \sigma_{tt} + \kappa_b^2 \sigma_{bb} + \kappa_t \kappa_b \sigma_{tb}$

The effective *Hgg* coupling scale parameter is

$$\kappa_g^2 = \frac{\sigma}{\sigma_{SM}} = \frac{\kappa_t^2 \sigma_{tt} + \kappa_b^2 \sigma_{bb} + \kappa_t \kappa_b \sigma_{tb}}{\sigma_{tt} + \sigma_{bb} + \sigma_{tb}}$$

$$\approx 1.058 \kappa_t^2 + 0.007 \kappa_b^2 - 0.065 \kappa_t \kappa_b \quad {}^*$$





$$\kappa_\gamma^2 = \frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{SM}} = \frac{\kappa_t^2 \Gamma_{\gamma\gamma}^{tt} + \kappa_W^2 \Gamma_{\gamma\gamma}^{WW} + \kappa_t \kappa_W \Gamma_{\gamma\gamma}^{tW}}{\Gamma_{\gamma\gamma}^{tt} + \Gamma_{\gamma\gamma}^{WW} + \Gamma_{\gamma\gamma}^{tW}}$$

$$\approx 0.07 \kappa_t^2 + 1.59 \kappa_W^2 - 0.66 \kappa_t \kappa_W \quad {}^*$$

* $m_H = 125.5$ GeV

Fermion and Boson Couplings

$\boxed{\kappa_F\,,\ \kappa_V}$

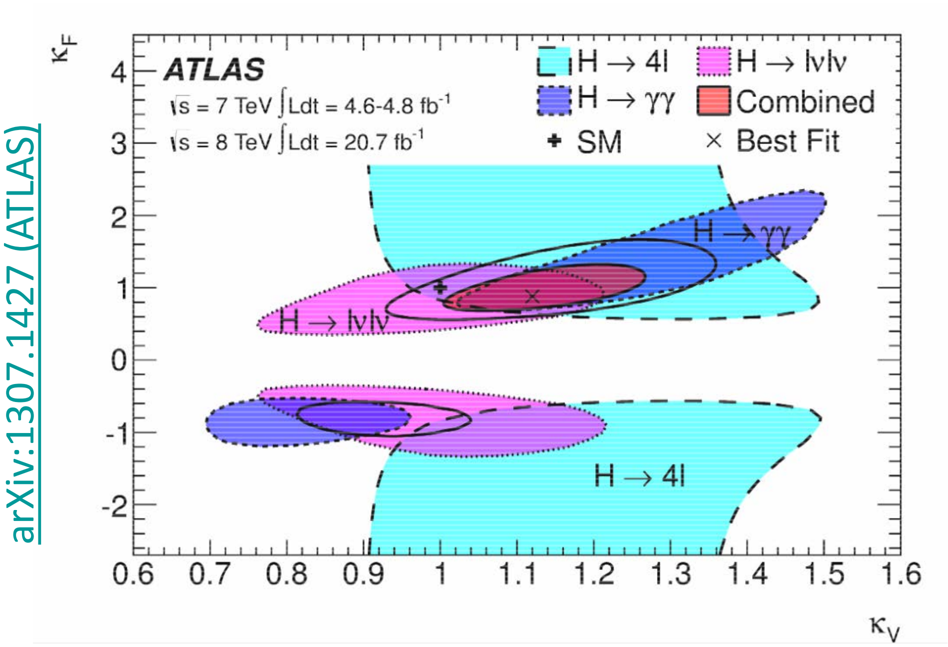
κ_F : for all fermions $\left(\kappa_F \equiv \kappa_t = \kappa_b = \kappa_\tau = \ldots\right)$

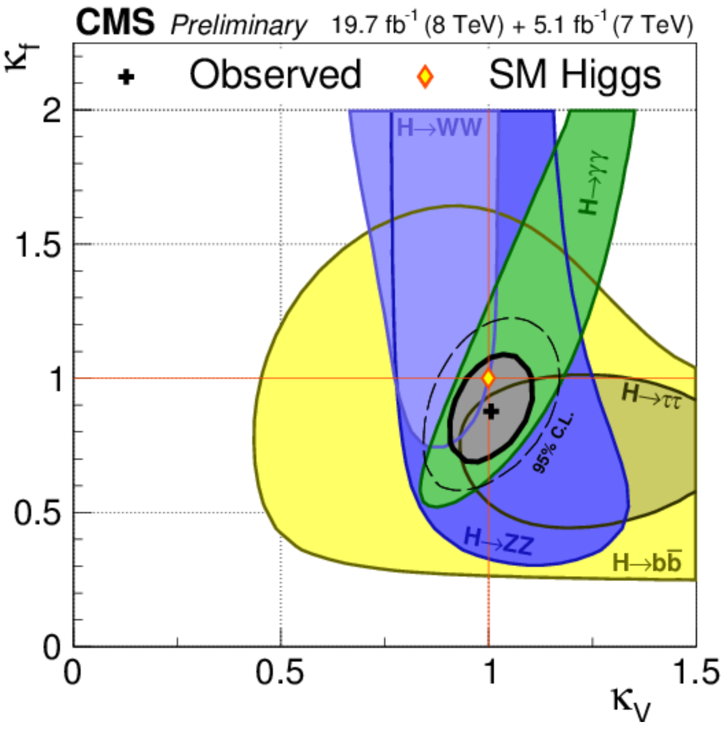
κ_V : for all vector bosons $\left(\kappa_V \equiv \kappa_W = \kappa_Z\right)$

κ_g and κ_γ are decomposed to their tree-level couplings

$$\Rightarrow \kappa_H^2 \approx 0.75\kappa_F^2 + 0.25\kappa_V^2$$

arXiv:1307.1427 (ATLAS)





CMS-PAS-HIG-14-009

BSM Decays

Higgs could have decays that are not accounted for in SM. The decays do not have to be invisible. They could be decays not detectable at LHC.
⇒ modified total Higgs decay width and therefore BRs of other decays, effectively leave the total decay width free.

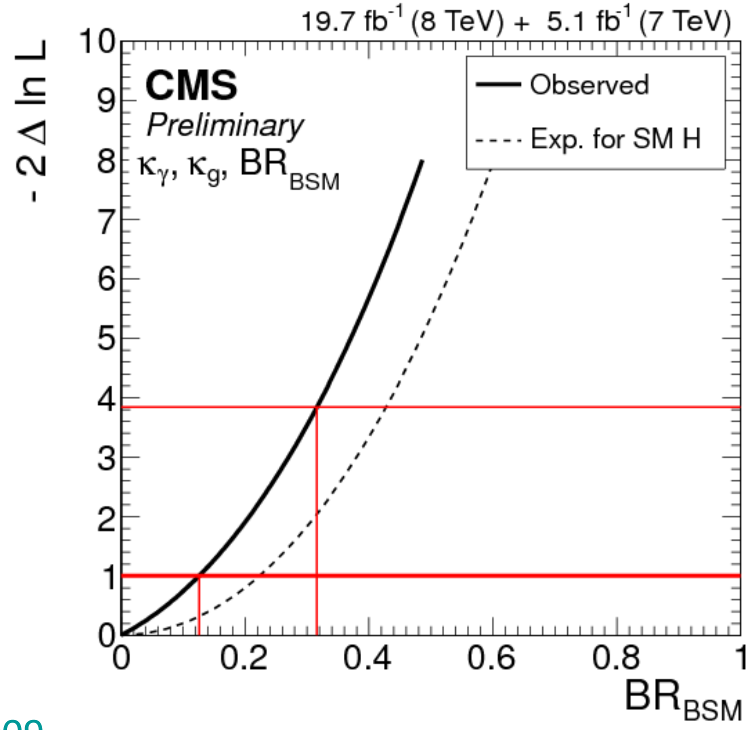
$$\Gamma_H = \Gamma_H^{SM} \times \frac{\kappa_H^2}{1 - BR_{BSM}}, \quad BR(H \to xx) = BR_{SM}(H \to xx) \times (1 - BR_{BSM}) \cdot \frac{\kappa_x^2}{\kappa_H^2}$$

A model assuming SM tree-level coupling, but allowing for potential new physics in vertex loops and additional decays

$$\boxed{\kappa_\gamma,\ \kappa_g,\ BR_{BSM}}$$

95% CL ranges:

$$\kappa_g = [0.69 - 1.10]$$
$$\kappa_\gamma = [0.89 - 1.42]$$
$$BR_{BSM} = [0 - 0.32]$$



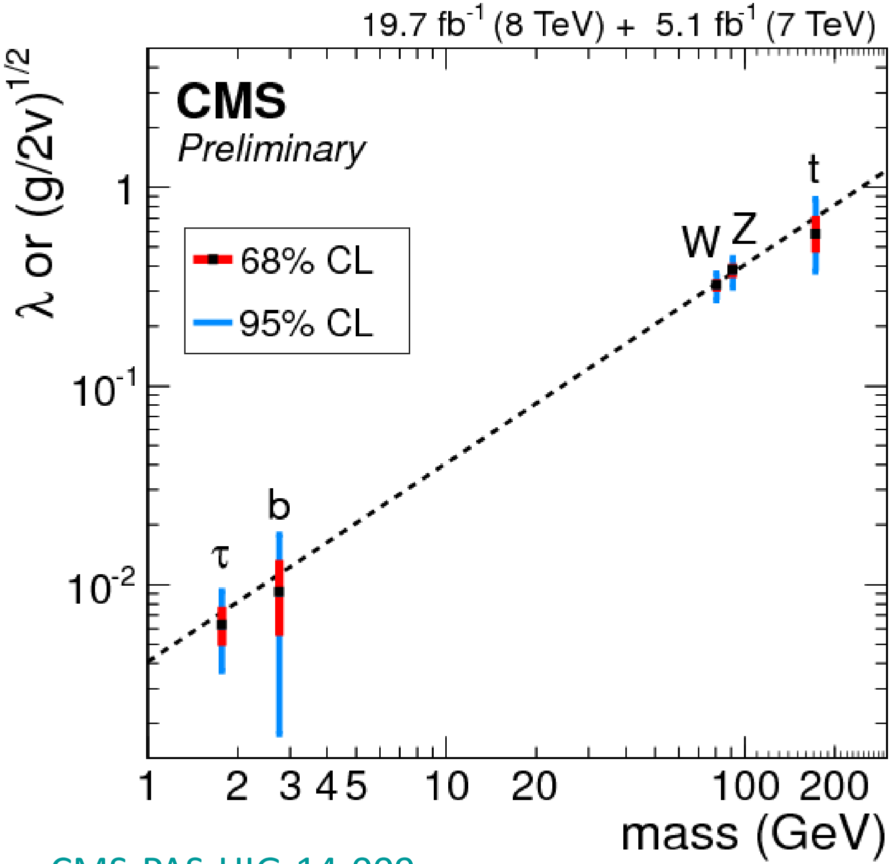
CMS-PAS-HIG-14-009

Summary of Couplings

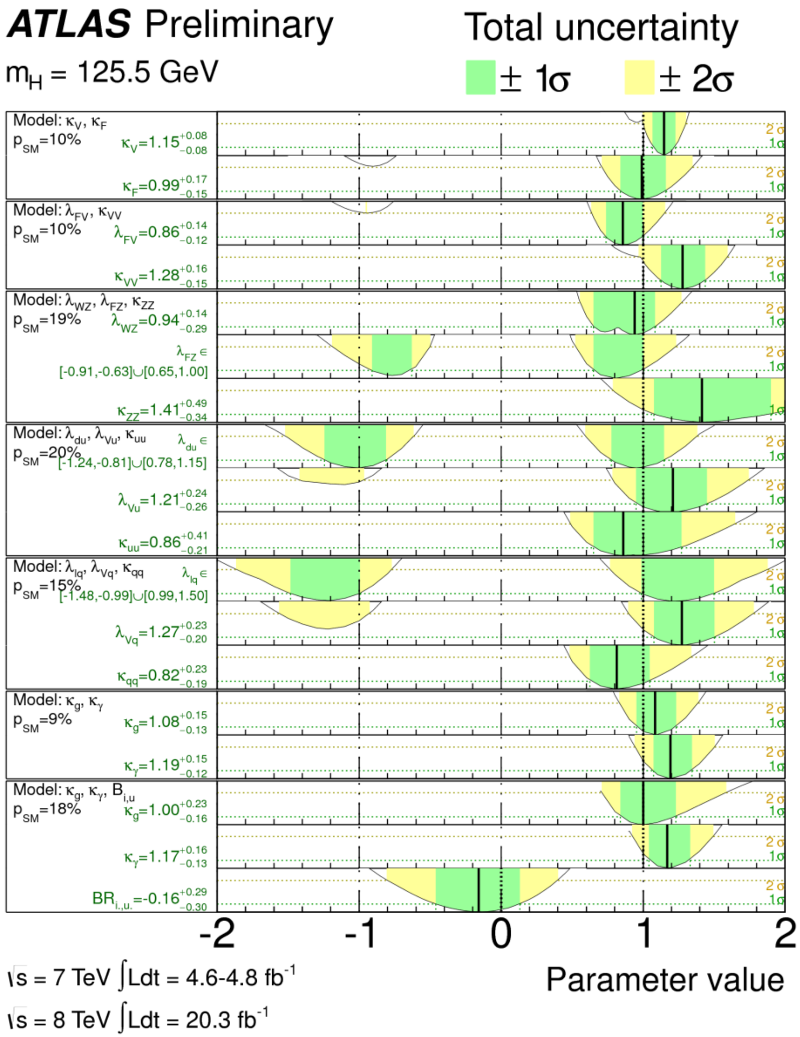
SM: $\lambda \propto m$ (fermions)

$g \propto m^2$ (bosons)

