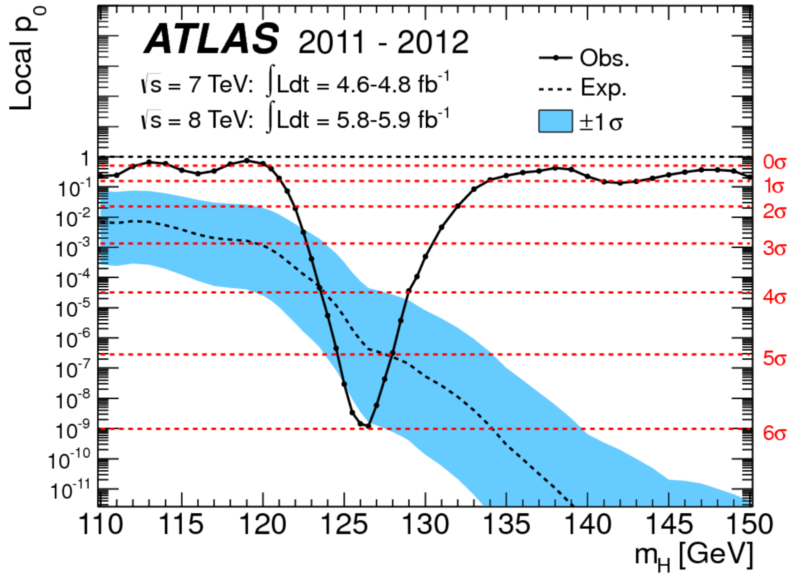
Karlsruher Institut für Technologie

3rd Anniversary
of Higgs Boson Discovery
- what we know today

Günter Quast

Fakultät für Physik
Institut für Experimentelle Kernphysik

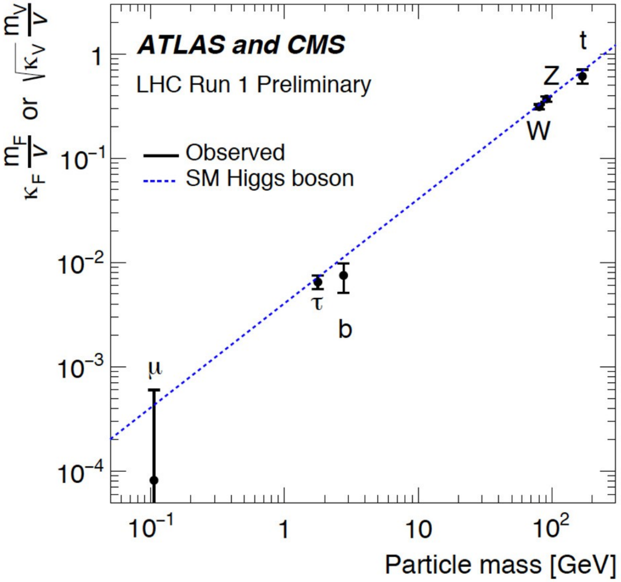
DESY Theory Workshop 2015



2012
discovery

→

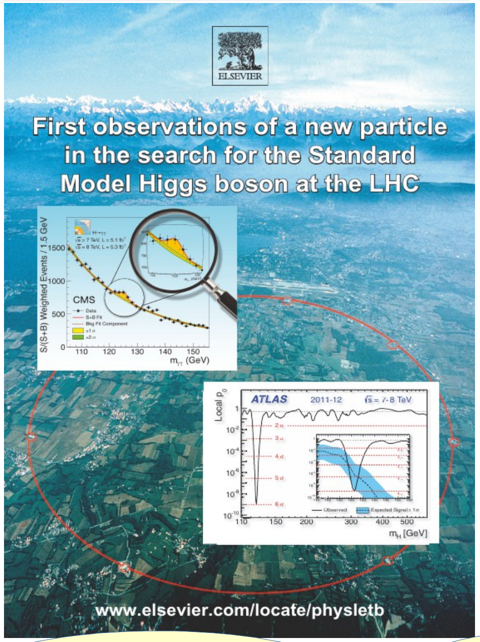
measurement
2015



Higgs Hunt @ the LHC

Summer '12 (~10 fb $^{-1}$)

Announcement of
“a new particle”



ELSEVIER

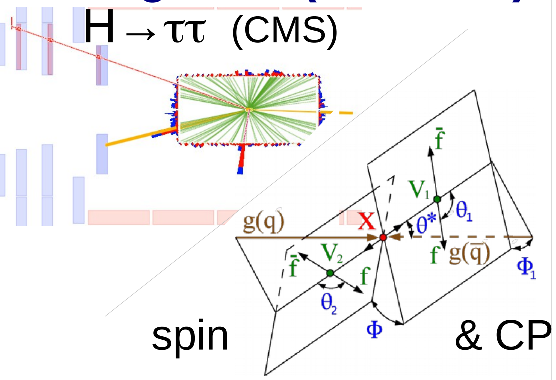
First observations of a new particle in the search for the Standard Model Higgs boson at the LHC

www.elsevier.com/locate/physletb

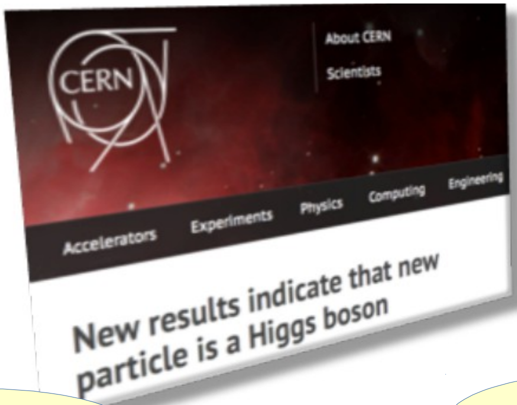
New particle !

during 2013 (~20 fb $^{-1}$)

$H \rightarrow \tau\tau$ (CMS)



spin & CP



New results indicate that new particle is a Higgs boson

Higgs-like ?

Dec. 2013

Nobel Prize

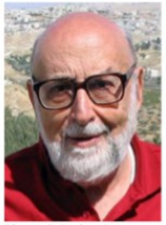


Photo: Pnicolet via Wikimedia Commons
François Englert

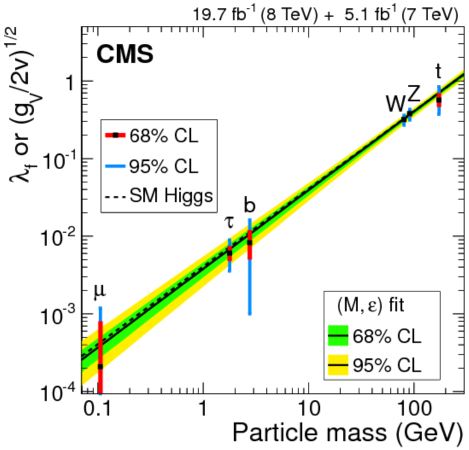
Photo: G-M Greuel via Wikimedia Commons
Peter W. Higgs

(& EPS Prize
+ many others)

A Higgs !

2014

refined analyses
&
(many) final publications



THE SM-Higgs ???

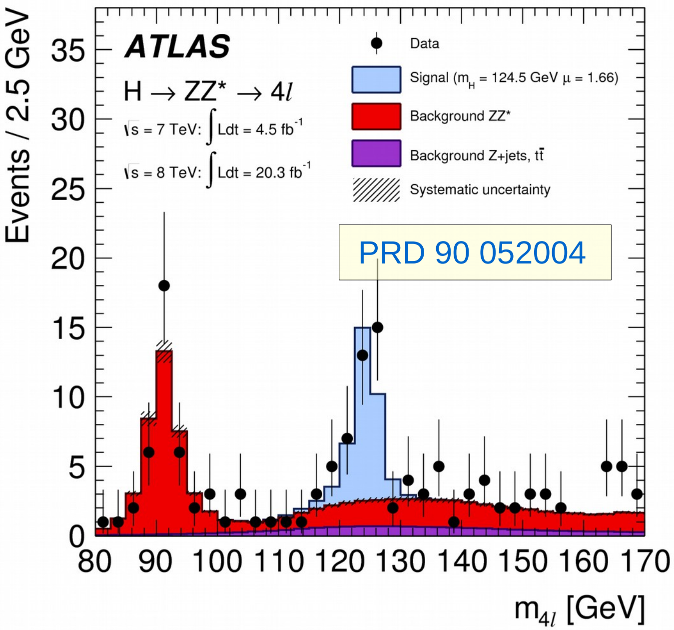
LHC Run 1: pp-collisions at E_{CM} of 7 and 8 TeV

- Peak Luminosity: 7 x 10^{33} cm^{-2} s^{-1}
- Integrated Luminosity: 5 fb $^{-1}$ (2011@7 TeV) (5+15) fb $^{-1}$ (2012@8 TeV)
- time between bunches: 50 ns ⇒ 9–21 overlayed pp-interactions on average

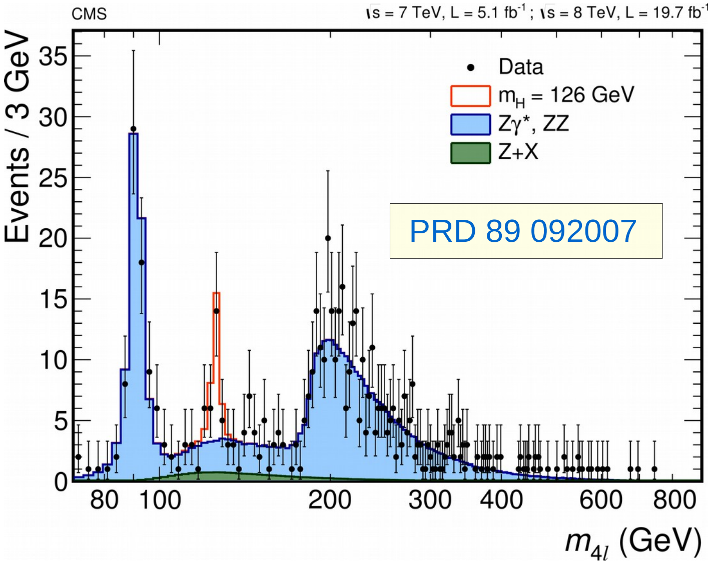
Where are we now – **in 2015** ?

Individual Channels: H → bosons

The original “discovery channels” - ***updated to full Run1 luminosity, final and published***

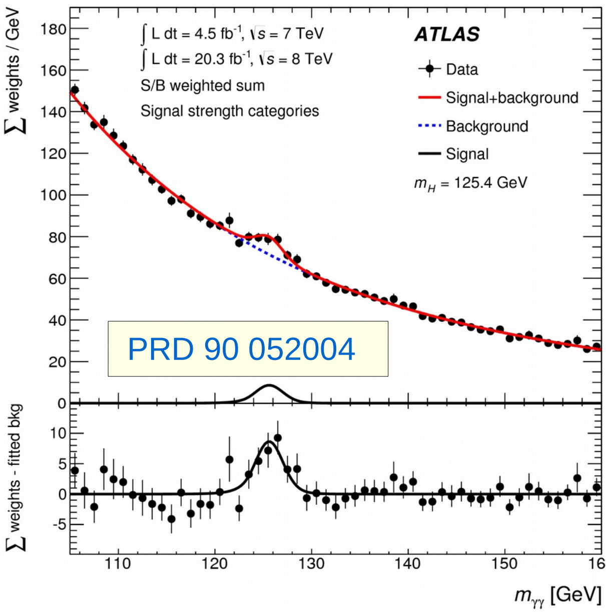


PRD 90 052004

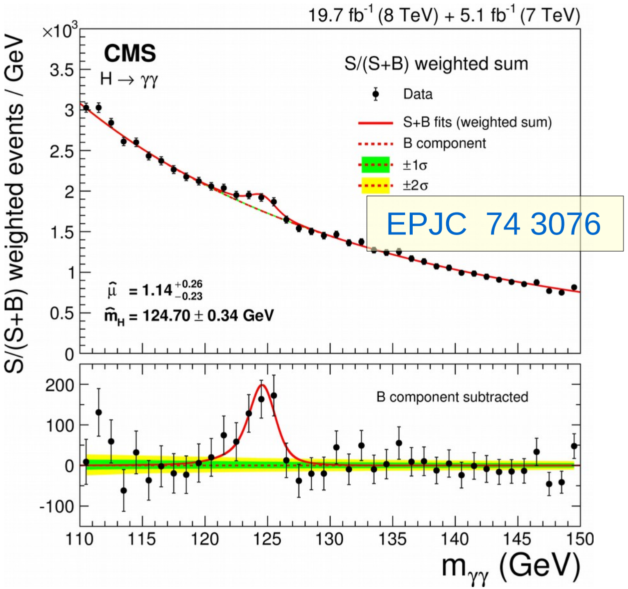


PRD 89 092007

$\mathbf{H \rightarrow Z^{(*)}Z \rightarrow 4\ell}$

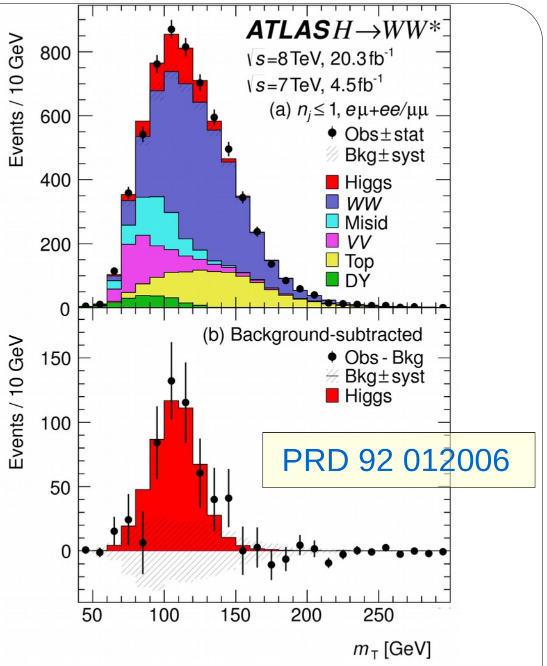


PRD 90 052004

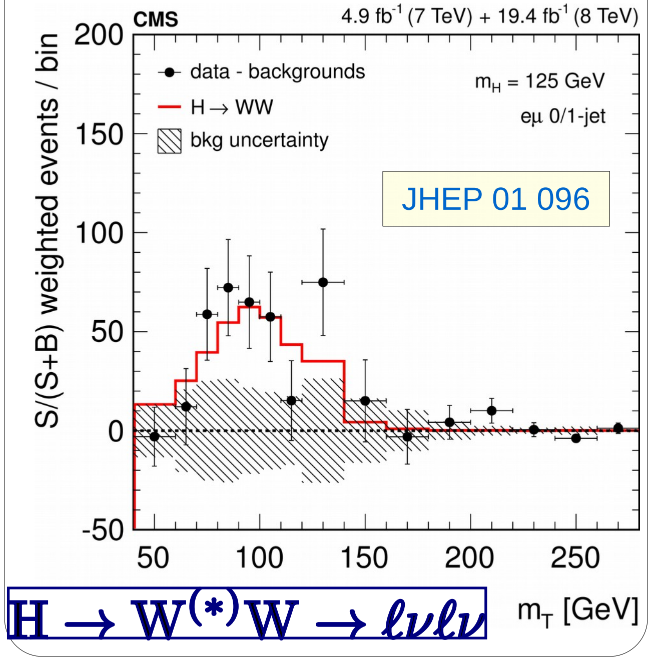


EPJC 74 3076

$\mathbf{H \rightarrow \gamma\gamma}$



PRD 92 012006

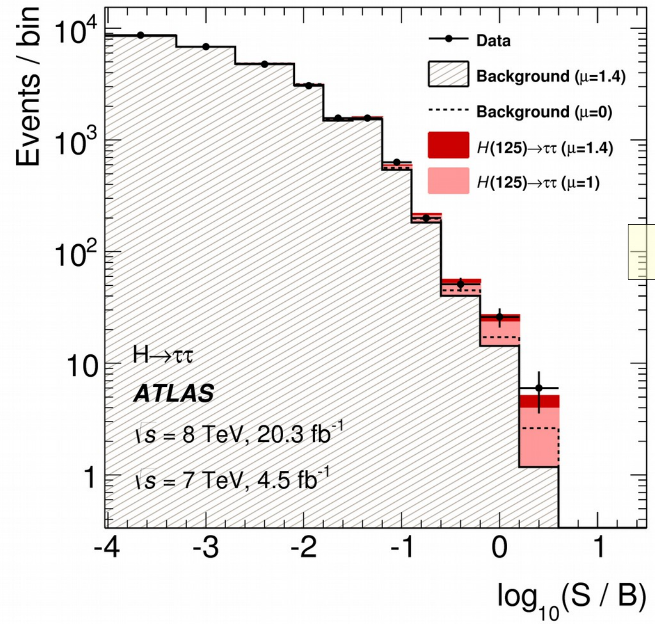


JHEP 01 096

$\mathbf{H \rightarrow W^{(*)}W \rightarrow \ell\nu\ell\nu}$

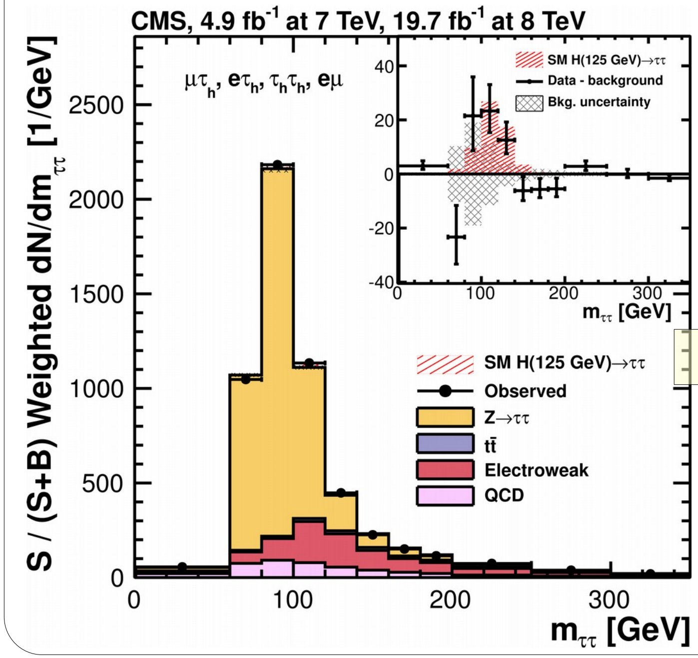
Individual Channels: Higgs → fermions

$H \rightarrow \tau\tau$



JHEP 04 117

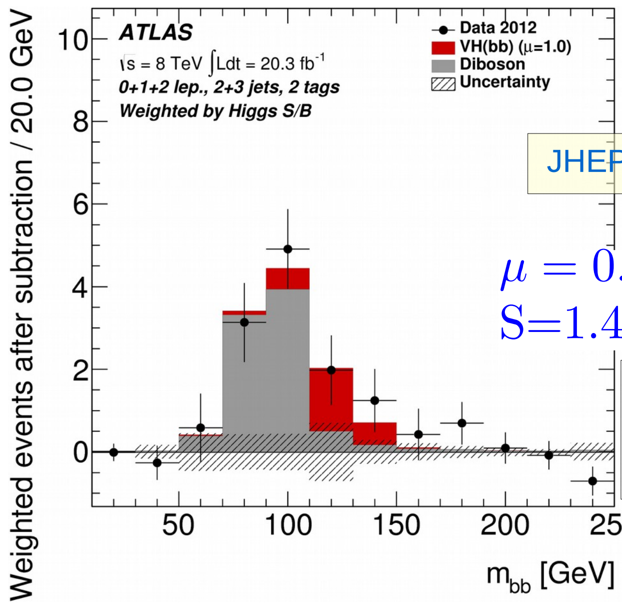
$\mu = 1.43^{+0.43}_{-0.37}$
S=$4.5\sigma(3.4\sigma)$



