Status of Higgs coupling strength determination from ATLAS and CMS

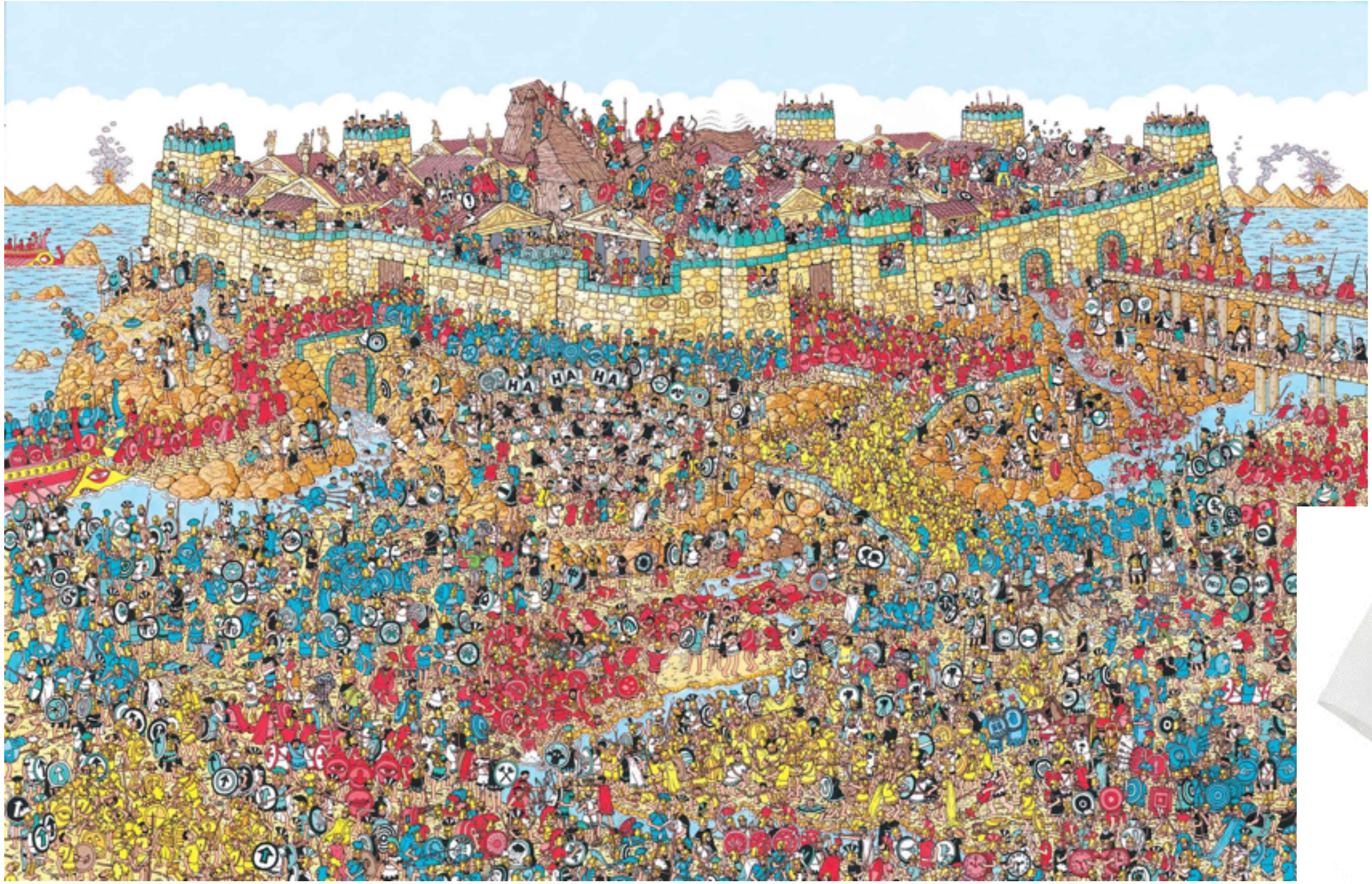
María Moreno Llácer,
II. Physikalisches Institut, Georg-August-Universität Göttingen

(for the ATLAS and CMS collaborations)

Outline

- **Introduction**
  - Higgs at the LHC
  - Higgs production channels and decays modes
  - Higgs couplings
- **Signal strength measurements**
- **Higgs coupling-strength fits**
  - Framework for the analysis of Higgs couplings
  - Benchmark models:
    - New physics in vertices?
    - Fermions vs. bosons?
    - Custodial symmetry?
    - New physics in loops?
    - Decay invisibly?
- **Summary**

The quest for the Higgs boson



Save the date: July 4th 2012

Just the beginning…

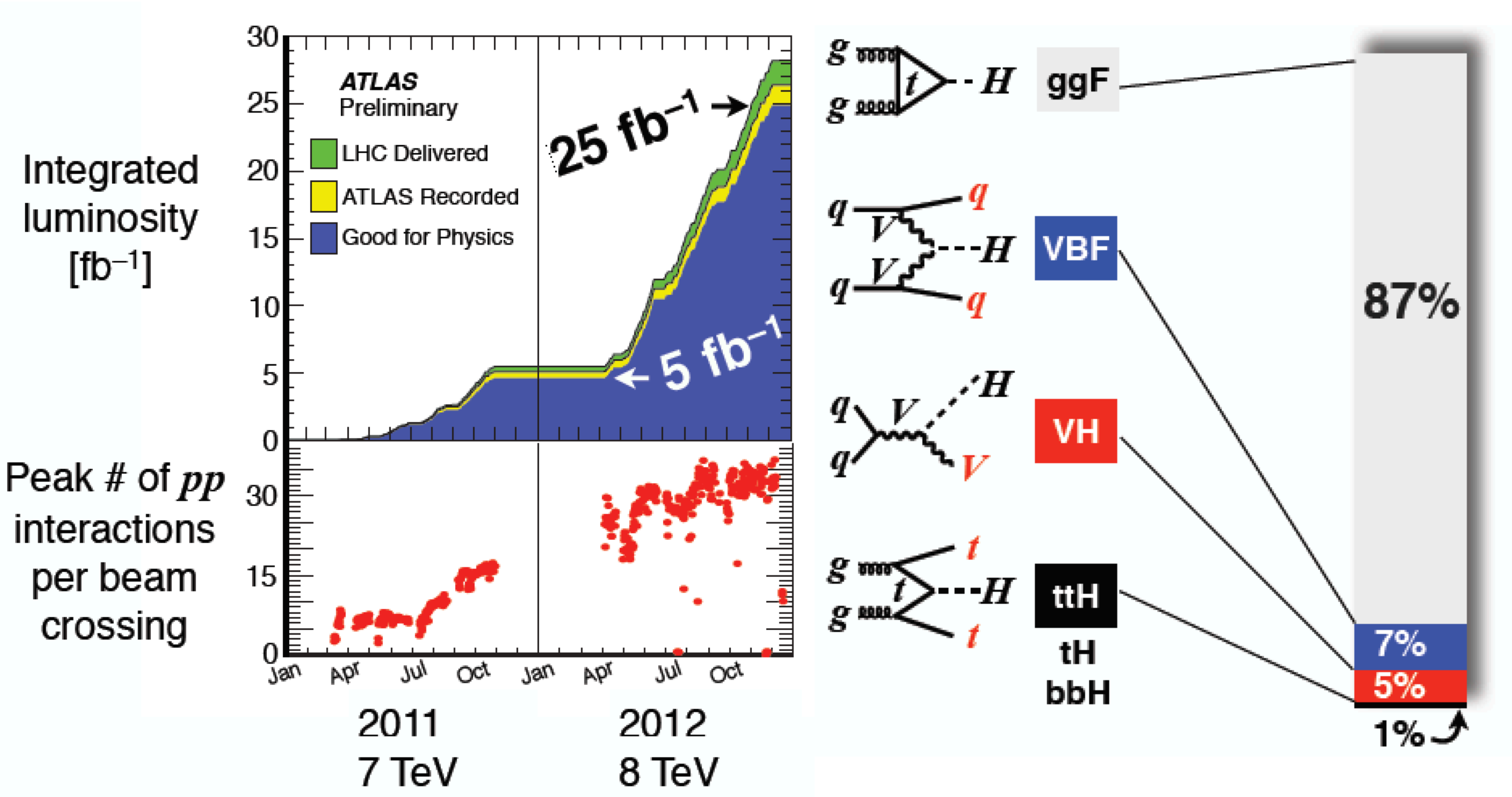
over the last ~1150 days…

Questions to answer after the discovery

- Is this the Higgs boson of the SM ?
- Are the signal strengths as expected in the SM?
- Is the new boson a scalar, and not a pseudo-scalar or a tensor?
- Does it couple to itself?
- Are there any other Higgs bosons to observe?
- Is this Higgs boson a window to new physics ?

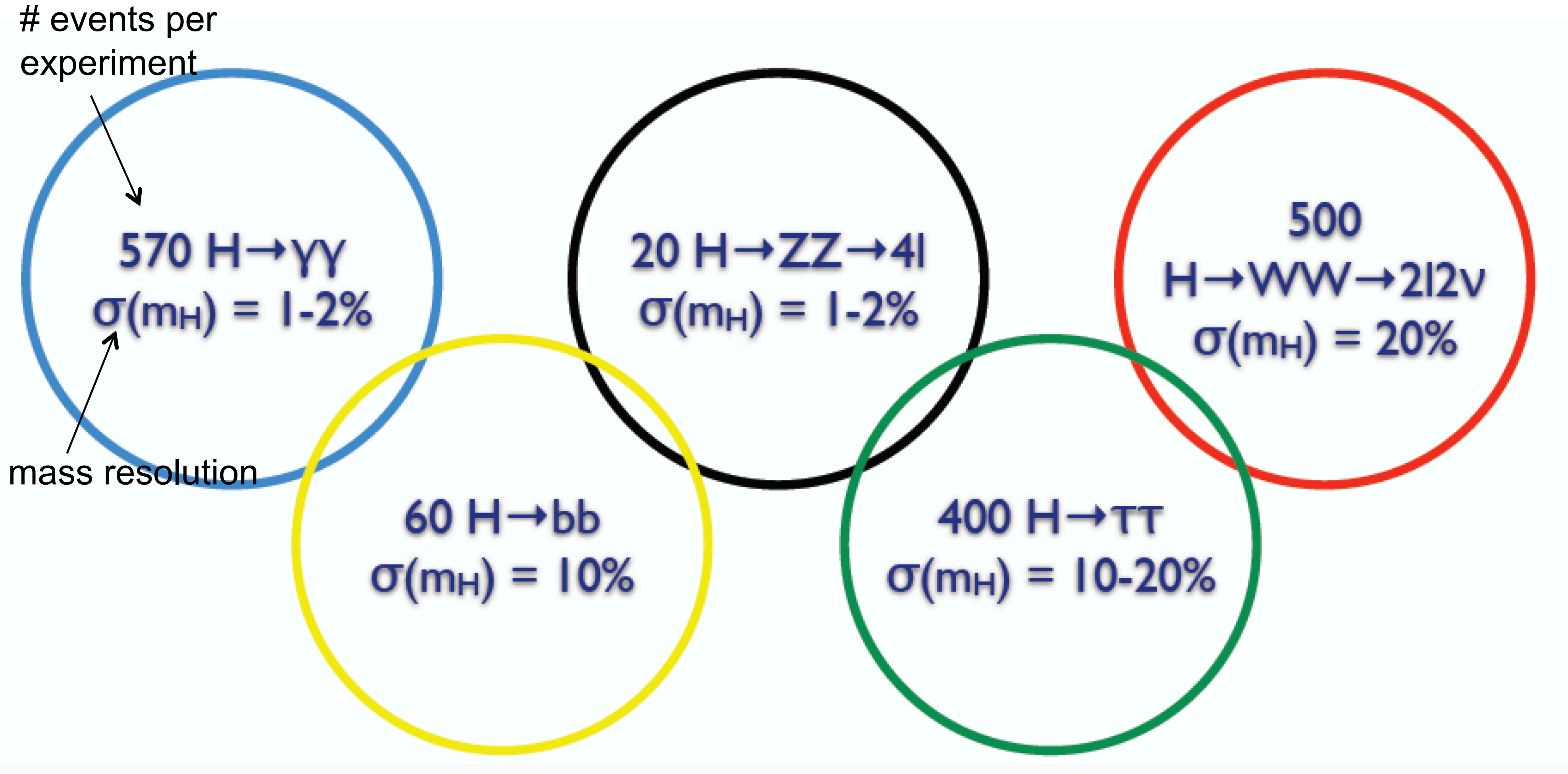
LHC is a Higgs factory

Luminosity (25 fb^{-1}) * cross-section (20 pb) = 0.5 M Higgs per experiment!!
Only one in ~10^10 events contains a Higgs boson



Higgs decays: major decay channels

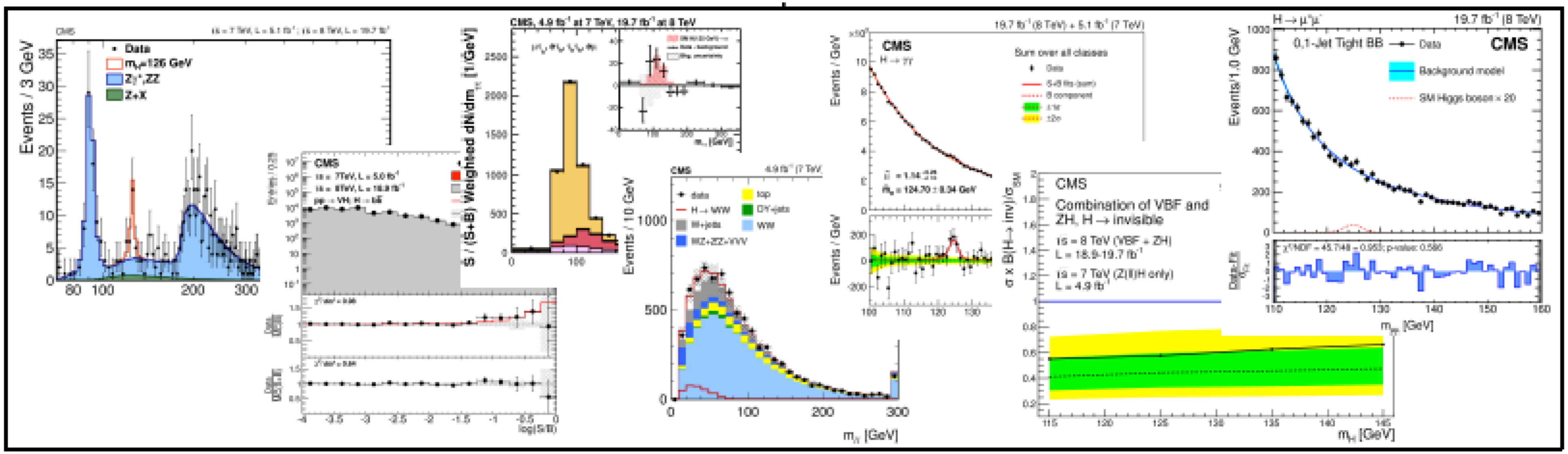
Plays a role in electroweak symmetry breaking



Higgs field serves as the source of mass generation in the fermion sector, through a Yukawa interaction

Run 1 legacy

2011 2012 2013 2014



- LHC Run I tells us there exists one CP even scalar boson.
- Its measured mass is 125.09 ± 0.21 (stat.) ± 0.11(syst.) GeV. Phys. Rev. Lett. 114 (2015) 191803
- It was observed in the bosonic decay channels: ZZ, $\gamma\gamma$ and WW.
- There is evidence that couples to $\tau^{+}\tau^{-}$.
- Preliminary combined analysis of all channels presented in July 2014.
- **In the last months: coupling measurements!!**

Today: coupling measurements !!

Eur. Phys. J. C (2015) 75:212
DOI 10.1140/epjc/s10052-015-3351-7

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Experimental Physics

Precise determination of the mass of the Higgs boson and tests of compatibility of its couplings with the standard model predictions using proton collisions at 7 and 8 TeV

CMS Collaboration*
CERN, 1211 Geneva 23, Switzerland

Eur. Phys. J. C 75 (2015) 212

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

Submitted to: Eur. Phys. J. C

CERN-PH-EP-2015-125
17th July 2015

Measurements of the Higgs boson production and decay rates and coupling strengths using *pp* collision data at $\sqrt{s}$ = 7 and 8 TeV in the ATLAS experiment

The ATLAS Collaboration

arXiv: 1507.04548

What is included in the combination?