ATLAS-CONF-2013-034



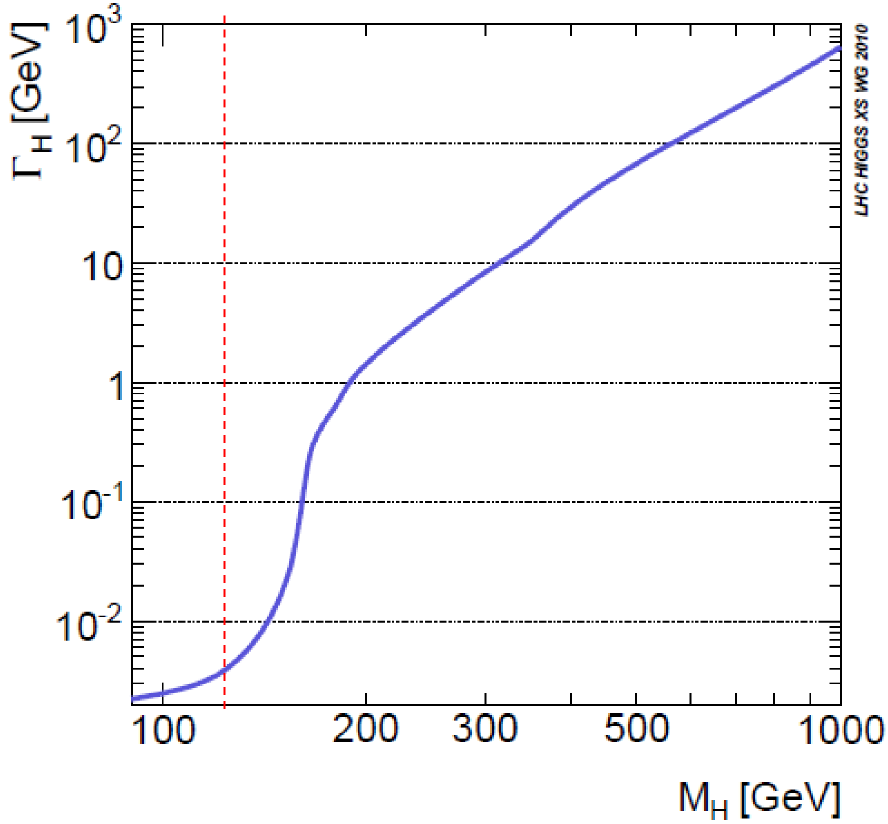
CMS-PAS-HIG-14-009



All couplings are very Standard Model like

Higgs Boson Width

SM @ 125 GeV: $\Gamma_h \approx 4.07$ MeV $\ll$ smaller than the experimental resolutions of direct measurements



For measurements: ☹

hard to measure experimentally though indirect measurements can significantly improve the precision

For searches: ☺

Even a small contribution to the width from potential new physics can lead to a sizable decay BR

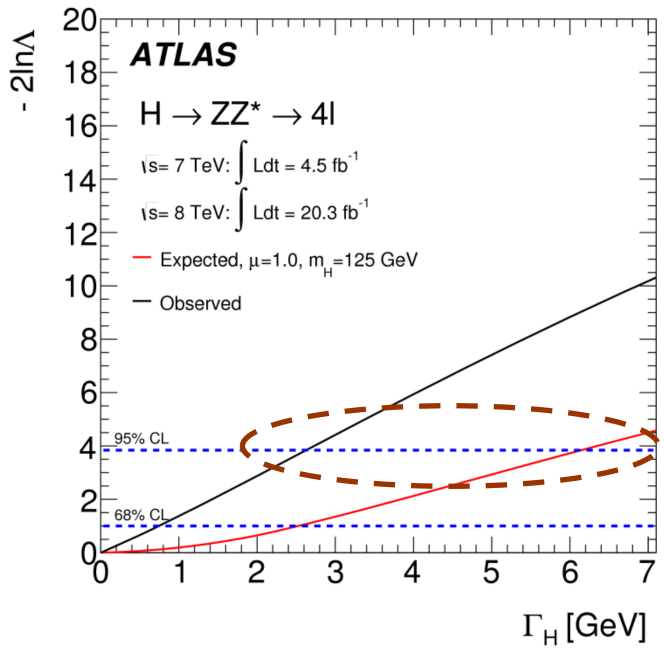
Direct Width Measurement

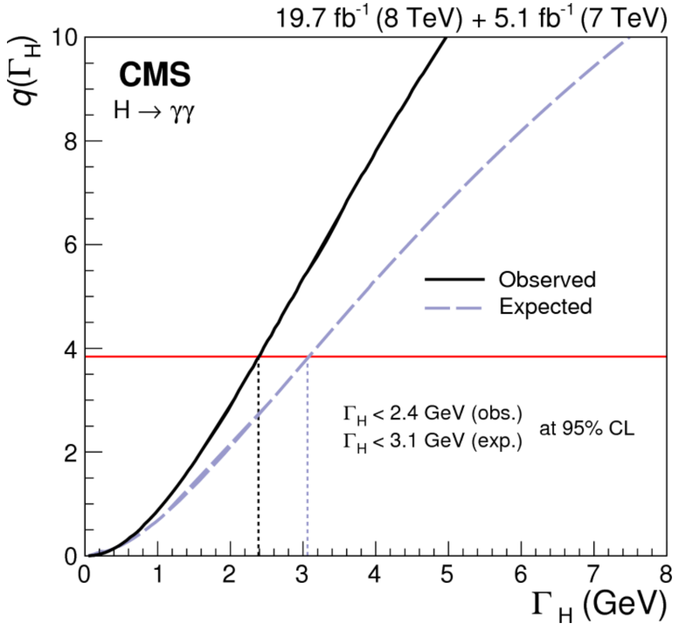
The Higgs width can be in principle extracted from the $m_{\gamma\gamma}$ or $m_{4\ell}$ distributions with the signal lineshape

$$\text{Breit-Wigner}\left(m,\Gamma_H\right)\otimes\text{Resultion}\left(\sigma\right)$$

Limited by detector mass resolution, statistics and backgrounds

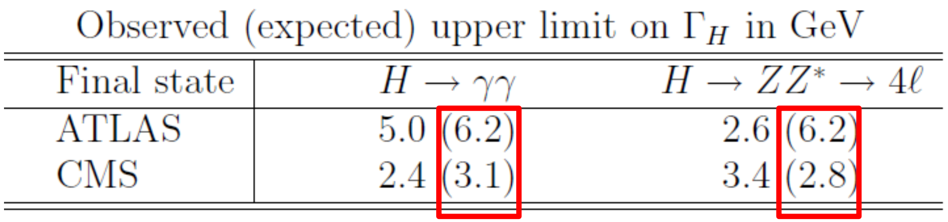
arXiv:1406.3827 (ATLAS)





arXiv:14070558 (CMS)

The observed high μ value plays an important role in the difference between the observation and the expectation.



Observed (expected) upper limit on Γ_H in GeV

Final state	$H \rightarrow \gamma\gamma$	$H \rightarrow ZZ^* \rightarrow 4\ell$
ATLAS	5.0 (6.2)	2.6 (6.2)
CMS	2.4 (3.1)	3.4 (2.8)

x2 difference in sensitivity between ATLAS and CMS?

Indirect Width Measurement

Process $i \rightarrow H \rightarrow f$: $$\frac{d\sigma}{dm^2} \sim \frac{g_i^2 g_f^2}{\left(m^2 - m_H^2\right)^2 + m_H^2 \Gamma_H^2}$$

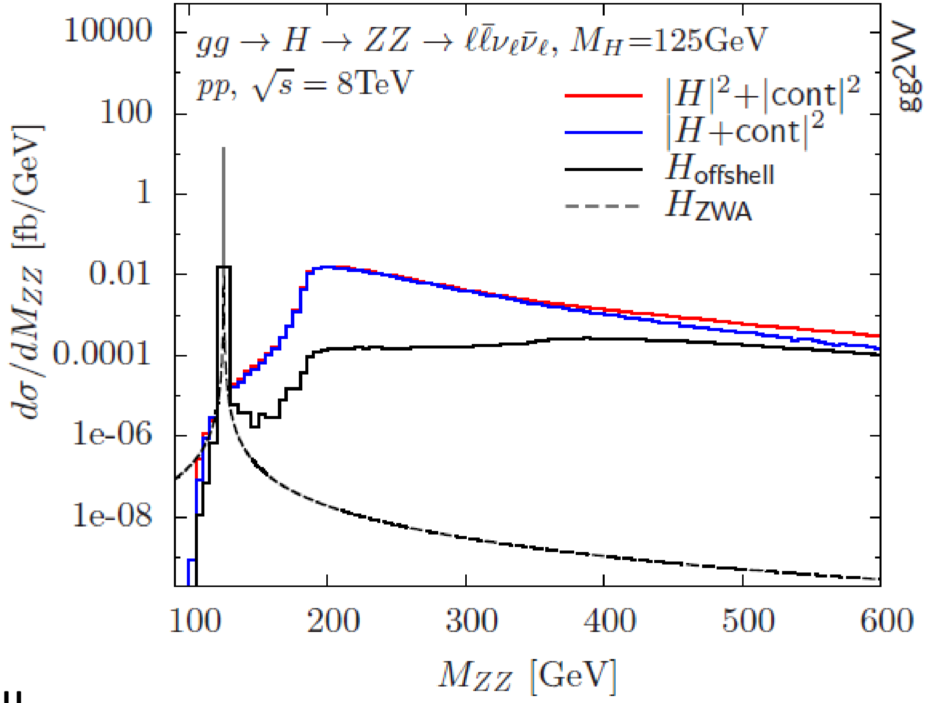
Kauer & Passarino, arXiv:1206.4803
Caola & Melnikov, arXiv:1307.4935
Campbell & Ellis, arXiv:1311.3589

On-peak: $$\frac{d\sigma}{dm^2} \sim \frac{\boxed{g_i^2 g_f^2}}{m_H^2 \boxed{\Gamma_H^2}}$$

Off-peak: $$\frac{d\sigma}{dm^2} \sim \frac{\boxed{g_i^2 g_f^2}}{\left(m^2 - m_H^2\right)^2}$$

on-shell measures $\left(g_i g_f / \Gamma_H\right)^2$,

off-shell measures $\left(g_i g_f\right)^2$



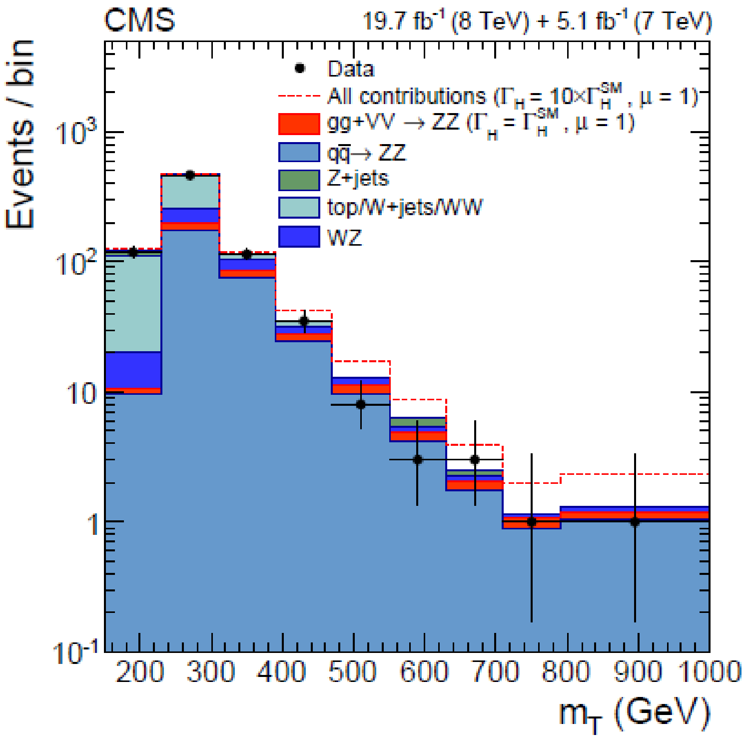
Extract Γ_H by comparing the on-shell and off-shell signal strength measurements (thanks to the large off-shell contribution)

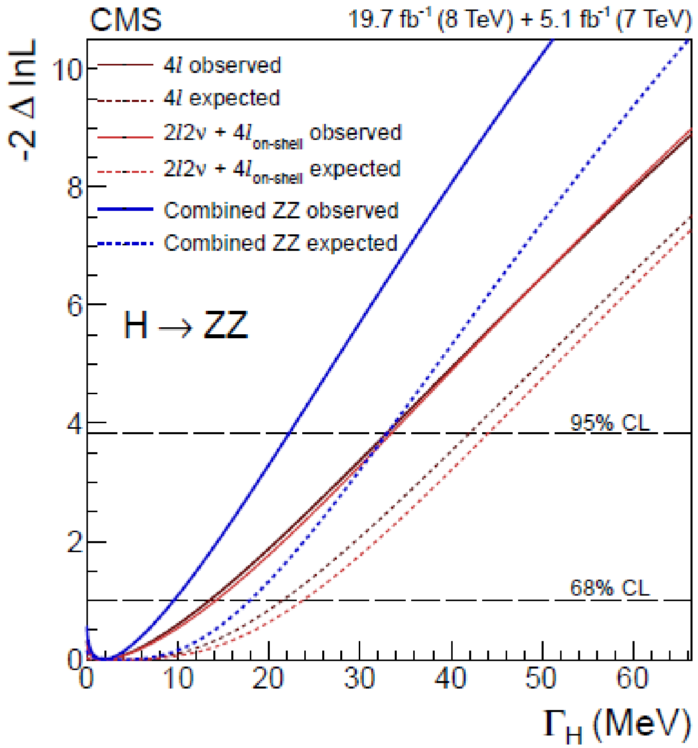
	Tot[pb]	$M_{ZZ} > 2M_Z$[pb]	R[%]
$gg \rightarrow H \rightarrow$ all	19.146	0.1525	0.8
$gg \rightarrow H \rightarrow ZZ$	0.5462	0.0416	7.6

Indirect Width Measurement

The key is to isolate off-shell Higgs signal from the continuum background, such as $q\bar{q}/gg \rightarrow WW,ZZ$ for the case of $H \rightarrow WW,ZZ$

arXiv:1405.3455 (CMS)





CMS has studied $H \rightarrow ZZ^* \rightarrow 4\ell,\ell\ell\nu\nu$ with the combined observed (expected) limit: $\Gamma_H < 22(33)$ MeV or $5.4(8.0)\times\Gamma_H^{SM}$ @ 95% CL