JHEP 05 104

$\mu = 0.78 \pm .27$
S=$3.2\sigma(3.7\sigma)$

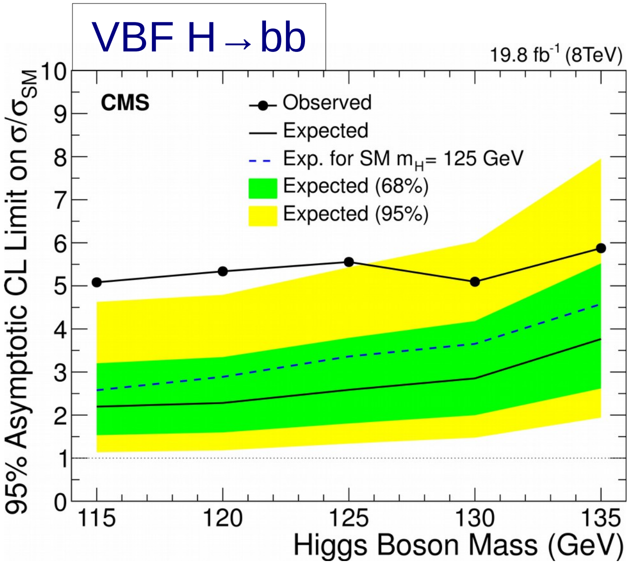
VH/VBF, $H \rightarrow bb$



JHEP 01 069

$\mu = 0.52 \pm .32 \pm .24$
S=$1.4\sigma(2.6\sigma)$

there is a deficit
in 2011 data
(not shown here)



subm. PRD
arXiv:1506.01010

$\mu = 2.8^{+1.6}_{-1.4}$
S=$2.2\sigma(0.8\sigma)$

combined with
VH(bb) from

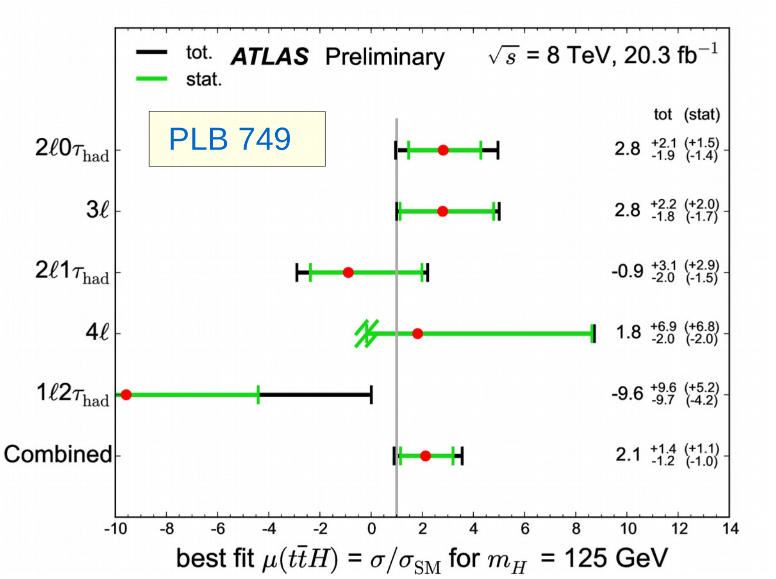
PRD 89 012003

$\mu = 1.0 \pm .4$
S=$2.6\sigma(2.7\sigma)$

Individual Channels: ttH

directly probing the largest Higgs-boson coupling using associated production with $t\bar{t}$

$t\bar{t}$H, multi-leptons (WW, ZZ, ττ)



$$\mu = 2.1^{+1.4}_{-1.2}, \ \ \mu < 4.7(2.4)$$

$t\bar{t}$H, H → $b\bar{b}$, neural network EPJC75 349

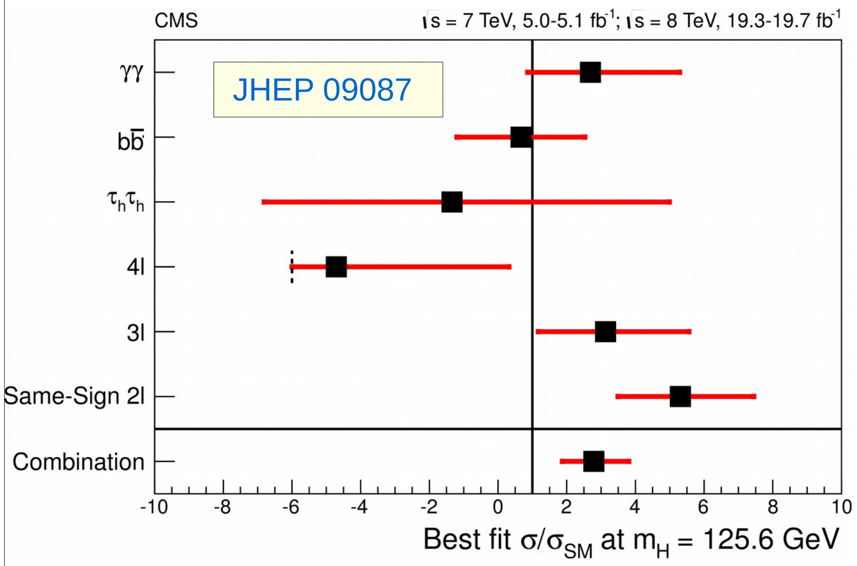
$$\mu = 1.5 \pm 1.1, \ \ \mu < 3.4(2.2)$$

$t\bar{t}$H, H →γγ PLB 740

$$\mu < 6.7(4.9)$$

ATLAS

$t\bar{t}$H, H → hadrons, photons, leptons



$$\mu = 2.9^{+1.1}_{-0.9}, \ \ \mu < 4.5(2.7)$$

$t\bar{t}$H, H → $b\bar{b}$, matrix element method

EPJC 75 251

$$\mu = 1.2^{+1.6}_{-1.5}, \ \ \mu < 4.2(3.3)$$

CMS

~ compatible with SM, but both experiments see an excess at the 2-3σ level, **to be watched !**

Individual Channels: rare H decays

rare decays modes:

	95% C.L limits	
H →	ATLAS	CMS
$\mu(\mu\mu)$	7.0 (7.2)	7.4 (6.5)
$\mu(\mathrm{ee})$		$\simeq 3.7 \cdot 10^5$
$\mu(\mathrm{Z}\gamma)$	11 (9)	9.5 (10)
$\mu(\ell\ell\gamma)$ $(m_{\ell\ell}<20\,GeV)$		7.7 (6.4)
$\mathrm{Br}(\mathrm{J}/\Psi\,\gamma)$	$1.5 \cdot 10^{-3}$	$1.5 \cdot 10^{-3}$
$\mathrm{Br}(\tau\mu)$	0.019	0.015
$\mathrm{Br}(\Upsilon_{(1S,2S,3S)}\,\gamma)$	$(1.3,\ 1.9,\ 1.3)\ \cdot 10^{-3}$	

Not a "failure to observe", but confirmation that μ coupling is small

( )=expected

In particular in the VBF an VH production channels,

a sensitive search for **"invisible" H decays** is possible:

	ATLAS	CMS
$\mathrm{Br}_{inv} <$	28% (31%)	36% (30%)

subm JHEP, arXiv:1508.07869

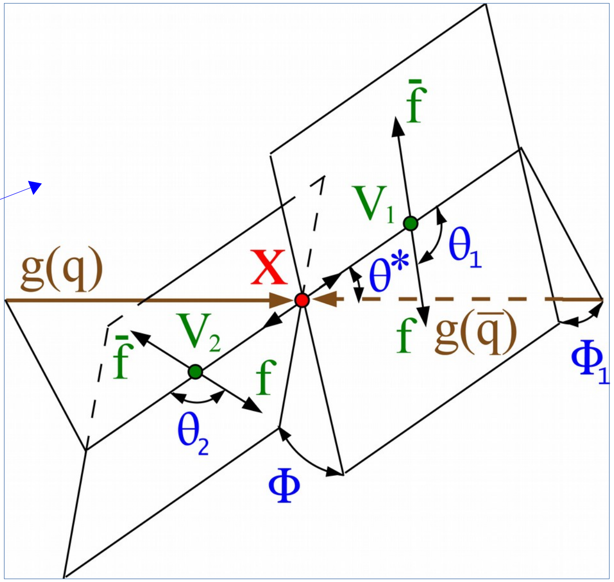
CSM PAS HIG-15-012

Spin – CP (methods)

sufficiently high statistical precision and cleanliness of di-boson channels allows exploitation of kinematic variables for discriminating spin-parity hypotheses

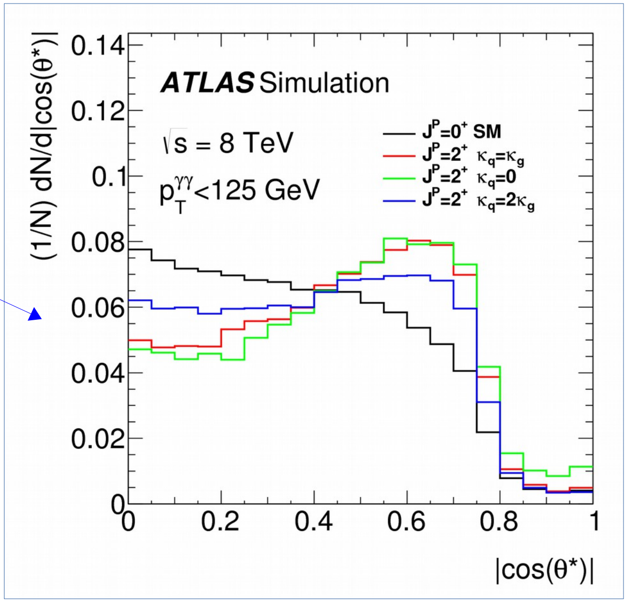
$H \rightarrow Z^{(*)}Z \rightarrow 4\ell$

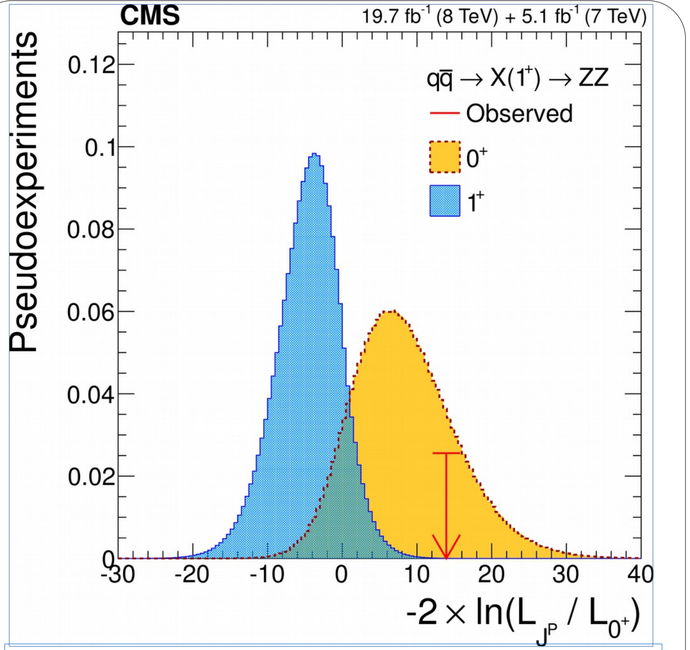
matrix element depends on
- 5 angles
- 3 masses



$H \rightarrow \gamma\gamma$

variables used:
- $p_T(\gamma\gamma)$
- cos θ^* in Collins-Soper frame





example of hypothesis test in ZZ* 1^+ vs. 0^+

classical hypothesis test using log-Likelihood ratio of the SM vs. the alternative scenario as the test-statistic

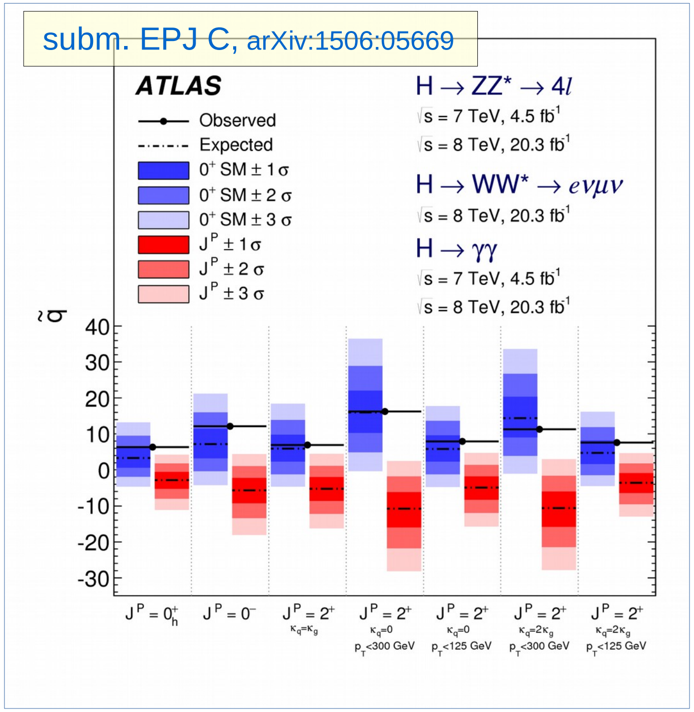
$H \rightarrow W^{(*)}W \rightarrow \ell\nu\ell\nu$

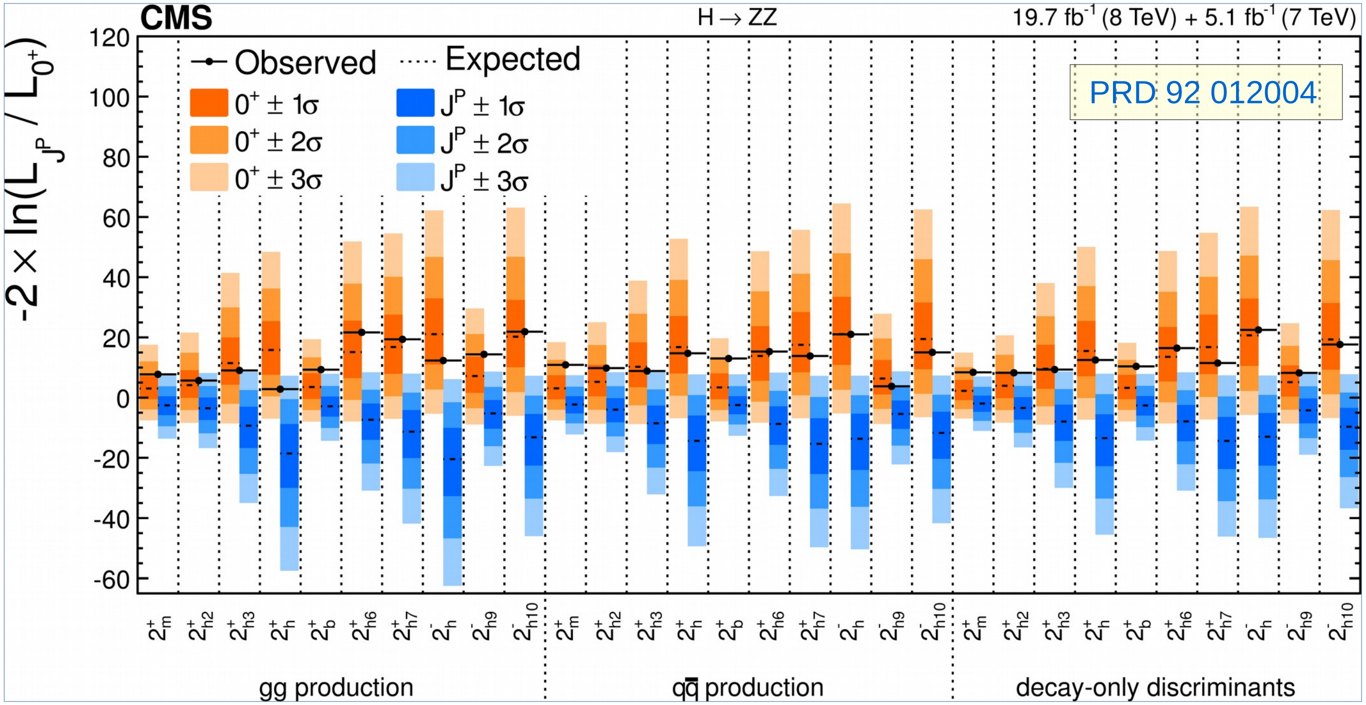
ATLAS:
BTD with $\Delta\Phi$(ll), p_T(ll), m(ll)

CMS:
2D-distribution of m(ll) & m_T

Spin – CP (results)

ATLAS and CMS exclude non-SM spin-0 models and spin-2 models with >99.9 % C.L.

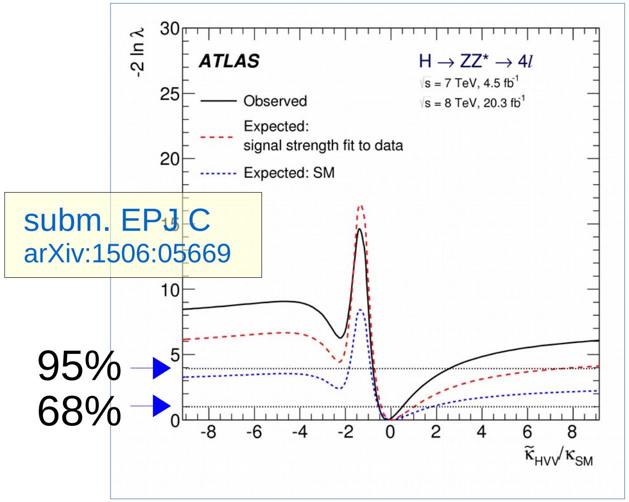

subm. EPJ C, arXiv:1506:05669

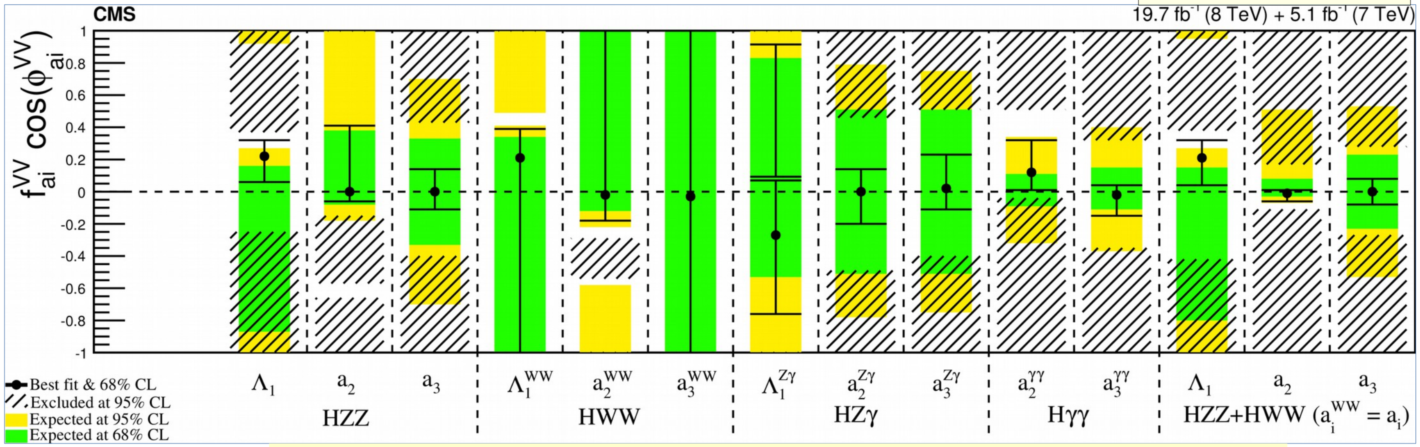

PRD 92 012004

first constraints on non-SM contributions to the tensor structure of HVV coupling in S^{CP}=0+

(parameterised as K_{HZZ}/K_{SM} , $K_{AZZ}/K_{SM}\cdot\tan\alpha$ (ATLAS) resp. Λ, a_1, a_1 (CMS))