Several channels…

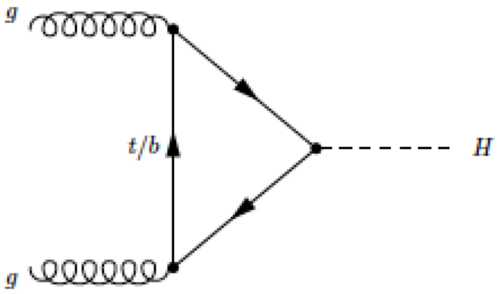
Production →

Decay ↓

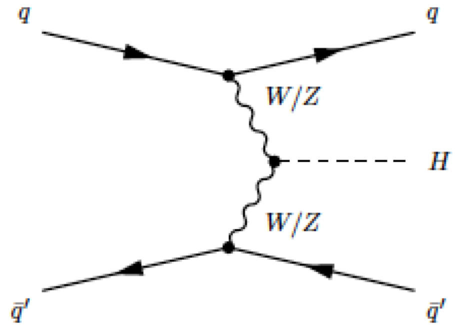
	ggH	VBF	VH	ttH
H→ZZ(4l)	✔	✔	✔	✔
H→WW(2l2ν)	✔	✔	✔	✔
H→γγ	✔	✔	✔	✔
H→ττ	✔	✔	✔	✔
H→bb			✔	✔
Rare channels: H→μμ H→Zγ	✔	✔		

Review: Higgs production

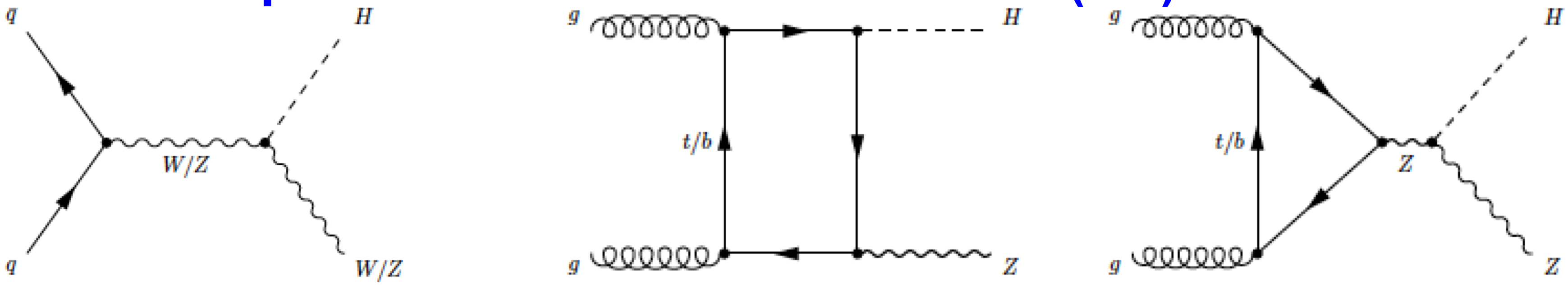
Gluon Fusion (ggF)



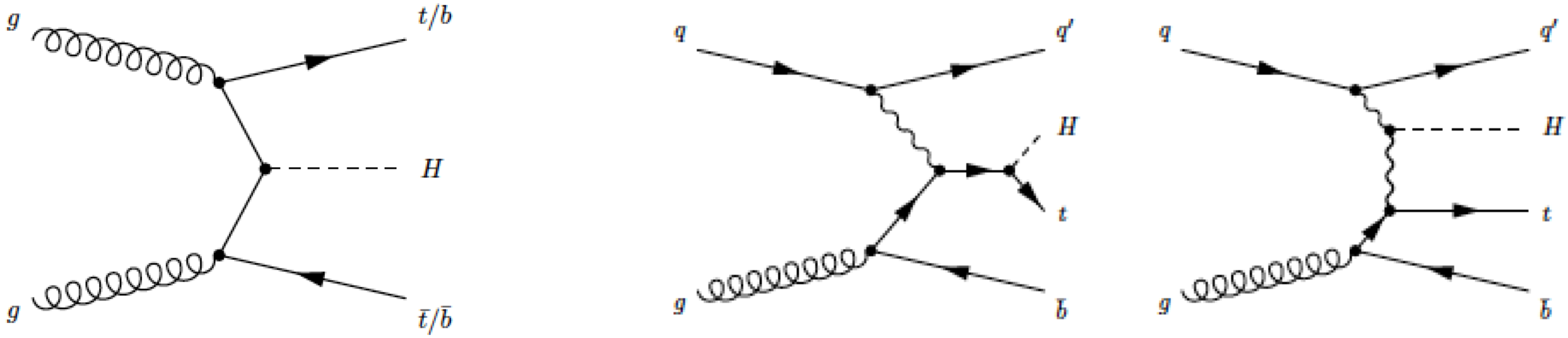
Vector Boson Fusion (VBF)



Associated production with vector bosons (VH)

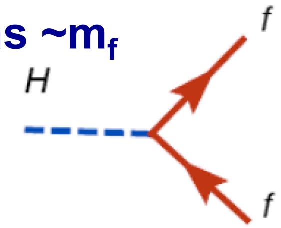


Associated production with top quarks (ttH, tH, WtH)



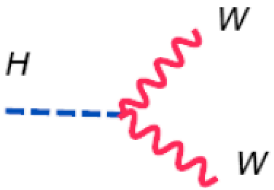
Review: Higgs decays and couplings

- **to fermions ~m_f**

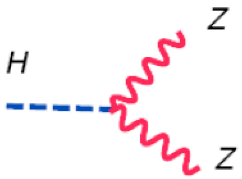


$$i\frac{m_f}{v}\delta_{ij}$$

- **to massive Gauge bosons ~m_V^2**

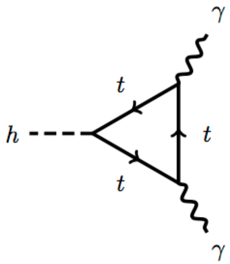


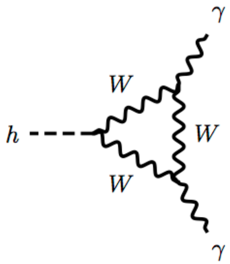
$$2i\frac{M_W^2}{v}g_{\mu\nu}$$



$$2i\frac{M_Z^2}{2v}g_{\mu\nu}$$

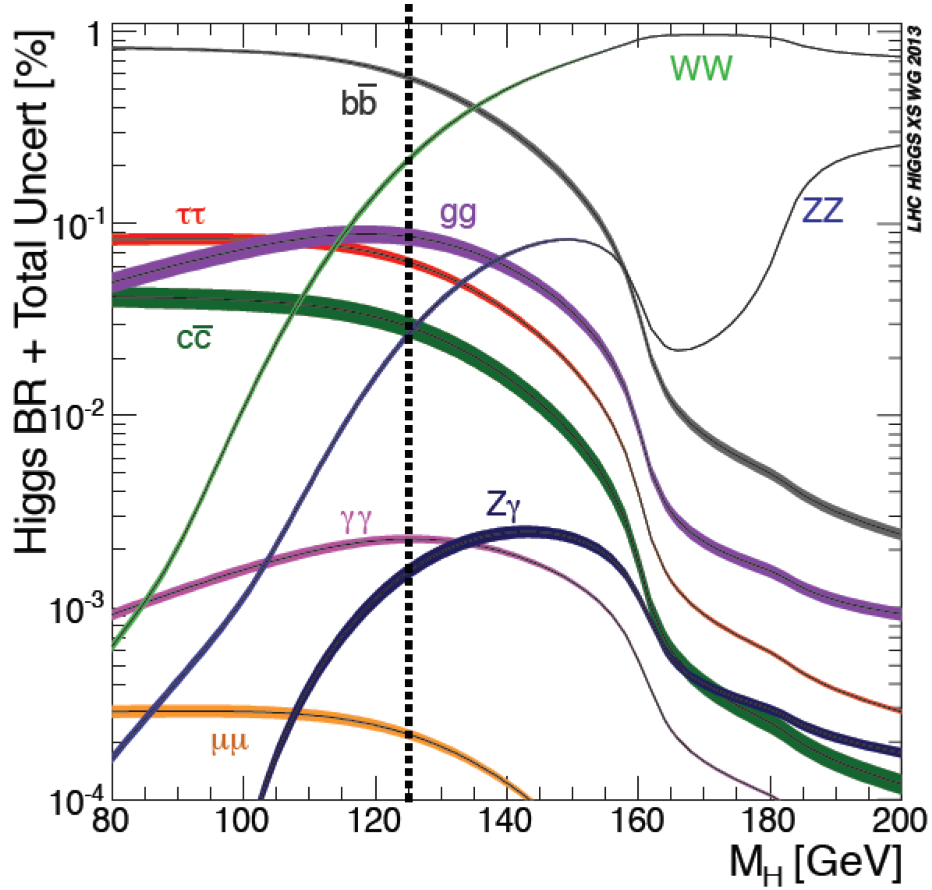
- **to massless Gauge bosons via loops: photons and gluons**





- **self-couplings ~m_H^2**

Very precise predictions (only unpredicted parameter: m_H)



SM branching ratio at m_H~125 GeV

H→bb 58%
H→WW* 22%
H→ττ 6.3%
H→ZZ* 2.6%
H→γγ 0.23%

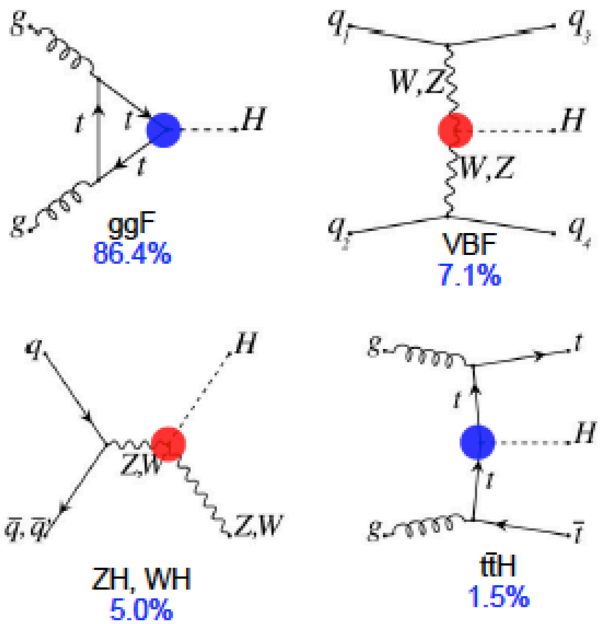
Are the observed yields compatible with the SM Higgs boson?

From yields to signal strengths

The compatibility between the measured rates and the SM prediction is tested using signal strength parameters for each **production** and **decay** mode:

$$\mu = \frac{N_{obs}}{N_{exp}} = \frac{\sigma_i \times BR_f}{\left(\sigma_i \times BR_f\right)^{SM}} = \frac{\sigma_i}{\sigma_i^{SM}} \times \frac{BR_f}{BR_f^{SM}} = \mu_i \times \mu_f$$

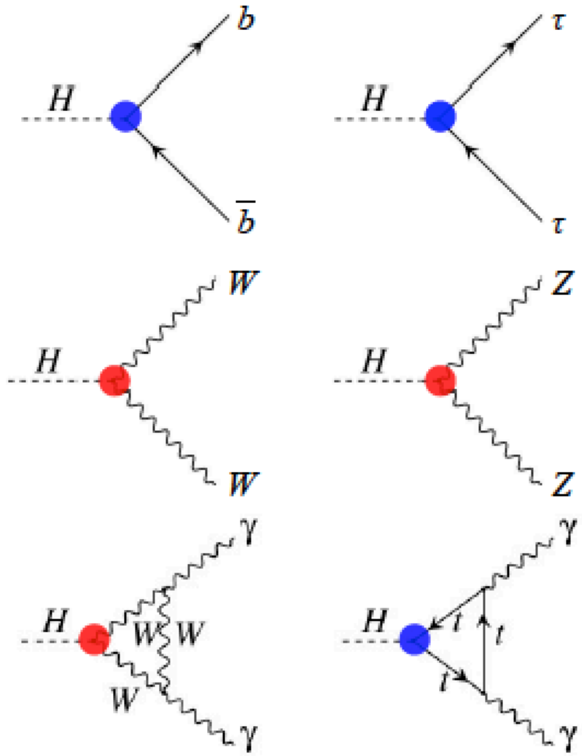
Production modes



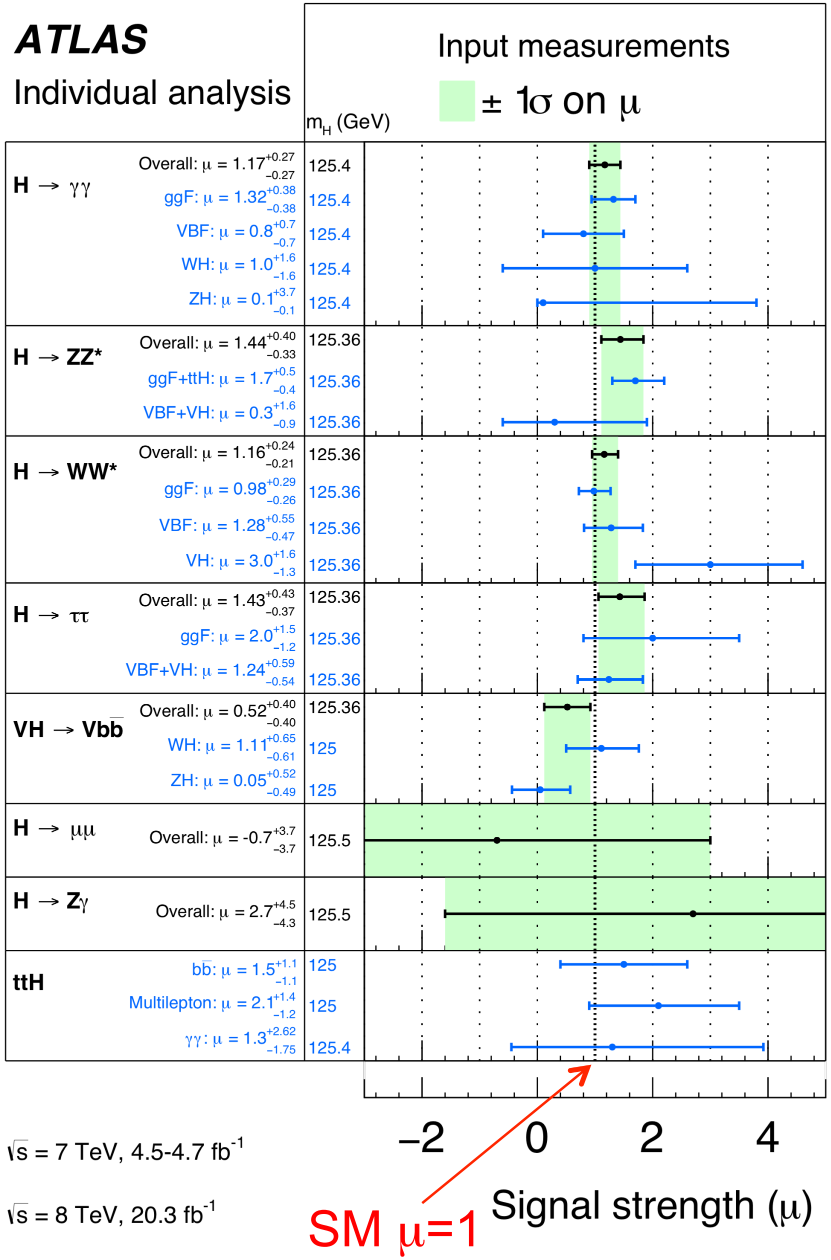
● : fermions
● : vector bosons

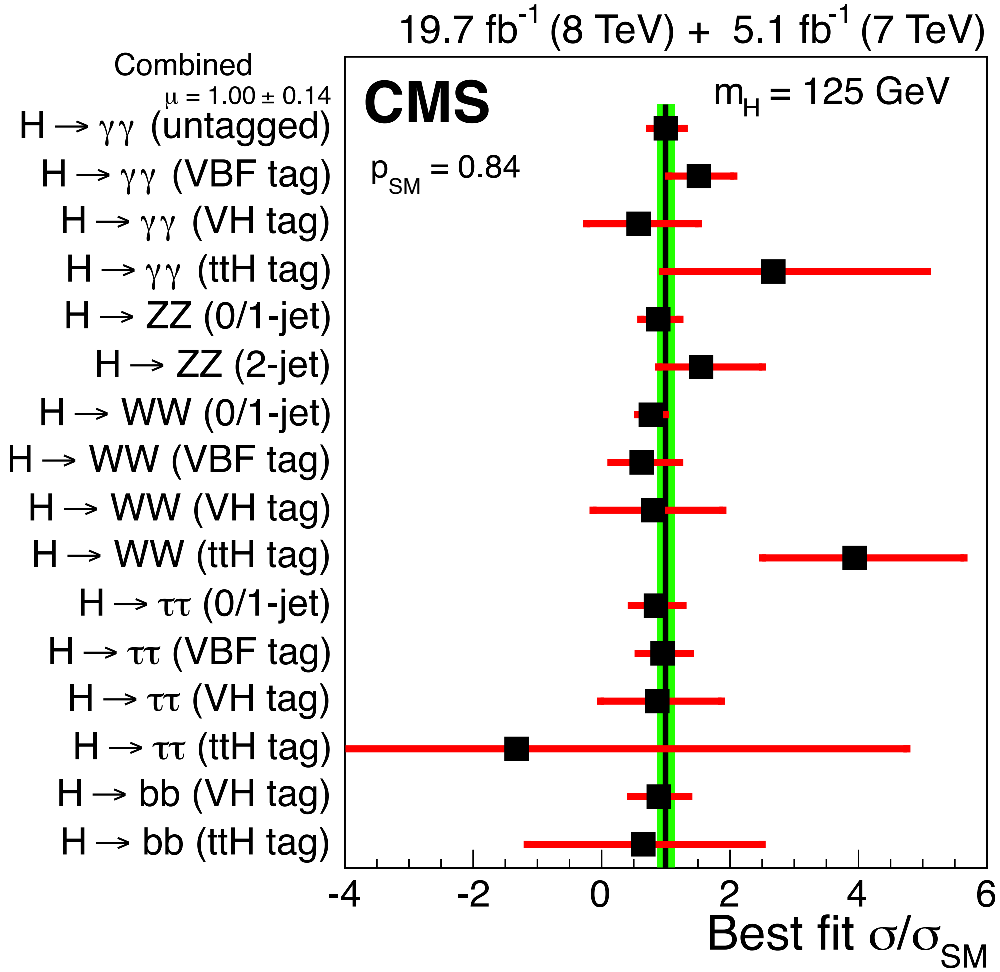
×

Decay modes



From yields to signal strengths





Combinations

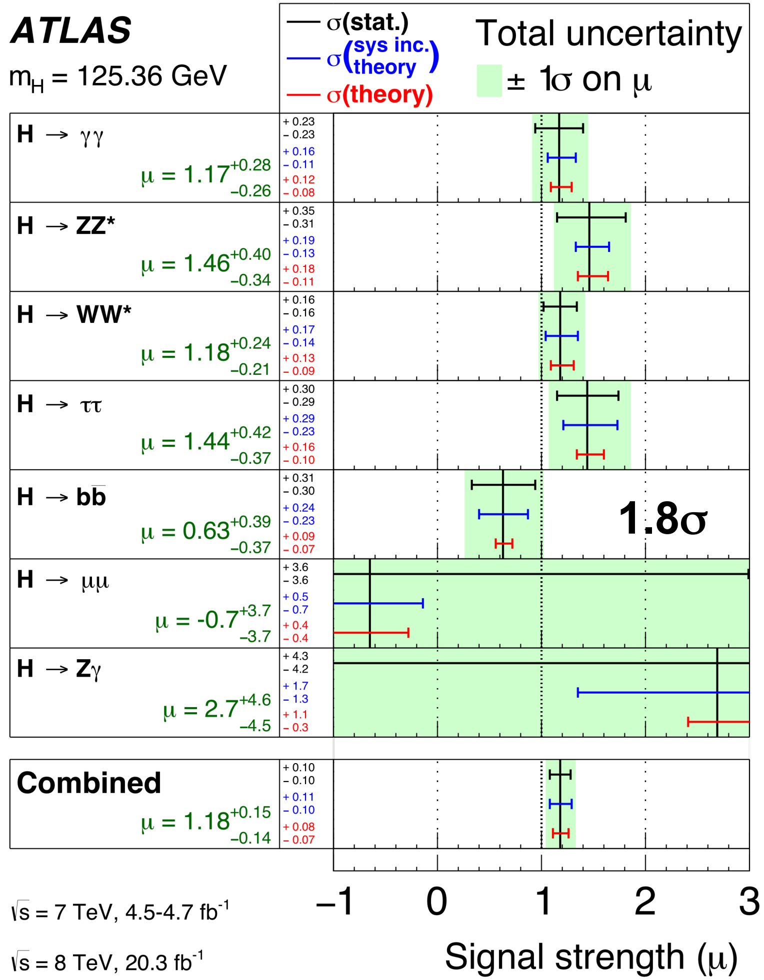
Combining diff. measurements…

Simplest model: one overall signal strength

best-fit μ

ATLAS: $\mu = 1.18 \pm 0.10$ (stat) ± 0.07 (syst) $^{+0.08}_{-0.07}$ (theory)
CMS: $\mu = 1.00 \pm 0.09$ (stat) ± 0.07 (syst) $^{+0.08}_{-0.07}$ (theory)

- Good agreement with theoretical predictions.
- Theoretical and experimental uncertainties have similar size as the statistical ones.