Or as a measurement $\Gamma_H = 1.8^{+7.7}_{-1.8}$ MeV

Indirect Width Measurements

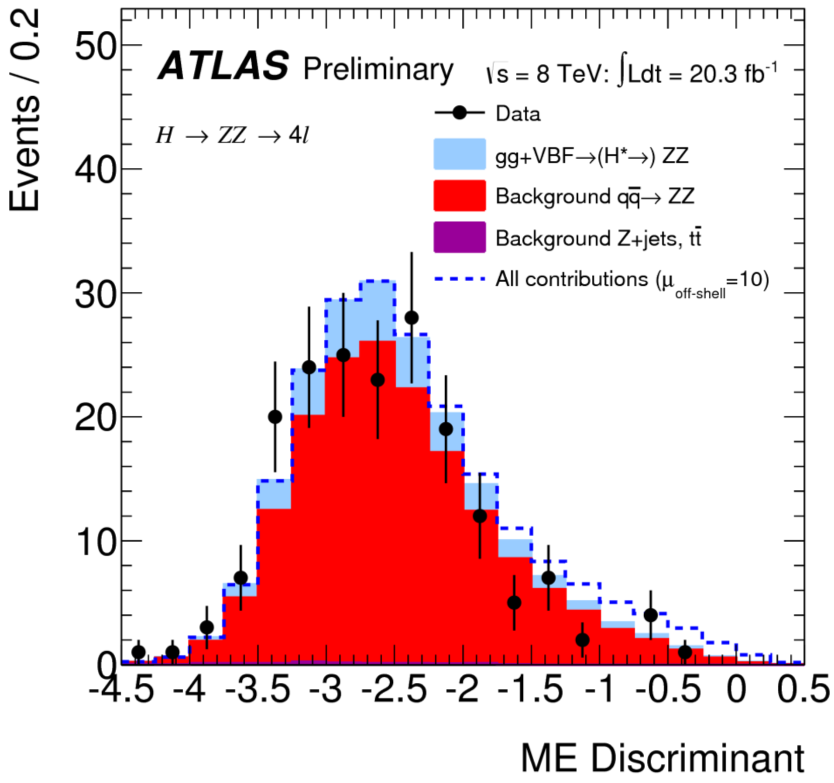
One key issue is the K-factor of the $gg \to ZZ$ productions:

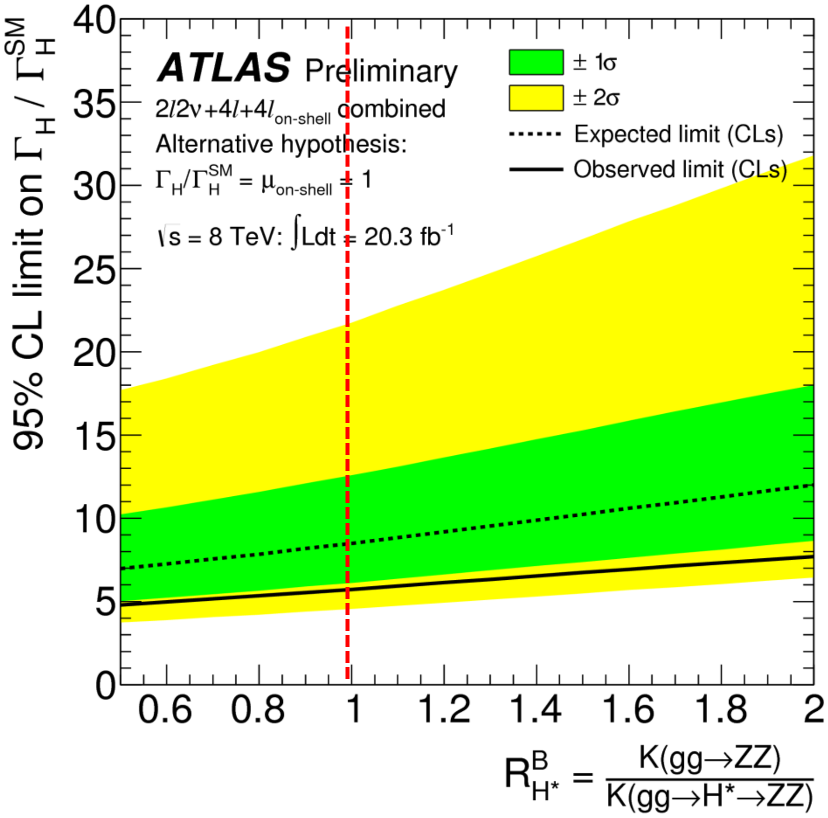
$$R^B_{H^*} = \frac{K(gg \to ZZ)}{K(gg \to H^* \to ZZ)}$$

CMS assumed $R^B_{H^*} = 1$ while ATLAS varied it between 0.5 - 2.0

ATLAS 95% CL limit on Γ_H/Γ_H^{SM}

$R^B_{H^*}$	4ℓ	$2\ell 2\nu$	Combined
0.5	6.1 (8.7)	10.4 (8.6)	4.8 (7.0)
1.0	7.2 (10.2)	11.3 (9.9)	5.7 (8.5)
2.0	9.9 (14.0)	12.8 (12.9)	7.7 (12.0)

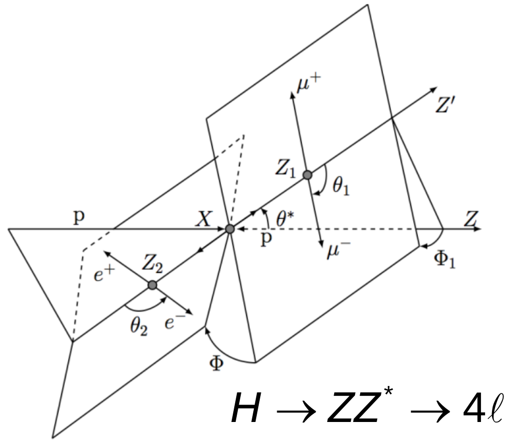




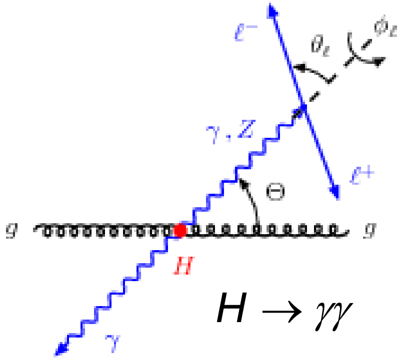
ATLAS-CONF-2014-042

H(125): Spin and CP

Higgs decay kinematics depends on its properties of spin and parity. $H\rightarrow\gamma\gamma$, $H\rightarrow ZZ^{*}\rightarrow 4\ell$ and $H\rightarrow WW^{*}\rightarrow\ell\nu\ell\nu$ final states have been analyzed to determine these properties.

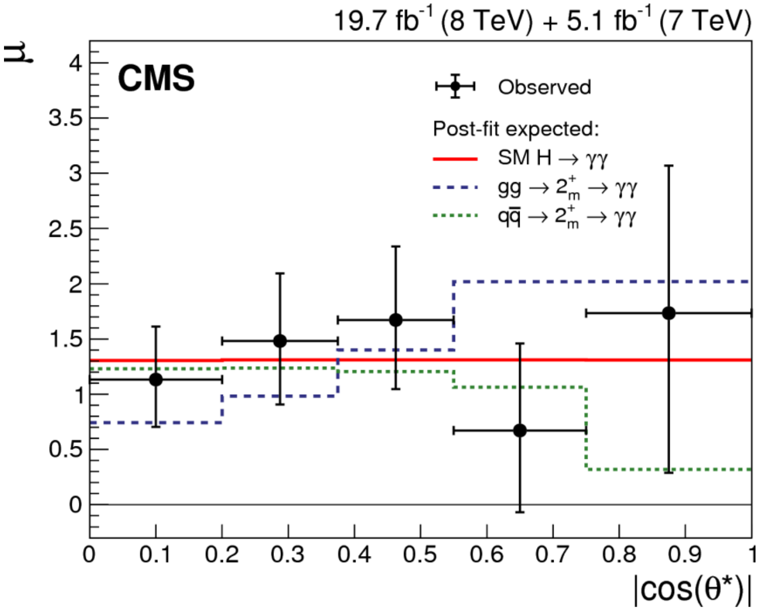


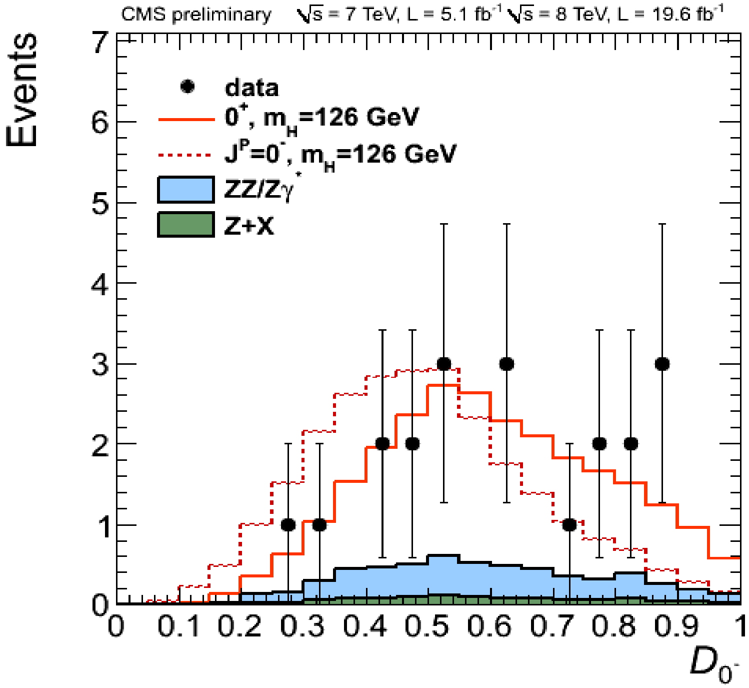
$H\rightarrow ZZ^{*}\rightarrow 4\ell$



$H\rightarrow\gamma\gamma$

arXiv:14070558 (CMS)



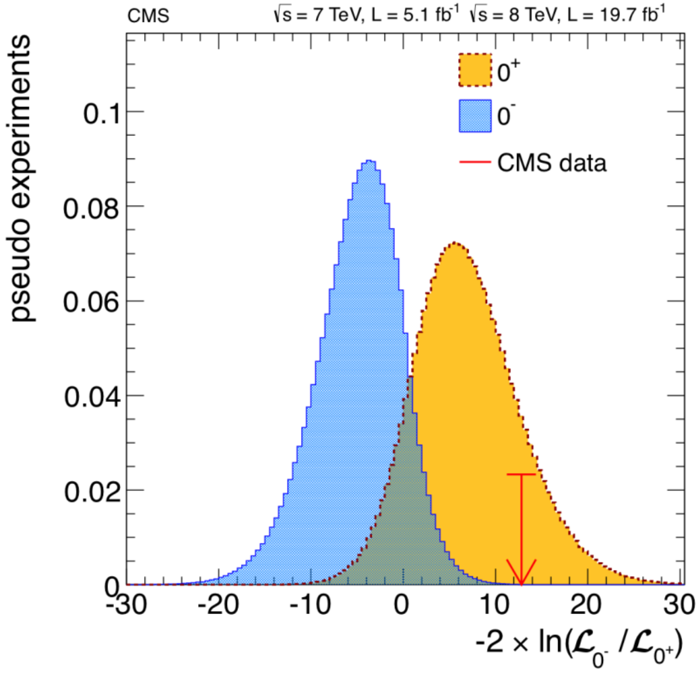


CMS-PAS-HIG-13-002

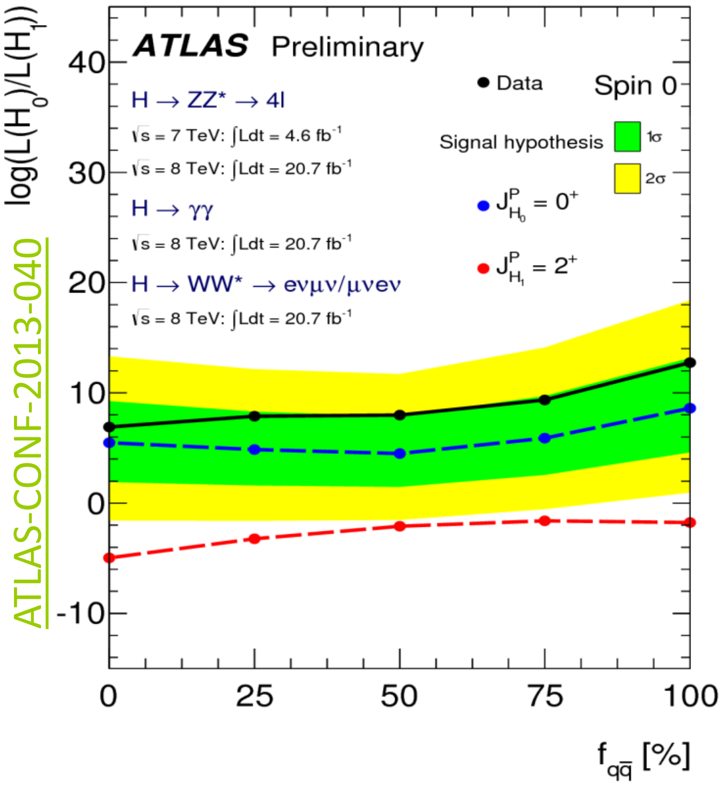
H(125): Spin and CP

Using distributions of kinematic variables to test alternative hypothesis with log likelihood ratio as the test statistic.