PRD 92 012004


subm. EPJ C
arXiv:1506:05669



A ll consistent with 0+, as expected in the SM

Differential H cross section measurements

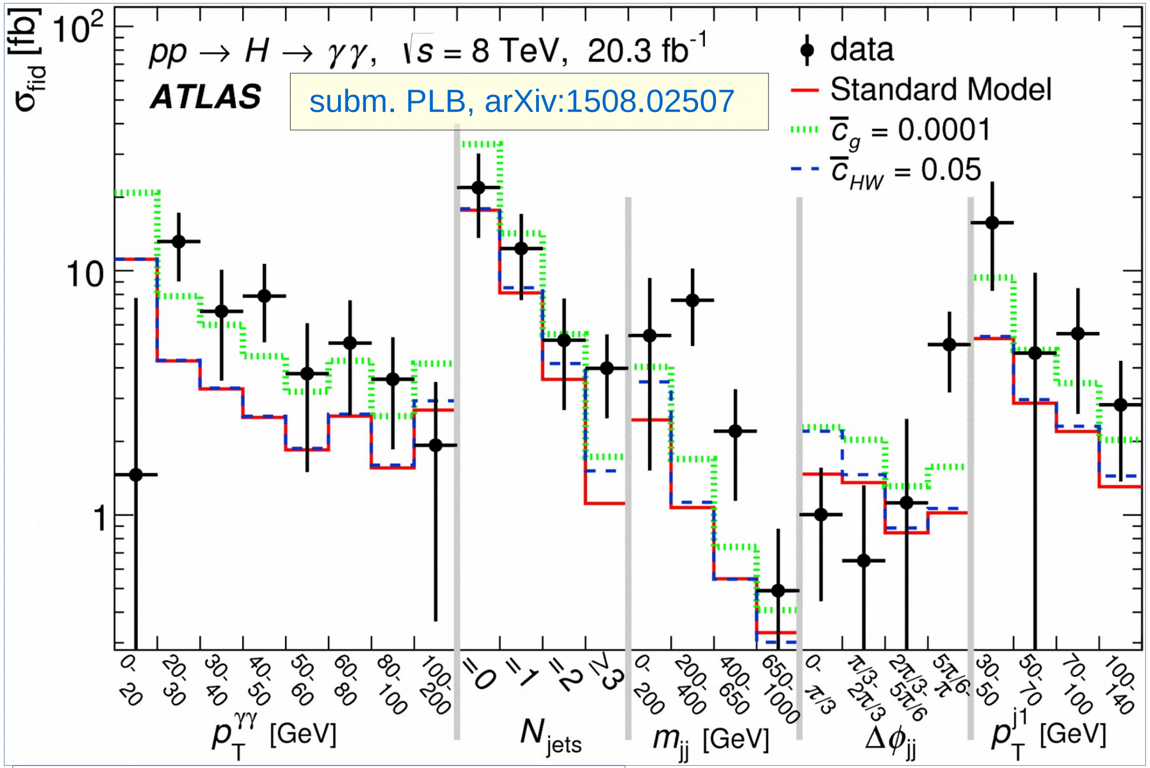
High-resolution channels H → $\gamma\gamma$ / 4ℓ

offer good precision for differential measurements of

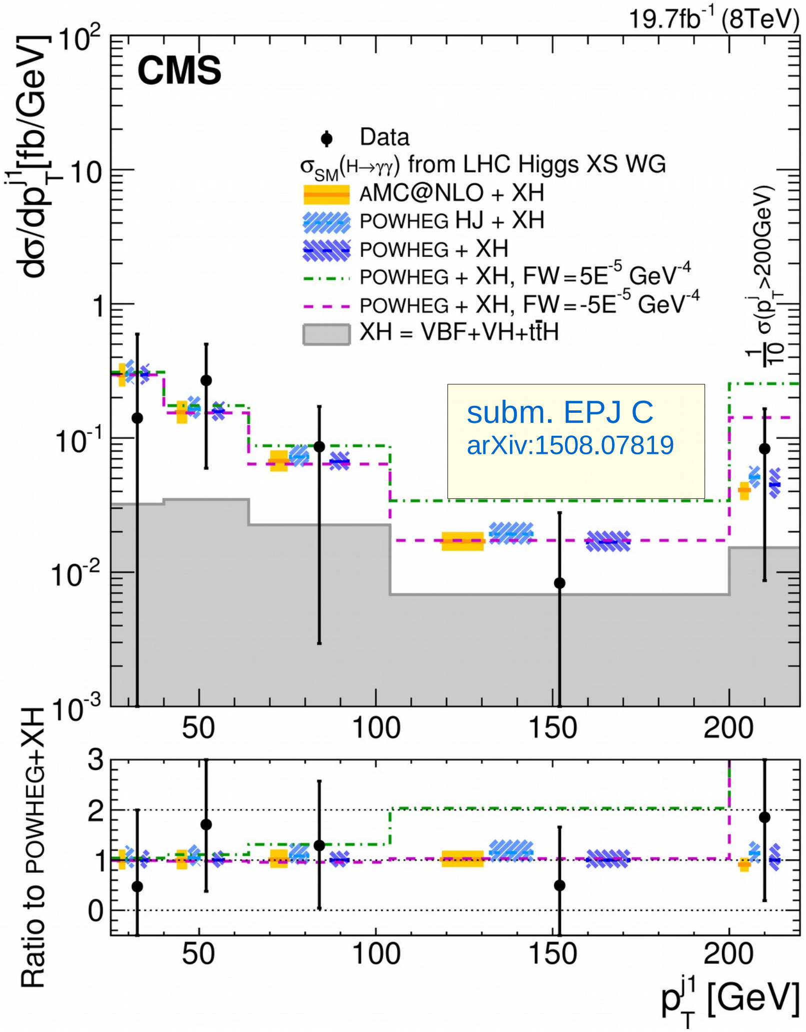
Higgs-boson *y* and p_T, jet multiplicity, leading jet p_T, Δy(H, jet)

- measurements within **(rather complex) fiducial region** to minimise (model-dependent) acceptance corrections
- unfolded to particle level

Sensitivity to production kinematics, QCD effects and PDFs



subm. PLB, arXiv:1508.02507



subm. EPJ C
arXiv:1508.07819

Test of non-SM contributions to effective Lagrangian

H → ZZ → 4ℓ PLB 738 234-235

measurements obviously still statistically limited

Searches for additional Higgs Bosons

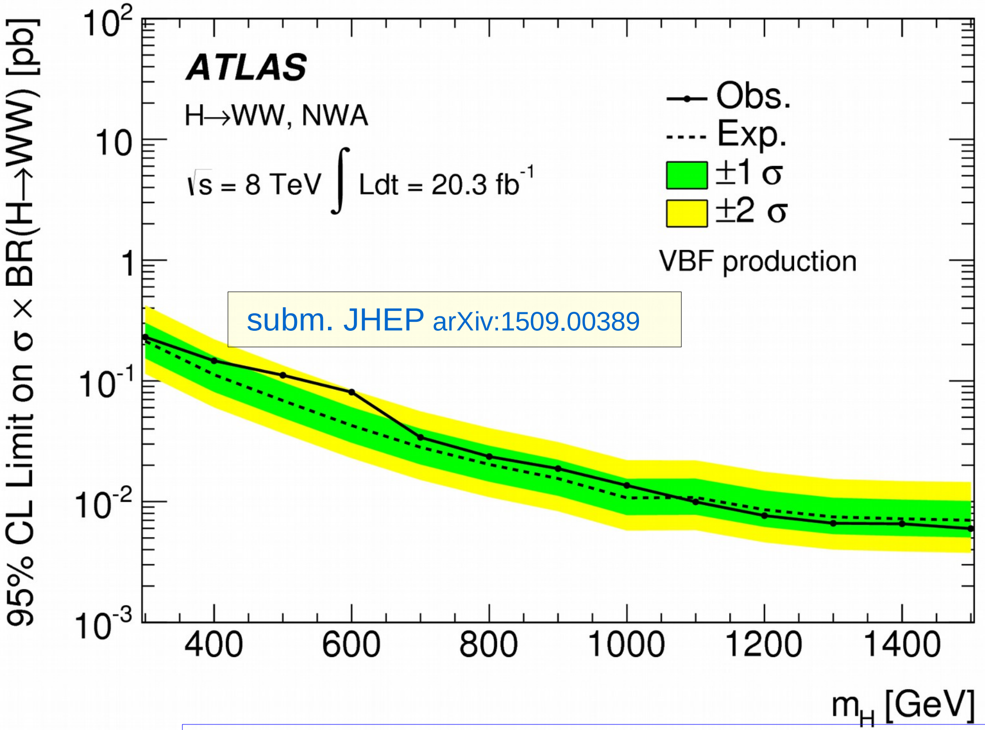
V V final state is particularly sensitive to (additional) high-mass Higgs bosons

(such an object would be an additional, non-SM H-like state)

different assumptions on signal properties:

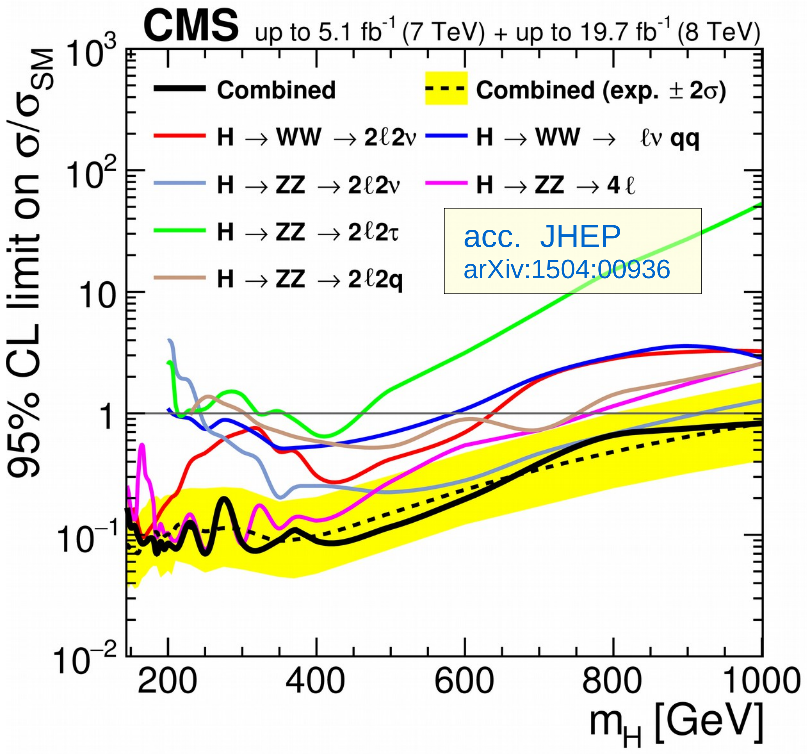
- Γ << exp. resolution,
- Γ scaling with mass (complex pole scheme)
- intermediate scenario

Exclusion limits from search in W W → ℓνℓν, ℓνqq for narrow-width signal



subm. JHEP arXiv:1509.00389

Combined exclusion limits from W W, ZZ for SM-like couplings



acc. JHEP arXiv:1504:00936

also searches in γγ channel:

ATLAS: PRL 113 171801

CMS: subm. PLB arXiv:1506:02301

Higgs-like objects decaying to V V, even with couplings much smaller than expected for SM Higgs, are excluded up ~1 TeV

BSM Higgs searches

Is the SM-like Higgs-Boson *in fact* a first sign of new physics ?

1. Deviations from SM in precision measurements of couplings

   needs a lot more data ...

2. Part of an extended Higgs sector:

   - 2 charged and 2 additional neutral ones in **MSSM**

     h, H, A = Φ (neutral), H^+ and H^- bosons, m_A and tan*β* as tree-level parameters

   - 2 charged and 4 additional neutral H bosons in **NMSSM**

     → direct search for additional Higgs bosons

   - more general 2 Higgs-doublet models (type I and type II) also require 4 additional Higgs bosons

Numerous searches performed on Run 1 data set @ LHC:

- large tan*β*: Φ → μμ, ττ and bb are sensitive
- small tan*β*: search for decays of heavy Higgs bosons to lighter ones

  A → Z+h(125), H/A → Z+A/H
- light Higgs bosons possible in NMSSM: h(125) → aa → μμττ, 4γ
- direct searchs for $H^\pm$

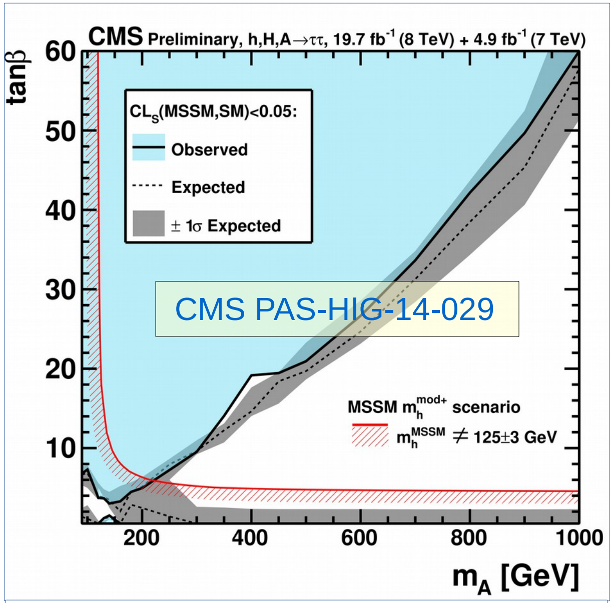
only a few most recent results shown here

(some) latest Results from (N)MSSM Searches

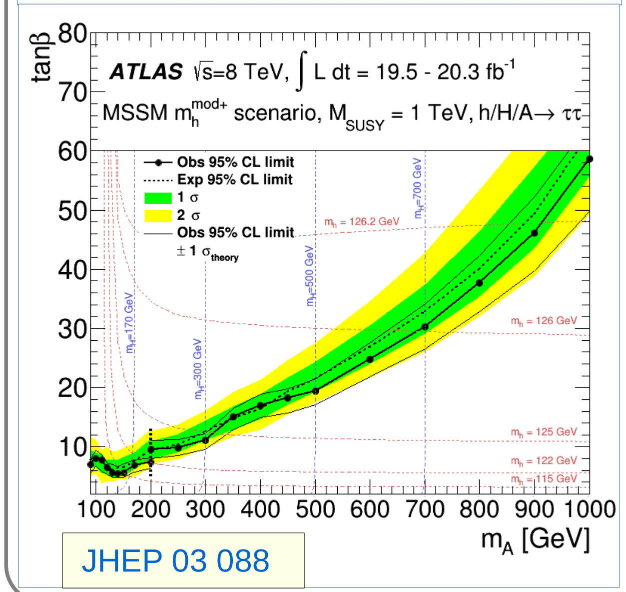
MSSM

$\Phi \rightarrow \tau\tau$

m_h^{mod+} benchmark scenario



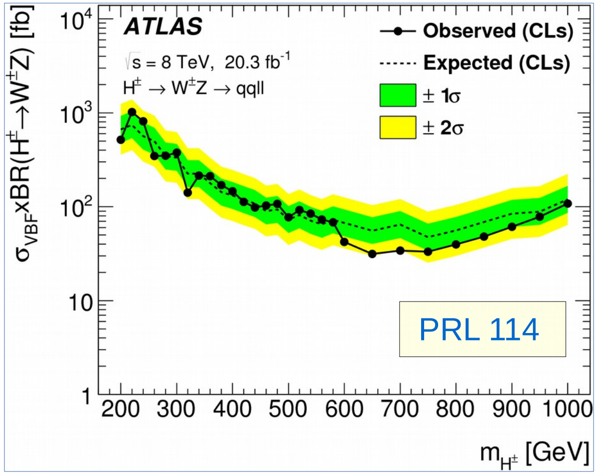
CMS PAS-HIG-14-029



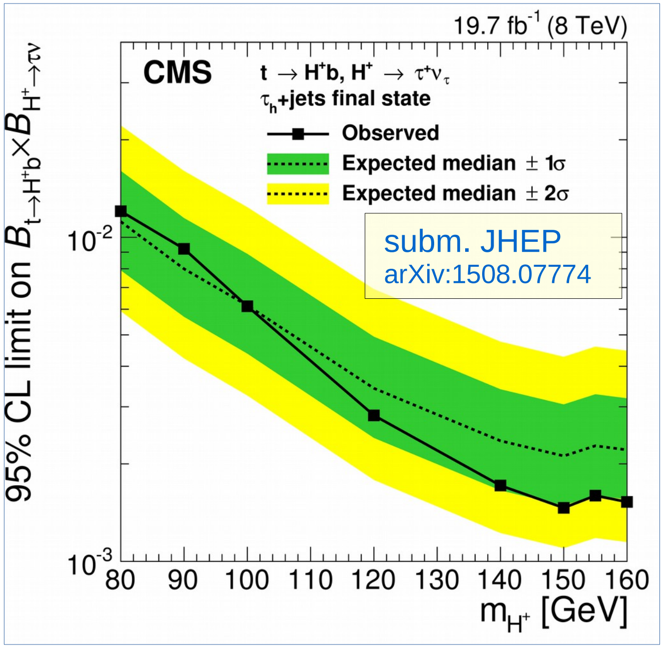
JHEP 03 088

MSSM

$H^{\pm}$



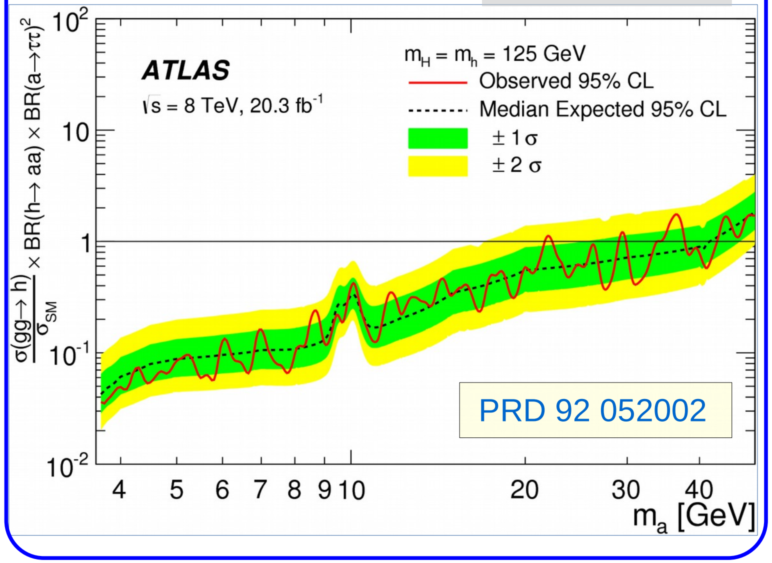
PRL 114



subm. JHEP
arXiv:1508.07774

NMSSM

H,h → a a



PRD 92 052002

Only limits so far

H(125) remains the only one of its kind for the moment,

but

LHC@13 TeV just started ...