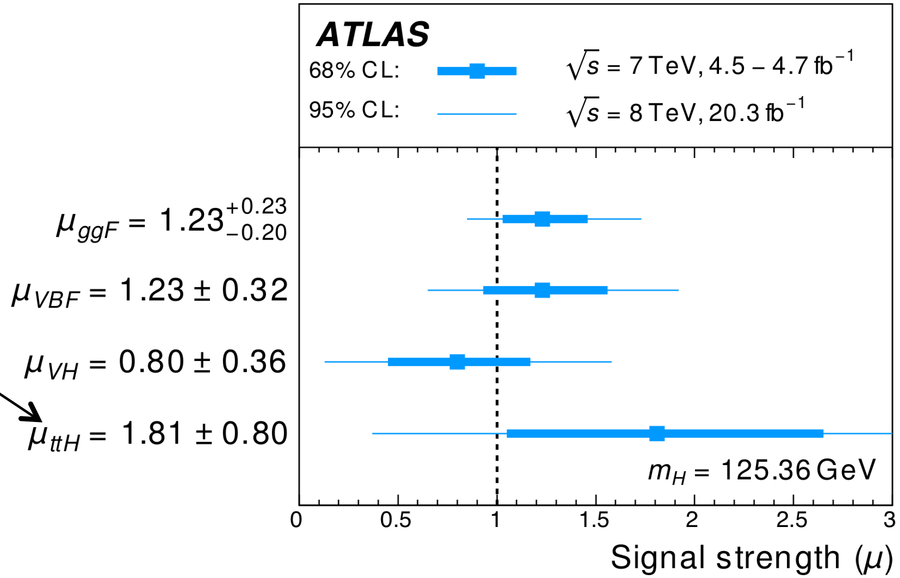
Grouping by decay mode

- Various signal strength parameters, one per decay channel: $\mu_{\gamma\gamma}$, μ_{ZZ}, μ_{WW}, $\mu_{\tau\tau}$, μ_{bb}, $\mu_{\mu\mu}$ and $\mu_{Z\gamma}$
- Very good compatibility with SM Higgs predictions.

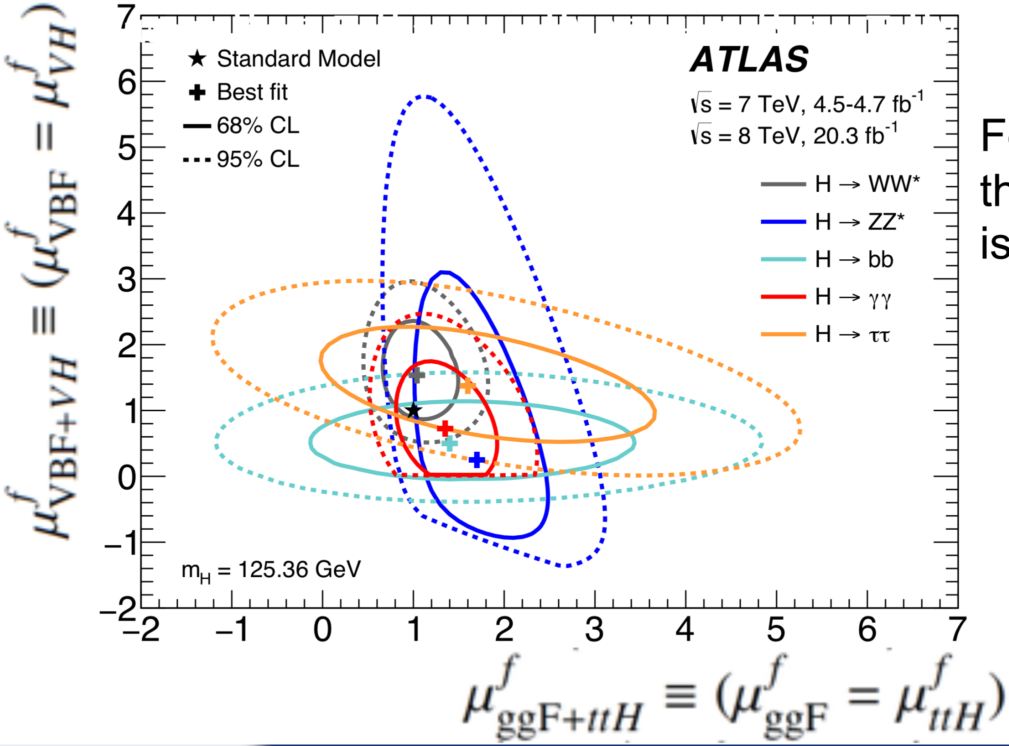
Decouple diff. production modes

Grouping by production mechanism

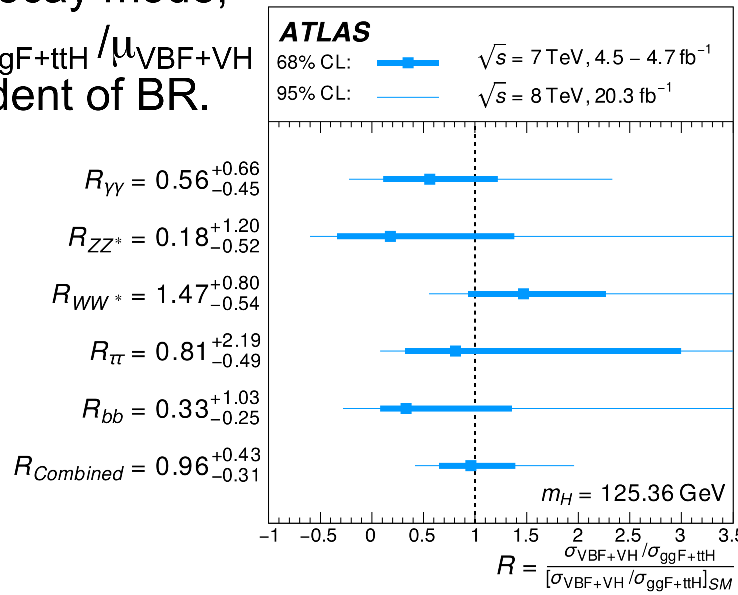
Four parameters: μ_{ggF}, μ_{VBF}, μ_{VH} and μ_{ttH}
- μ_{ttH}~1-2σ higher than SM prediction, mostly driven by multilepton analysis



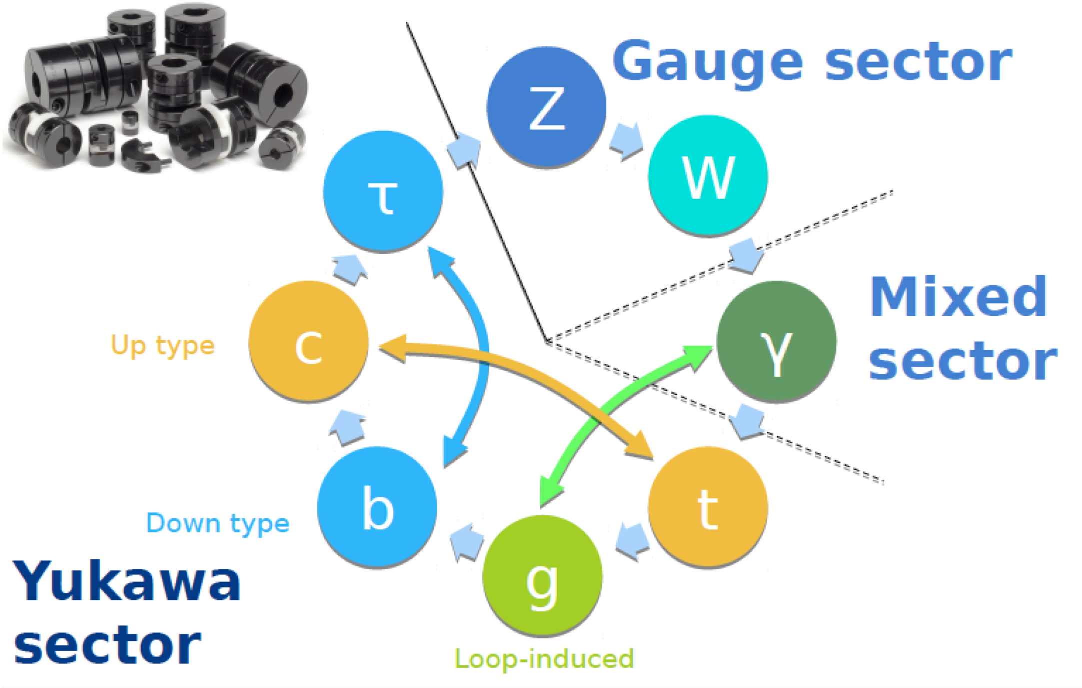
Bosonic and fermionic production modes



For each decay mode, the ratio $\mu_{ggF+ttH}/\mu_{VBF+VH}$ is independent of BR.



Is the observed data compatible with the SM Higgs boson couplings?



From signal strengths to couplings

Beyond the parametrisations using signal strength parameters, "**coupling modifiers κ_i**" (also called scale factors) based on a LO motivated framework are used to interpret the data and check for deviations from the SM.

κ-framework (coupling formalism)

$$\mu = \frac{\sigma_i \times BR_f}{\left(\sigma_i \times BR_f\right)^{SM}} = \frac{\left(\sigma_i \times \frac{\Gamma_f}{\Gamma_H}\right)}{\left(\sigma_i \times \frac{\Gamma_f}{\Gamma_H}\right)^{SM}} = \frac{\kappa_i^2 \times \kappa_f^2}{\kappa_H^2}$$

$$\Gamma_i = \kappa_i^2 \cdot \Gamma_i^{SM}$$

- Parametrise μ's in terms of κ, fit all them simultaneously and test diff. assumptions on relation between κ's

Assumptions:
- single and narrow resonance
- kinematics unmodified (tensor structure as in the SM)

$$\lambda_{ij} = \frac{\kappa_i}{\kappa_j}$$

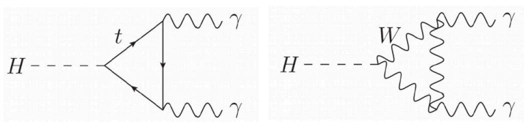
- κ_H parametrises change in total width: independent parameter or as a function of other κ's

- invisible or undetected decays have $BR_{i.,u.}$

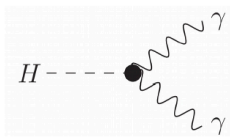
- overall width scales as $\Gamma_H = \frac{\kappa_H^2}{1 - BR_{i.,u.}} \cdot \Gamma_H^{SM}$

- loop-induced couplings either resolved (in terms of SM particle κ) or unresolved (own κ)

resolved



unresolved

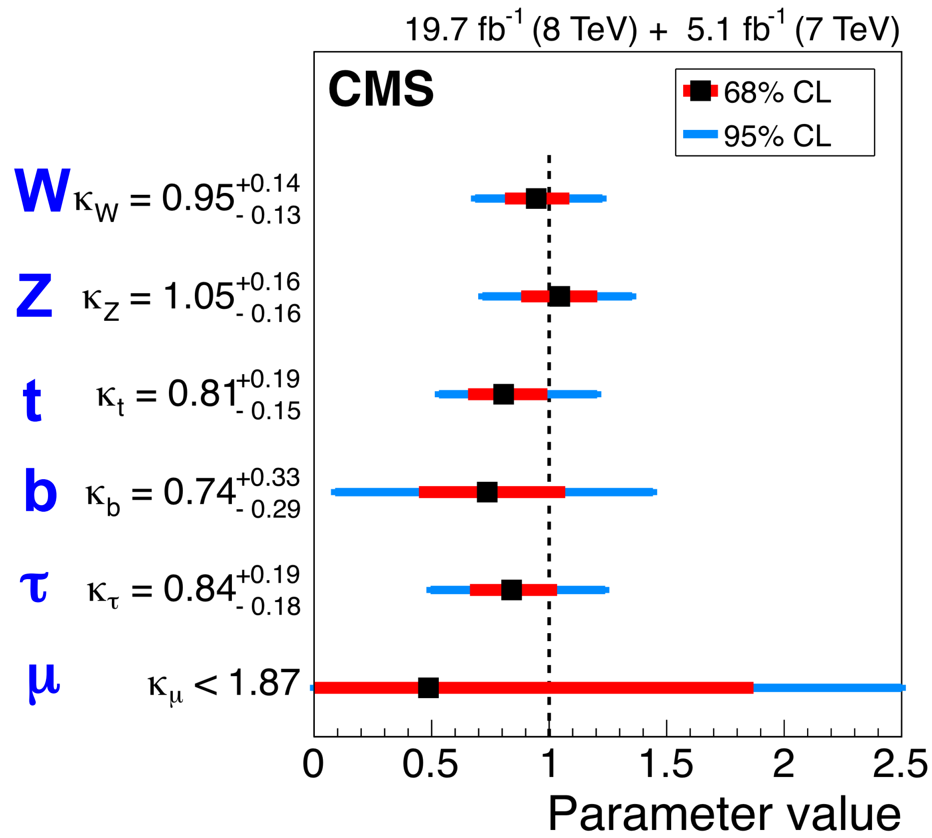


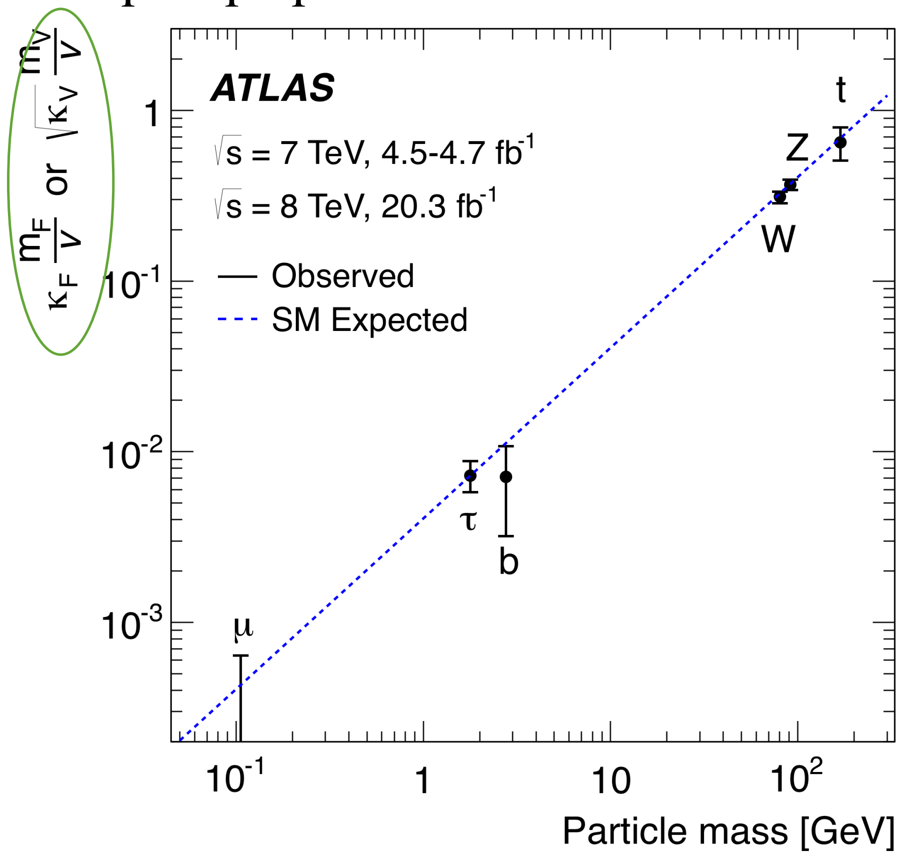
Production	Loops	Interference	Expression in fundamental coupling-strength scale factors
$\sigma(ggF)$	✓	b–t	$\kappa_g^2 \sim 1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$
$\sigma(VBF)$	-	-	$\sim 0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	-	-	$\sim \kappa_W^2$
$\sigma(q\bar{q} \to ZH)$	-	-	$\sim \kappa_Z^2$
$\sigma(gg \to ZH)$	✓	Z–t	$\kappa_{ggZH}^2 \sim 2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t$
$\sigma(bbH)$	-	-	$\sim \kappa_b^2$
$\sigma(ttH)$	-	-	$\sim \kappa_t^2$
$\sigma(gb \to WtH)$	-	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	$\sim 3.4 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t \kappa_W$
Partial decay width			
$\Gamma_{b\bar{b}}$	-	-	$\sim \kappa_b^2$
Γ_{WW}	-	-	$\sim \kappa_W^2$
Γ_{ZZ}	-	-	$\sim \kappa_Z^2$
$\Gamma_{\tau\tau}$	-	-	$\sim \kappa_\tau^2$
$\Gamma_{\mu\mu}$	-	-	$\sim \kappa_\mu^2$
$\Gamma_{\gamma\gamma}$	✓	W–t	$\kappa_\gamma^2 \sim 1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$
$\Gamma_{Z\gamma}$	✓	W–t	$\kappa_{Z\gamma}^2 \sim 1.12 \cdot \kappa_W^2 + 0.00035 \cdot \kappa_t^2 - 0.12 \cdot \kappa_W \kappa_t$
Total decay width			
Γ_H	✓	$W-t$ $b-t$	$\kappa_H^2 \sim$ $0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 +$ $0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 +$ $0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{Z\gamma}^2 + 0.00022 \cdot \kappa_\mu^2$

Check couplings relative to SM
Higgs gives mass? Check scaling of couplings with particle masses

$$g_V \sim \kappa_V 2m_V^2/\upsilon \Rightarrow \sqrt{g_V/2\upsilon} \sim \sqrt{\kappa_V}\, m_V/\upsilon$$

$$\lambda_F \sim \kappa_F m_F/\upsilon$$





Assume only SM particles, no new decay modes.
Best constraints ~15% precision.

λ_f and $\sqrt{g_V}$ scale with mass as expected !