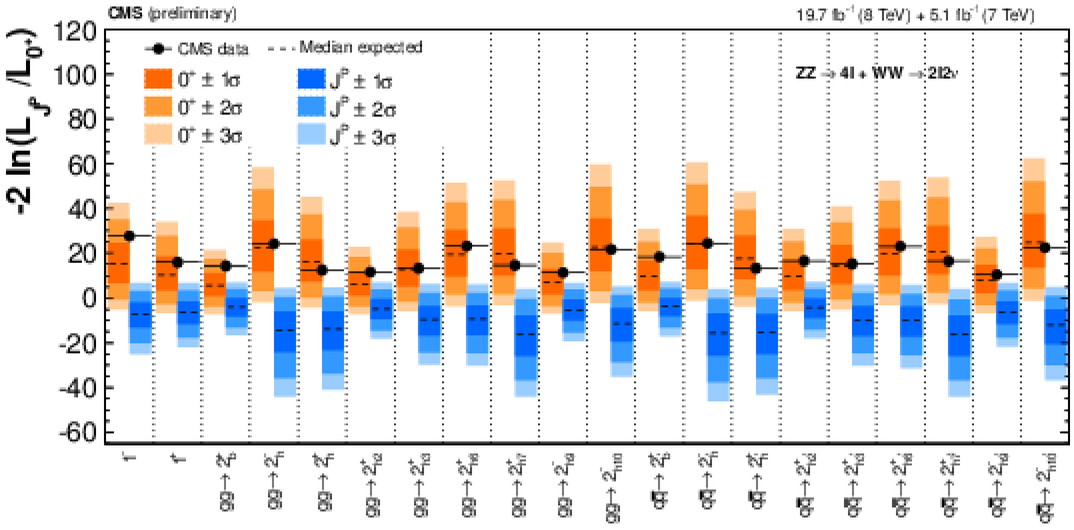
SM prediction of $J^p=0^+$ is strongly favored, most alternatives studied are excluded @ 95% CL or higher



arXiv:1312.5353 (CMS)



ATLAS-CONF-2013-040



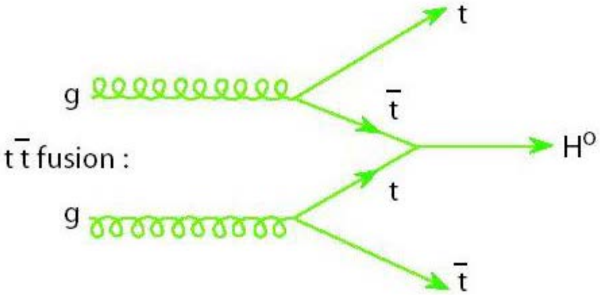
CMS-PAS-HIG-14-014

ttH Production

$\sigma(t\bar{t}H) \sim$ 130 fb @ 125 GeV

Searches for additional Higgs boson in $t\bar{t}$ events

⇒ allow direct study of top-Higgs Yukawa couplings,

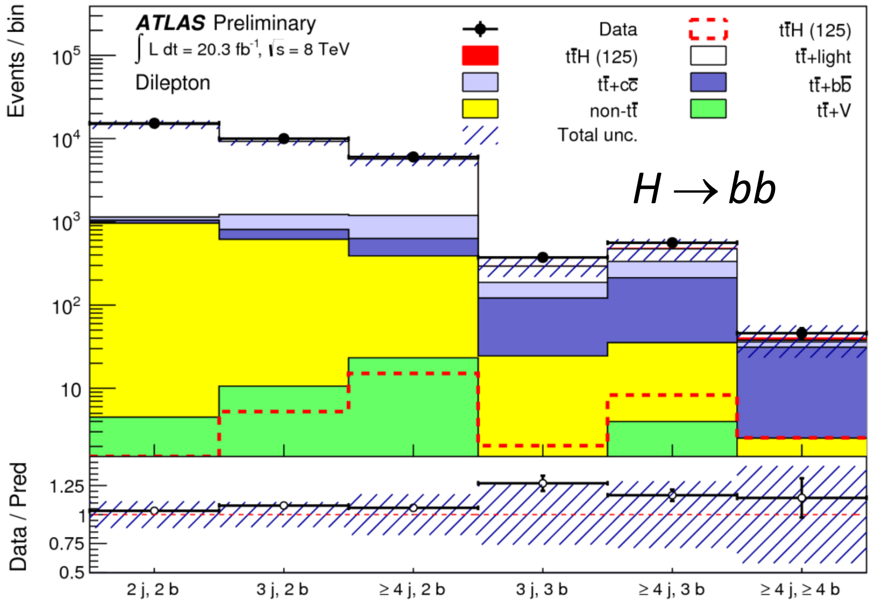


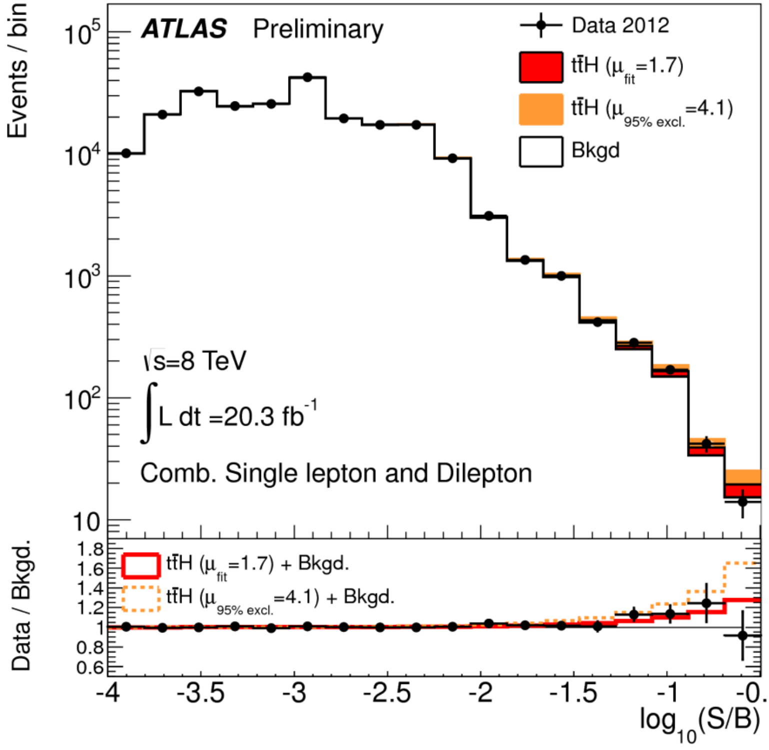
Broad categories:

$H \to \gamma\gamma$,
$H \to$ hadrons ($b\bar{b}$, WW, ...),
$H \to$ leptons (WW, $\tau\tau$, ZZ, ...)

Multijets, b-tagging, missing ET or additional jets to select $t\bar{t}$ events. Use MVA techniques to reduce the hugh $t\bar{t}$ backgrounds.

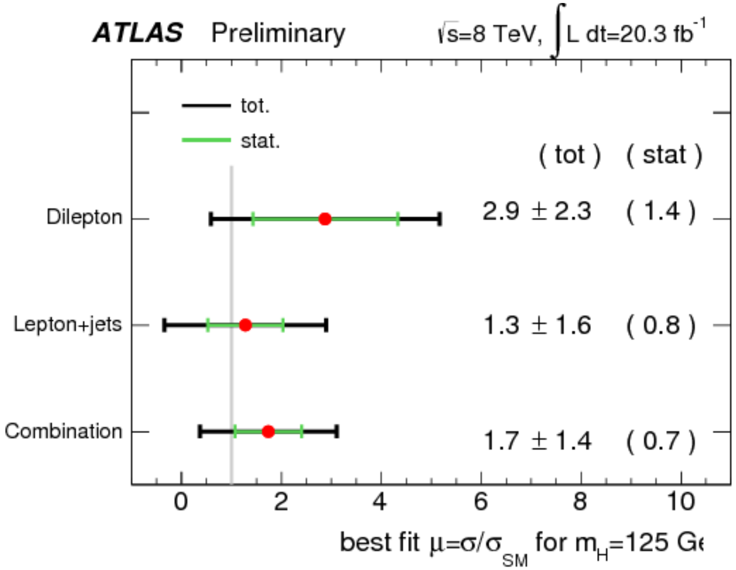
ATLAS-CONF-2014-011





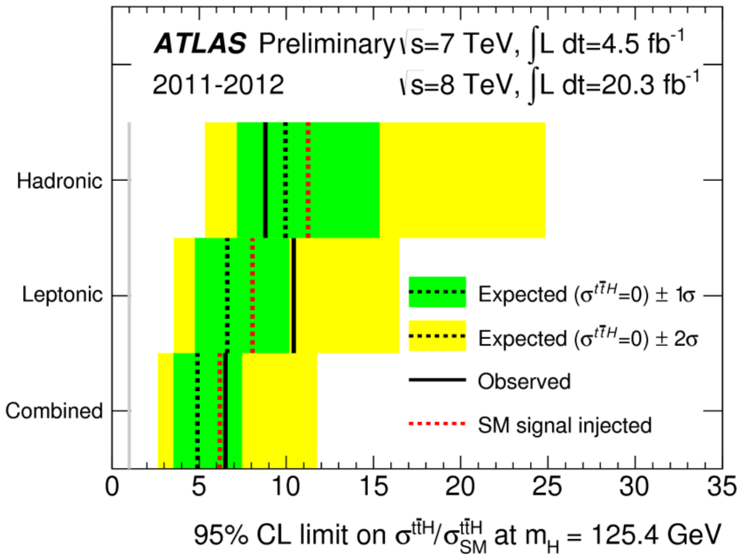
ttH Production

ATLAS *ttH* search with H → bb



ATLAS-CONF-2014-011

ATLAS *ttH* search with H → $\gamma\gamma$



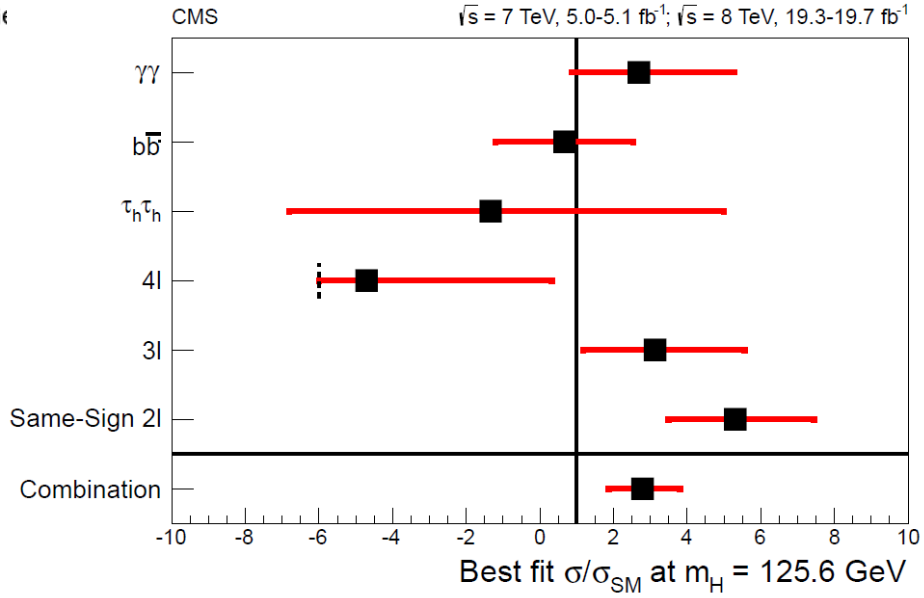
ATLAS-CONF-2013-080

CMS combination of $\gamma\gamma$, bb, $\tau\tau$ and multi-lepton final states:

$$\mu=2.8^{+1.0}_{-0.9}$$

$$p\left(\mu=0\right)=0.04\% \Rightarrow 3.4\sigma$$

Direct hint of the Higgs coupling to the top quark !



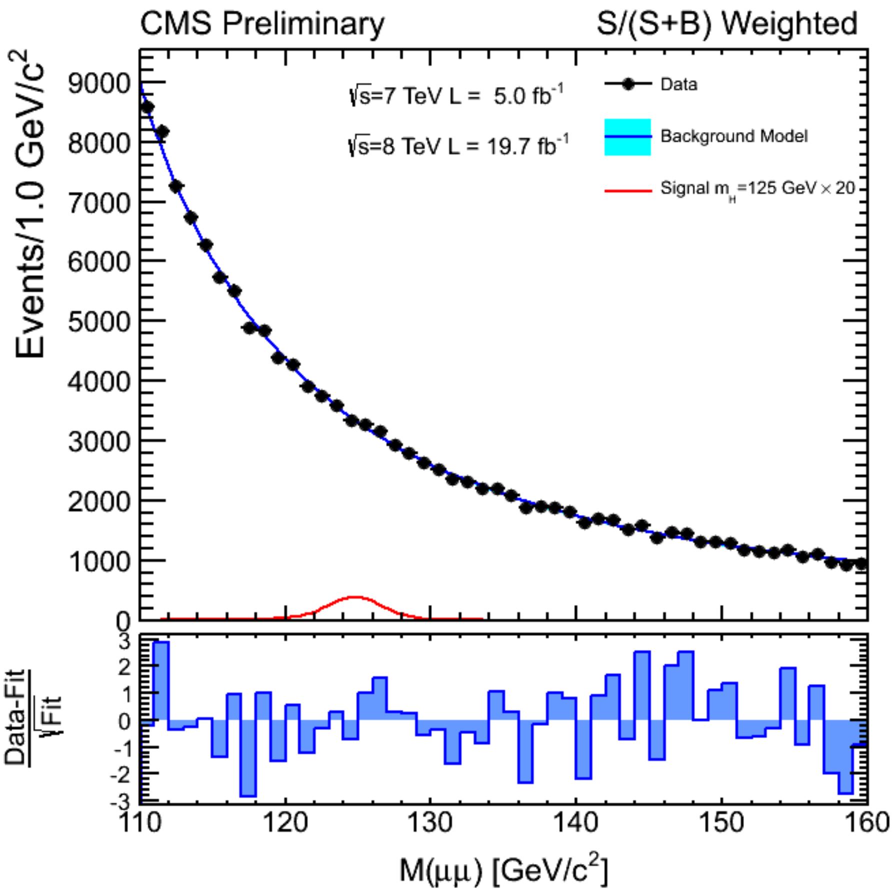
arXiv:1408.1682 (CMS)