Part 2

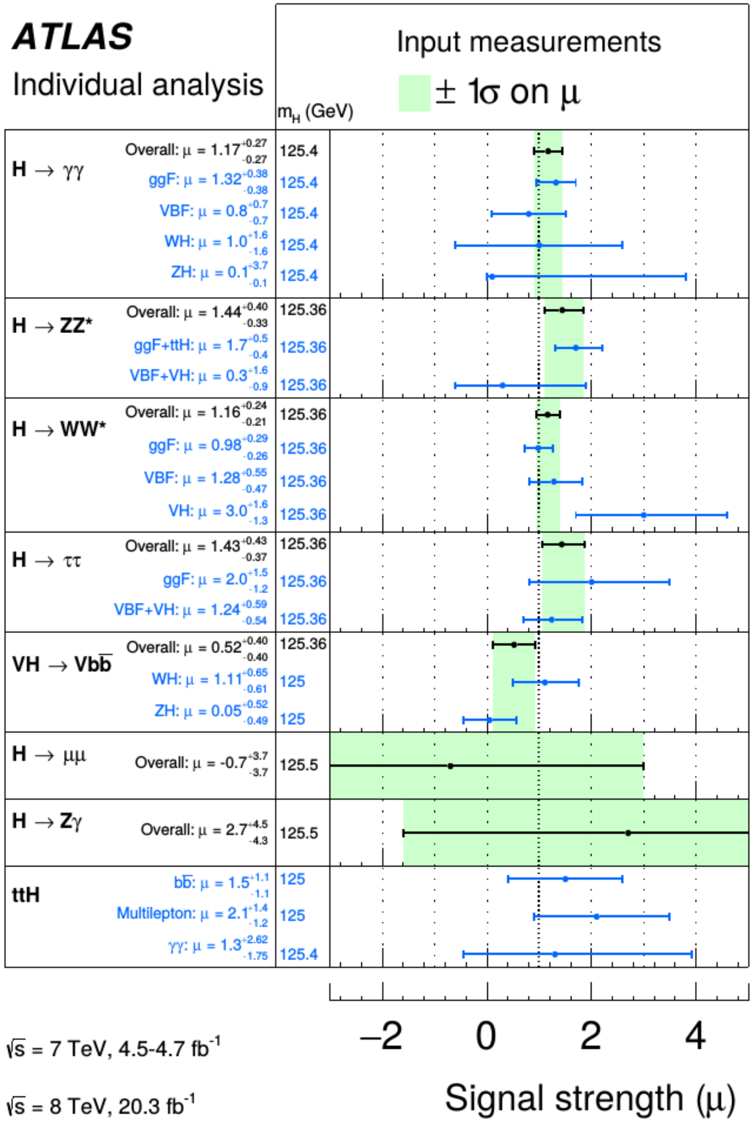
Combination of

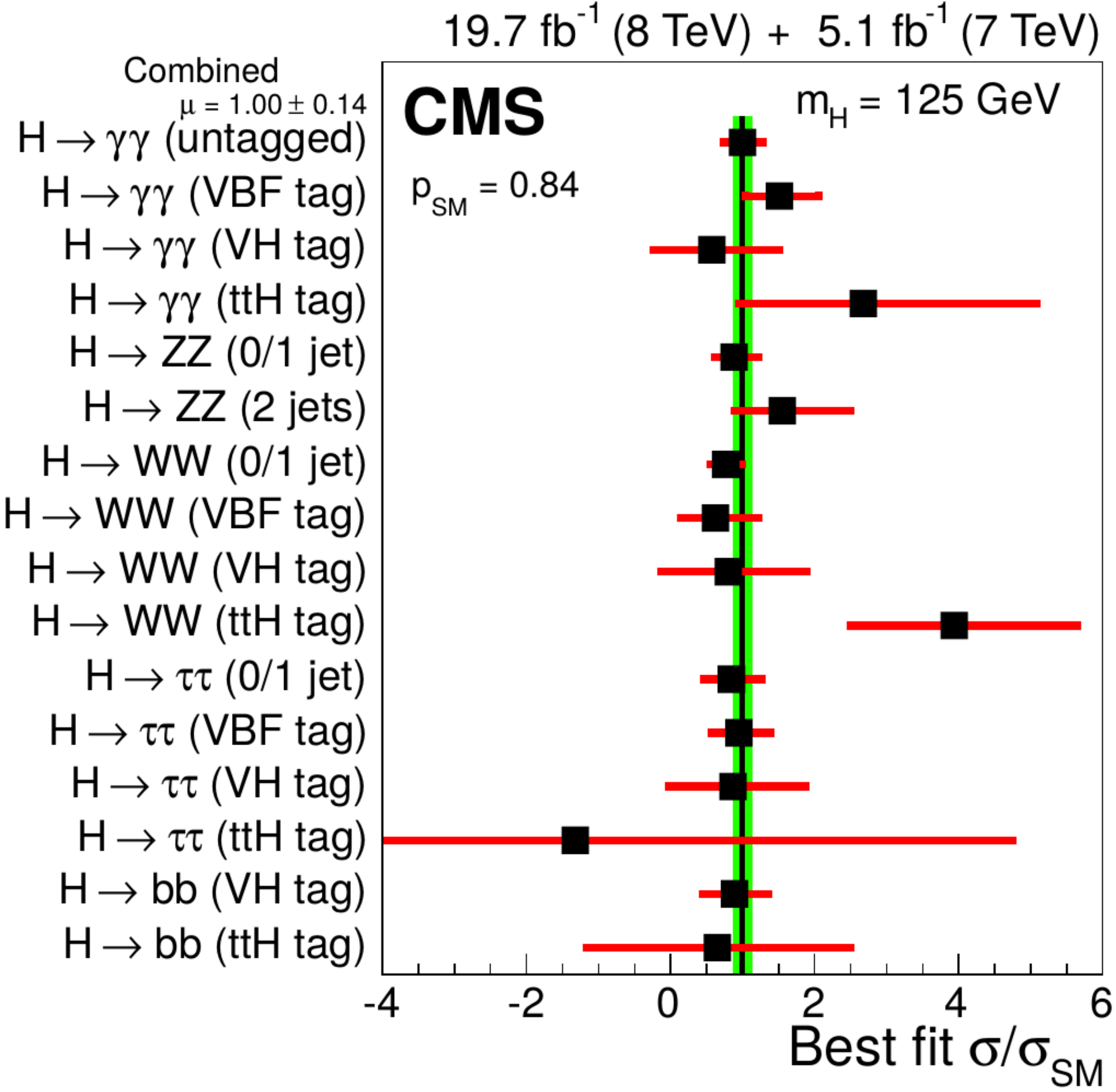
ATLAS and CMS

Results on SM Higgs measurements

combination of results: ATLAS and CMS

Results based on integrated luminosities of
~5/fb @ 7 TeV (2011) and ~20/fb @ 8 TeV (2012) per experiment
for the "big five" H→ ZZ, γγ, WW, ττ and bb + some (rare) others





ATLAS Mass: PRL 114, 191803
ATLAS Couplings: arXiv:1507.04548

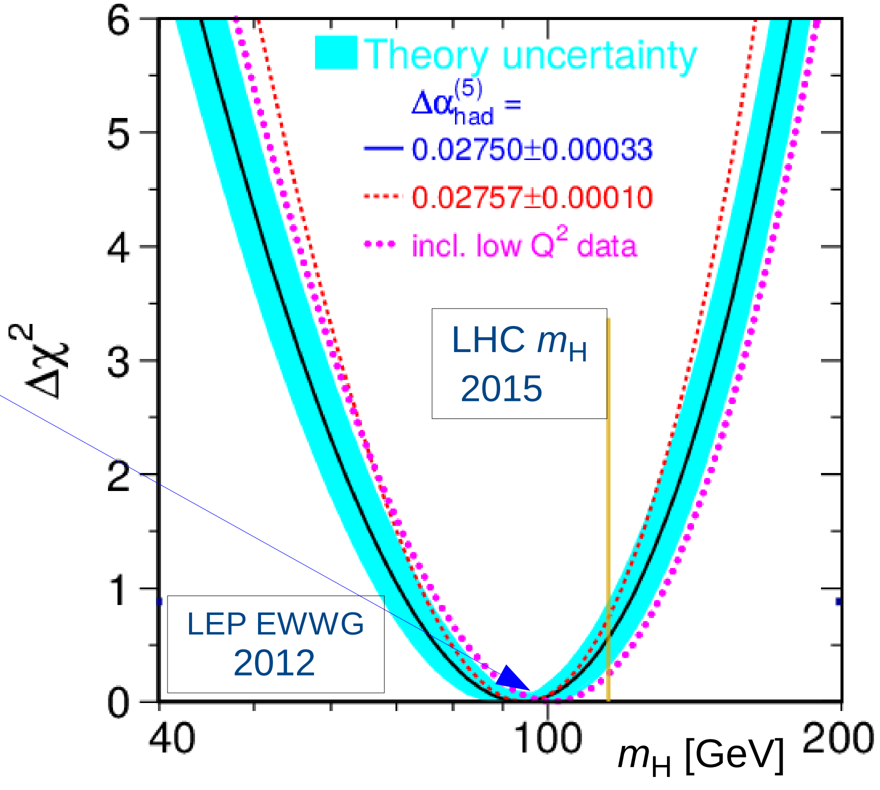
CMS Mass & Couplings
EPJ 75 (2015) 212

Higgs-Boson Mass

m_{H} is not predicted by theory,
but constrained by precision
measurements in the SM: $m_{\mathrm{H}} = 94^{+29}_{-24}\,\mathrm{GeV}$

– m_{H} is important input to calculations
of cross-sections & branching fractions

- **precision measurement needed !**



Measurement @ LHC relies on
high-precision channels

$$\mathrm{H} \rightarrow \gamma\gamma \ \ \& \ \ \mathrm{H} \rightarrow \mathrm{ZZ} \rightarrow 4\ell$$

Now available: Combination of ATLAS & CMS results

(first task of LHC Higgs Combination Group, "LHC-HCG")

Method: combination at the level of mass distributions

– identify correlated uncertainties (i.e. the associated nuisance parameters)

– then profile combined likelihood for m_{H}

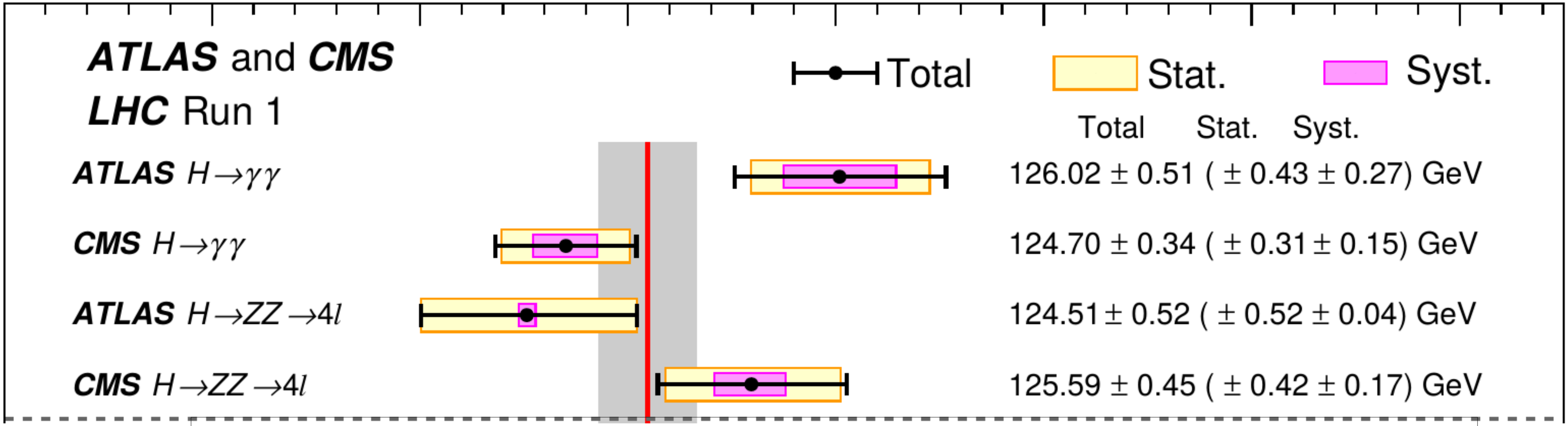
statistical and experimental systematic uncertainties (γ, e, μ energy scales) dominate

PRL 114 (2015) 191803

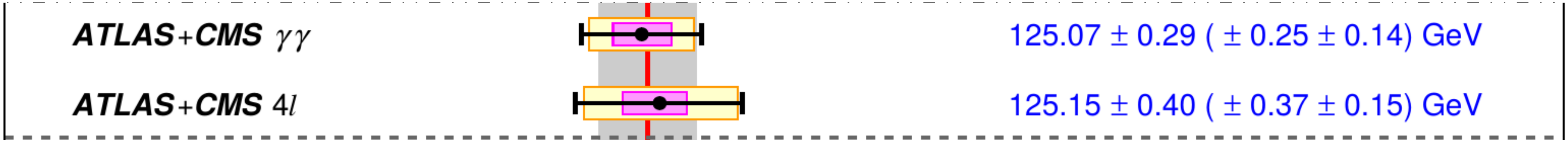
$$m_{\mathrm{H}} = 125.09 \pm 0.21_{(stat.)} \pm 0.11_{(scale)} \pm 0.02_{(other)} \pm 0.01_{(theory)}\ \mathrm{GeV}$$

correlated errors are negligible

ATLAS & CMS Higgs Mass Measurements

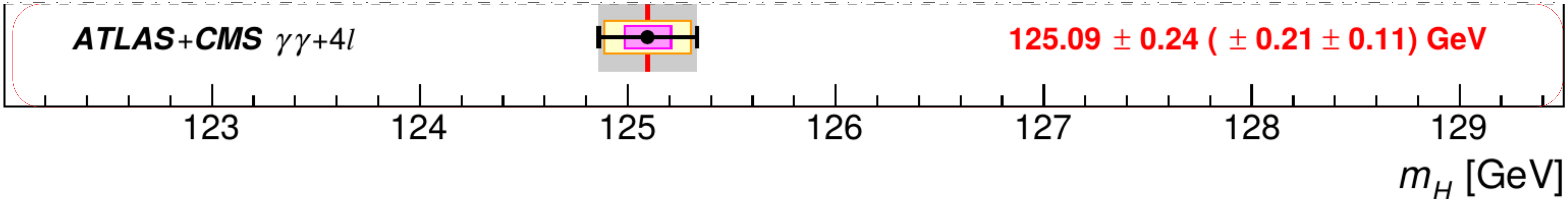


some “tension” between the four measurements (p-value ~10%)



approximate relative weights in average:

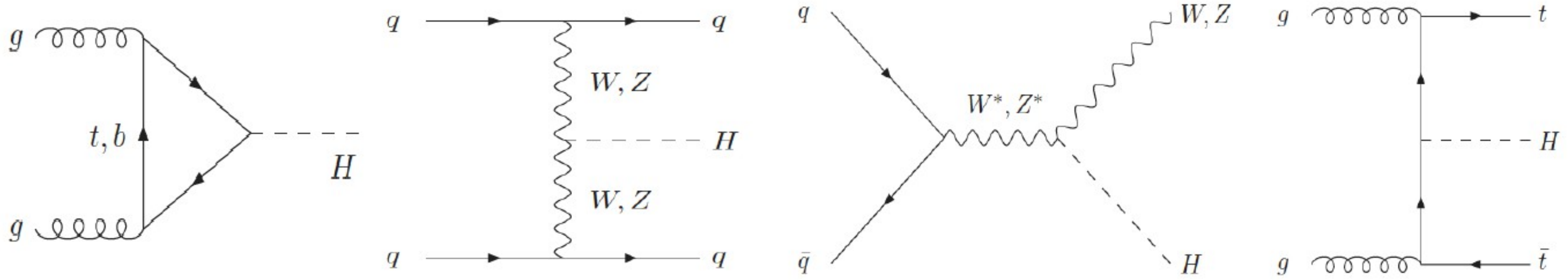
ATLAS H $\rightarrow\gamma\gamma$	19%
ATLAS H$\rightarrow 4\ell$	18%
CMS H$\rightarrow\gamma\gamma$	40%
CMS H$\rightarrow 4\ell$	23%



Couplings from Combination of ATLAS & CMS data

- **Combination of Measurements** of Higgs-Boson Production by ATLAS and CMS in

ggF **VBF** **W/Z H** **ttH**



production modes

in the decay Channels **H→ ZZ, γγ, WW, ττ** and **bb (**and μμ)

note: **γγ proceeds though W, t & b loop**

- individual results corrected to common Higgs-boson mass of 125.09 GeV (and latest theory predictions, common treatment of background models etc. in some cases)

- gain factor ~√2 in precision *w.r.t.* the individual results, as measurements are dominated by independent errors

Results are **preliminary**, see
– ATLAS-CONF-2015-044
– CMS-PAS-HIG-15-002
on the collaborations web sites
publication in preparation

Signal parametrisations

In the narrow width approximation, which decouples production and decay,

a measurement of **σ·Br** in the process *i* → H → *f* is characterised by

signal strength modifiers μ:

$$\mu_i^f = \frac{\sigma_i}{(\sigma_i)_{\mathrm{SM}}} \cdot \frac{\mathrm{Br}^f}{(\mathrm{Br}^f)_{\mathrm{SM}}} = \mu_i \cdot \mu^f$$

i = ggF, VBF, VH, ttH, … , *f = bb, WW, gg, ττ, cc, ZZ, γγ, Zγ,μμ*

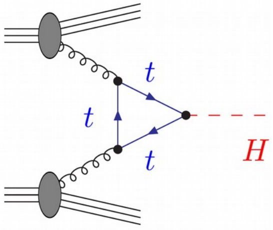
Or, at (LO) coupling level, introduce

coupling modifiers κ:

$$\sigma_i \cdot \mathrm{Br}^f = \frac{\sigma_i(\{\kappa\}) \cdot \Gamma^f(\{\kappa\})}{\Gamma_H(\{\kappa\})}$$

alternatively:

loops resolved to contributing particles, *e.g.* ggF:



$$\kappa_g^2 \simeq 1.06\kappa_t^2 + 0.01\kappa_b^2 - 0.07\kappa_t\kappa_b$$

$$\kappa_i^2 = \frac{\sigma_j}{\sigma_i^{\mathrm{SM}}} \text{ or } \kappa_f^2 = \frac{\Gamma^f}{\Gamma^f_{\mathrm{SM}}}$$

$$\kappa_H^2 = \frac{\Gamma_H}{\Gamma_H^{\mathrm{SM}}}$$

SM particles only:

$$\kappa_H^2 = \sum_f \mathrm{Br}^f_{\mathrm{SM}} \kappa_f^2$$

with BSM-contributions:

$$\Gamma_H = \kappa_H^2 \frac{\Gamma_H^{\mathrm{SM}}}{(1 - \mathrm{Br}_{\mathrm{BSM}})}$$

as a reminder: H Production and Decay in κ- Framework

Production	Loops	Interference	Multiplicative factor
$\sigma(ggF)$	✓	$b-t$	$\kappa_g^2 \sim 1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$
$\sigma(VBF)$	–	–	$\sim 0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	–	–	$\sim \kappa_W^2$
$\sigma(qq/qg \to ZH)$	–	–	$\sim \kappa_Z^2$
$\sigma(gg \to ZH)$	✓	$Z-t$	$\sim 2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t$
$\sigma(ttH)$	–	–	$\sim \kappa_t^2$
$\sigma(gb \to WtH)$	–	$W-t$	$\sim 1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t \kappa_W$
$\sigma(qb \to tHq)$	–	$W-t$	$\sim 3.4 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t \kappa_W$
$\sigma(bbH)$	–	–	$\sim \kappa_b^2$
Partial decay width			
Γ^{ZZ}	–	–	$\sim \kappa_Z^2$
Γ^{WW}	–	–	$\sim \kappa_W^2$
$\Gamma^{\gamma\gamma}$	✓	$W-t$	$\kappa_\gamma^2 \sim 1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$
$\Gamma^{\tau\tau}$	–	–	$\sim \kappa_\tau^2$
Γ^{bb}	–	–	$\sim \kappa_b^2$
$\Gamma^{\mu\mu}$	–	–	$\sim \kappa_\mu^2$
Total width for $BR_{BSM} = 0$			
Γ_H	✓	–	$\kappa_H^2 \sim 0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 +$ $+ 0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 +$ $+ 0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{Z\gamma}^2 +$ $+ 0.0001 \cdot \kappa_s^2 + 0.00022 \cdot \kappa_\mu^2$

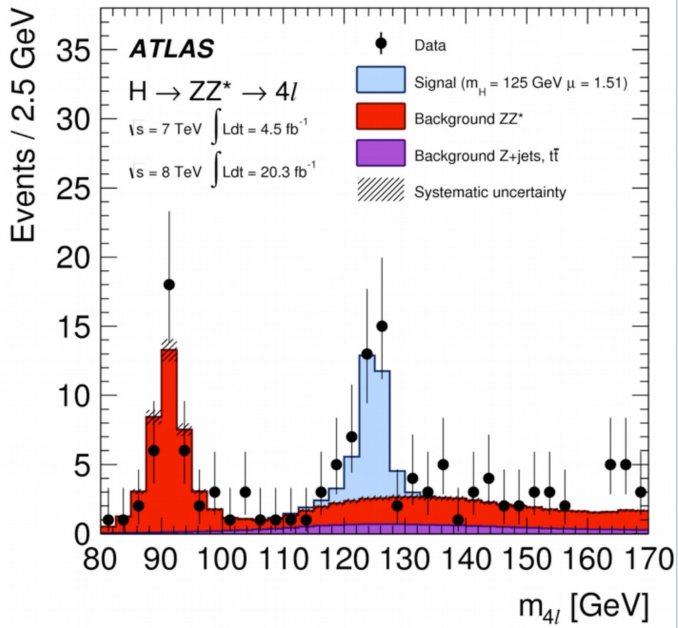
Combination Procedure

Construct combined likelihood of all measurements, each measurement consisting of

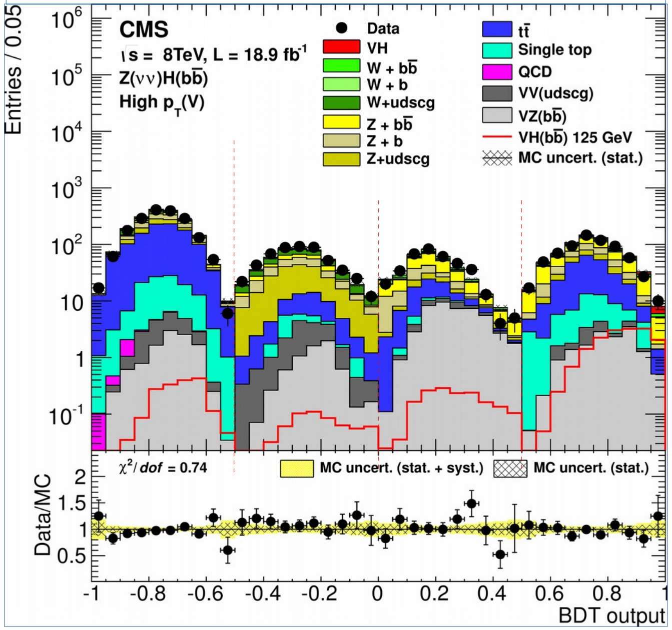
- one or more signal regions, designed to select Higgs production mode *i* and decay channel *f*
  often further broken down to different "categories" (e.g. low or high p_T)
- distribution of a (multivariate) discriminant, composed of signal and a large number of background contributions

Examples:

ZZ*: low background, high mass resolution



VH(bb): large background, worse resolution



Input Channels for Combination

Decay / Production f / i	untagged mainly ggF	VBF	VH	ttH
H→ ZZ	√	√	√	√
H→ $\gamma\gamma$	√	√	√	√
H→WW→ $2\ell 2\nu$	√	√	√	√
H→$\tau\tau$	√	√	√	√
H→ bb	*large bkg.*		√	√
H→ $\mu\mu$	(√)	(√)	*very low rate*	
H→ inv.	not included in combination			

CMS VBV H(bb) came too late for combination

some other production modes not explicitly selected, but their contribution is included in the signal model *(e.g. tHq and tHW picked up by ttH analyses)*

O(100) categories *C* per experiment with number of signal events n_s given by

$$n_s^C = L^C \times \sum_i \sum_f \mu_i \, \sigma_i^{(SM)} \times \mu_f \mathrm{Br}_f^{(SM)} \times A_{if}^C \times \epsilon_{if}^C$$

i: production process, f : final state, L: integ. luminosity, A: acceptance, ε : efficiency

Note: typically, many production channels contribute to a category, while the decay channels can be identified cleanly

Treatment of systematics

Sources of systematic errors are treated as nuisance parameters in profile likelihood formalism

- already used for combination within each experiment

The challenge addressed by LHC-HCG:

- identify common errors between ATLAS & CMS
- ensure common treatment

→ individual measurements were adjusted prior to the combination

(same Higgs mass, latest theory predictions, common background models etc.)