Couplings: new physics tests

The current dataset does not allow the determination of all the coupling modifiers
→ test specific scenarios: **different benchmark models** defined by LHC-XS-WG arXiv:1307.1347

custodial symmetry: W and Z couplings

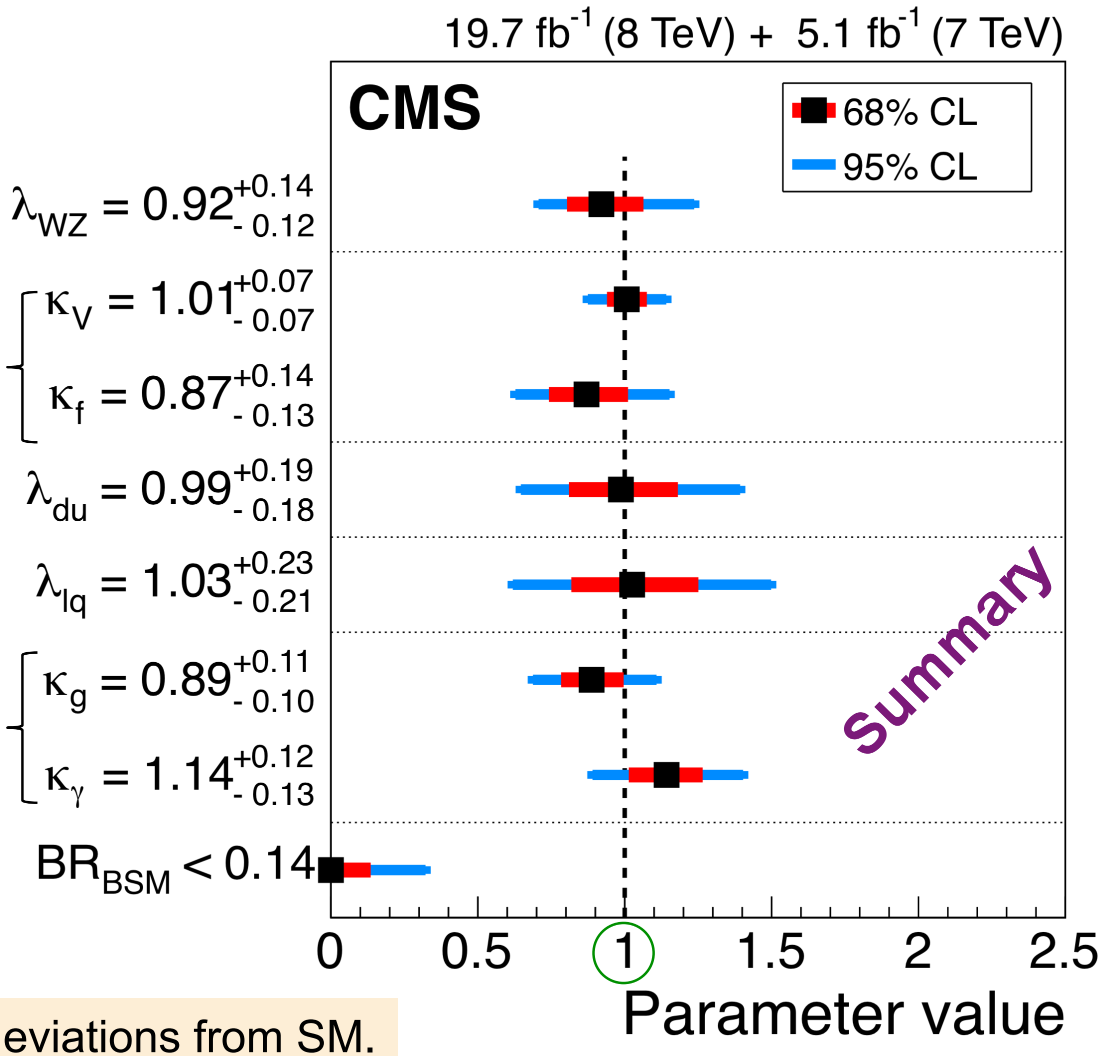
bosons/fermions

up-/down-type fermions

leptons/quarks

loops

BR_{BSM} (extra width)



$\lambda_{XY} = \kappa_X / \kappa_Y$

No significant deviations from SM.

Couplings: new physics tests

The current dataset does not allow the determination of all the coupling modifiers
→ test specific scenarios: **different benchmark models** defined by LHC-XS-WG arXiv:1307.1347

custodial symmetry: W and Z couplings $\lambda_{WZ} = 0.92^{+0.14}_{-0.12}$

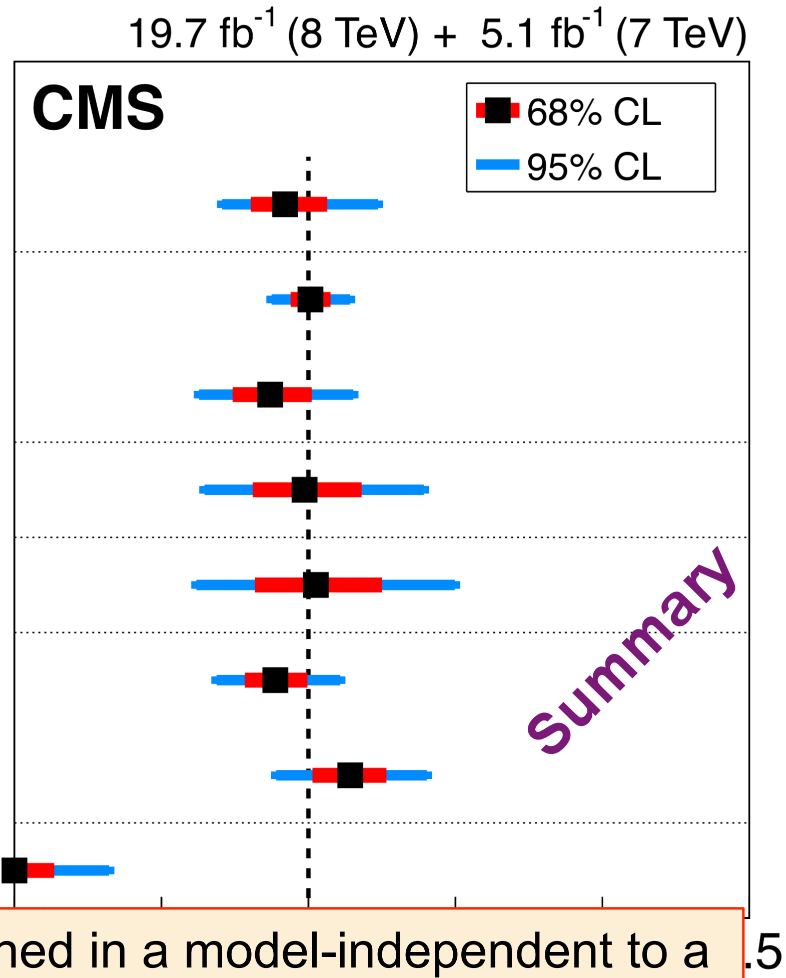
bosons/fermions $\kappa_V = 1.01^{+0.07}_{-0.07}$, $\kappa_f = 0.87^{+0.14}_{-0.13}$

up-/down-type fermions $\lambda_{du} = 0.99^{+0.19}_{-0.18}$

leptons/quarks $\lambda_{lq} = 1.03^{+0.23}_{-0.21}$

loops $\kappa_g = 0.89^{+0.11}_{-0.10}$, $\kappa_\gamma = 1.14^{+0.12}_{-0.13}$

BR_{BSM} (extra width) $BR_{BSM} < 0.14$



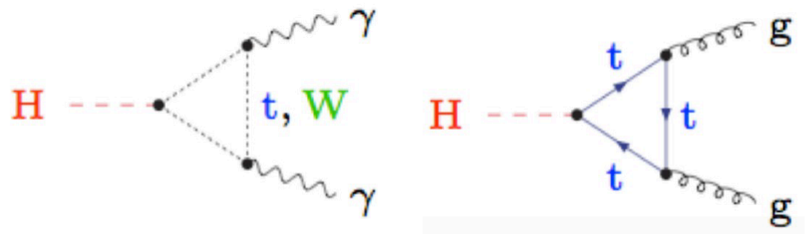
$\lambda_{XY} = \kappa_X/\kappa_Y$

Since Γ_H is not experimentally constrained in a model-independent to a meaningful precision at the LHC, only ratios of couplings strengths can be measured in the more general models.

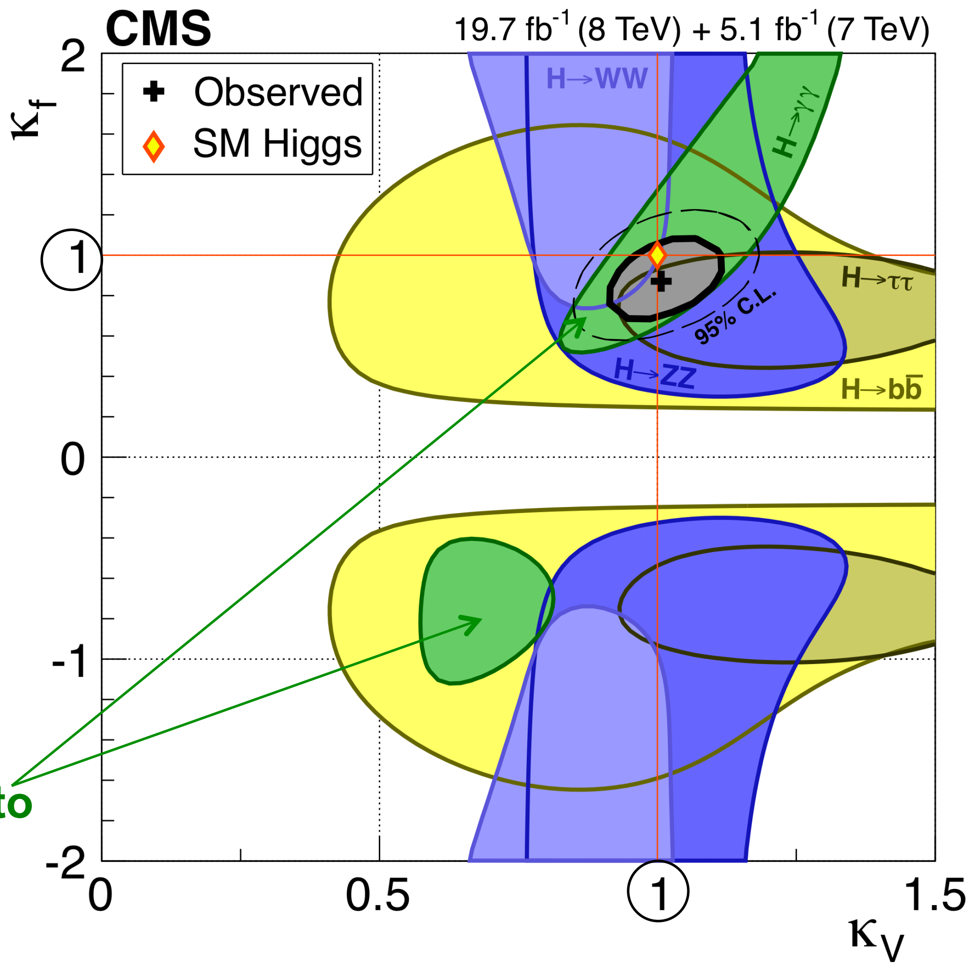
Test the universal scale for bosons and for fermions (κ_V vs κ_F)

As result of the EWSB, the nature of Higgs couplings to fermions (via Yukawa int.) and massive vector bosons is different.

→ Tested by fitting two scale factors: **κ_V and κ_F**
→ Parametrise loop-mediated couplings as in SM



CMS approach: Γ_{BSM}=0
Notice interplay of different channels.
κ_V[0.87, 1.14] and κ_F[0.63, 1.15] @ 95% CL

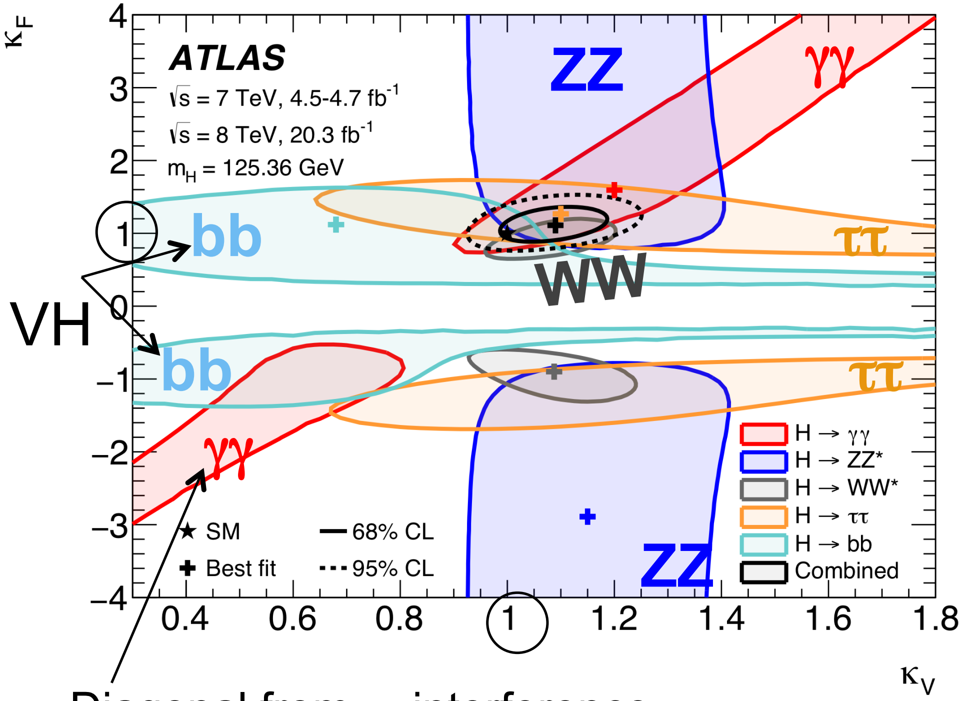


H→γγ is sensitive to the relative sign

Massive vector bosons vs. fermions

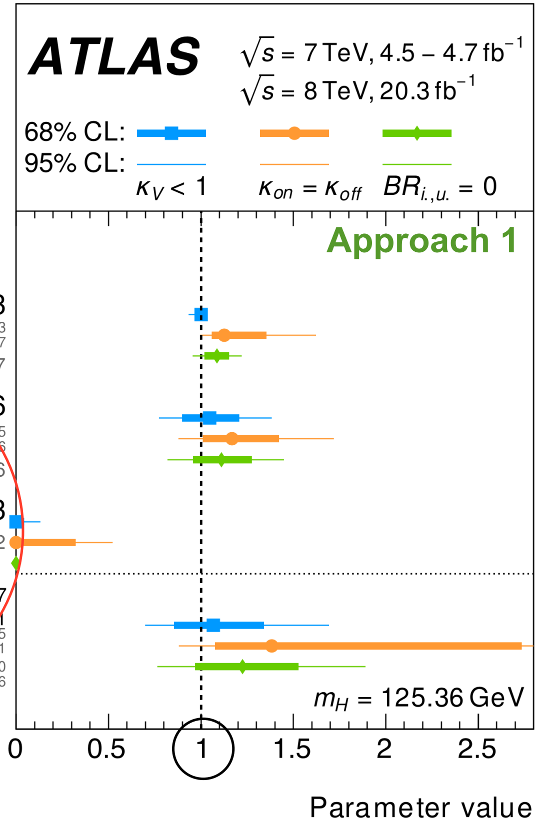
ATLAS

Approach 1: $\Gamma_{BSM}=0$ → 2 pars: $\boldsymbol{\kappa_V=1.09\pm0.07}$, $\boldsymbol{\kappa_F=1.11\pm0.16}$



Diagonal from γγ interference

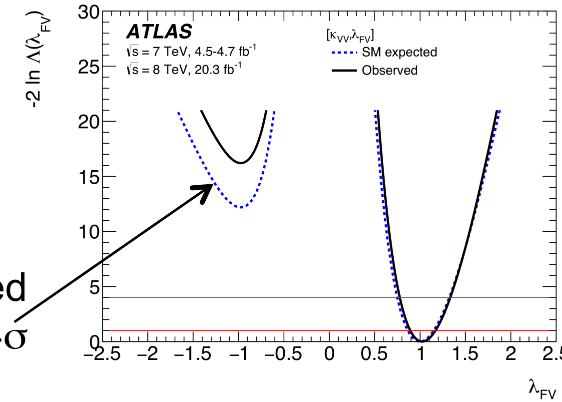
relaxing assumptions...
$BR_{i.,u}\neq0$



Approach 2: allowing for extra contributions $BR_{i.,u}\neq0$;
constraints for upper bound on Γ_H: $\kappa_V<1$ or $\kappa_{on}=\kappa_{off}$
→ $\boldsymbol{BR_{i.,u.}<0.13\ (0.52)}$ **if** $\boldsymbol{\kappa_V<1\ (\kappa_{on}=\kappa_{off})}$

Approach 3: no assumption on Γ_H
$\boldsymbol{\lambda_{FV}=\kappa_F/\kappa_V=1.02^{+0.15}_{-0.13}}$
$\boldsymbol{\kappa_{VV}=\kappa_V\kappa_V/\kappa_H=1.07^{+0.14}_{-0.13}}$

λ_{FV}=-1 disfavoured at ~4σ



Custodial symmetry: W vs Z bosons couplings (κ_W vs κ_Z)

At tree level in SM, the ratio of W and Z masses (and thus couplings) is related due to the "custodial symmetry" (approx. symmetry): $\rho = M_W^2/(M_Z^2 * \cos\theta_W^2) = 1$

However, large radiative corrections are possible in NP models: $\rho = 1+\Delta\rho$ ← radiative corrections

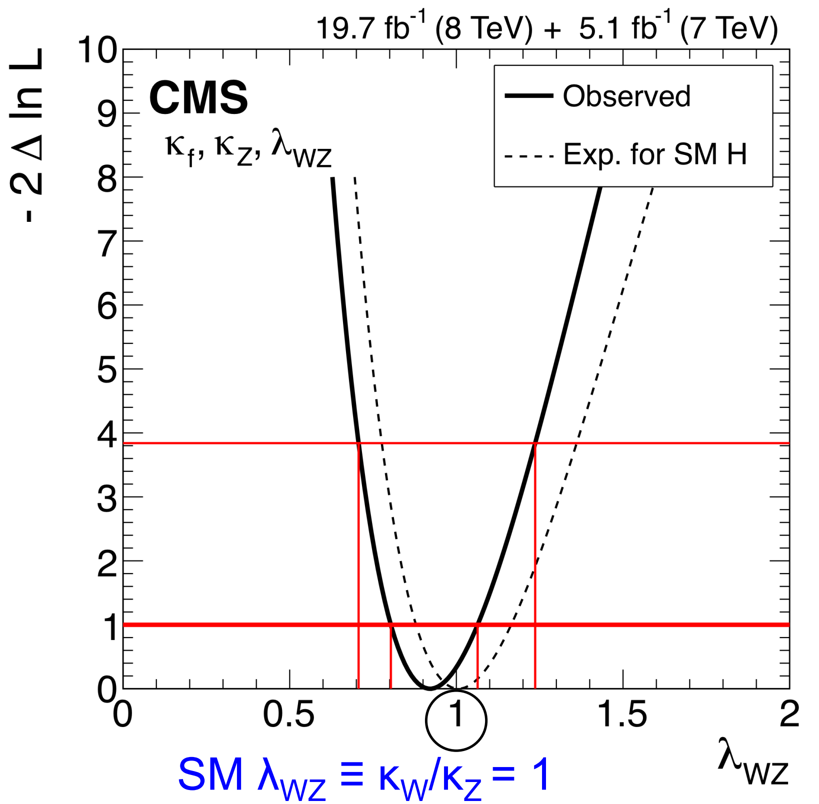
→ Test if data are compatible with the amount of violation allowed by the SM at NLO

→ 3 free params.: $\lambda_{WZ}=\kappa_W/\kappa_Z$ (POI), κ_F and κ_Z (profiled)

fermion couplings grouped together

assuming loops contain only SM particles

$$\lambda_{WZ} = \kappa_W/\kappa_Z = \mathbf{0.92^{+0.14}_{-0.12}}$$



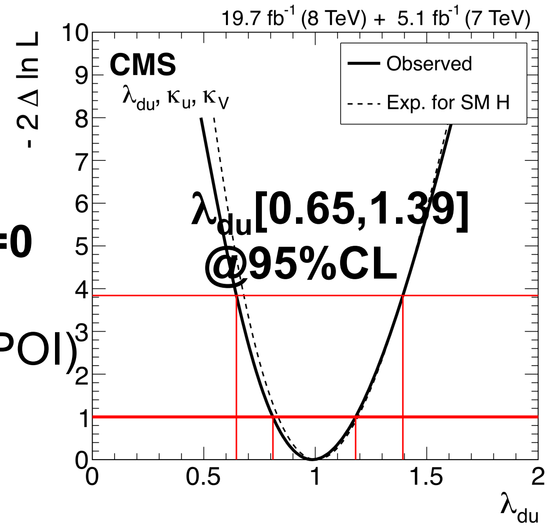
Up- and down-type fermions

Isospin universality? check up/down fermion coupling ratio λ_{du}

In many extensions of the SM, the Higgs bosons couple differently to dif. types of fermions.
In Two-Higgs-Doublet Models (2HDM), couplings to up- and down-type fermions are modified.