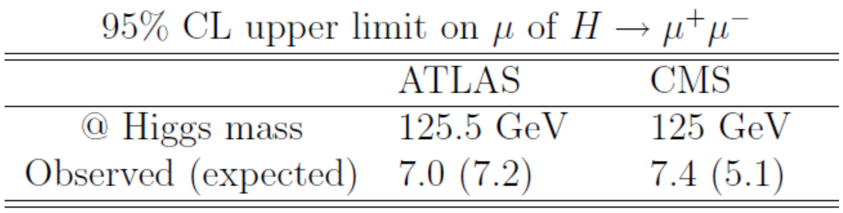
Rare Decay: $H\to\mu\mu$

CMS-PAS-HIG-13-007
arXiv:1406.7663 (ATLAS)

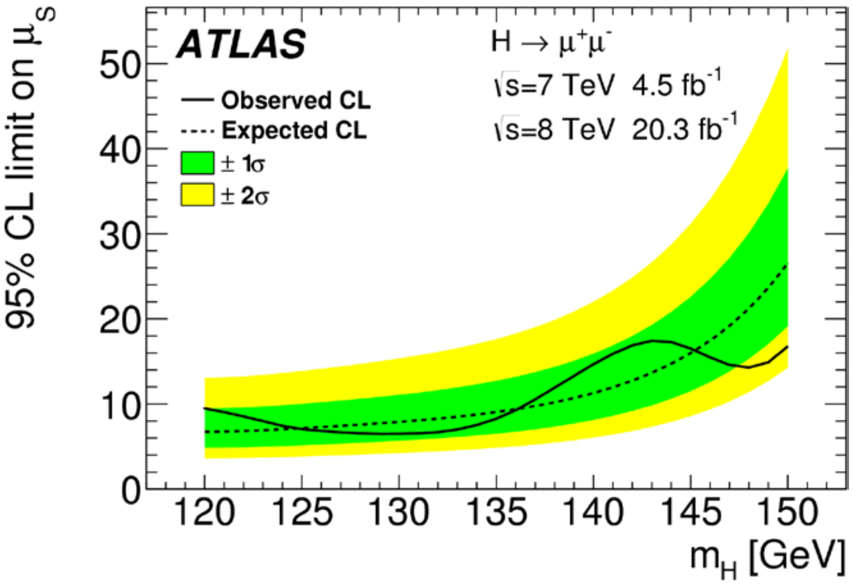
Small $BR(H\to\mu\mu)=2.2\times10^{-4}$ @ 125 GeV, good mass resolution ~ 2 GeV, 10 times smaller than $BR(H\to\gamma\gamma)$ with a larger background

Clean signature, but suffer from large Drell-Yan background



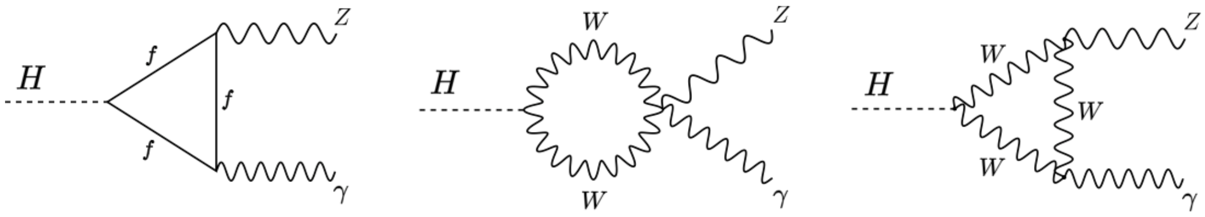


95% CL upper limit on μ of $H\to\mu^+\mu^-$	ATLAS	CMS
@ Higgs mass	125.5 GeV	125 GeV
Observed (expected)	7.0 (7.2)	7.4 (5.1)



Rare Decay: $H\rightarrow Z\gamma$

$$BR\left(H\rightarrow Z\gamma\right)\approx 0.15\%\ @\ 125\ \text{GeV}$$



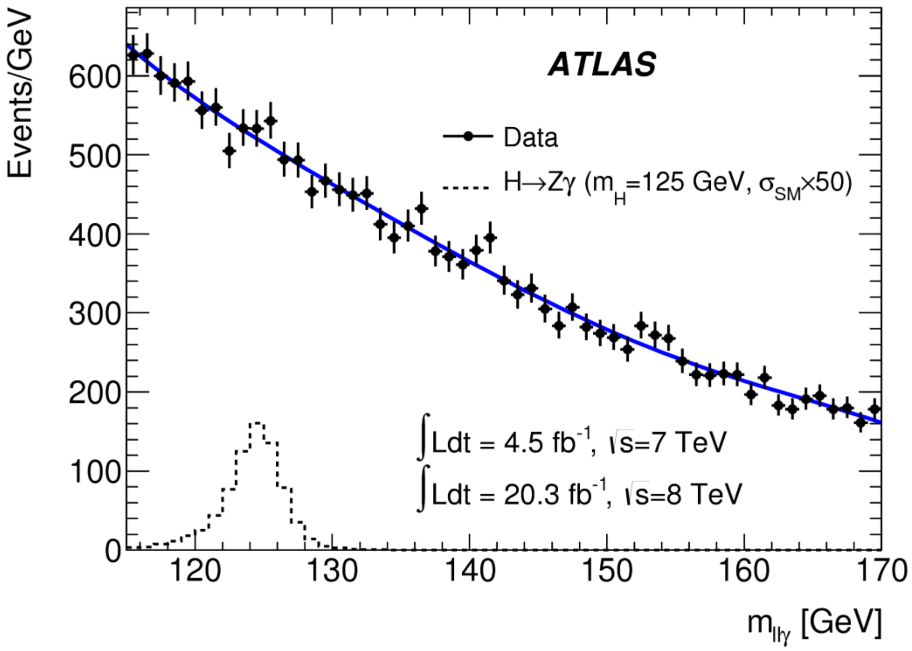
$$\sigma_H \times Br\left(H\rightarrow Z\gamma\rightarrow \ell\ell\gamma\right) \sim 2.3\ \text{fb}$$

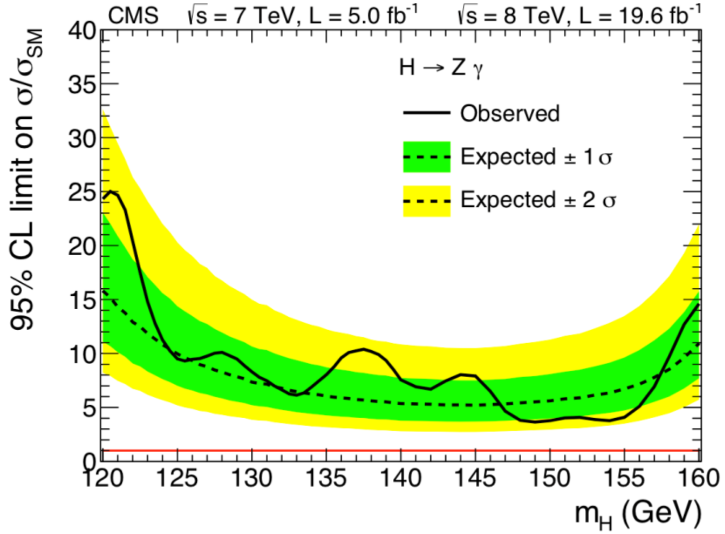
~ 55 events in Run 1 dataset

Search for a narrow resonance over continuum (mostly $Z\gamma$) backgrounds

Current sensitivity is about 10× the standard model expectation

arXiv: 1402.3051 (ATLAS)





arXiv: 1307.5515 (CMS)

Other Rare Decays

$H \to J/\psi\,\gamma$ decay has been proposed as a way to access *Hcc* coupling, but the rate is very low: $N(H \to J/\psi\gamma \to \mu\mu\gamma) \approx N(H \to Z\gamma \to \mu\mu\gamma)/340$

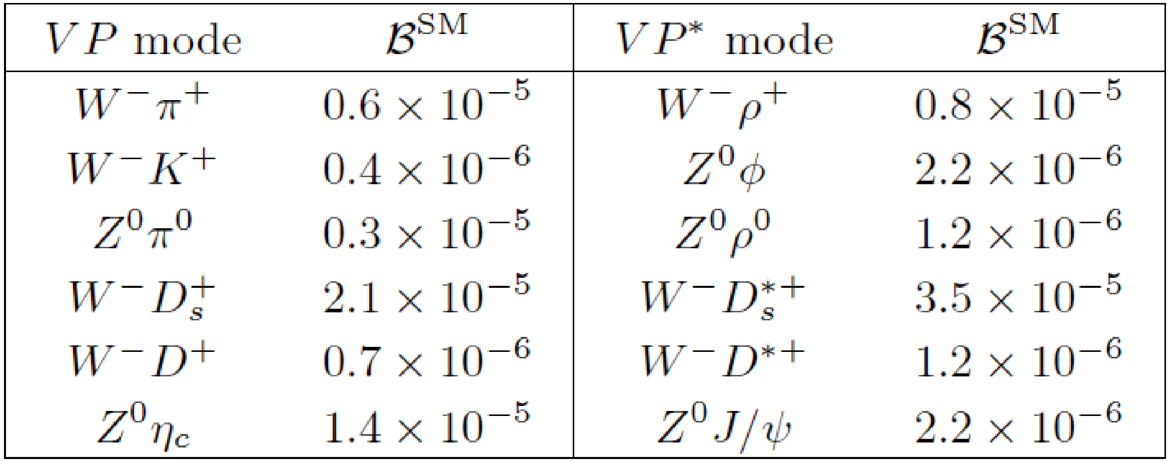
$$\mathrm{BR}_{\mathrm{SM}}(H \to J/\psi\,\gamma) = (2.46^{+0.26}_{-0.25}) \times 10^{-6},$$

$$\mathrm{BR}_{\mathrm{SM}}(H \to \Upsilon(1S)\,\gamma) = (1.41^{+2.03}_{-1.14}) \times 10^{-8}.$$

Bodwin, Petriello, Stoynev and Velasco, arXiv:1306.5770

Relative easy to search, but rate is too late even for high luminosity LHC or even for any proposed lepton collider

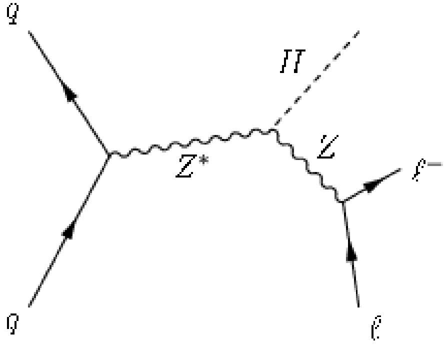
There are other potential rare decays, but backgrounds are likely too large to be feasible



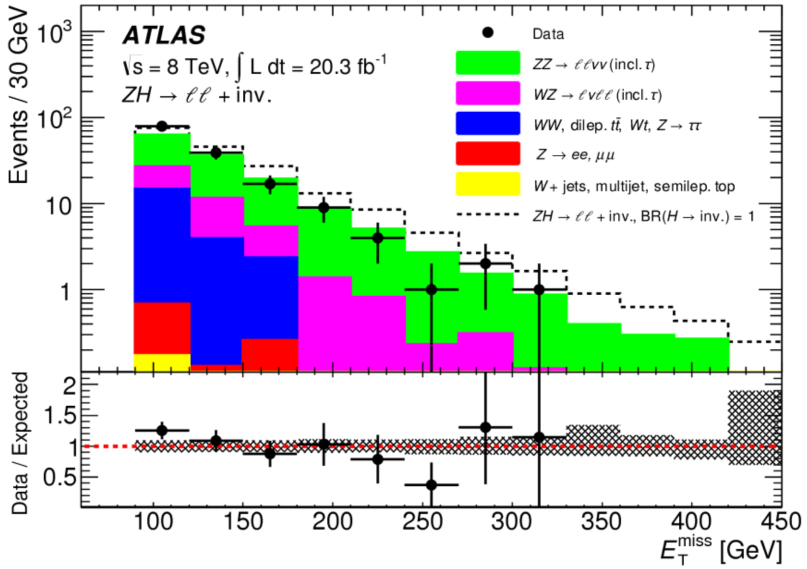
VP mode	$\mathcal{B}^{\mathrm{SM}}$	VP^* mode	$\mathcal{B}^{\mathrm{SM}}$
$W^-\pi^+$	0.6×10^{-5}	$W^-\rho^+$	0.8×10^{-5}
W^-K^+	0.4×10^{-6}	$Z^0\phi$	2.2×10^{-6}
$Z^0\pi^0$	0.3×10^{-5}	$Z^0\rho^0$	1.2×10^{-6}
$W^-D_s^+$	2.1×10^{-5}	$W^-D_s^{*+}$	3.5×10^{-5}
W^-D^+	0.7×10^{-6}	W^-D^{*+}	1.2×10^{-6}
$Z^0\eta_c$	1.4×10^{-5}	Z^0J/ψ	2.2×10^{-6}

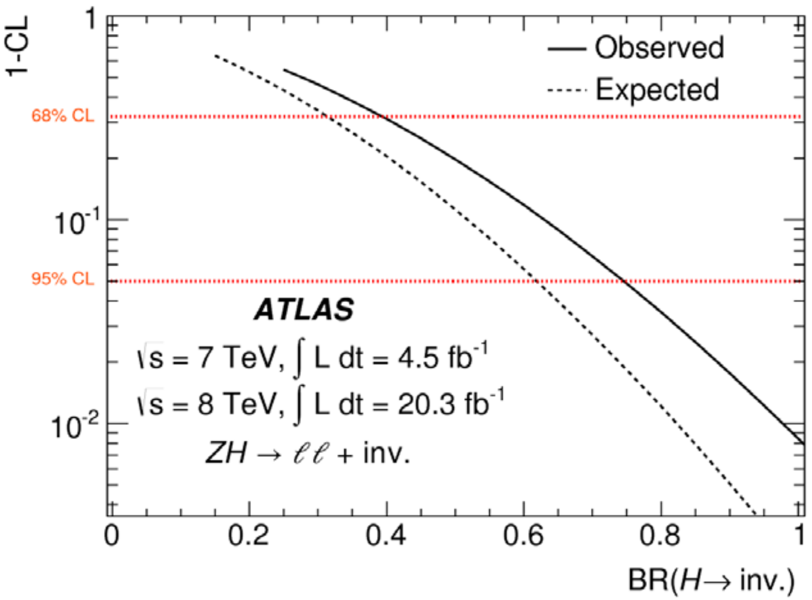
Isidori, Manohar and Trott, arXiv:1305.0663

ZH with Z→ℓℓ and H→invisible



Assuming the SM ZH production, searching for H→invisible decays.