Example of common error:

$$\begin{array}{lll} \mathcal{L} = & \mathcal{L}_{\mathrm{A,ZZ^*}}(\vec{\alpha}, \theta_{\mathrm{Adet}}, \theta_{\mathrm{QCDscale}}, \theta_{\ldots}) \times & \ldots \\ & \ldots & \mathcal{L}_{\mathrm{C,WW^*}}(\vec{\alpha}, \theta_{\mathrm{Cdet}}, \theta_{\mathrm{QCDscale}}, \theta_{\ldots}) \times \\ & \ldots & \mathcal{L}_{\mathrm{A,VH(bb)}}(\vec{\alpha}, \theta_{\mathrm{Cdet}}, \theta_{\mathrm{QCDscale}}, \theta_{\ldots}) \times \\ & \ldots & \ldots \end{array}$$

θ_{Adet} *correlated within ATLAS*

θ_{Cdet} *correlated within CMS*

$\theta_{\mathrm{QCDscale}}$ *correlated between ATLAS & CMS*

Full ATLAS and CMS combination:

- ~580 signal and control regions (ATLAS and CMS)
- ~4200 nuisance parameters related to systematic uncertainties

Parametrisation as ratios of σ and Br

with **minimal assumptions**, express all measured Higgs production rates as

not dependent on Γ_H, exp. & theor. systematics largely cancel

$$\sigma_i \cdot \mathrm{BR}^f = \sigma(gg \rightarrow H \rightarrow ZZ) \times \left(\frac{\sigma_i}{\sigma_{ggF}}\right) \times \left(\frac{\mathrm{BR}^f}{\mathrm{BR}^{ZZ}}\right)$$

with gg→H→ZZ as the reference channel *(cleanest, smallest systematics)*

The 9 parameters of the σ and Br ratio model

$$\sigma(gg \rightarrow H \rightarrow ZZ)$$

$$\sigma_{VBF}/\sigma_{ggF}$$

$$\sigma_{WH}/\sigma_{ggF}$$

$$\sigma_{ZH}/\sigma_{ggF}$$

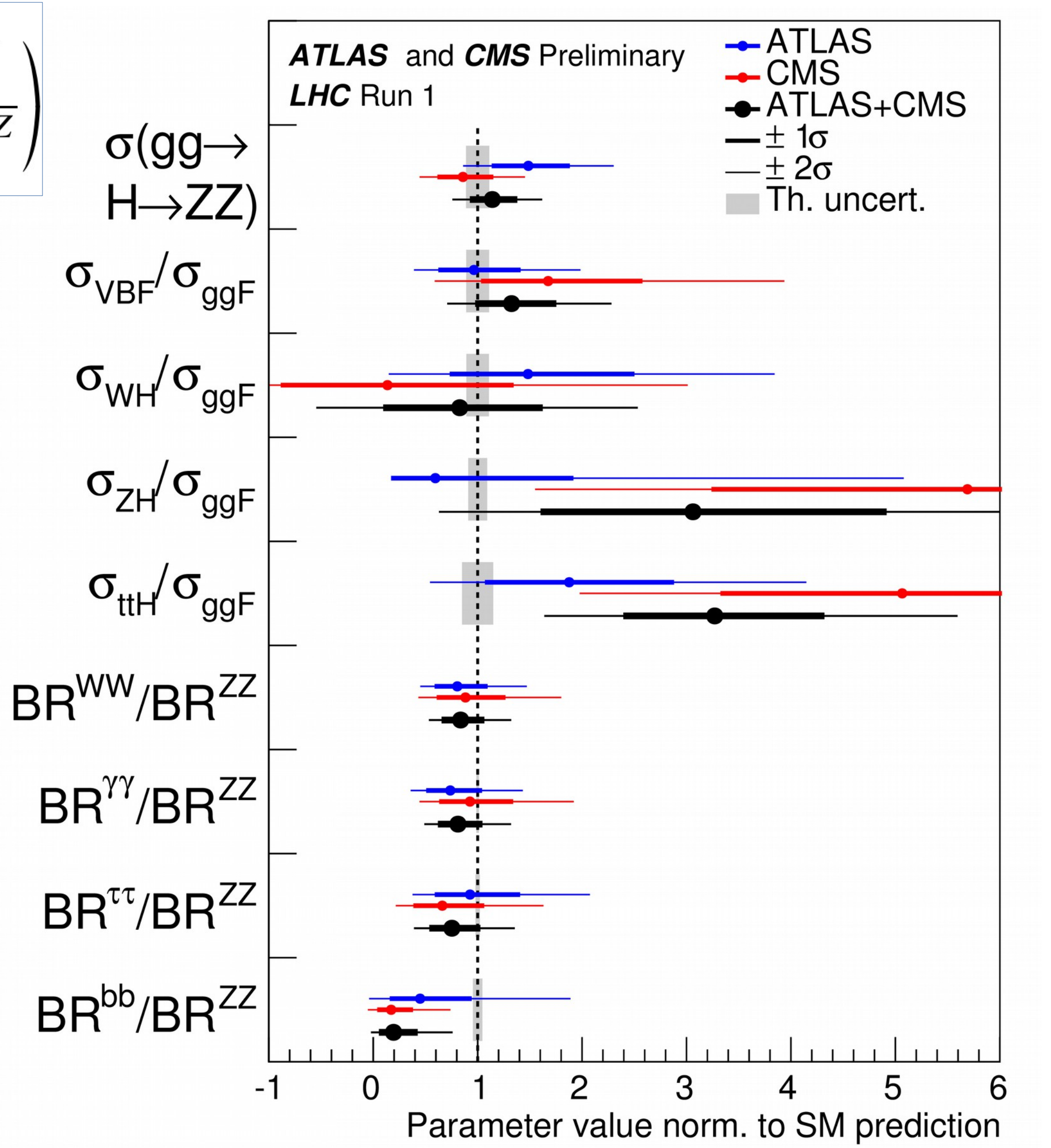
$$\sigma_{ttH}/\sigma_{ggF}$$

$$\mathrm{BR}^{WW}/\mathrm{BR}^{ZZ}$$

$$\mathrm{BR}^{\gamma\gamma}/\mathrm{BR}^{ZZ}$$

$$\mathrm{BR}^{\tau\tau}/\mathrm{BR}^{ZZ}$$

$$\mathrm{BR}^{bb}/\mathrm{BR}^{ZZ}$$



towards legacy representation of LHC Higgs results

presently missing piece : correlation matrix **(expected for publication)**

Result of σ and Br model

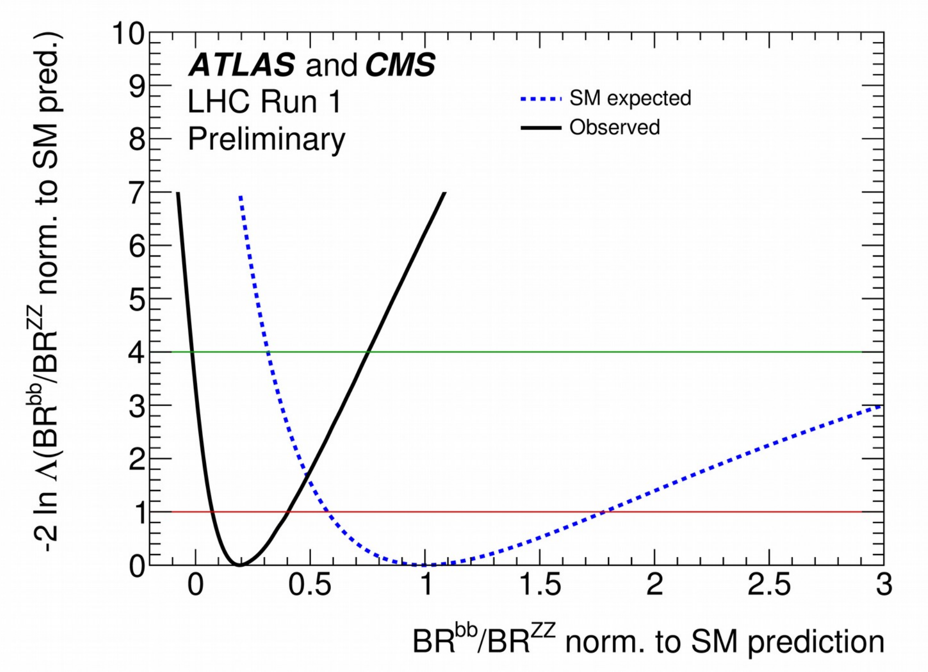
- consistent with SM value of 1
- largest discrepancy of ~2.4 σ in Br^{bb} / Br^{ZZ}

  but:

  – denominator > SM due to ttH → leptons & σ_{ZH}

  – numerator <SM due to small VH(bb)

  negLog $\mathcal{L}$ is strongly non-Gaussian:

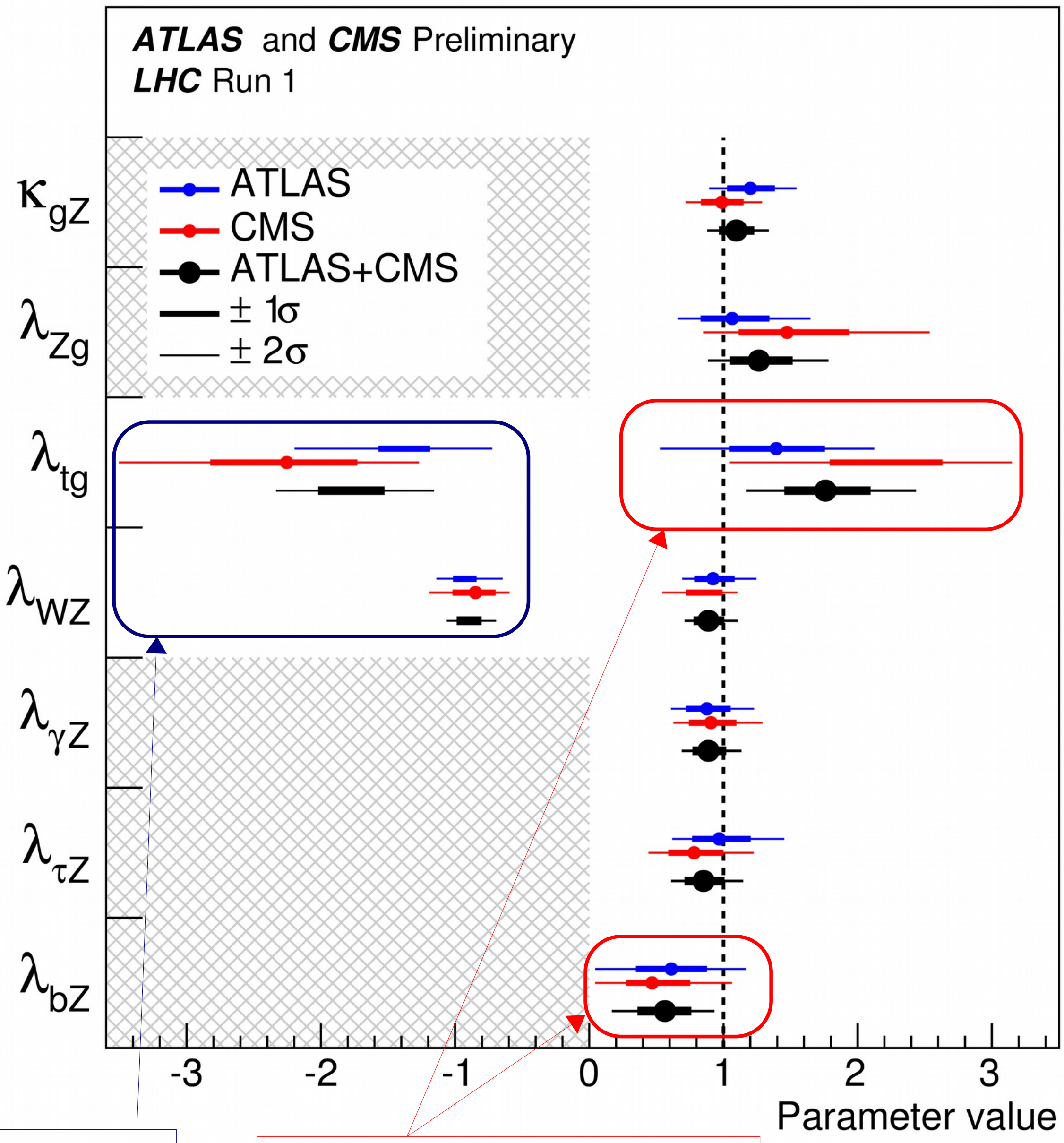


Alternative: coupling-strength ratios

7 parameters of the κ ratio model

$$\kappa_{gZ} = \kappa_g \cdot \kappa_Z / \kappa_H$$
$$\lambda_{Zg} = \kappa_Z / \kappa_g$$
$$\lambda_{tg} = \kappa_t / \kappa_g$$
$$\lambda_{WZ} = \kappa_W / \kappa_Z$$
$$\lambda_{\gamma Z} = \kappa_\gamma / \kappa_Z$$
$$\lambda_{\tau Z} = \kappa_\tau / \kappa_Z$$
$$\lambda_{bZ} = \kappa_b / \kappa_Z$$

not dependent on Γ_H, many exp. and theor. systematic errors cancel



sign ambiguities

same features as previously discussed

Overall Signal Strength μ

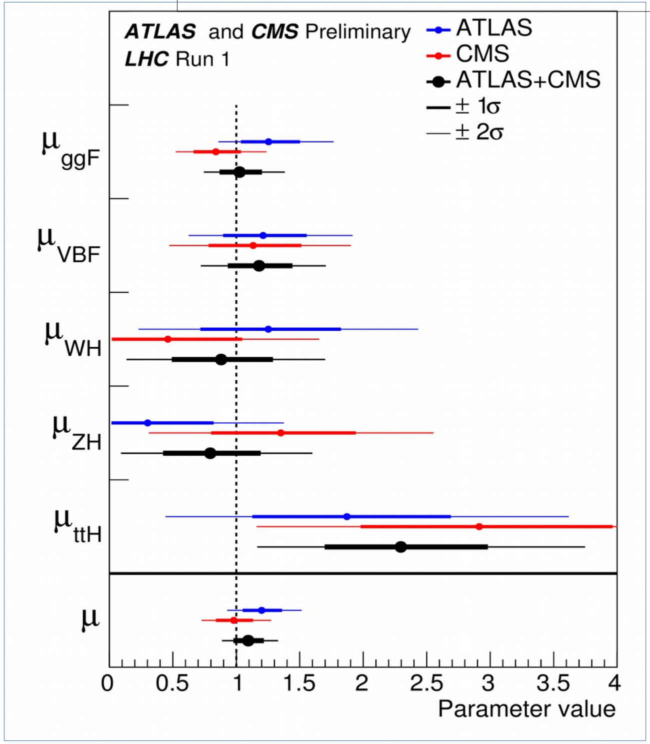
only one fit parameter

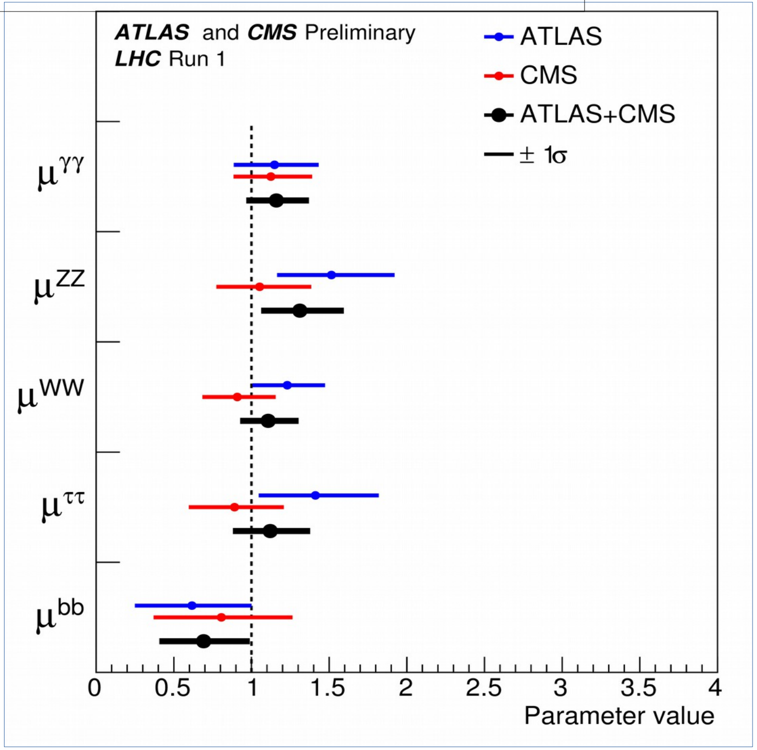
assumption: $\mu_i = \mu_f := \mu$

$$\boxed{\mu = 1.09^{+0.11}_{-0.10}} = 1.09^{+0.07}_{-0.07}\,(\text{stat})\;^{+0.04}_{-0.04}\,(\text{expt})\;^{+0.03}_{-0.03}\,(\text{thbgd})^{+0.07}_{-0.06}\,(\text{thsig})$$

most precise measurement, theoretical error as large as the statistical one !