→ In this benchmark, the ratio $\lambda_{du}=\kappa_d/\kappa_u$ is probed
- → κ_u: constrained by ggF (top quark loop), also weakly from ttH
- → κ_d: constrained through the $H\to bb$, $H\to\tau\tau$ and $H\to\mu\mu$
- → vector boson couplings grouped together

CMS approach: $\Gamma_{BSM}=0$
3 free params
ratio λ_{du} ($=\kappa_d/\kappa_u$) (POI)
κ_u, κ_V (profiled)

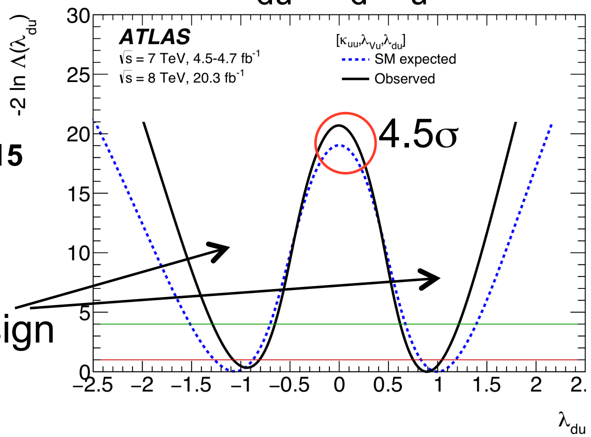


ATLAS approach: no assumption on Γ_H
three fits depending on POI, profiling other two

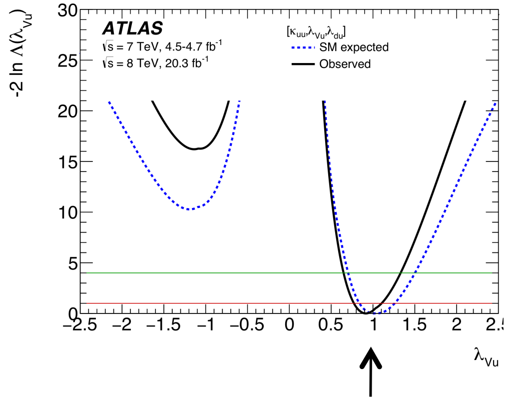
$\lambda_{du}=\kappa_d/\kappa_u$

$\lambda_{du}=0.90^{+0.14}_{-0.15}$

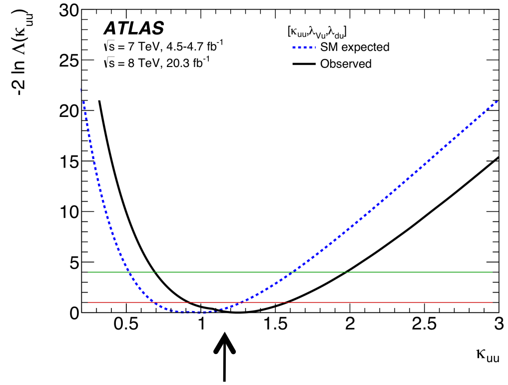
insensitive to the sign



$\lambda_{Vu}=\kappa_V/\kappa_u$



$\kappa_{uu}=\kappa_u\kappa_u/\kappa_H$

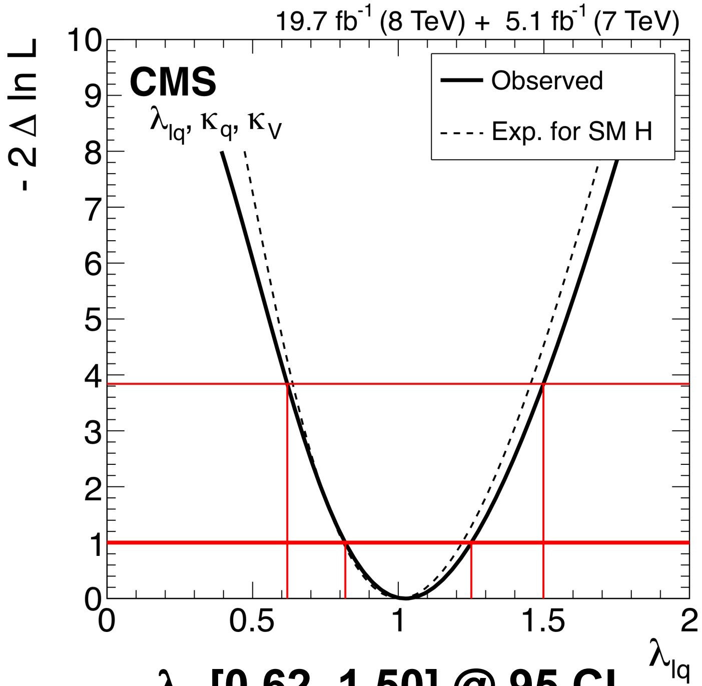


Lepton/quark universality in coupling scale factors? Test ratio λ_{lq}

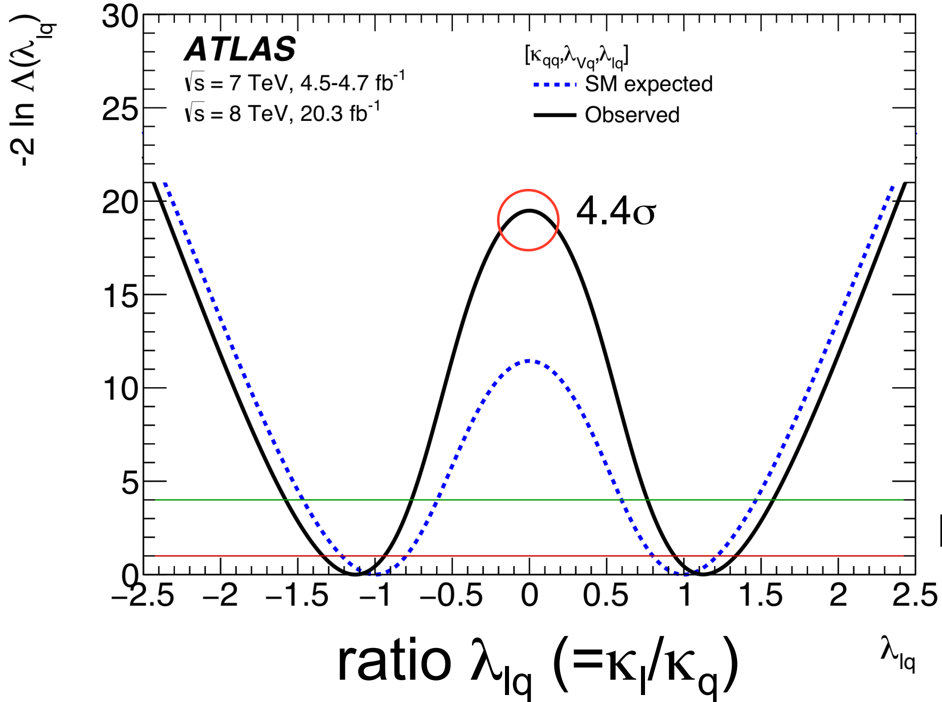
Extensions of the SM can also contain diff. couplings strengths to leptons and quarks…
As before, one can test the lepton/quark universality by testing the ratio $\lambda_{lq} = \kappa_l/\kappa_q$

ATLAS approach:
no assumption on Γ_H
3 params.
- ratio λ_{lq} (=κ_l/κ_q)
- ratio λ_{Vq} (=κ_V/κ_q)
- κ_{qq}

CMS approach: Γ_{BSM}=0
3 free params
- ratio λ_{lq} (=κ_l/κ_q) (POI)
- κ_q (profiled)
- κ_V (profiled)



λ_{lq}[0.62, 1.50] @ 95 CL

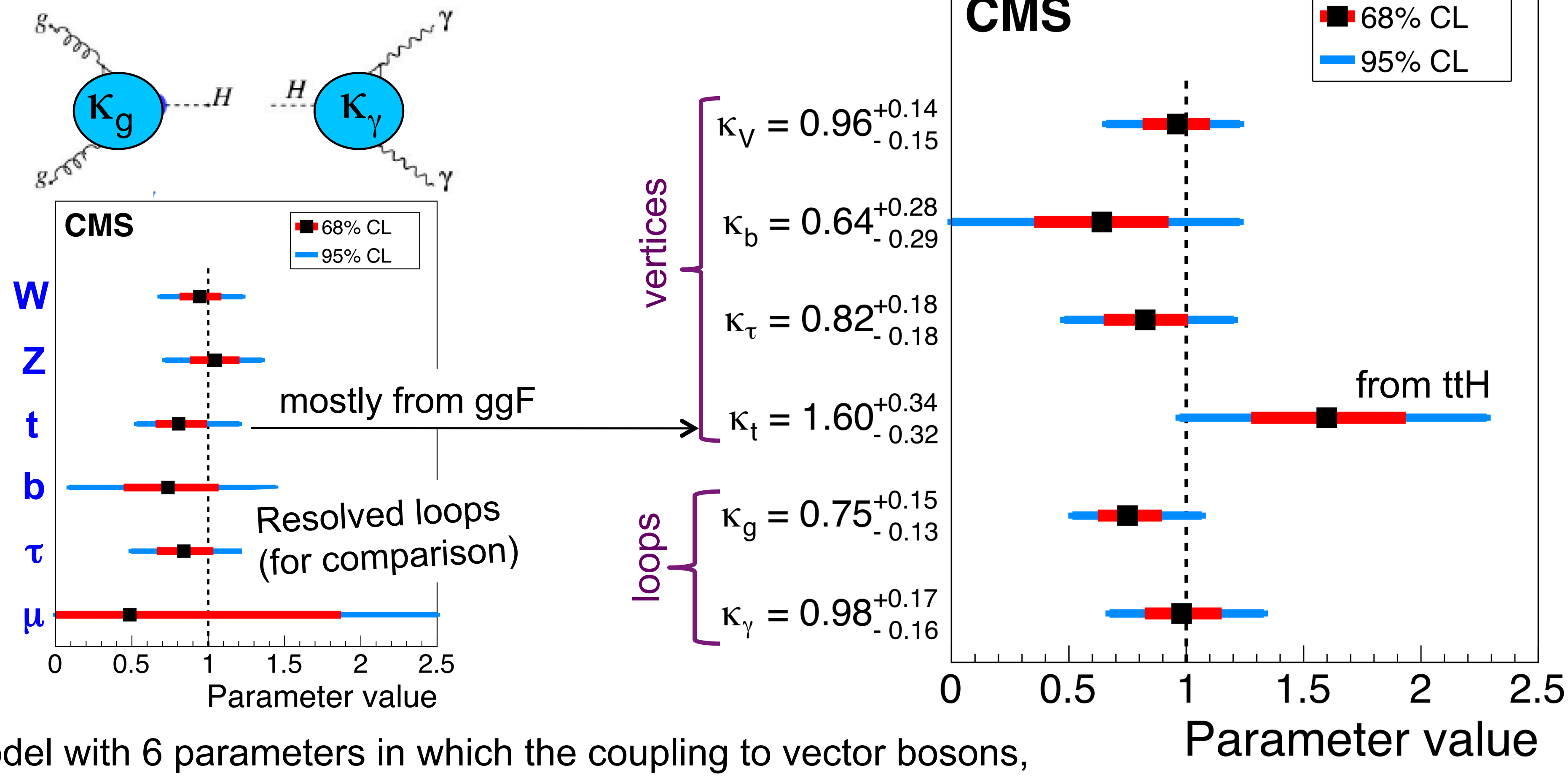


Best fit: λ_{lq}=$1.12^{+0.22}_{-0.18}$

New physics in loops?

Presence of BSM particles in gg→H and H→γγ loops (κ_g vs κ_γ) and scaling factors for SM particles

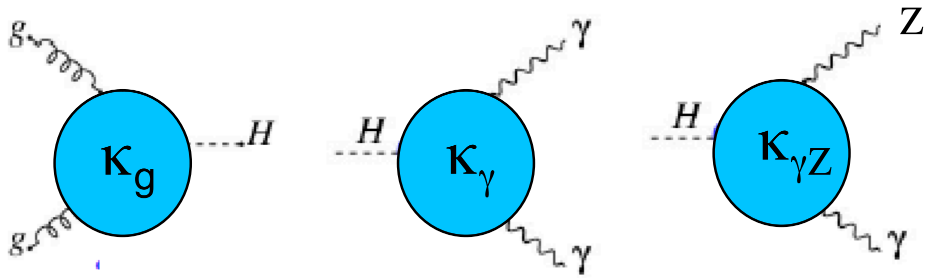
Loop-induced processes: unresolved



Model with 6 parameters in which the coupling to vector bosons, to different types fermions (charged leptons, up- and down-type quarks), and to gluons and photons are allowed to scale **keeping Γ_{BSM}=0**.

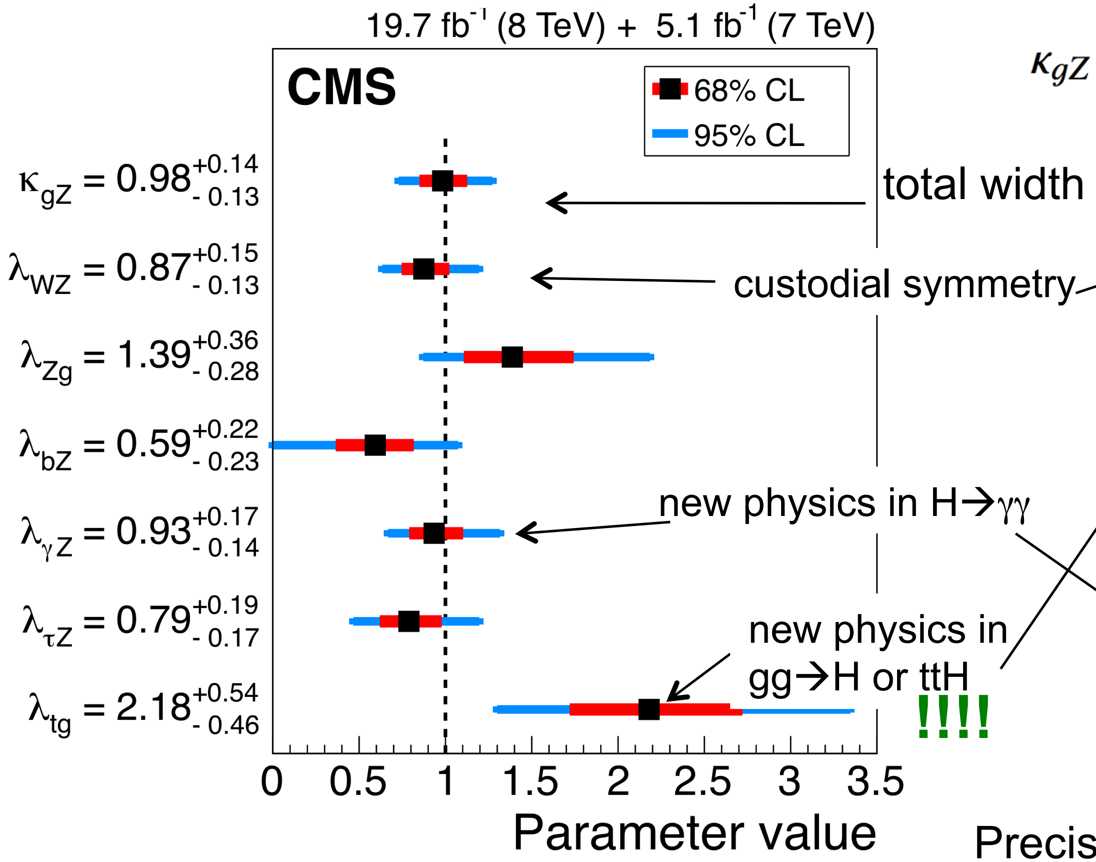
More general: no assumptions on Γ_H

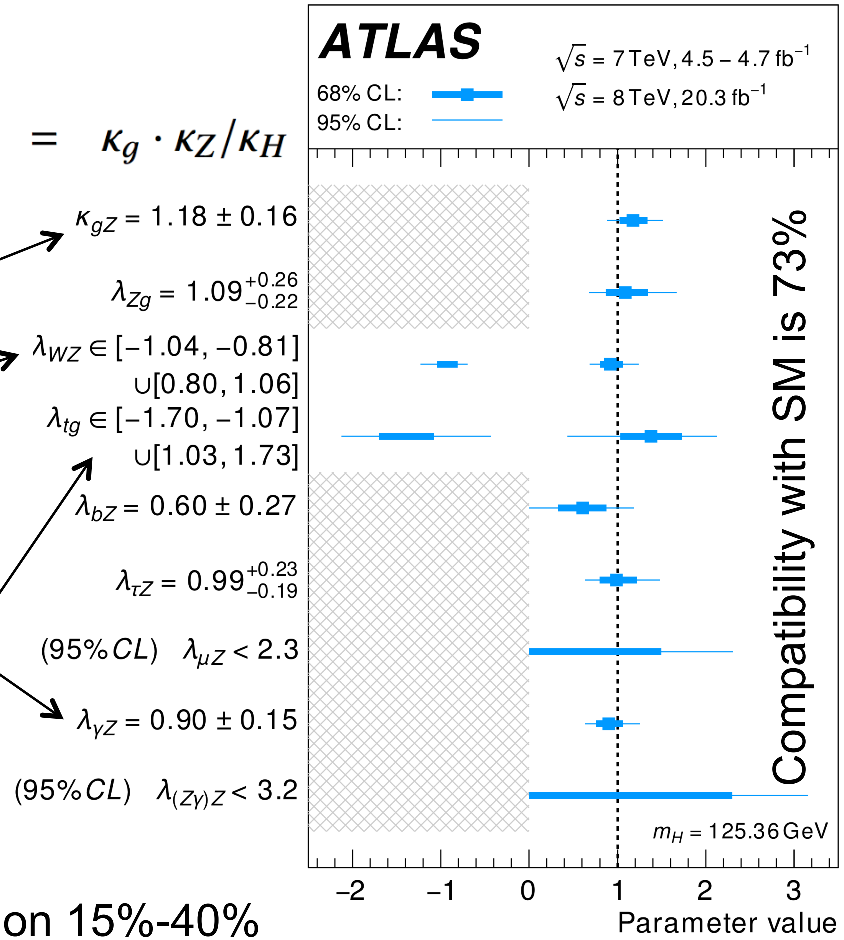
New particles in loops and no assumptions on total width