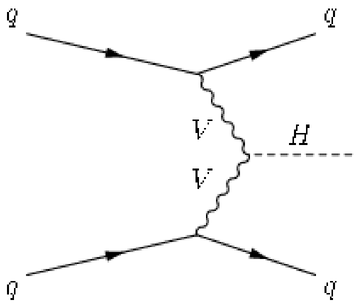
The observed (expected) limits on $\mathrm{BR}(H \to inv)$ at $m_H = 125.5$ GeV is:

75% (62%) at 95% CL

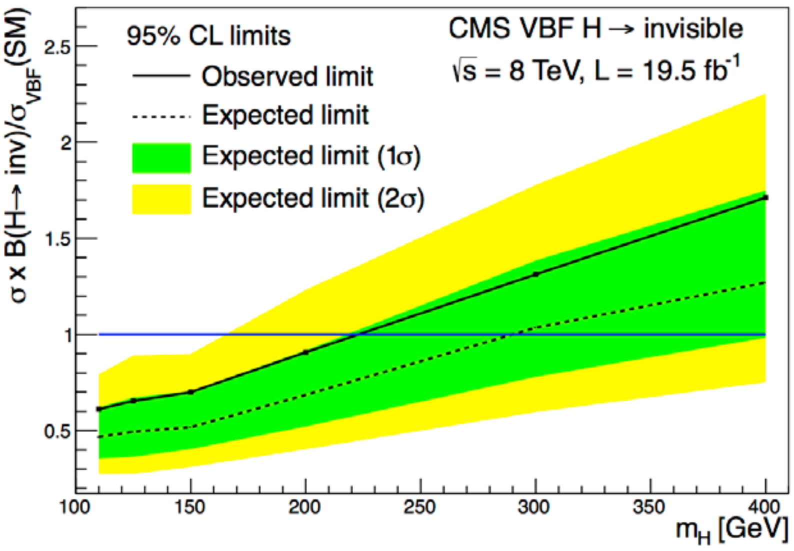
CMS analysis: 83% (86%)

ATLAS: arXiv/1402.3244

VBF with H→invisible



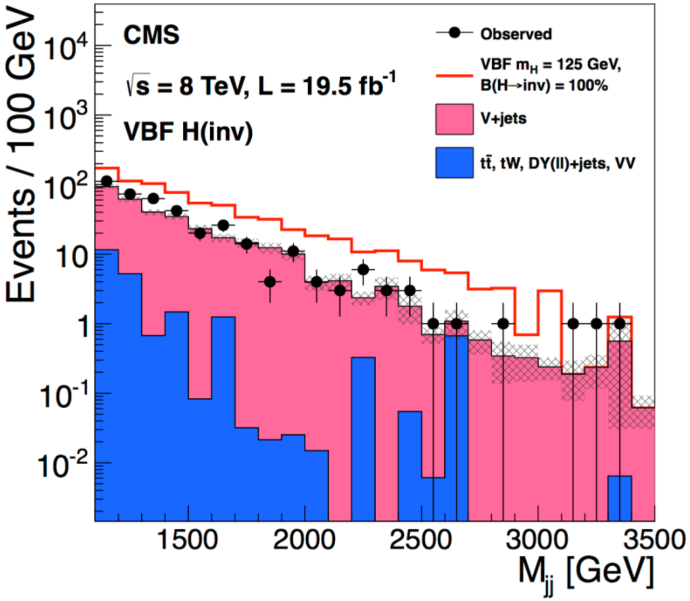
Two tagging jets with large missing ET

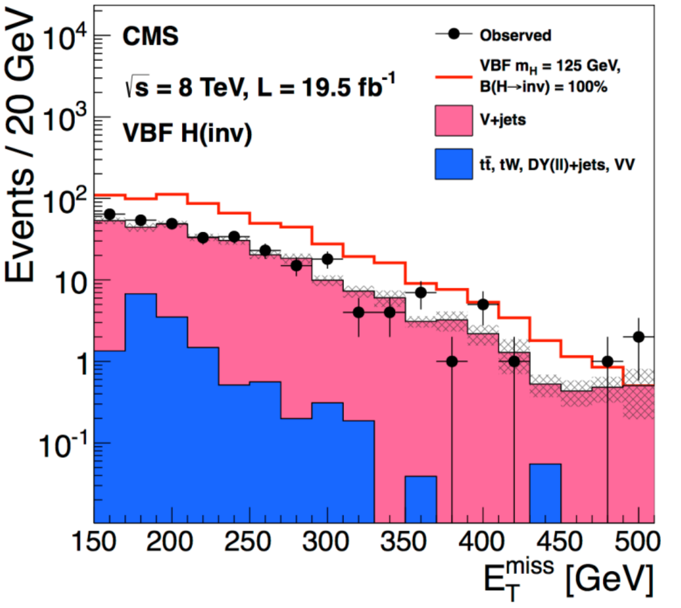


The observed (expected) 95% CL limit:

$$BR(H \to inv) < 65\% \ (49\%)$$

at $m_H = 125$ GeV.





CMS: arXiv/1404.1344

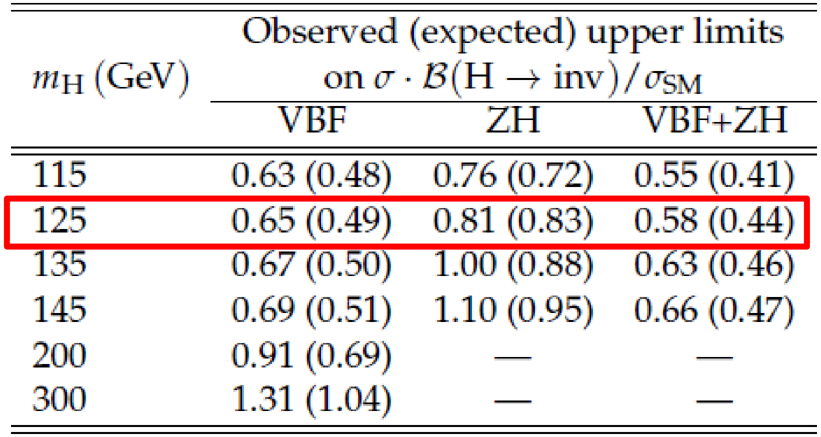
H→inv Decay Combination

CMS: arXiv/1404.1344

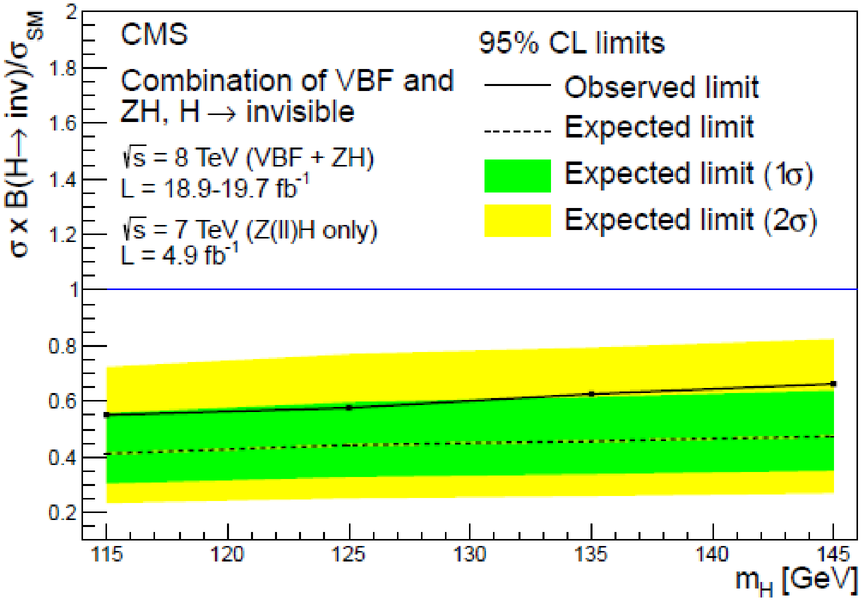
CMS has combined searches of

ZH $\to \ell\ell/bb$ inv

VBF H $\to$ inv



m_{H} (GeV)	Observed (expected) upper limits on $\sigma \cdot \mathcal{B}(\mathrm{H} \to \mathrm{inv})/\sigma_{\mathrm{SM}}$		
	VBF	ZH	VBF+ZH
115	0.63 (0.48)	0.76 (0.72)	0.55 (0.41)
125	0.65 (0.49)	0.81 (0.83)	0.58 (0.44)
135	0.67 (0.50)	1.00 (0.88)	0.63 (0.46)
145	0.69 (0.51)	1.10 (0.95)	0.66 (0.47)
200	0.91 (0.69)	—	—
300	1.31 (1.04)	—	—



At $m_H = 125$ GeV, the combined limit

$$BR(H \to inv) < 58\% \ (44\%)$$

The constraints on $\mathrm{BR}(H \to inv)$ can be turned into constraints on Γ_{inv}

$$\Gamma_{inv} = \frac{BR(H \to inv)}{1 - BR(H \to inv)} \Gamma_H^{SM}$$

$\Rightarrow$ constrain dark-matter and nucleon interactions

Dark Matter Interpretation

CMS: arXiv/1404.1344

$$\Gamma^{\text{inv}}(h \to SS) = \lambda_{hSS}^2 \frac{v^2 \beta_S}{128 \pi m_h}$$

$$\Gamma^{\text{inv}}(h \to ff) = \frac{\lambda_{hff}^2}{\Lambda^2} \frac{v^2 \beta_f^3 m_h}{64 \pi}$$

$$\Gamma^{\text{inv}}(h \to VV) = \lambda_{hVV}^2 \frac{v^2 \beta_V m_h^3}{512 \pi m_V^4} \left(1 - 4 \frac{m_V^2}{m_h^2} + 12 \frac{m_V^4}{m_h^4} \right).$$

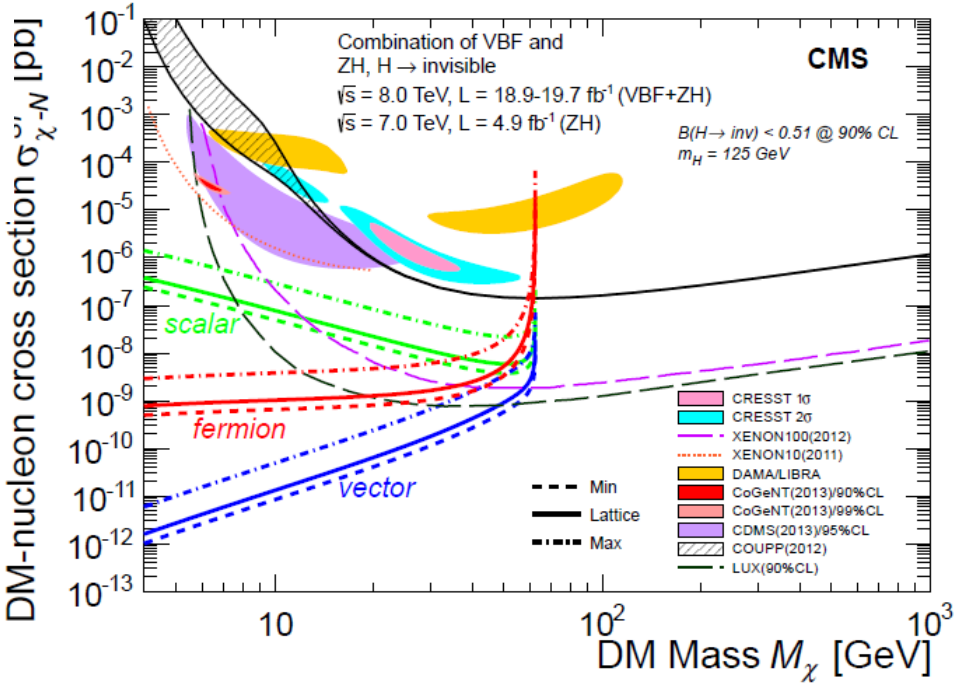
⬇

$$\sigma_{S-N} = \lambda_{hSS}^2 \frac{m_N^4 f_N^2}{16 \pi m_h^4 (m_S + m_N)^2}$$

$$\sigma_{f-N} = \frac{\lambda_{hff}^2}{\Lambda^2} \frac{m_N^4 f_N^2 m_f^2}{4 \pi m_h^4 (m_f + m_N)^2}$$

$$\sigma_{V-N} = \lambda_{hVV}^2 \frac{m_N^4 f_N^2}{16 \pi m_h^4 (m_V + m_N)^2},$$

$$BR(H \to inv) < 58\%$$



Only sensitive to dark matter particle up to half of the Higgs boson mass.

Beyond the Standard Model

The Standard Model Higgs sector consists of one $\mathrm{SU}(2)$ Higgs doublet field

$$\Phi = \begin{pmatrix} \phi^{+} \\ \phi^{0} \end{pmatrix}$$

Natural extensions to the SM Higgs sector:

- SM + a singlet S (real or complex);
- SM + an additional Higgs doublet, known as 2 Higgs doublet model (2HDM);
- 2HDM + a singlet S;
- Higgs triplet model; ......

Why extensions?

May provide a dark-matter candidate (Higgs portal model);

May offer explanation for the electroweak phase transition; ......

Phenomenological and experimental consequences:

Non-SM-like Higgs bosons $\Rightarrow$ coupling modifications;

Additional neutral and/or charged Higgs bosons;

New production processes and decay modes; ....

SM + Singlet

The simplest extension of the standard model Higgs sector is the addition of a singlet S:

$$V(\phi,S)=\left\{\mu^2\phi^\dagger\phi+\lambda\left(\phi^\dagger\phi\right)^2\right\}+\left\{m_S^2S^2+\rho S^4\right\}+\kappa\left(\phi^\dagger\phi\right)S^2$$

Interesting phenomenology depends on whether $\langle S\rangle=0$.