μ_i & μ^f





- VBF production and H → ττ now at S > 5σ
- excess over SM in ttH to be watched !
- largest decay channel (H → bb) still at S< 3σ

Fermion- and Boson-mediated production modes

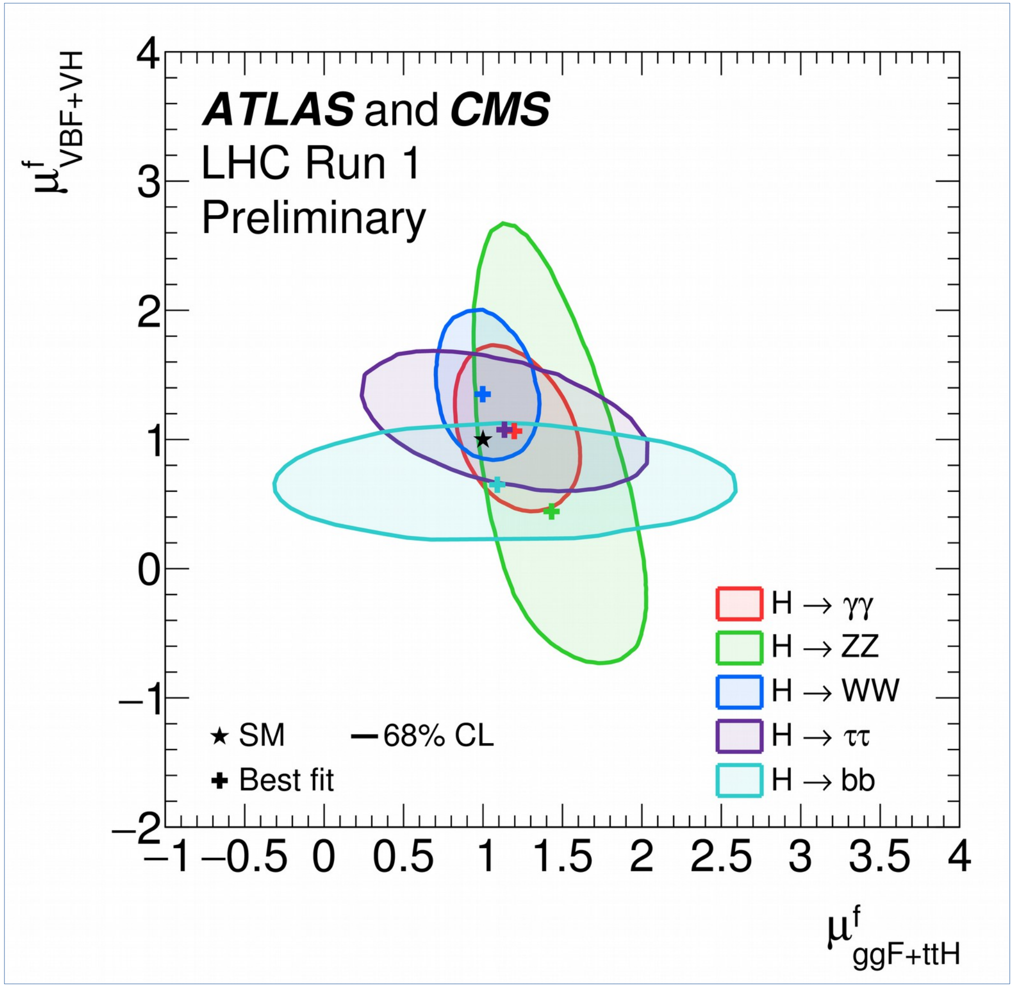
two fit parameters for each decay channel f

assumption: $\mu^f_{\mathrm{VBF}} = \mu^f_{\mathrm{VH}}$ and $\mu^f_{\mathrm{ttH}} = \mu^f_{\mathrm{ggF}}$

boson fermion

mediated

$$\mu_V \text{ and } \mu_F$$



fitting for the ratio yields:

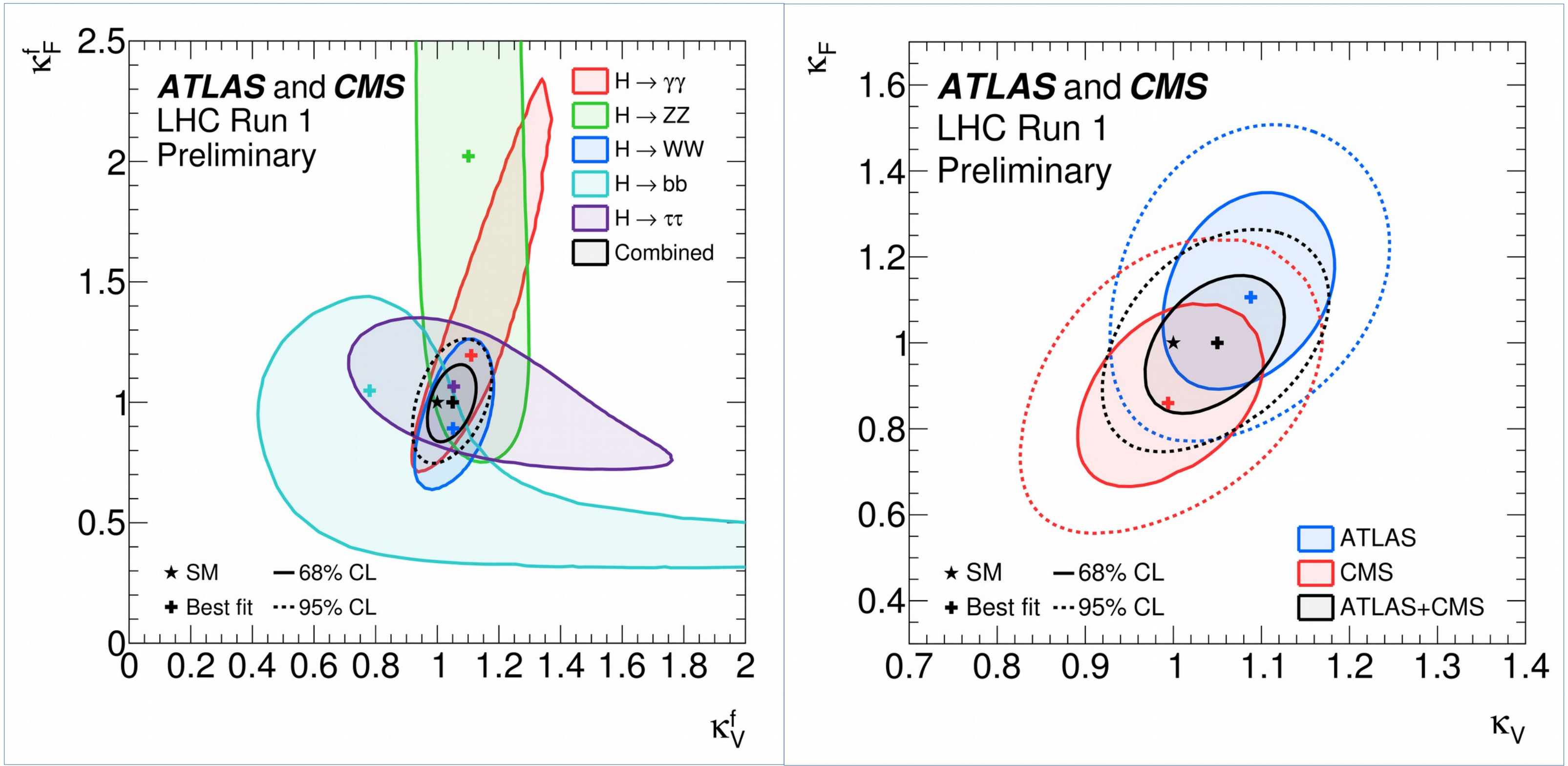
$$\frac{\mu_V}{\mu_F} = 1.06^{+0.35}_{-0.27}$$

method independent of assumptions on Br's

H Couplings to Fermions and Bosons

1. assume universal scaling factors for couplings to fermions and bosons: κ_F and κ_V
2. only SM physics in loops

$$\kappa_F \text{ and } \kappa_V$$



Channels & Experiments consistent among each other and with SM expectation

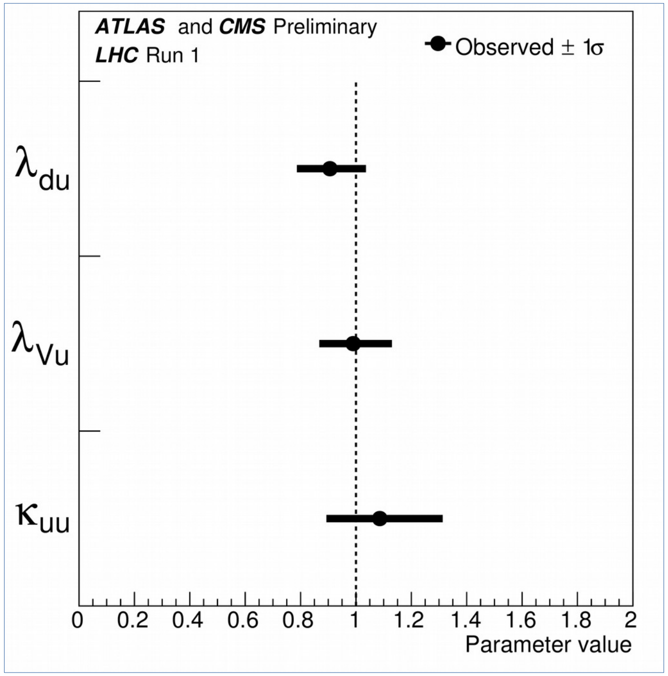
Fermion couplings

κ_d and κ_u

up- and down-type fermions

assume universal coupling modifiers
for up-type and down-type fermions separately

$$\lambda_{\mathrm{du}} = \frac{\kappa_{\mathrm{d}}}{\kappa_{\mathrm{u}}}, \; \lambda_{\mathrm{Vu}} = \frac{\kappa_{\mathrm{V}}}{\kappa_{\mathrm{u}}}, \; \kappa_{\mathrm{uu}} = \frac{\kappa_{\mathrm{u}} \cdot \kappa_{\mathrm{u}}}{\kappa_{\mathrm{H}}}$$

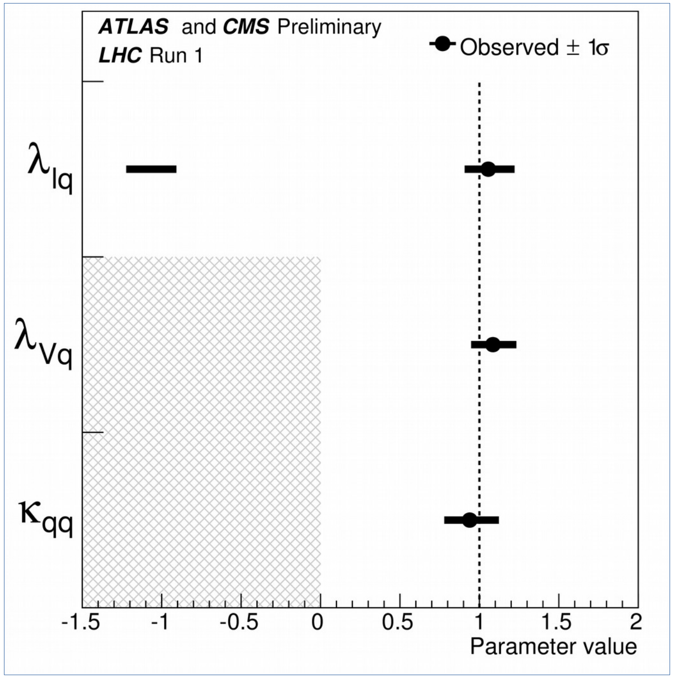


κ_ℓ and κ_q

leptons and quarks

assume universal coupling modifiers
for leptons and quarks separately

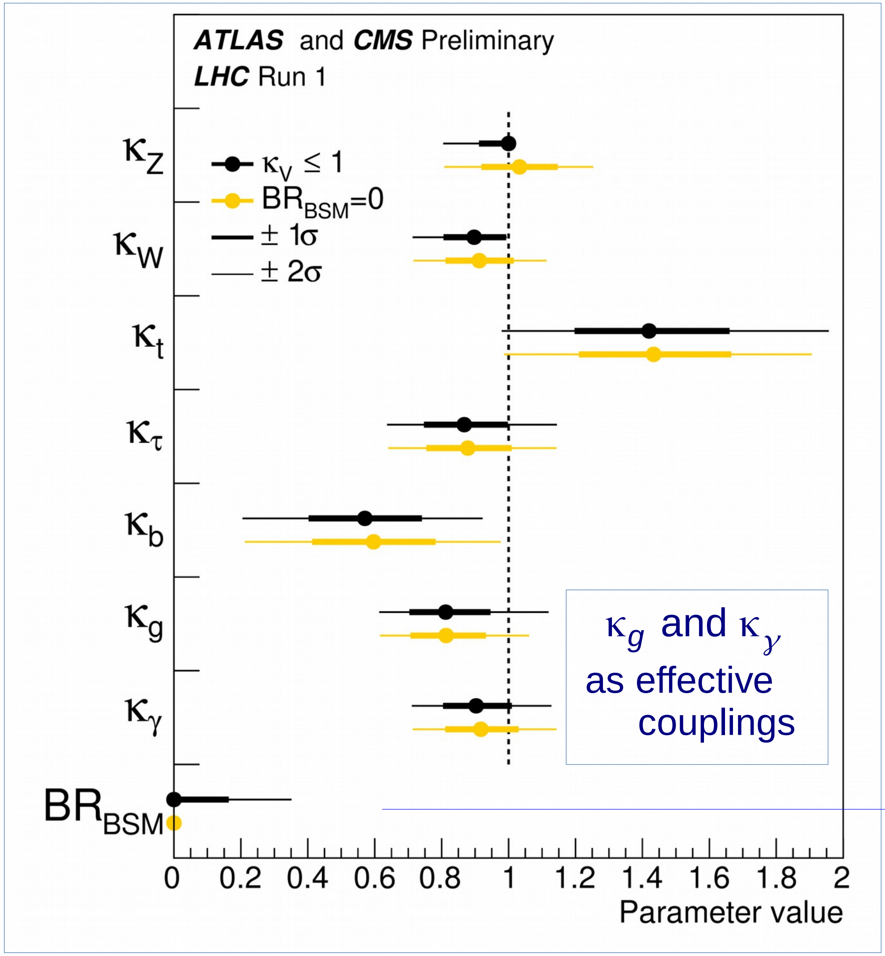
$$\lambda_{\ell\mathrm{u}} = \frac{\kappa_{\ell}}{\kappa_{\mathrm{q}}}, \; \lambda_{\mathrm{Vq}} = \frac{\kappa_{\mathrm{V}}}{\kappa_{\mathrm{q}}}, \; \kappa_{\mathrm{qq}} = \frac{\kappa_{\mathrm{q}} \cdot \kappa_{\mathrm{q}}}{\kappa_{\mathrm{H}}}$$



Beyond SM ?

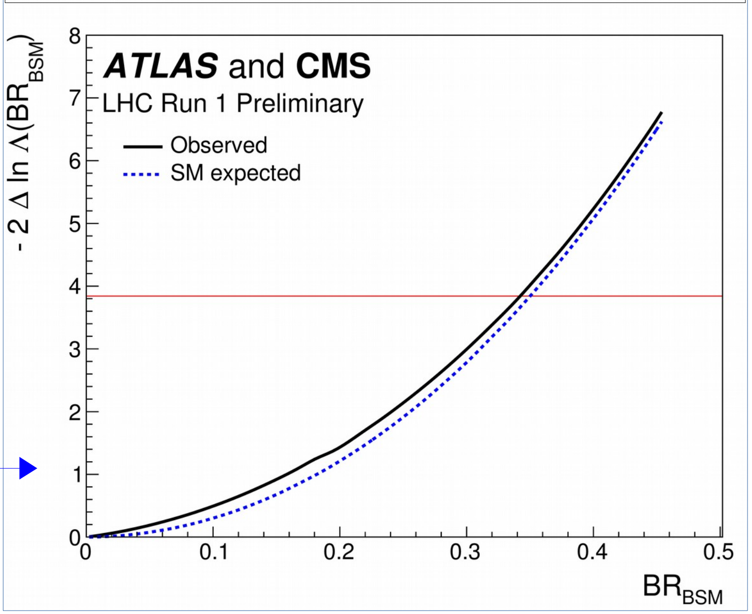
Total Higgs boson width depends on invisible (or undetected) H decays, but not known precisely enough experimentally.

Alternative: assume $\kappa_W < 1$ and $\kappa_Z < 1$ ⇒ (some) sensitivity to Br_{BSM}



κ_g and κ_γ as effective couplings

profile likelihood scan of Br_{BSM}



$Br_{BSM} < 0.34$ @ 95% C.L.

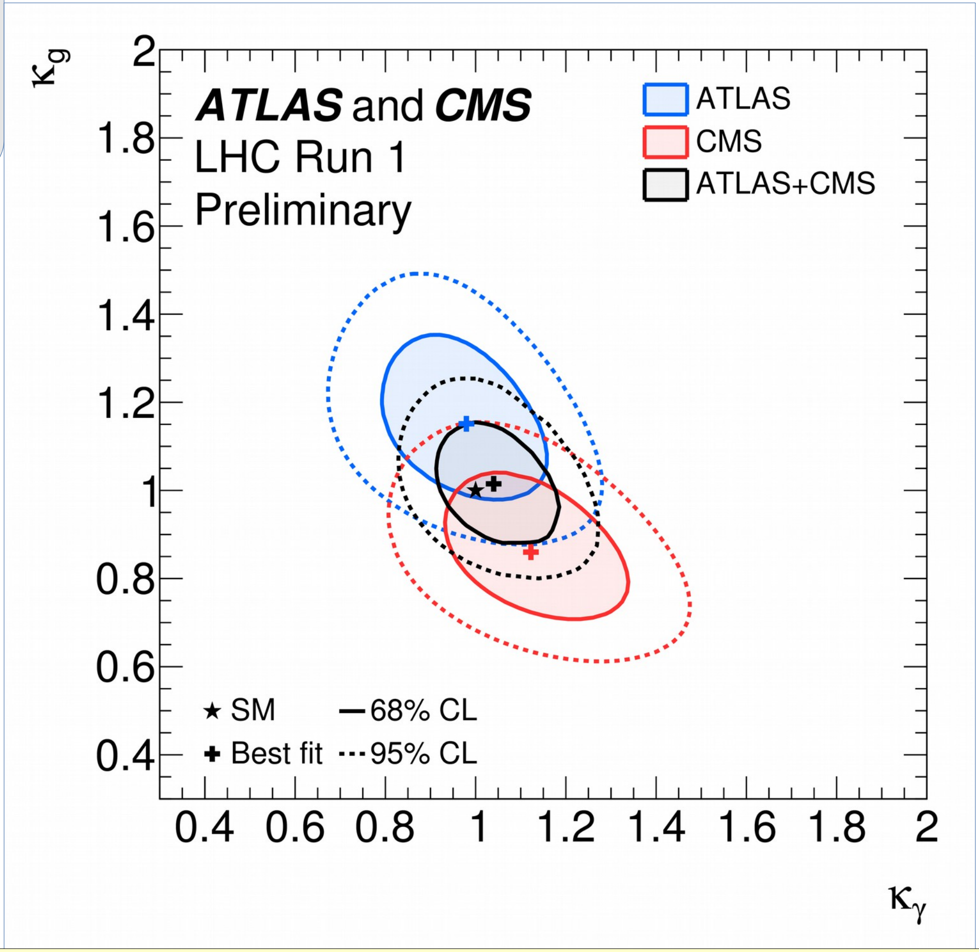
Physics beyond SM in loops ?