- $\kappa_W, \kappa_Z, \kappa_b, \kappa_\tau, \kappa_t$ and κ_μ are treated independently
- do not resolve any loops ($\kappa_g, \kappa_\gamma, \kappa_{\gamma Z}$)
- no assumptions on total width, embedded in κ_{gZ}
- **only ratios can be determined**

$$\kappa_{gZ} = \kappa_g \cdot \kappa_Z / \kappa_H$$

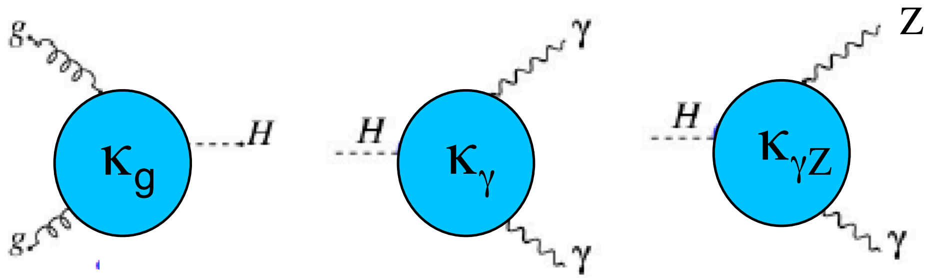




Precision 15%-40%

More general: no assumptions on Γ_H

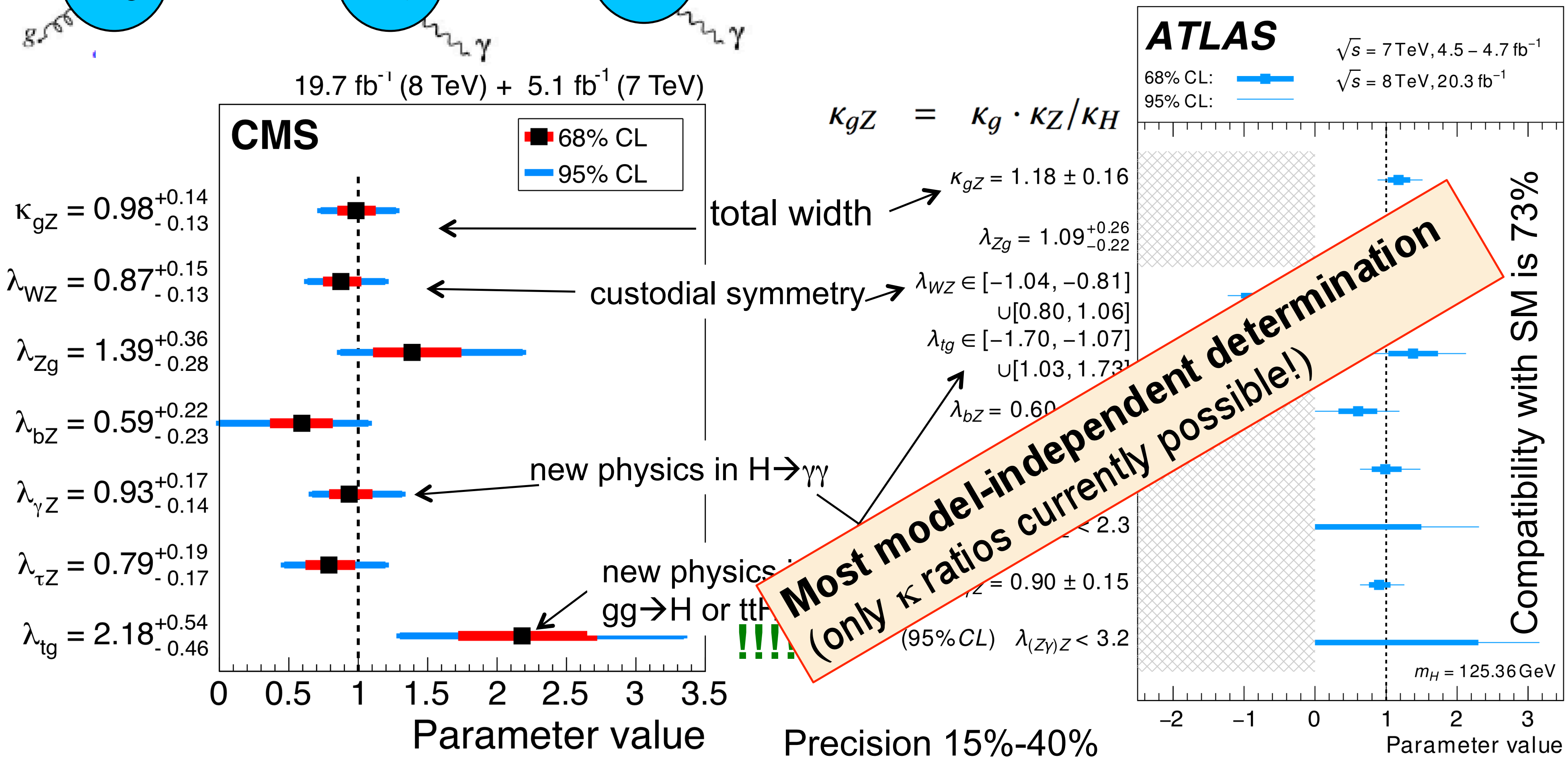
New particles in loops and no assumptions on total width



- κ_W, κ_Z, κ_t, κ_b, κ_γ and κ_μ are treated independently
- do not resolve any loops (κ_g, κ_γ, $\kappa_{\gamma Z}$)
- no assumptions on total width, embedded in κ_{gZ}
- **only ratios can be determined**

19.7 fb^{-1} (8 TeV) + 5.1 fb^{-1} (7 TeV)

$$\kappa_{gZ} = \kappa_g \cdot \kappa_Z / \kappa_H$$



Precision 15%-40%

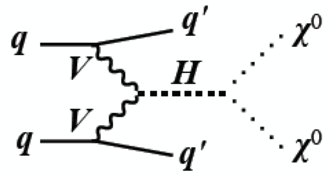
Allowing beyond SM Higgs decays (invisible or undetected)

$BR_{BSM} = BR_{i.,u.} = BR_{inv.} + BR_{undet.} > 0$

BR_{inv} → direct limits from $H \rightarrow E_{T,miss}$ (mostly from VBF)

ATLAS: $BR_{inv} < 29\%$ @ 95C.L.

CMS: $BR_{inv} < 57\%$ @ 95C.L.



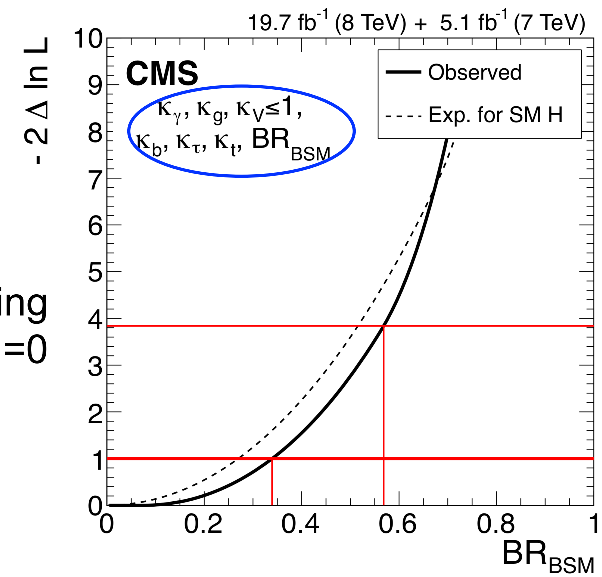
indirect from coupling fits ($\kappa_V \leq 1$)

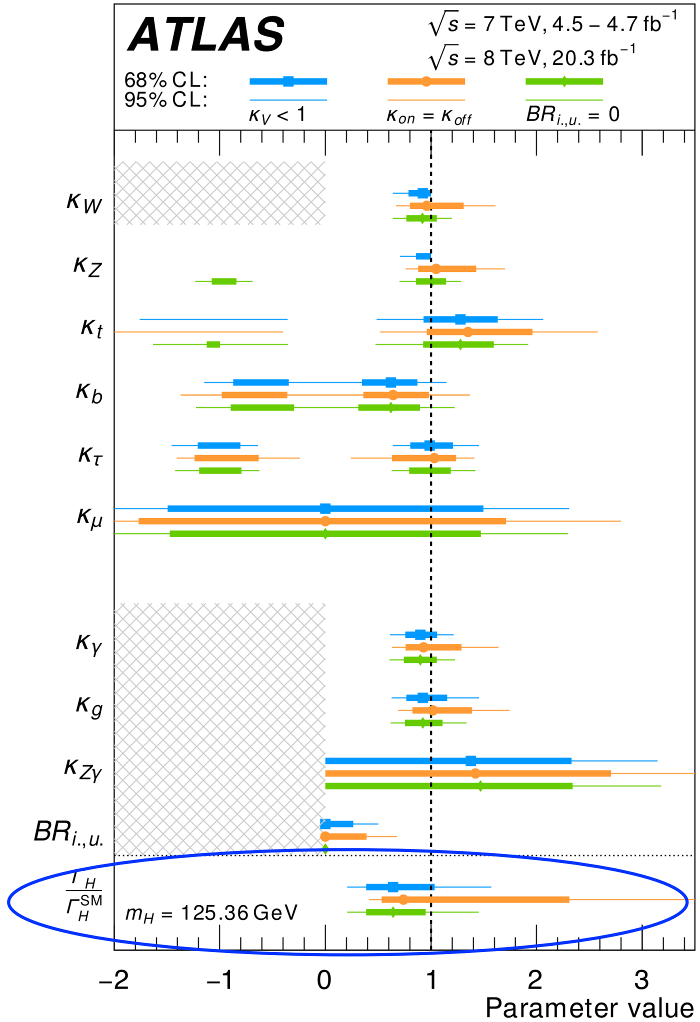
ATLAS: $BR_{i.,u.} < 49\%$ @ 95C.L.

CMS: $BR_{i.,u.} < 57\%$ @ 95C.L.

Combining with BR_{inv} direct meas.: $BR_{i.,u.} < 32\%$

Assuming $BR_{undet.} = 0$





These results represent the most model-independent measurements of the Γ_H.

Summary

Higgs boson discovery was an amazing experimental success although…
the found Higgs boson looks very similar to SM prediction.

Now, focus on measuring its fundamental properties in the most precise way:

- coupling measurements established and tested in diff. benchmark models:

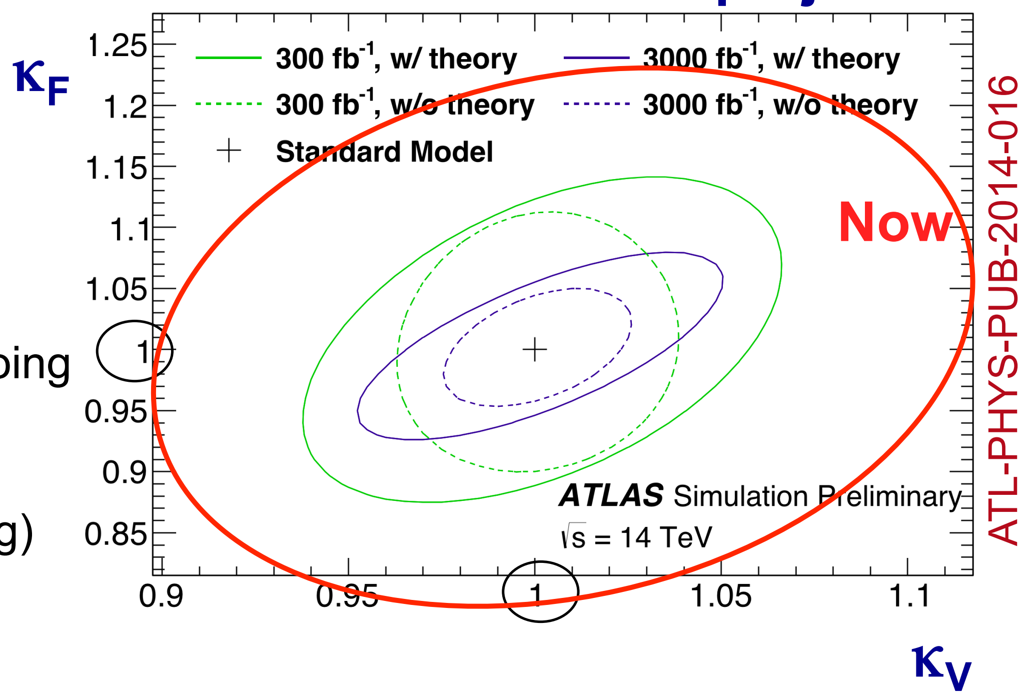
✓ fermions vs. bosons → good to 10-20%
✓ vertices, loops? → good to 10-20%
✓ BSM decays? $BR_{i.,u.}$<50%

- ATLAS+CMS coupling combination ongoing

- Run 2 will be sensitive to additional production and decay channels (promising)

- its self-couplings (very challenging!)

Future projections

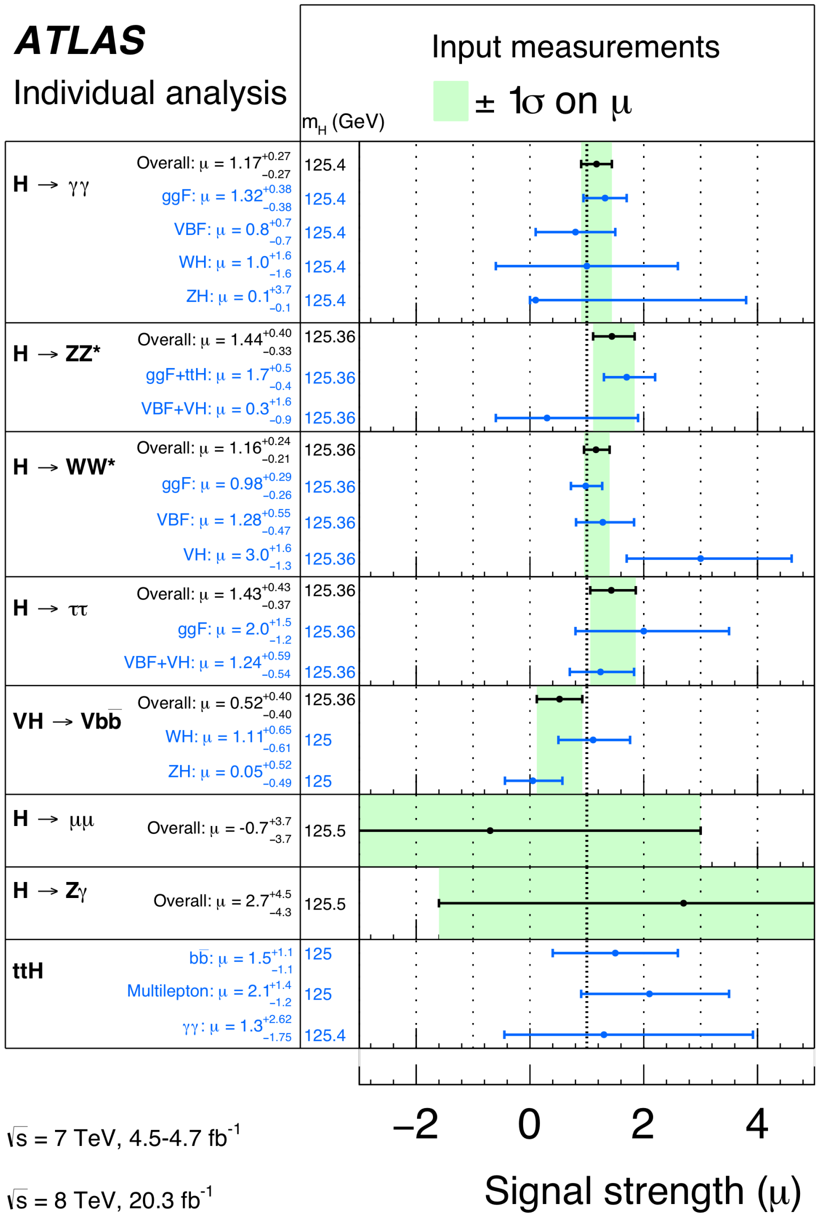


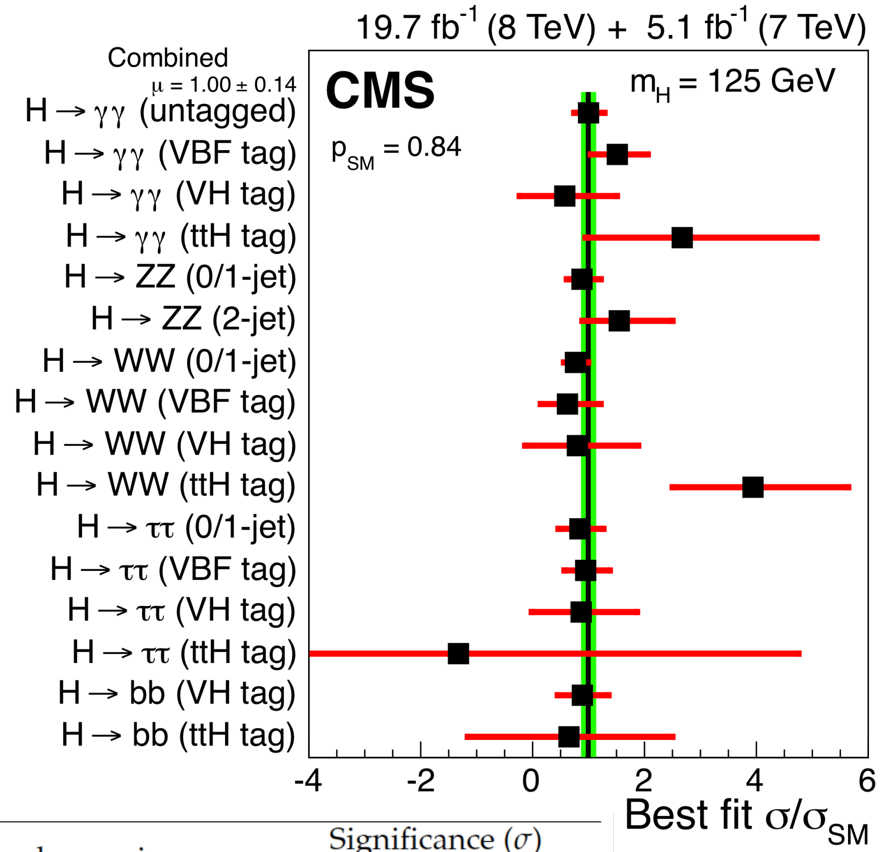
→ **Higgs physics moved on from discovery to precision studies!!**
→ **Check if portal to non-SM physics.**