If $\langle S\rangle\neq 0$, in general the singlet scalar and the "SM" Higgs boson can mix to form two mass eigenstates: $(h,\ H)$ assuming $h=h(125)$:

$$\begin{pmatrix} h \\ H \end{pmatrix}=\begin{pmatrix} \cos\theta & \sin\theta \\ \sin\theta & -\cos\theta \end{pmatrix}\begin{pmatrix} H_{SM} \\ S \end{pmatrix}$$

and new decay $H\to hh$ opens up if kinematically allowed.

If $\langle S\rangle=0$, there will be no mixing and the physical scalar $\boxed{s}$ can be stable and is therefore a dark matter candidate.

Constraints on the Heavy Higgs

The mixing of H_{SM} and S leads to the modifications $\left(\kappa^2=\cos^2\theta \text{ and } \kappa'^2=\sin^2\theta\right)$

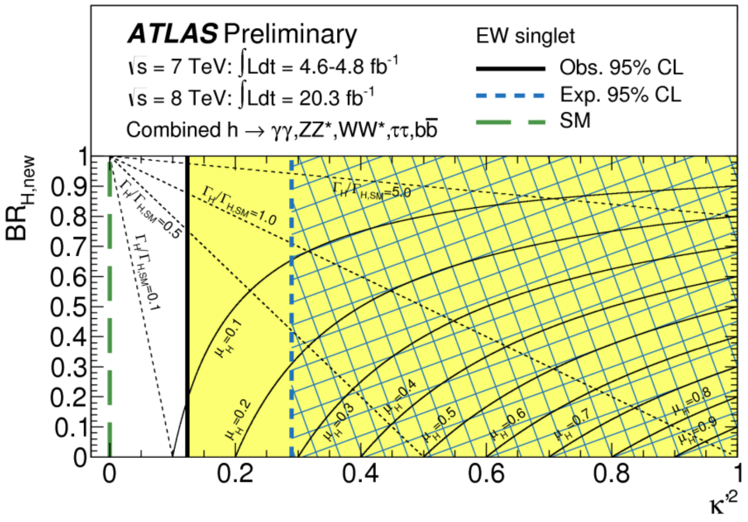
$$\sigma_h=\kappa^2\times\sigma_h^{SM},\qquad \Gamma_h=\kappa^2\times\Gamma_h^{SM},\qquad \mathrm{BR}_h=BR_h^{SM},$$

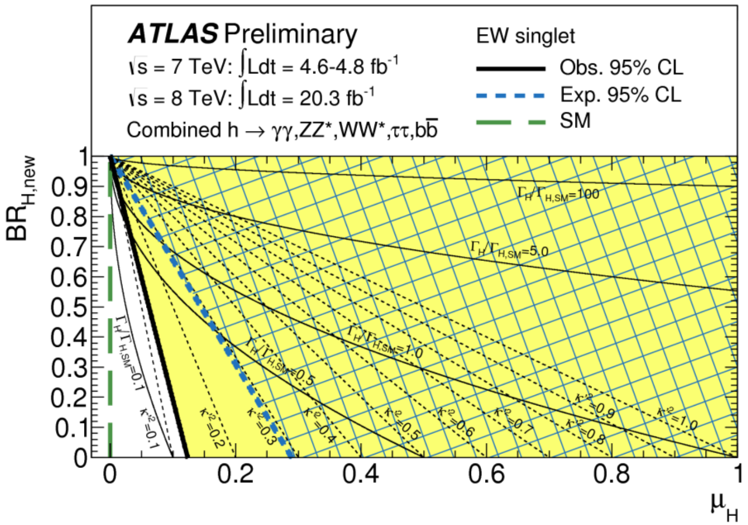
$$\sigma_H=\kappa'^2\times\sigma_H^{SM},\qquad \Gamma_H=\frac{\kappa'^2}{1-BR_{new}}\times\Gamma_H^{SM},\qquad \mathrm{BR}_H=\left(1-BR_{new}\right)\times BR_H^{SM}$$

The measurement of the light Higgs boson can constrain the heavy Higgs boson:

$$\mu_h=\frac{(\sigma\times BR)_h}{(\sigma\times BR)_h^{SM}}=\kappa^2 \quad\Rightarrow\quad \mu_H=\frac{(\sigma\times BR)_H}{(\sigma\times BR)_H^{SM}}=\kappa'^2\left(1-BR_{new}\right)=\left(1-\mu_h\right)\left(1-BR_{new}\right)$$

ATLAS-CONF-2014-010





independent of the mass of the heavy Higgs boson m_H.

2 Higgs Doublet Models (2HDM)

2HDM is one of the simplest extensions to the SM Higgs sector. Two Higgs SU(2) doublets are introduced. The most general tree-level Higgs potential of 2HDM has the form

$$
\begin{aligned}
V(\Phi_1,\Phi_2) = {} & m_1^2\Phi_1^\dagger\Phi_1 + m_2^2\Phi_2^\dagger\Phi_2 - \left[m_{12}^2\Phi_1^\dagger\Phi_2 + \text{h.c.}\right] \\
& + \frac{1}{2}\lambda_1\left(\Phi_1^\dagger\Phi_1\right)^2 + \frac{1}{2}\lambda_2\left(\Phi_2^\dagger\Phi_2\right)^2 + \lambda_3\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2\right) + \lambda_4\left(\Phi_1^\dagger\Phi_2\right)\left(\Phi_2^\dagger\Phi_1\right) \\
& + \left\{\lambda_5\left(\Phi_1^\dagger\Phi_2\right)^2 + \left[\lambda_6\left(\Phi_1^\dagger\Phi_1\right) + \lambda_7\left(\Phi_2^\dagger\Phi_2\right)\right]\left(\Phi_1^\dagger\Phi_2\right) + \text{h.c.}\right\}
\end{aligned}
$$

It has free 10 parameters and leads to undesirable consequences:

- CP-violating Higgs interactions;
- Tree-level flavor changing neutral currents (FCNCs)

Both are severely constrained by experimental data.

New symmetries can be applied to remove these problems:

- all parameters are real $\Rightarrow$ CP conservation;
- soft-broken discrete Z_2 symmetry ($\Phi_1 \to \Phi_1$, $\Phi_2 \to -\Phi_2$)
  $\Rightarrow$ $m_{12}^2 \neq 0$, $\lambda_6 = \lambda_7 = 0$ $\Rightarrow$ no FCNCs

$\Rightarrow$ 8 free real parameters

2 Higgs Doublet Models (2HDM)

These models result in 5 Higgs bosons after the symmetry breaking:

- two neutral CP-even scalars: h and H;
- one neutral CP-odd pseudoscalar: A;
- two charged H^+ and H^- scalars.

and are described by 8 free parameters (2 in SM), often chosen to be

5 mass parameters: m_h, m_H, m_A, $m_{H^\pm}$ and m_{12}^2
2 angular parameters: α and $\tan\beta$
(One more parameter is fixed by W boson mass: $\upsilon = 246$ GeV)

α : mixing parameter of two CP-even Higgs scalars;

$\tan\beta = \dfrac{\upsilon_2}{\upsilon_1}$: ratio of V.E.V. of the two Higgs doublets

2HDMs are classified into 4 types according to Higgs-Fermion couplings

Type	I	II	III	IV
u	Φ_2	Φ_2	Φ_2	Φ_2
d	Φ_2	Φ_1	Φ_2	Φ_1
e	Φ_2	Φ_1	Φ_1	Φ_2
Also known as	"Fermiophobic"	MSSM-like	Lepton-specific	Flipped

Decoupling and Alignment Limits

Typically, the neutral Higgs bosons of 2HDMs have very different properties compared with the SM Higgs boson. However, SM-like Higgs boson can arise from 2HDMs in two ways

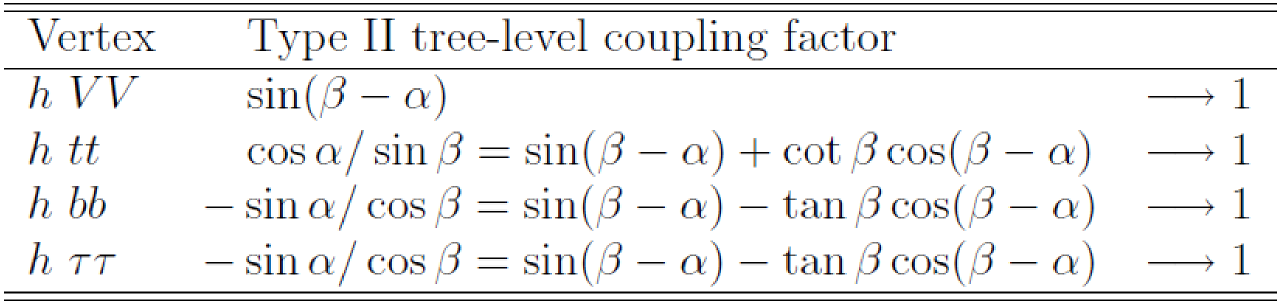
Decoupling limit

All but the lightest Higgs boson are heavy: $m_h \ll m_H, m_A, m_{H^\pm} \Rightarrow \boxed{h \approx H_{SM}}$

Integrating out the heavy states yields an effective 1 Higgs doublet theory.

Alignment limit

$$\sin(\beta-\alpha) \to 1$$
$$\cos(\beta-\alpha) \to 0$$
$$\Downarrow$$
$$\boxed{h \approx H_{SM}}$$



Vertex	Type II tree-level coupling factor	
$h\,VV$	$\sin(\beta-\alpha)$	$\longrightarrow 1$
$h\,tt$	$\cos\alpha/\sin\beta = \sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha)$	$\longrightarrow 1$
$h\,bb$	$-\sin\alpha/\cos\beta = \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha)$	$\longrightarrow 1$
$h\,\tau\tau$	$-\sin\alpha/\cos\beta = \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha)$	$\longrightarrow 1$

These relations hold true for all 2HDM types

$$g_{hVV} \Rightarrow g_{H_{SM}VV},\quad g_{htt} \Rightarrow g_{H_{SM}tt},\quad g_{hbb} \Rightarrow g_{H_{SM}bb},\quad g_{h\tau\tau} \Rightarrow g_{H_{SM}\tau\tau}$$

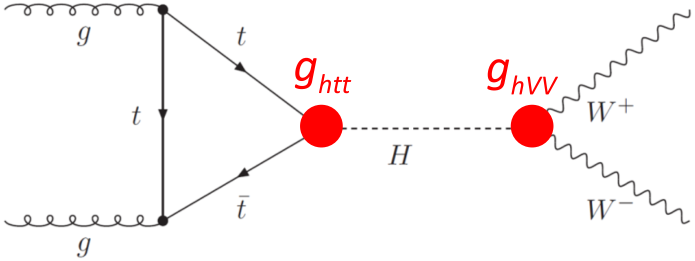
Indirect Constraints from Coupling Fits

Assuming no change in Higgs decay kinematics and no new production process, the measured rates of *h*(125) can be turned into constraints on the two 2HDM parameters: α and β

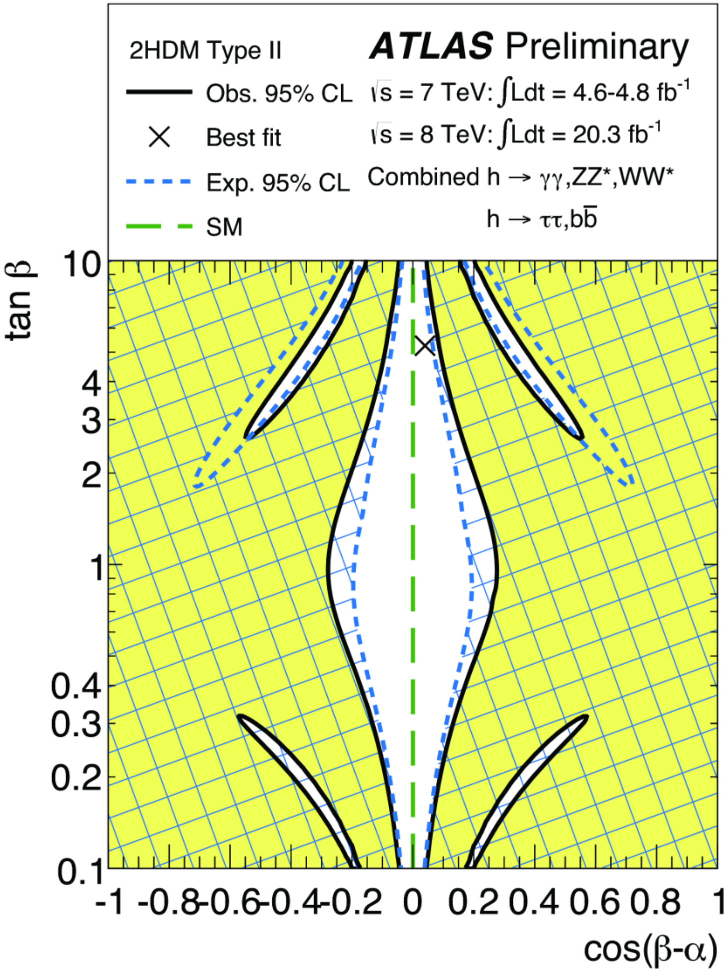
ATLAS-CONF-2014-010

Parametrized using $\tan\beta$ and $\sin(\beta-\alpha)$

Vertex	Type II tree-level coupling factor
$h\,VV$	$\sin(\beta-\alpha)$
$h\,tt$	$\cos\alpha/\sin\beta = \sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha)$
$h\,bb$	$-\sin\alpha/\cos\beta = \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha)$
$h\,\tau\tau$	$-\sin\alpha/\cos\beta = \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha)$