$$\kappa_g \text{ and } \kappa_\gamma$$

Test for new physics in loops in ggF and H→γγ:

assume $_{BSM} = 0$ and $\kappa_i = 1$

new physics my enter through effective couplings κ_γ and κ_g

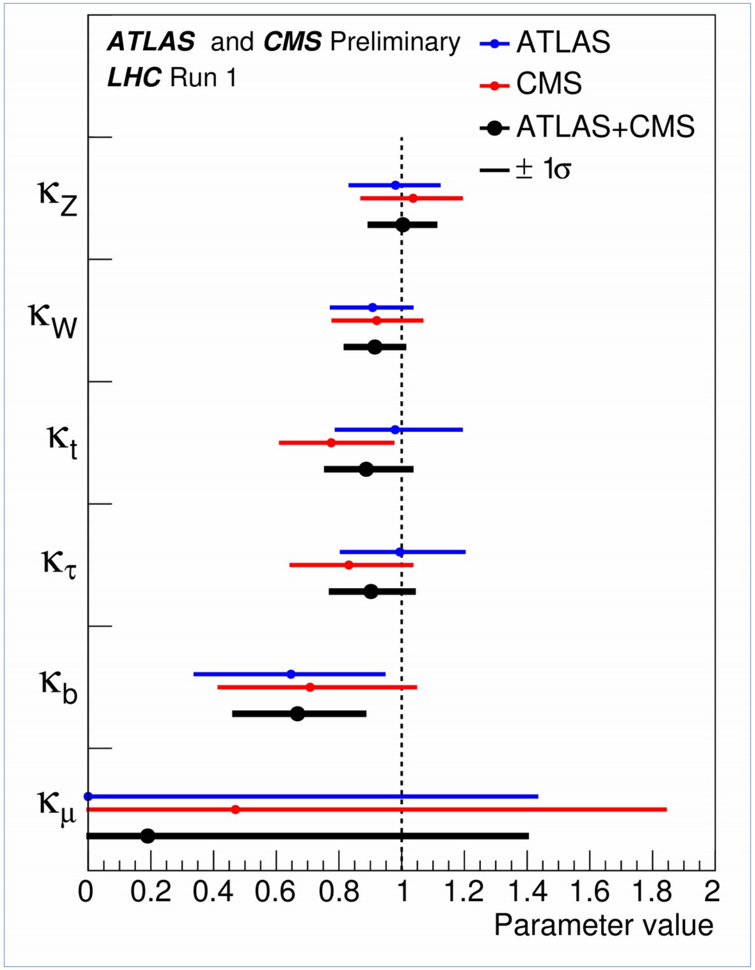


p-value for compatibility of data and SM is 82%

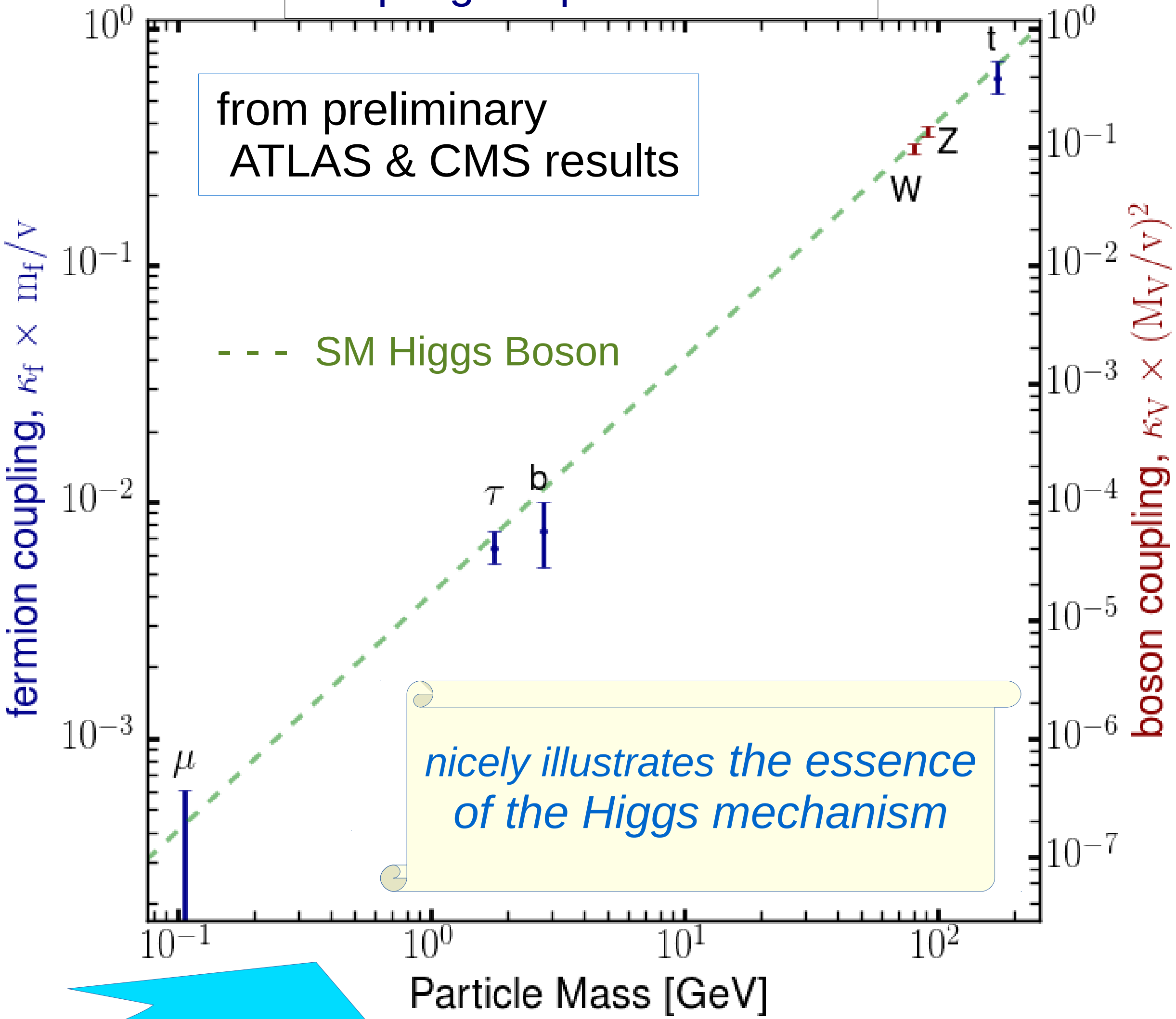
Higgs Couplings (in SM)

Assumption: No other than SM particles couple to Higgs boson, $Br_{BSM} = 0$

remark: low value of κ_b reduces total width Γ_H ⇒ **all κ_i come out a bit low**



coupling vs. particle mass



from preliminary ATLAS & CMS results

nicely illustrates the essence of the Higgs mechanism

transform

Conclusion, Summary & Outlook

- **H(125)** is (so far) the only one of its kind
- Combination of ATLAS & CMS measurements from LHC run 1

  reaches a new level of precision: ~√2 better than individual ones
  ⇒ constraints on couplings at the level of ~10%
- tests of relations between Higgs couplings to SM particles
  show no significant deviations from SM predictions

LHC run 2 @ 13 TeV just started **(need patience ...)**

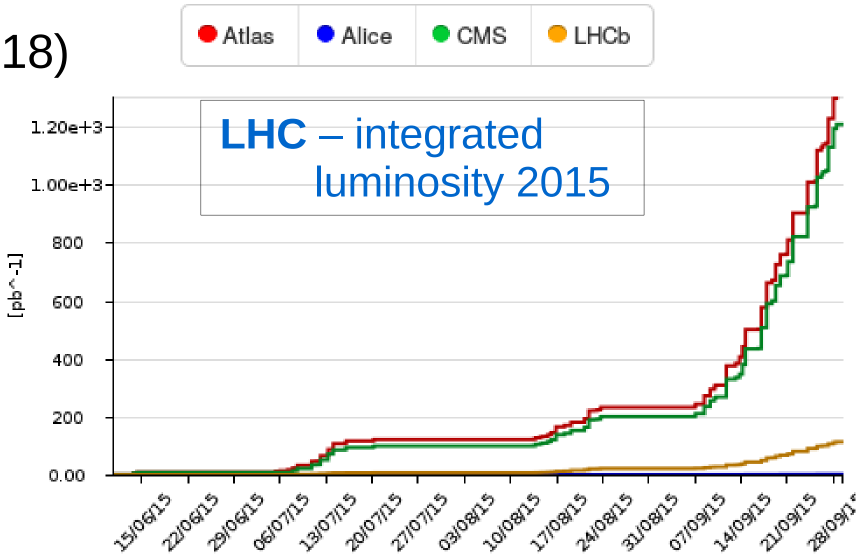
– higher energy (~2 x larger parton luminosity),

– larger integrated luminosity (~30fb^{-1}/y in 2016/'17/'18)

– progress in precision of theoretical calculations
– and the ability to go beyond the κ-framework
will allow more stringent tests of H couplings

expect factor ~3 higher precision on H rates

Some obvious immediate tasks remain, *e.g.*
- clarify excess in ttH production
- measure H→bb



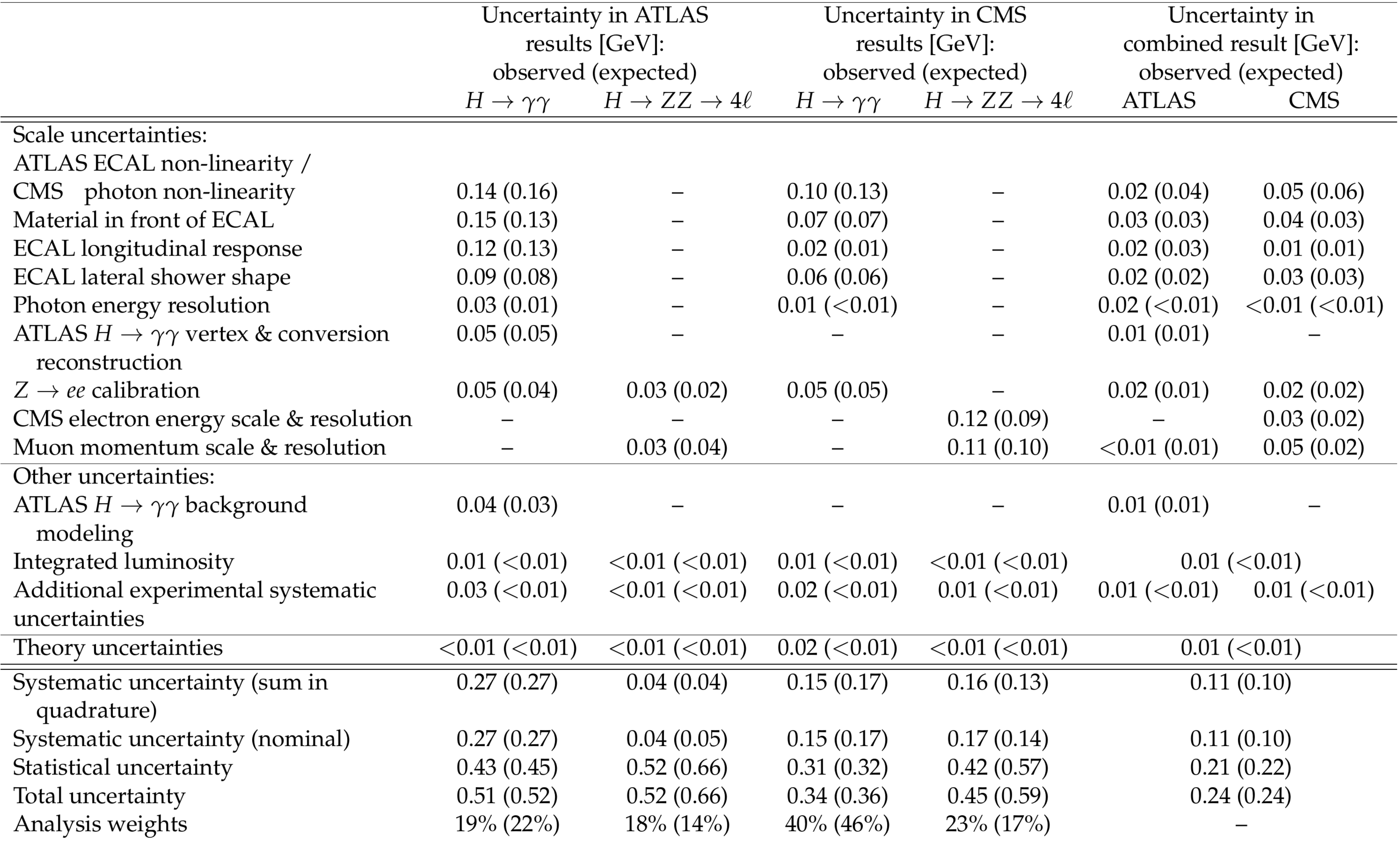
LHC – integrated luminosity 2015

Searches for additional Higgs Bosons (in (N)MSSM and more general models)
may see something sooner !

Keep eyes open !

Backup Material

Systematic Errors in H Mass Determination

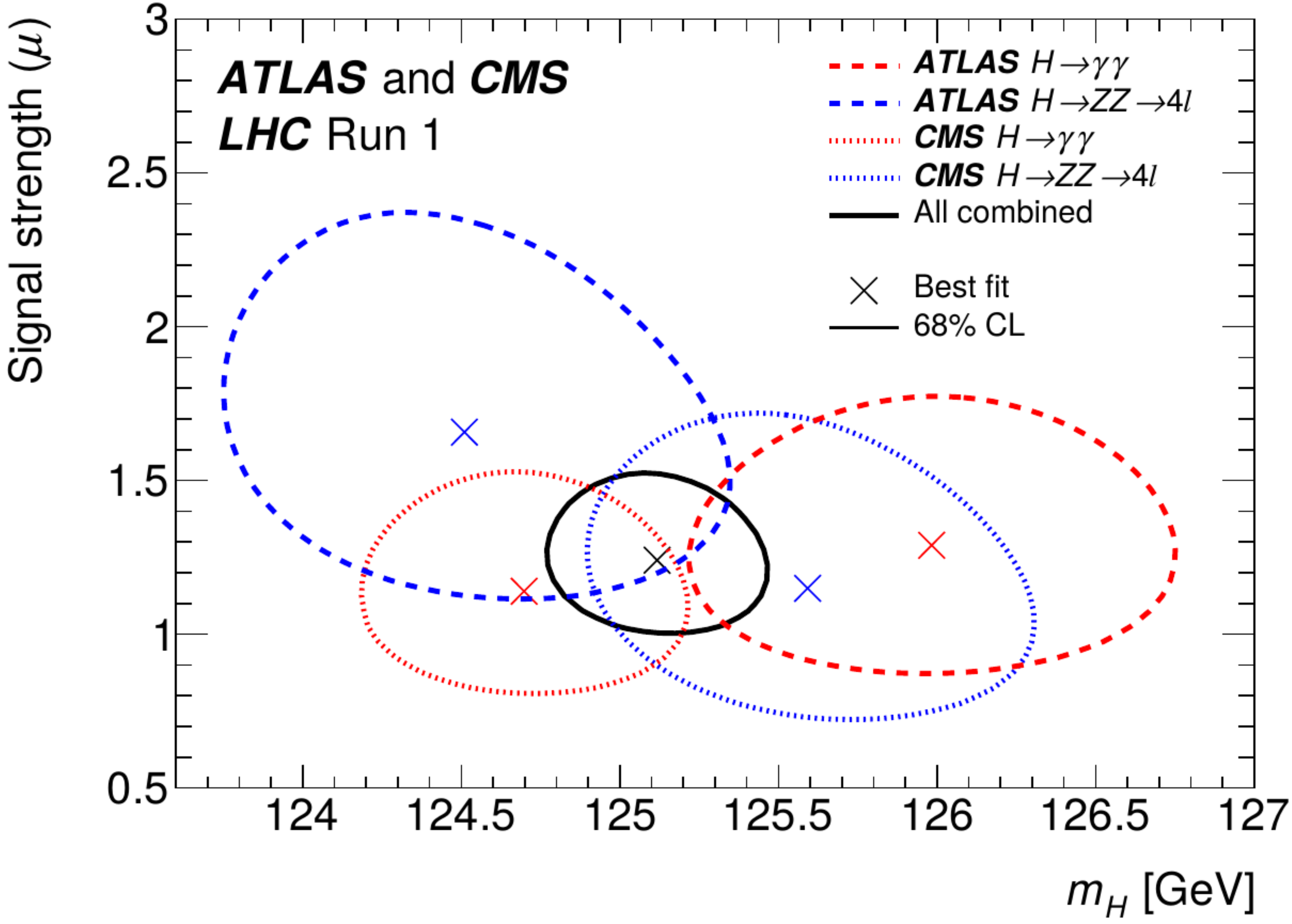


	Uncertainty in ATLAS results [GeV]: observed (expected)		Uncertainty in CMS results [GeV]: observed (expected)		Uncertainty in combined result [GeV]: observed (expected)	
	$H \rightarrow \gamma\gamma$	$H \rightarrow ZZ \rightarrow 4\ell$	$H \rightarrow \gamma\gamma$	$H \rightarrow ZZ \rightarrow 4\ell$	ATLAS	CMS
Scale uncertainties:						
ATLAS ECAL non-linearity / CMS photon non-linearity	0.14 (0.16)	–	0.10 (0.13)	–	0.02 (0.04)	0.05 (0.06)
Material in front of ECAL	0.15 (0.13)	–	0.07 (0.07)	–	0.03 (0.03)	0.04 (0.03)
ECAL longitudinal response	0.12 (0.13)	–	0.02 (0.01)	–	0.02 (0.03)	0.01 (0.01)
ECAL lateral shower shape	0.09 (0.08)	–	0.06 (0.06)	–	0.02 (0.02)	0.03 (0.03)
Photon energy resolution	0.03 (0.01)	–	0.01 (<0.01)	–	0.02 (<0.01)	<0.01 (<0.01)
ATLAS $H \rightarrow \gamma\gamma$ vertex & conversion reconstruction	0.05 (0.05)	–	–	–	0.01 (0.01)	–
$Z \rightarrow ee$ calibration	0.05 (0.04)	0.03 (0.02)	0.05 (0.05)	–	0.02 (0.01)	0.02 (0.02)
CMS electron energy scale & resolution	–	–	–	0.12 (0.09)	–	0.03 (0.02)
Muon momentum scale & resolution	–	0.03 (0.04)	–	0.11 (0.10)	<0.01 (0.01)	0.05 (0.02)
Other uncertainties:						
ATLAS $H \rightarrow \gamma\gamma$ background modeling	0.04 (0.03)	–	–	–	0.01 (0.01)	–
Integrated luminosity	0.01 (<0.01)	<0.01 (<0.01)	0.01 (<0.01)	<0.01 (<0.01)	0.01 (<0.01)	
Additional experimental systematic uncertainties	0.03 (<0.01)	<0.01 (<0.01)	0.02 (<0.01)	0.01 (<0.01)	0.01 (<0.01)	0.01 (<0.01)
Theory uncertainties	<0.01 (<0.01)	<0.01 (<0.01)	0.02 (<0.01)	<0.01 (<0.01)	0.01 (<0.01)	
Systematic uncertainty (sum in quadrature)	0.27 (0.27)	0.04 (0.04)	0.15 (0.17)	0.16 (0.13)	0.11 (0.10)	
Systematic uncertainty (nominal)	0.27 (0.27)	0.04 (0.05)	0.15 (0.17)	0.17 (0.14)	0.11 (0.10)	
Statistical uncertainty	0.43 (0.45)	0.52 (0.66)	0.31 (0.32)	0.42 (0.57)	0.21 (0.22)	
Total uncertainty	0.51 (0.52)	0.52 (0.66)	0.34 (0.36)	0.45 (0.59)	0.24 (0.24)	
Analysis weights	19% (22%)	18% (14%)	40% (46%)	23% (17%)	–	

in parantheses: errors expected fom pre-fit Asimov dataset

Higgs Boson Mass (2)

Result of 2D-Likelihod scan with signal strength as additional parameter ...