THANKS FOR YOUR ATTENTION

BACK-UP

Inputs to the coupling measurements





Channel grouping	Significance (σ) Observed	Expected
$H \to ZZ$ tagged	6.5	6.3
$H \to \gamma\gamma$ tagged	5.6	5.3
$H \to WW$ tagged	4.7	5.4
Grouped as in Ref. [22]	4.3	5.4
$H \to \tau\tau$ tagged	3.8	3.9
Grouped as in Ref. [23]	3.9	3.9
$H \to bb$ tagged	2.0	2.6
Grouped as in Ref. [21]	2.1	2.5
$H \to \mu\mu$ tagged	< 0.1	0.4

CMS summary table

Model parameters	Table in Ref. [169]	Parameter	Best-fit result 68% CL	Best-fit result 95% CL	Comment
κ_Z, λ_{WZ} ($\kappa_f = 1$)	—	λ_{WZ}	$0.94^{+0.22}_{-0.18}$	$[0.61, 1.45]$	$\lambda_{WZ} = \kappa_W/\kappa_Z$ from ZZ and 0/1-jet WW channels.
$\kappa_Z, \lambda_{WZ}, \kappa_f$	44 (top)	λ_{WZ}	$0.92^{+0.14}_{-0.12}$	$[0.71, 1.24]$	$\lambda_{WZ} = \kappa_W/\kappa_Z$ from full combination.
κ_V, κ_f	43 (top)	κ_V	$1.01^{+0.07}_{-0.07}$	$[0.87, 1.14]$	κ_V scales couplings to W and Z bosons.
		κ_f	$0.87^{+0.14}_{-0.13}$	$[0.63, 1.15]$	κ_f scales couplings to all fermions.
$\kappa_V, \lambda_{du}, \kappa_u$	46 (top)	λ_{du}	$0.99^{+0.19}_{-0.18}$	$[0.65, 1.39]$	$\lambda_{du} = \kappa_u/\kappa_d$, relates up-type and down-type fermions.
$\kappa_V, \lambda_{\ell q}, \kappa_q$	47 (top)	$\lambda_{\ell q}$	$1.03^{+0.23}_{-0.21}$	$[0.62, 1.50]$	$\lambda_{\ell q} = \kappa_\ell/\kappa_q$, relates leptons and quarks.
$\kappa_W, \kappa_Z, \kappa_t,$	Extends 51	κ_W	$0.95^{+0.14}_{-0.13}$	$[0.68, 1.23]$	
		κ_Z	$1.05^{+0.16}_{-0.16}$	$[0.72, 1.35]$	
		κ_t	$0.81^{+0.19}_{-0.15}$	$[0.53, 1.20]$	Up-type quarks (via t).
$\kappa_b, \kappa_\tau, \kappa_\mu$		κ_b	$0.74^{+0.33}_{-0.29}$	$[0.09, 1.44]$	Down-type quarks (via b).
		κ_τ	$0.84^{+0.19}_{-0.18}$	$[0.50, 1.24]$	Electron and tau lepton (via τ).
		κ_μ	$0.49^{+1.38}_{-0.49}$	$[0.00, 2.77]$	κ_μ scales the coupling to muons.
M, ϵ	Ref. [202]	M (GeV)	245 ± 15	$[217, 279]$	$\kappa_f = v\frac{m_f^\epsilon}{M^{1+\epsilon}}$ and $\kappa_V = v\frac{m_V^{2\epsilon}}{M^{1+2\epsilon}}$
		ϵ	$0.014^{+0.041}_{-0.036}$	$[-0.054, 0.100]$	(Section 7.4)
κ_g, κ_γ	48 (top)	κ_g	$0.89^{+0.11}_{-0.10}$	$[0.69, 1.11]$	Effective couplings to
		κ_γ	$1.14^{+0.12}_{-0.13}$	$[0.89, 1.40]$	gluons (g) and photons (γ).
$\kappa_g, \kappa_\gamma, BR_{BSM}$	48 (middle)	BR_{BSM}	≤ 0.14	$[0.00, 0.32]$	Allows for BSM decays.
with H(inv) searches	—	BR_{inv}	$0.03^{+0.15}_{-0.03}$	$[0.00, 0.32]$	H(inv) use implies $BR_{undet} = 0$.
with H(inv) and $\kappa_i = 1$	—	BR_{inv}	$0.06^{+0.11}_{-0.06}$	$[0.00, 0.27]$	Assumes $\kappa_i = 1$ and uses H(inv).
$\kappa_{gZ},$	50 (bottom)	κ_{gZ}	$0.98^{+0.14}_{-0.13}$	$[0.73, 1.27]$	$\kappa_{gZ} = \kappa_g\kappa_Z/\kappa_H$, i.e. floating κ_H.
		λ_{WZ}	$0.87^{+0.15}_{-0.13}$	$[0.63, 1.19]$	$\lambda_{WZ} = \kappa_W/\kappa_Z$.
$\lambda_{WZ}, \lambda_{Zg}, \lambda_{bZ},$		λ_{Zg}	$1.39^{+0.36}_{-0.28}$	$[0.87, 2.18]$	$\lambda_{Zg} = \kappa_Z/\kappa_g$.
		λ_{bZ}	$0.59^{+0.22}_{-0.23}$	≤ 1.07	$\lambda_{bZ} = \kappa_b/\kappa_Z$.
$\lambda_{\gamma Z}, \lambda_{\tau Z}, \lambda_{tg}$		$\lambda_{\gamma Z}$	$0.93^{+0.17}_{-0.14}$	$[0.67, 1.31]$	$\lambda_{\gamma Z} = \kappa_\gamma/\kappa_Z$.
		$\lambda_{\tau Z}$	$0.79^{+0.19}_{-0.17}$	$[0.47, 1.20]$	$\lambda_{\tau Z} = \kappa_\tau/\kappa_Z$.
		λ_{tg}	$2.18^{+0.54}_{-0.46}$	$[1.30, 3.35]$	$\lambda_{tg} = \kappa_t/\kappa_g$.
$\kappa_V, \kappa_b, \kappa_\tau,$	Similar to 50 (top)	κ_V	$0.96^{+0.14}_{-0.15}$	$[0.66, 1.23]$	
		κ_b	$0.64^{+0.28}_{-0.29}$	$[0.00, 1.23]$	Down-type quarks (via b).
		κ_τ	$0.82^{+0.18}_{-0.18}$	$[0.48, 1.20]$	Charged leptons (via τ).
$\kappa_t, \kappa_g, \kappa_\gamma$		κ_t	$1.60^{+0.34}_{-0.32}$	$[0.97, 2.28]$	Up-type quarks (via t).
		κ_g	$0.75^{+0.15}_{-0.13}$	$[0.52, 1.07]$	
		κ_γ	$0.98^{+0.17}_{-0.16}$	$[0.67, 1.33]$	
with $\kappa_V \leq 1$ and BR_{BSM}	—	BR_{BSM}	≤ 0.34	$[0.00, 0.57]$	Allows for BSM decays.
with $\kappa_V \leq 1$ and H(inv)	—	BR_{inv}	0.17 ± 0.17	$[0.00, 0.49]$	H(inv) use implies $BR_{undet} = 0$.
with $\kappa_V \leq 1$, H(inv),	—	BR_{inv}	0.17 ± 0.17	$[0.00, 0.49]$	Separates BR_{inv} from BR_{undet},
BR_{inv}, and BR_{undet}	—	BR_{undet}	≤ 0.23	$[0.00, 0.52]$	$BR_{BSM} = BR_{inv} + BR_{undet}$.

SM predictions (from ATLAS paper)

Table 1: SM predictions of the Higgs boson production cross sections and decay branching ratios and their uncertainties for $m_H = 125.36$ GeV, obtained by linear interpolations from those at 125.3 and 125.4 GeV from Ref. [11] except for the tH production cross section which is obtained from Refs. [23, 26]. The uncertainties of the cross sections are the sum in quadrature of the uncertainties resulting from variations of QCD scales, parton distribution functions and α_s. The uncertainty on the tH cross section is calculated following the procedure in Refs. [11, 23].

Production process	Cross section [pb] $\sqrt{s} = 7$ TeV	Cross section [pb] $\sqrt{s} = 8$ TeV	Decay channel	Branching ratio [%]
ggF	15.0 ± 1.6	19.2 ± 2.0	$H \to b\bar{b}$	57.1 ± 1.9
VBF	1.22 ± 0.03	1.57 ± 0.04	$H \to WW^*$	22.0 ± 0.9
WH	0.573 ± 0.016	0.698 ± 0.018	$H \to gg$	8.53 ± 0.85
ZH	0.332 ± 0.013	0.412 ± 0.013	$H \to \tau\tau$	6.26 ± 0.35
bbH	0.155 ± 0.021	0.202 ± 0.028	$H \to c\bar{c}$	2.88 ± 0.35
ttH	0.086 ± 0.009	0.128 ± 0.014	$H \to ZZ^*$	2.73 ± 0.11
tH	0.012 ± 0.001	0.018 ± 0.001	$H \to \gamma\gamma$	0.228 ± 0.011
			$H \to Z\gamma$	0.157 ± 0.014
Total	17.4 ± 1.6	22.3 ± 2.0	$H \to \mu\mu$	0.022 ± 0.001

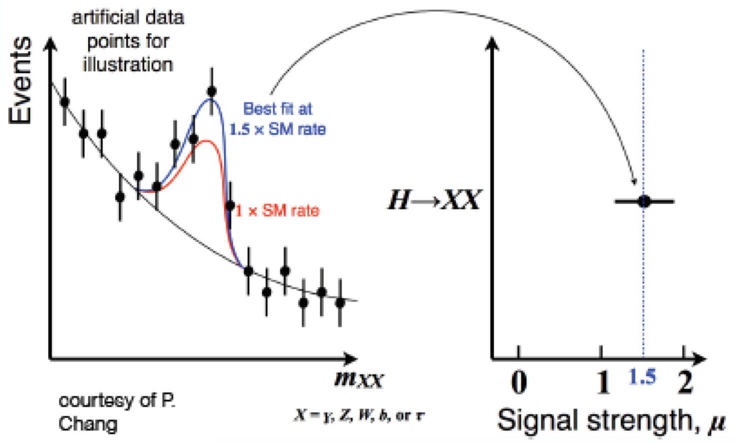
Statistical analysis

Binned profile likelihood fit *L*(μ,θ)

$$L(\mu,\theta) = L_{Pois}(\mu,\theta) \cdot \prod_{p} \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{\theta_p^2}{2}\right) \cdot \prod_{i,j} \frac{1}{\sqrt{2\pi}\sigma_{\gamma,ij}} \exp\left(-\frac{(\gamma_{ij}-1)^2}{2\sigma_{\gamma,ij}^2}\right)$$

$$L_{Pois}(\mu) = \prod_{j}^{reg} \prod_{i}^{bins(j)} \frac{(\mu s_{ij}+b_{ij})^{n_{ij}}}{n_{ij}!} \exp\left(-(\mu s_{ij}+b_{ij})\right)$$

- parameter of interest: signal strength $\mu=\sigma/\sigma_{SM}$
- nuisance parameters θ_p: systematic uncertainties
- nuisance parameters $\sigma_{\gamma,ij}$: MC statistical uncertainty per bin



→ Find the best values for μ and θ_p by minimizing the log L
→ obtain fitted uncertainty on μ
→ data can contrain the "a priori" nuisance parameters values

→ Calculate the experimental sensitivity in terms of the significance (i.e. level of disagreement between the data and the background-only hypothesis expressed as Gaussian standard deviations σ)

$$\mu_{P,X} \sim \frac{(\sigma_P \times Br_X)_{Data}}{(\sigma_P \times Br_X)_{Theory}}$$

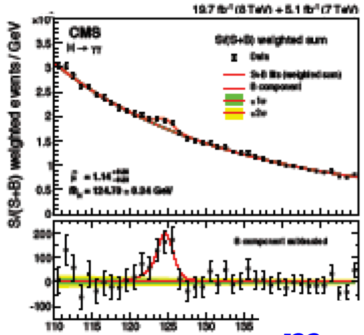
$P \in \{ggF, VBF, VH, ttH\}$
$X \in \{\gamma\gamma, ZZ, WW, bb, \tau\tau\}$

To obtain the final result, a simultaneous fit to the data is performed to the distributions of the discriminants in all regions under the signal-plus-background hypothesis.

Five major decay channels and rare processes

Higgs yields

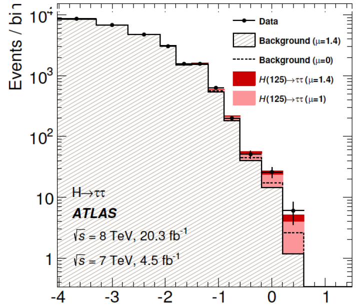
Higgs properties can be inferred from the event rates measured in all the channels.



$m_{\gamma\gamma}$

$\gamma\gamma$

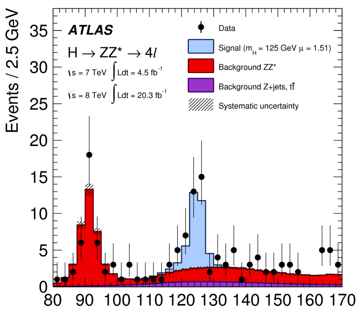
N_{sig}≈200-500
N_{bkg}≈5000
5.2-5.6σ observed



log(S/B)

$\tau\tau$

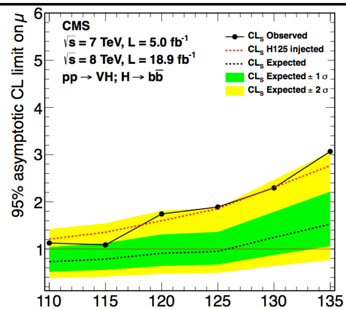
N_{sig}≈400-650
N_{bkg}≈huge
3.8-4.5σ observed



m_{4l}

ZZ

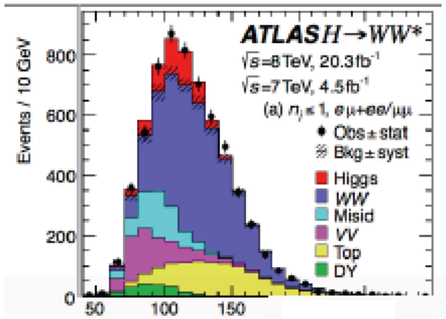
N_{sig}≈20
N_{bkg}≈20
6.5-8.1σ observed



m_H

bb

N_{sig}≈60-100
N_{bkg}≈huge
1.4-2.1σ observed



m_T

WW

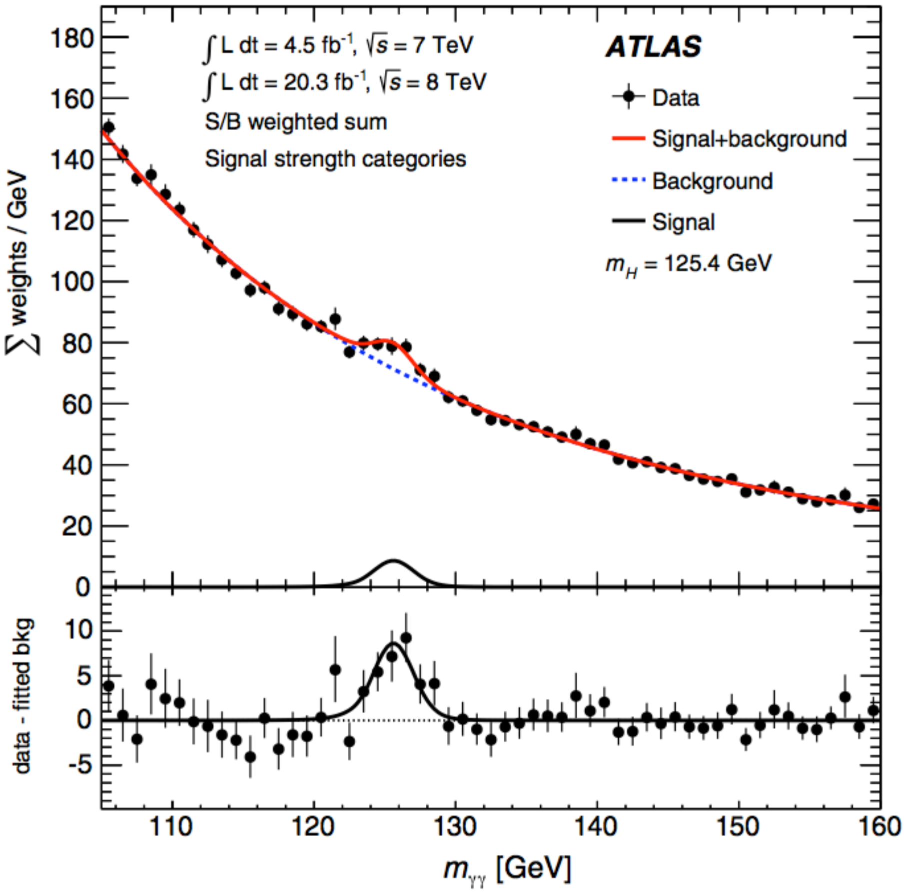
N_{sig}≈500
N_{bkg}≈7000
4.7-6.5σ observed