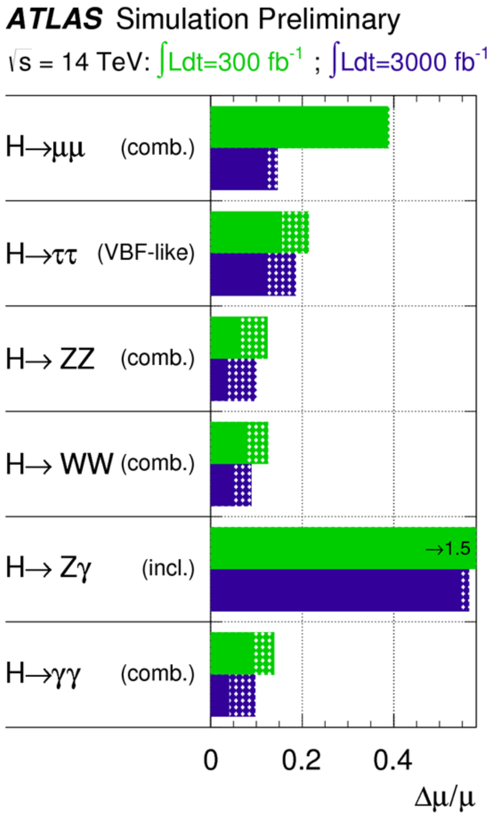


$$\frac{(\sigma\cdot BR)(gg\to H\to WW)}{\left[\sigma(gg\to H)\cdot BR(H\to WW)\right]_{SM}} \approx \left(\frac{g_{htt}}{g_{Htt}^{SM}}\right)^2 \times \left(\frac{g_{hVV}}{g_{hVV}^{SM}}\right)^2$$



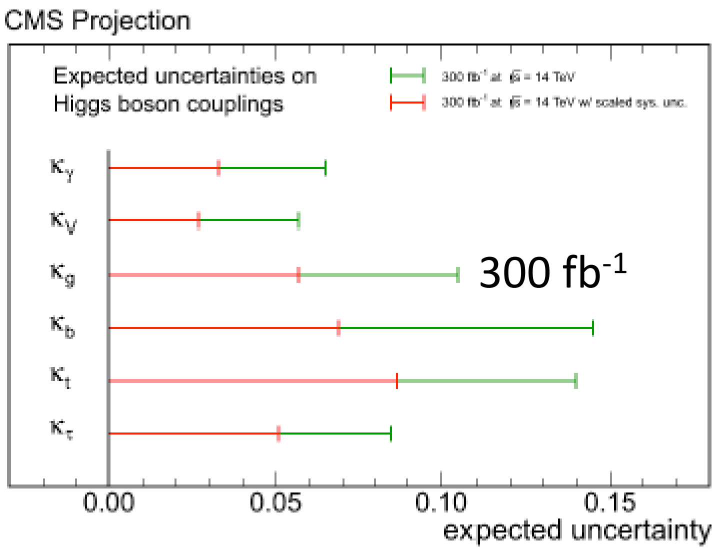
Coupling Projections

Many studies done for US Snowmass process, Europe ECFA studies.



Snowmass Higgs report, arXiv:1310.8361

(Based on parametric simulation)



(Extrapolated from 2011/2012 results)

Two assumptions on systematics:

1. no change
2. $\Delta(\text{theory})/2$, rest $\propto 1/\sqrt{Lumi}$

Even with the projected precisions at HL-LHC, the couplings are not expected to be constrained better than ~ 5%.

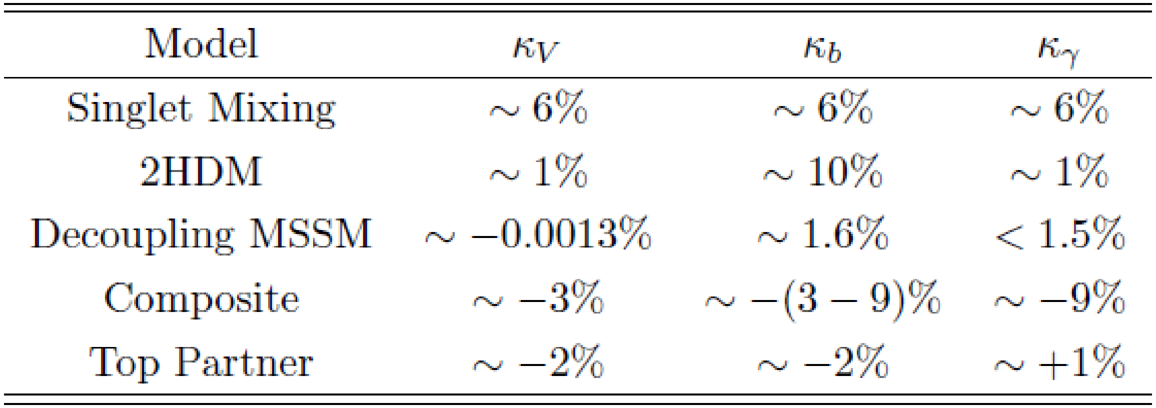
Expected Coupling Deviations

Typical effect on coupling from heavy state (or new physics scale) M:

$$\boxed{\Delta \sim \left(\frac{\upsilon}{M}\right)^2 \sim 6\% \text{ @ } M \sim 1 \text{ TeV}}$$

(Han et al., hep-ph/0302188, Gupta et al. arXiv:1206.3560, …)

Typical sizes of coupling modification from some selected BSM models



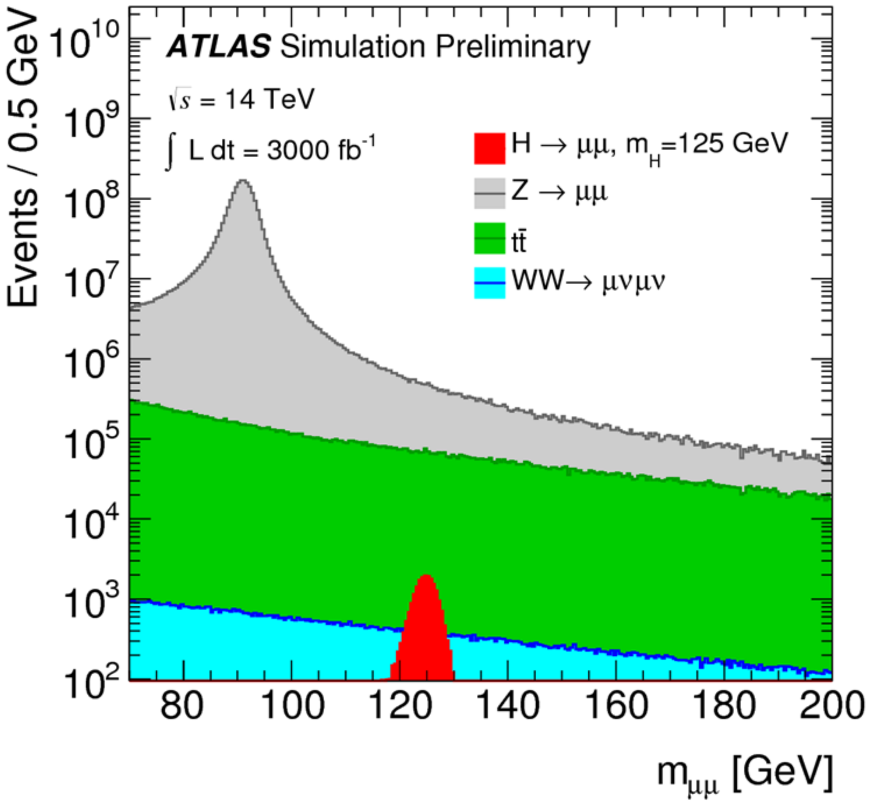
Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$< 1.5\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

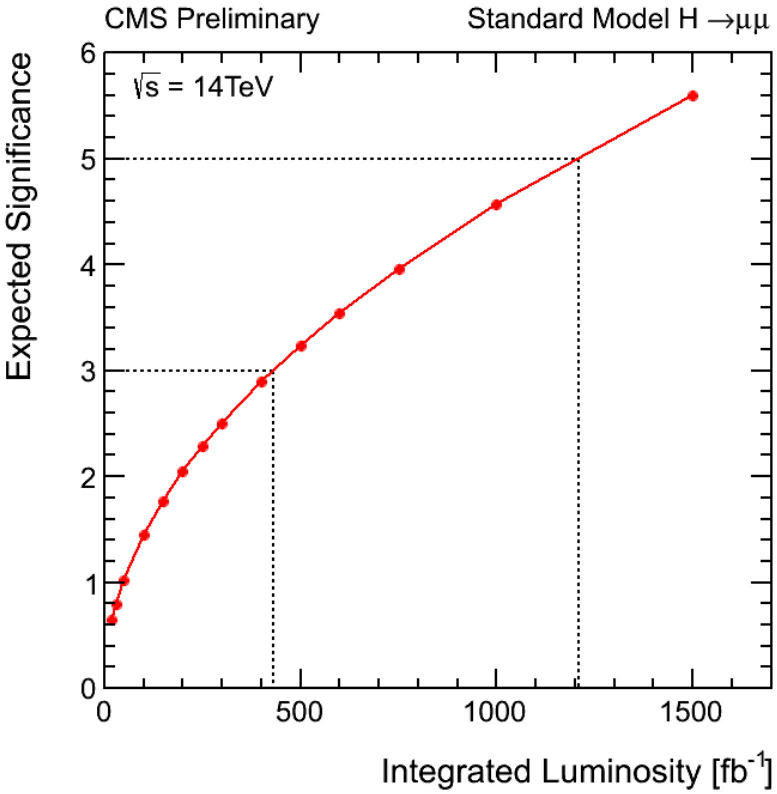
Snowmass Higgs report, arXiv:1310.8361

The precisions of the current coupling fits are insensitive to new physics at TeV scale…

Rare Decay Prospects

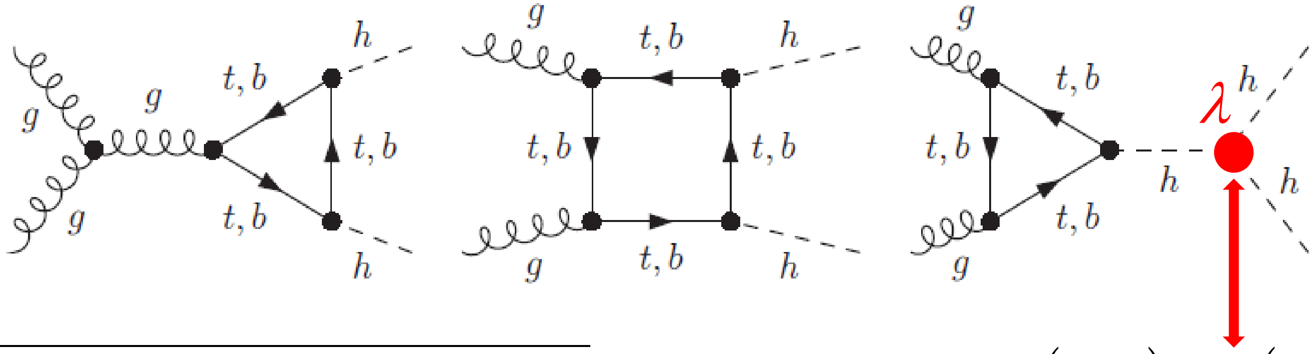
$H \rightarrow \mu\mu$: Projections from both ATLAS and CMS indicate a 5σ observation with $\sim 1000\ \text{fb}^{-1}$ at 14 TeV.





$H \rightarrow Z\gamma$: $\sim 4\sigma$ per experiment significance is expected with $3000\ \text{fb}^{-1}$

Higgs Self-Coupling



$$V(\phi) = \mu^2 (\phi^\dagger \phi) + \lambda (\phi^\dagger \phi)^2$$

$\sigma(pp \to hh)$@14 TeV	40.2 fb (NNLO)

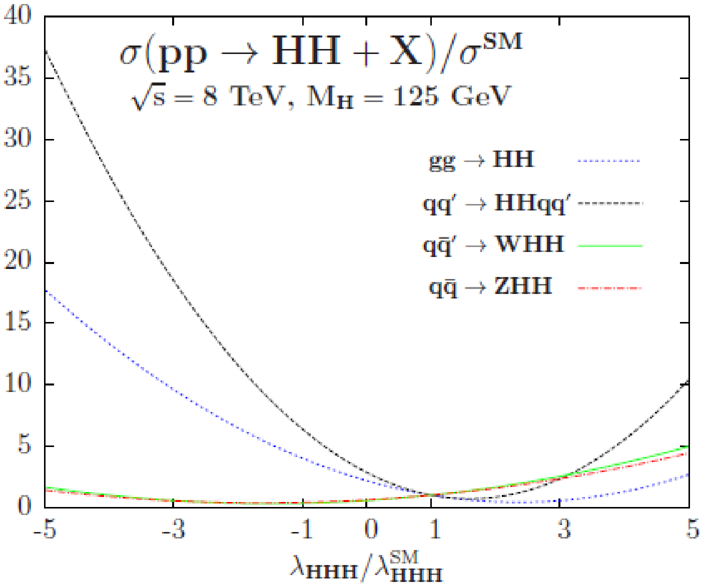
Events in 3000 fb^{-1}	
$hh \to bb\gamma\gamma$	320
$hh \to bb\tau\tau$	8,800
$hh \to bbWW$	29,900
$hh \to bbbb$	40,200

Small cross section and the destructive interference between self- and non-self-coupling diagrams.

$bb\gamma\gamma$ appears to have the best sensitivity, *$bb\tau\tau$* should help too, *bbWW* and *bbbb* have higher rates, but also large backgrounds.

$$\boxed{\text{Expect to achieve } \frac{\Delta\lambda}{\lambda} \sim 30\%}$$

(two experiments at HL-LHC)



Baglio et al, arXiv: 1212.5581

Summary

Impressive results from both ATLAS and CMS experiments. In short two years, the Higgs physics program has been transformed from search & discovery to precision measurements.

With current precision, all property measurements of the newly discovered Higgs boson are consistent with expectations from the Standard Model. However, deviations from TeV-scale new physics are expected to be small from most models, smaller than the precisions of current measurements.

LHC Run 2 will increase the statistics by a factor of ~30 and thus should significantly improve the precisions of many measurements, enable to study rare productions and decays, and more importantly to search for new physics beyond the Standard Model.