… illustrates consistencies between

– ATLAS and CMS

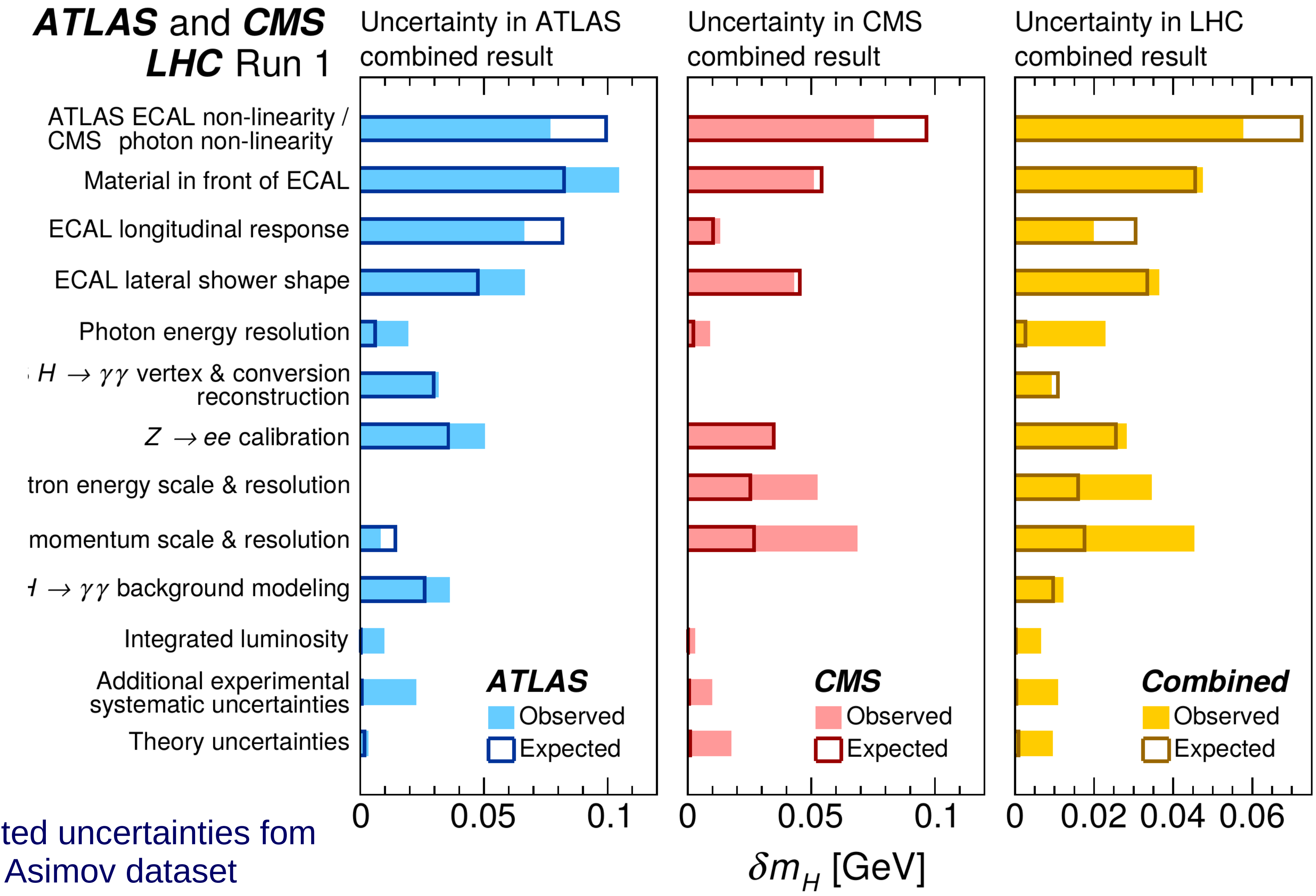
– ZZ and γγ channels

Combination of Couplings in all Channels

Mass combination was the test case for the more complex combinations

Systematic errors and their treatment in common fits carefully studied

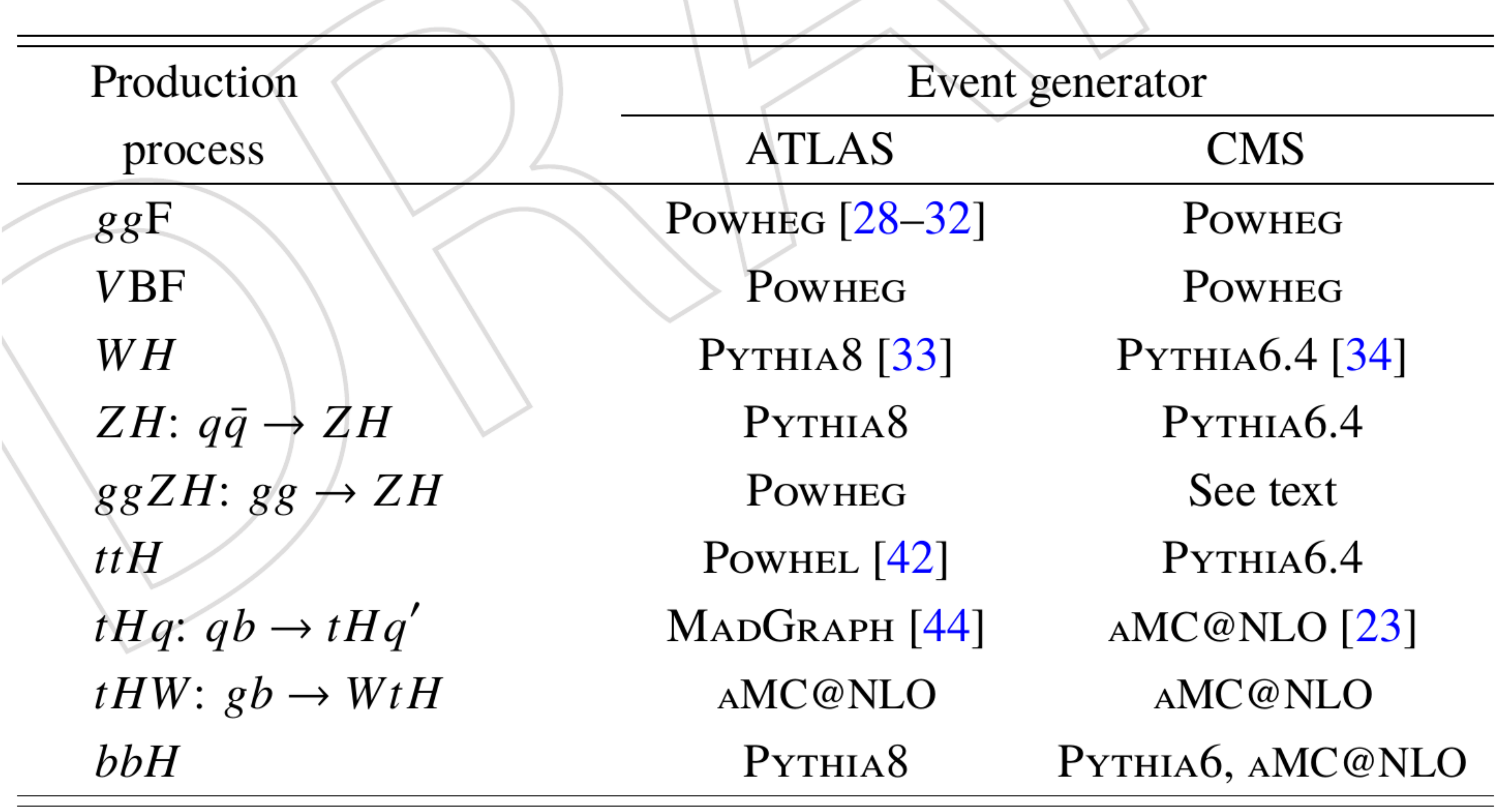
Example: shift in m_H seen in parameter variation by $\pm 1\sigma$



expected uncertainties fom
pre-fit Asimov dataset

Event Generators

Summary of event generators used to model
Higgs boson production and decays
in the ATLAS and CMS experiments.



Production process	Event generator	
	ATLAS	CMS
ggF	Powheg [28–32]	Powheg
VBF	Powheg	Powheg
WH	Pythia8 [33]	Pythia6.4 [34]
ZH: $q\bar{q} \to ZH$	Pythia8	Pythia6.4
$ggZH$: $gg \to ZH$	Powheg	See text
ttH	Powhel [42]	Pythia6.4
tHq: $qb \to tHq'$	MadGraph [44]	aMC@NLO [23]
tHW: $gb \to WtH$	aMC@NLO	aMC@NLO
bbH	Pythia8	Pythia6, aMC@NLO

Adjustments to ATLAS and CMS inputs

Adjustments made to individual ATLAS and CMS measurements prior to combination:

- All ATLAS & CMS channels modified to assume a Higgs boson mass of 125.09 GeV (the value of the combined mass)
- CMS includes bbH, tH, ggZH production processes, where relevant
- ATLAS now uses Stewart-Tackman prescription of jet-bin uncertainties for the H → WW channel (⇒ understandable correlations with CMS)
- CMS adopts signal cross-section calculations from YR3 for all channels
- CMS adopts unified prescription of treatment of Higgs boson p_T
- Cross section values for dominant backgrounds estimated from simulation harmonised between ATLAS & CMS
- ATLAS & CMS adopted same correlation scheme for theory uncertainties on signal

Statistical Method

developed jointly by ATLAS and CMS, used also for the individual combinations

Central values and confidence intervals of **parameters of interest** (α) are estimated using the **profile likelihood ratio** as the test statistic.

Likelihood $\mathcal{L}$ is constructed from products of probability density functions of signal and background distributions

experimental and theoretical uncertainties represented by a set of "**nuisance parameters**" (θ)

$$\Lambda(\vec{\alpha}) = \frac{\mathcal{L}\left(\vec{\alpha}, \hat{\vec{\theta}}_{\alpha}(\vec{\alpha})\right)}{\mathcal{L}(\hat{\vec{\alpha}}, \hat{\vec{\theta}})}$$

conditional minimum for given α

global minimum

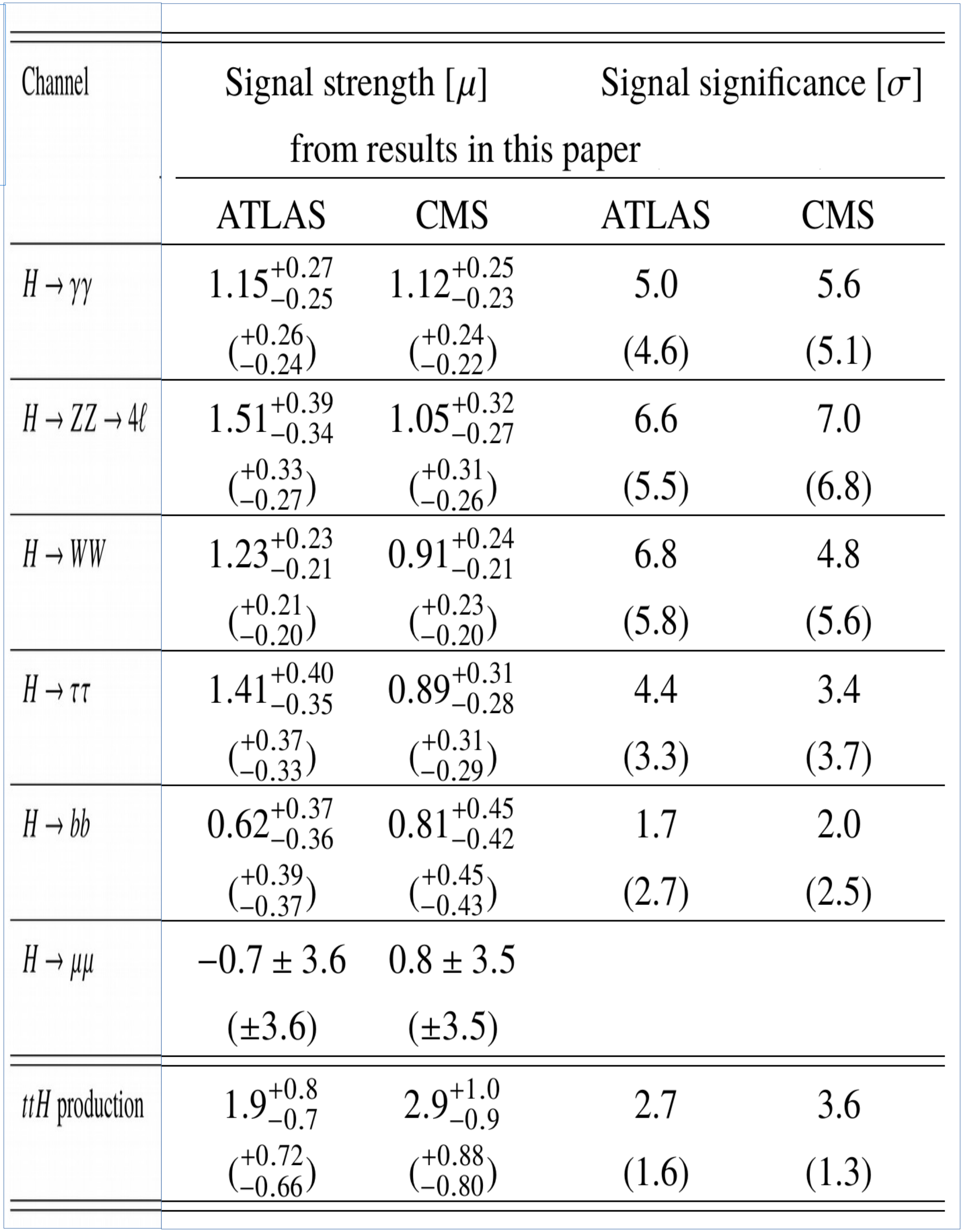
Choice of parameters of interest depends on the signal parametrisation, e.g.

- *signal strengths (μ) or*
- *coupling strength modifiers (κ)*

In general many more nuisance parameters than parameters of interest !

Individual Results from Combined Analysis

Overview of the signal strengths of Higgs decay channels from combined analysis



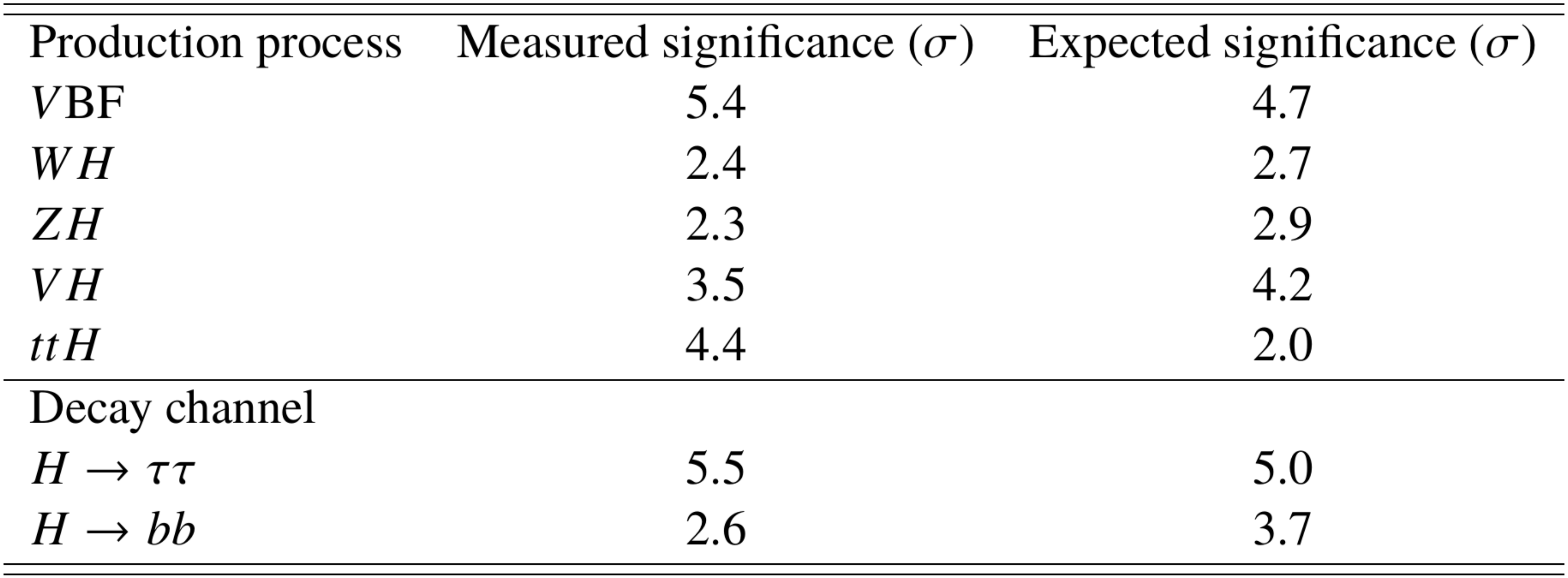
Channel	Signal strength [μ] from results in this paper		Signal significance [σ]	
	ATLAS	CMS	ATLAS	CMS
$H \to \gamma\gamma$	$1.15^{+0.27}_{-0.25}$ $\left(^{+0.26}_{-0.24}\right)$	$1.12^{+0.25}_{-0.23}$ $\left(^{+0.24}_{-0.22}\right)$	5.0 (4.6)	5.6 (5.1)
$H \to ZZ \to 4\ell$	$1.51^{+0.39}_{-0.34}$ $\left(^{+0.33}_{-0.27}\right)$	$1.05^{+0.32}_{-0.27}$ $\left(^{+0.31}_{-0.26}\right)$	6.6 (5.5)	7.0 (6.8)
$H \to WW$	$1.23^{+0.23}_{-0.21}$ $\left(^{+0.21}_{-0.20}\right)$	$0.91^{+0.24}_{-0.21}$ $\left(^{+0.23}_{-0.20}\right)$	6.8 (5.8)	4.8 (5.6)
$H \to \tau\tau$	$1.41^{+0.40}_{-0.35}$ $\left(^{+0.37}_{-0.33}\right)$	$0.89^{+0.31}_{-0.28}$ $\left(^{+0.31}_{-0.29}\right)$	4.4 (3.3)	3.4 (3.7)
$H \to bb$	$0.62^{+0.37}_{-0.36}$ $\left(^{+0.39}_{-0.37}\right)$	$0.81^{+0.45}_{-0.42}$ $\left(^{+0.45}_{-0.43}\right)$	1.7 (2.7)	2.0 (2.5)
$H \to \mu\mu$	-0.7 ± 3.6 (± 3.6)	0.8 ± 3.5 (± 3.5)		
ttH production	$1.9^{+0.8}_{-0.7}$ $\left(^{+0.72}_{-0.66}\right)$	$2.9^{+1.0}_{-0.9}$ $\left(^{+0.88}_{-0.80}\right)$	2.7 (1.6)	3.6 (1.3)

Very close to results from individual publications

(selected) Combined Significances

ggF, H → ZZ, γγ, WW already at >5σ by each experiment individually;

selected significances from ATLAS and CMS combination



Production process	Measured significance (σ)	Expected significance (σ)
VBF	5.4	4.7
WH	2.4	2.7
ZH	2.3	2.9
VH	3.5	4.2
ttH	4.4	2.0
Decay channel		
$H \to \tau\tau$	5.5	5.0
$H \to bb$	2.6	3.7

- VBF production and H → ττ now at S > 5σ
- excess over SM in ttH to be watched !
- largest decay channel (H → bb) still at S< 3σ

Γ_H and off-shell cross-section

Γ_H ~4 MeV for m_H= 125 GeV in the SM

is much smaller than experimental resolution, i.e. cannot be measured directly at the LHC

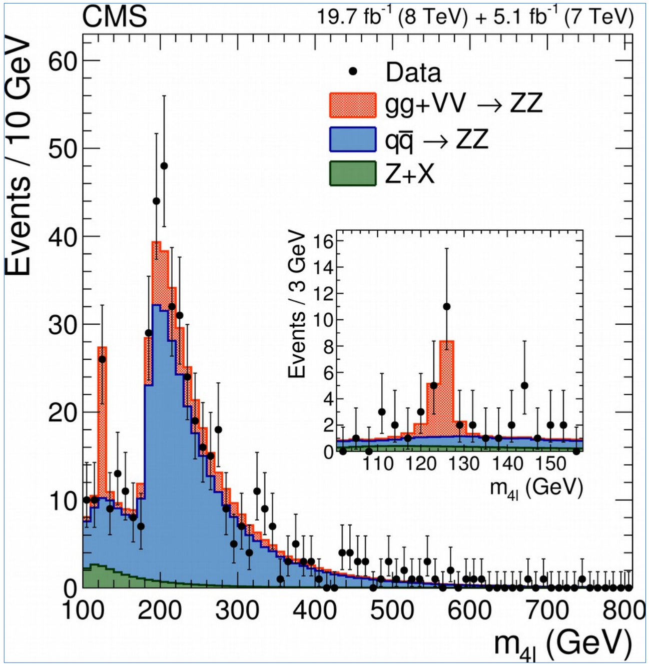
However, there is a substantial (and measurable) off-shell-contribution from

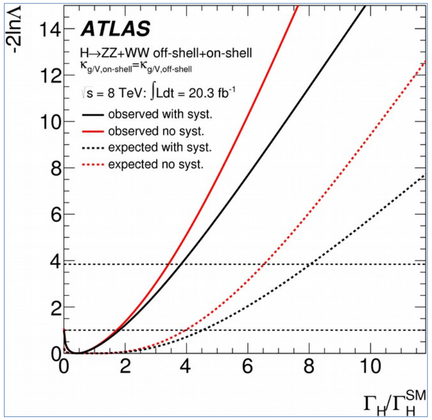
(Higgs) production in gg (→H)→V V(V=W,Z), $\sigma^{\mathrm{off}}_{\mathrm{gg}\to\mathrm{VV}} : g_{\mathrm{gg}} g_{\mathrm{HZZ}}$

to be compared to on-peak cross-section $\sigma^{\mathrm{on}}_{\mathrm{gg}\to\mathrm{VV}} : \dfrac{g_{\mathrm{gg}} g_{\mathrm{HZZ}}}{\Gamma_{\mathrm{H}}}$

assuming that the relevant couplings are independent of the energy scale:

$$\frac{\Gamma_{\mathrm{H}}}{\Gamma_{\mathrm{H}}^{\mathrm{SM}}} = \frac{\mu_{\mathrm{off}}}{\mu_{\mathrm{on}}}$$



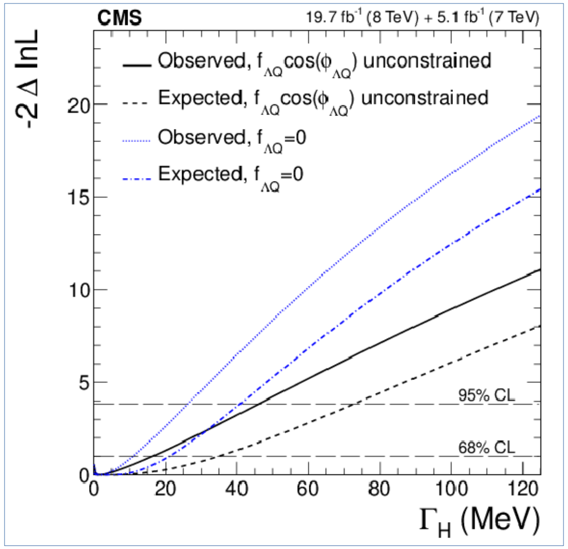


95% CL limit on Γ_H :

ATLAS: < 22.7 (33.0 exp.) MeV
CMS: < 22 (33 exp.) MeV
EPJC 75:335 & PLB 736 64

New CMS result

identical technique, but explicitly allowing for non-SM couplings in g_{HZZ} with a parameter **$f_{\Lambda Q}(m(ZZ))$**



Γ_H < 46 (73) MeV

acc. PRD
arXiv:1507.06656