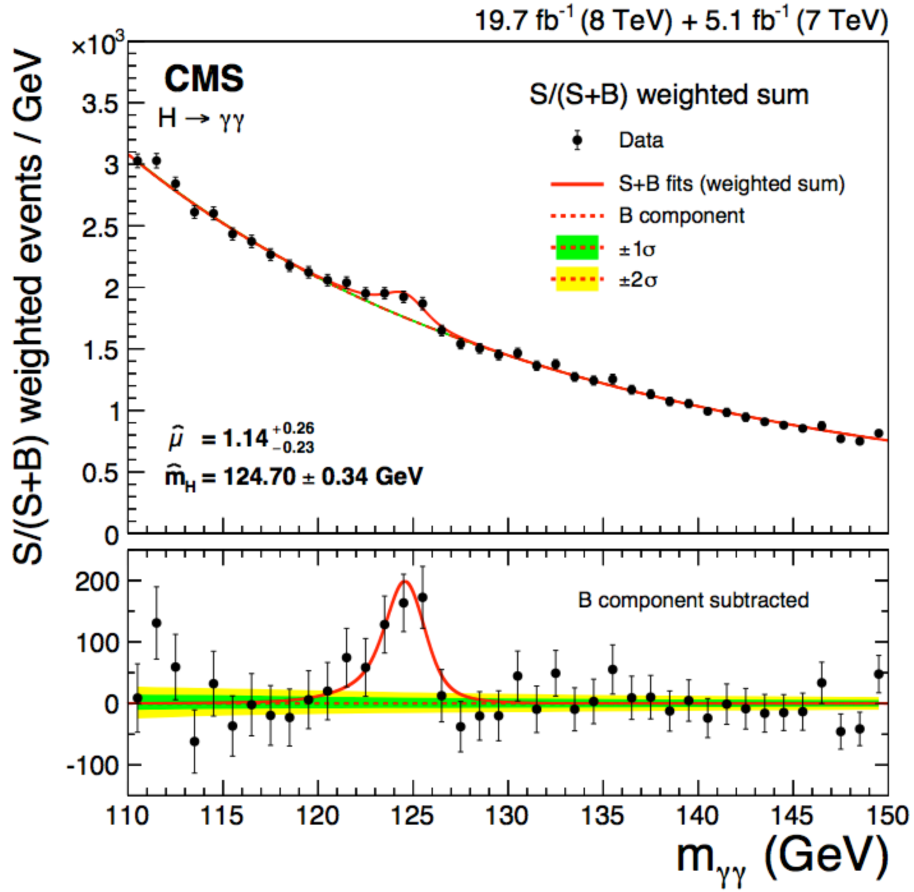
Rare decays: $\mu\mu$, $Z\gamma$, …

H → γγ

ATLAS: PRD 90 (2014) 112015
CMS: EPJC 74 (2014) 3076

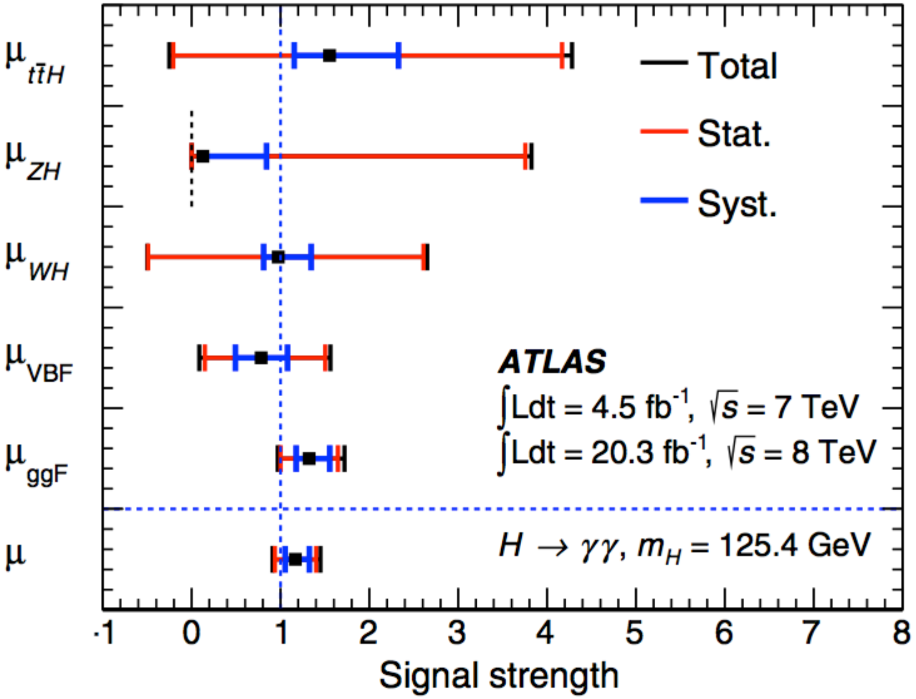
BR = 2.3x10^{-3}

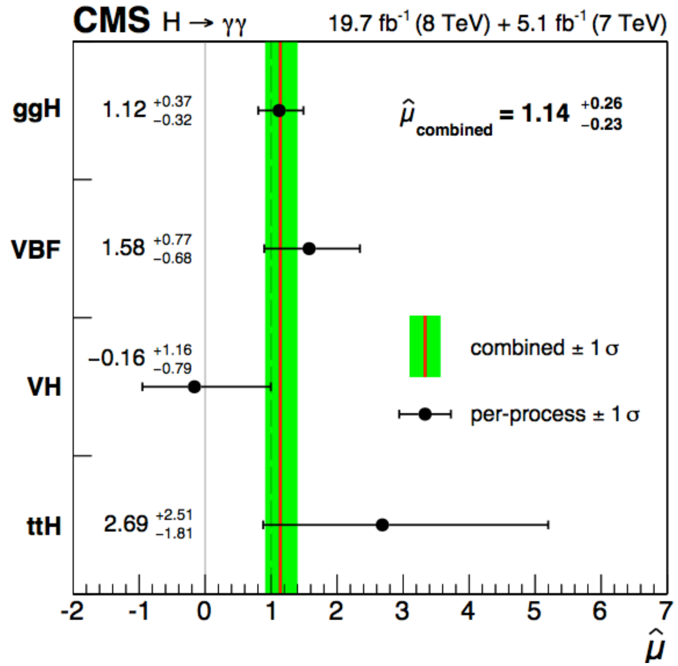


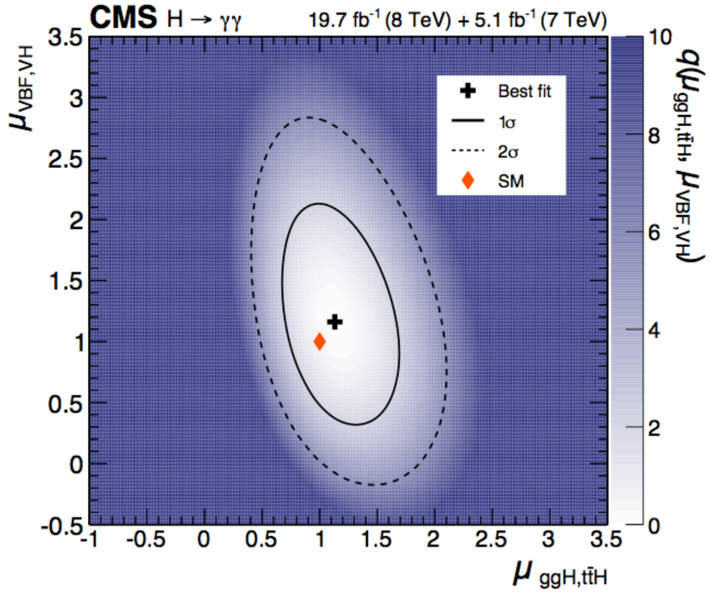


- look for a narrow signal on top of a smoothly failing bkg.
- split events into exclusive categories
- background estimated from a fit to $m_{\gamma\gamma}$

Obs. (exp.) significance	
ATLAS (7+8 TeV)	5.2σ (4.6σ)
CMS (7+8 TeV)	5.6σ (5.3σ)







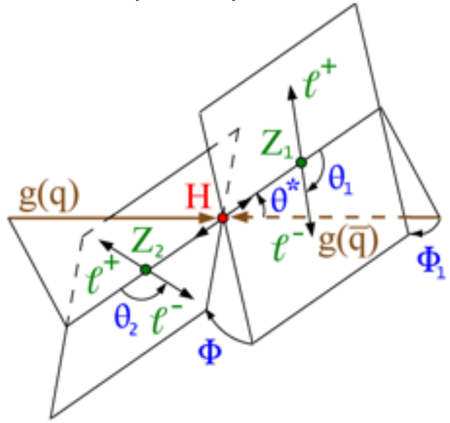
best-fit $\mu = \sigma/\sigma_{SM}$	
ATLAS (7+8 TeV)	1.17 ± 0.27
CMS (7+8 TeV)	$1.14^{+0.26}_{-0.23}$

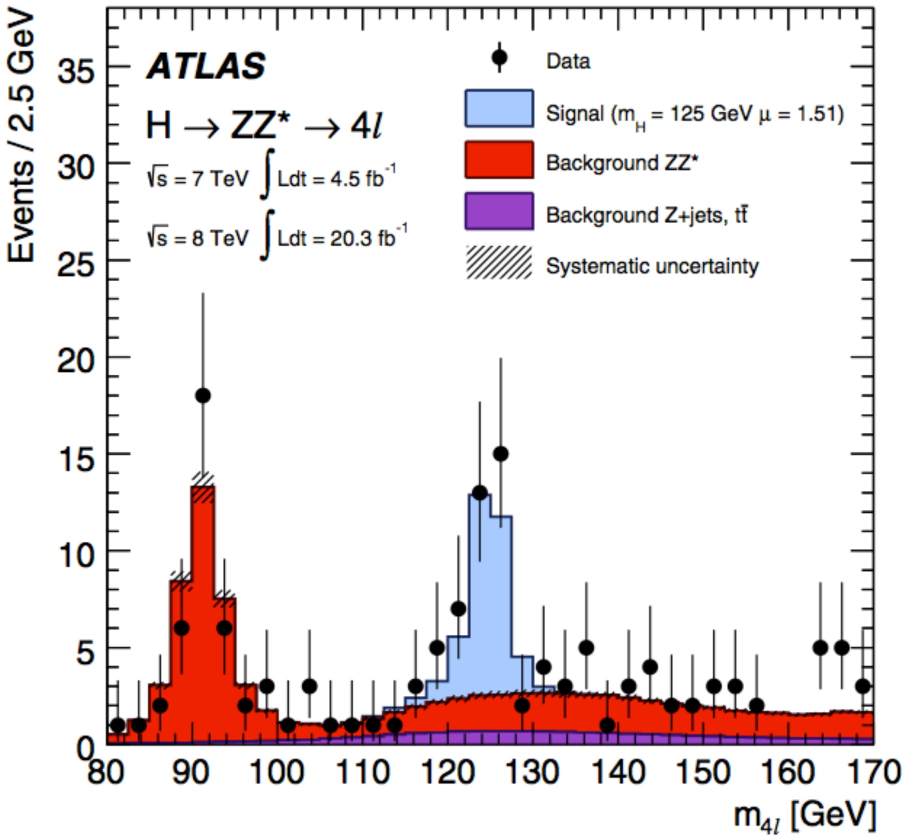
H → ZZ* → 4l

ATLAS: PRD 91 (2015) 012006
CMS: PRD 89 (2014) 092007

BR = 1.3×10^{-4}, l = e,μ

- excellent mass resolution : 1-2%
- select four isolated leptons (low p_T is important)
- split events into exclusive categories
- fold angular information in a kinematic discriminant to separate signal and background



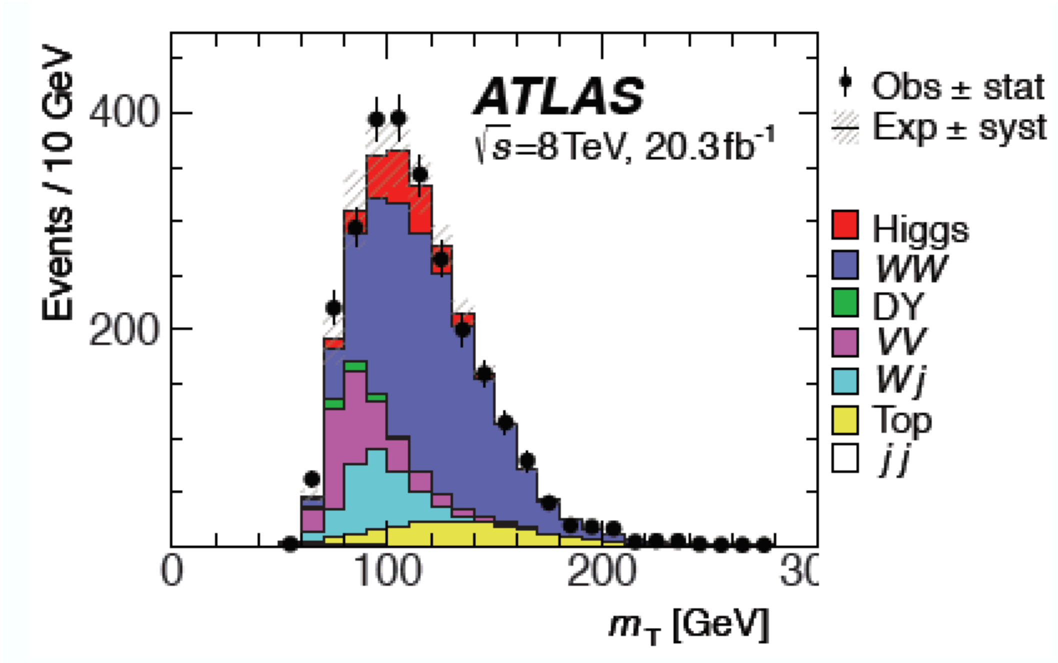


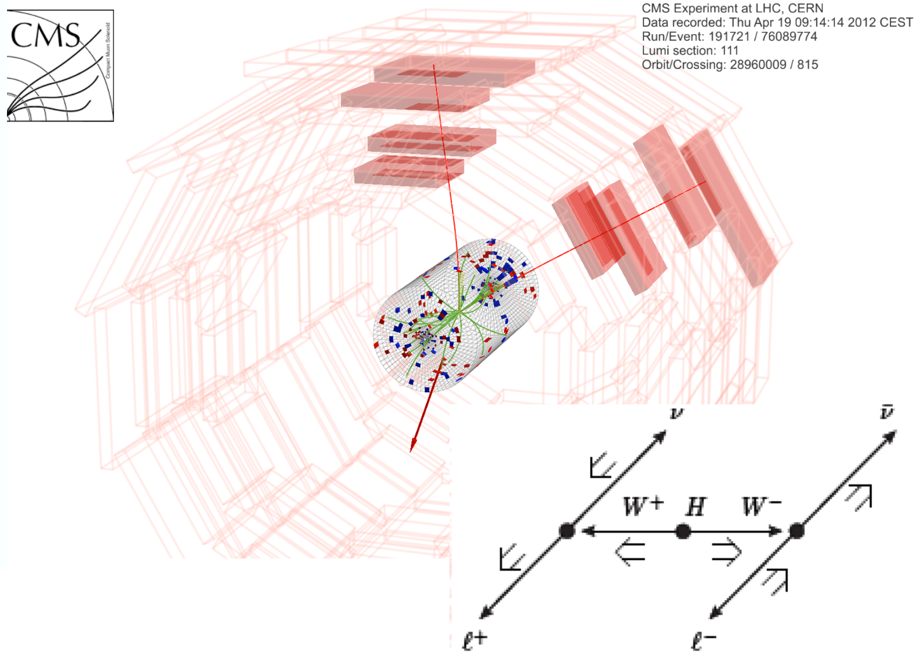
	best-fit $\mu = \sigma/\sigma_{SM}$	Obs. (exp.) significance
ATLAS (7+8 TeV)	$1.66^{+0.39}_{-0.34}$(stat.) $^{+0.21}_{-0.14}$(syst.)	8.2σ (5.8σ)
CMS (7+8 TeV)	$0.93^{+0.26}_{-0.23}$(stat.) $^{+0.13}_{-0.09}$(syst.)	6.8σ (6.7σ)

H → WW → 2l2ν

BR = 1.1×10^{-2}, l = e,μ

ATLAS: arXiv:1412.2641
CMS: JHEP 1401 (2014) 096





- mass resolution : 20%
- final state cannot be fully reconstructed
- main observable : m_T, m_{ll}, lepton p_T
- analysis performed in categories
- angular correlations used to reject bkg.
- large expected yield for property measurements once the mass is known

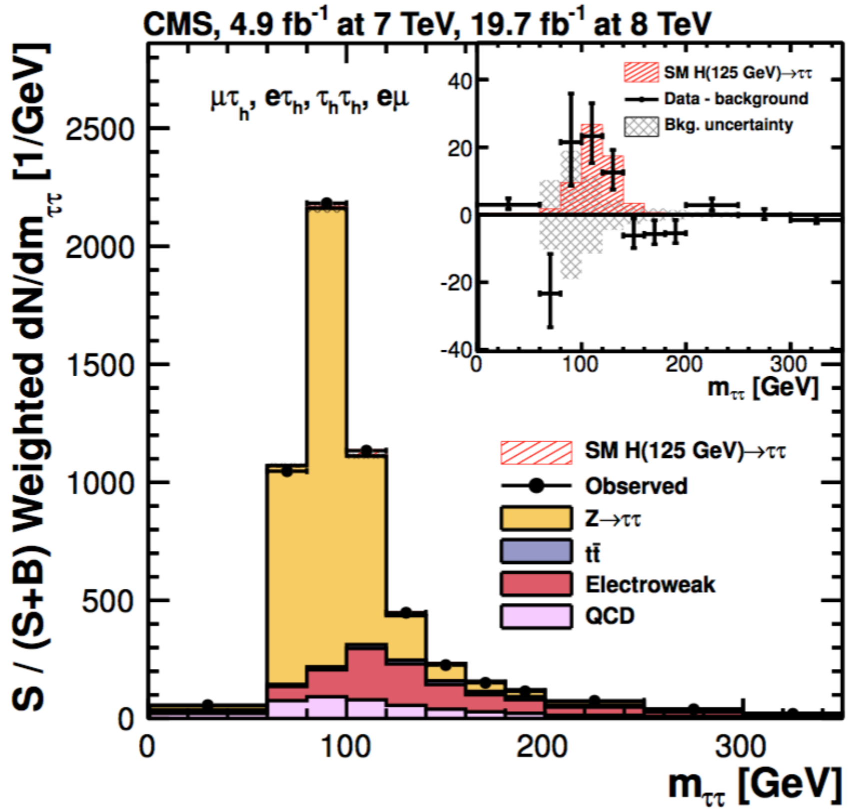
	best-fit $\mu = \sigma/\sigma_{SM}$	**Obs. (exp.) significance**
ATLAS (7+8 TeV)	$1.09^{+0.23}_{-0.21}$	6.1σ (5.8σ)
CMS (7+8 TeV)	0.72+0.20-0.18	4.3σ (5.8σ)

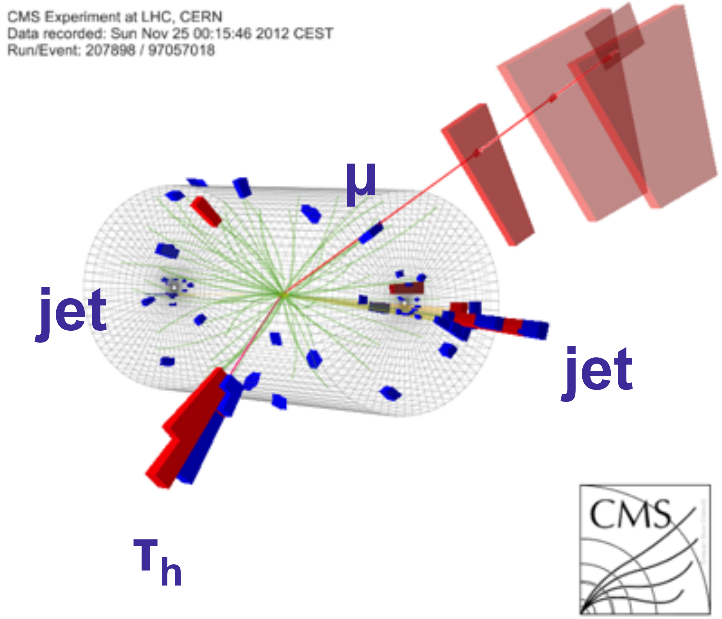
$H \rightarrow \tau\tau$

ATLAS: JHEP 1504 (2015) 117
CMS: JHEP 1405 (2014) 104

BR = 6.3×10^{-2}

- look into $e\tau_h$, $e\tau_h$, ee, $e\mu$, $\mu\mu$, $\tau_h\tau_h$
- mass resolution : 10-20%
- experimental challenges: hadronic τ ID, $m_{\tau\tau}$ reconstruction
- categories motivated by production
  - sensitivity mainly driven by VBF





	best-fit $\mu = \sigma/\sigma_{SM}$	Obs. (exp.) significance
ATLAS (7+8 TeV)	$1.43^{+0.43}_{-0.37}$	4.5σ (3.4σ)
CMS (7+8 TeV)	0.86 ± 0.29	3.4σ (3.6σ)

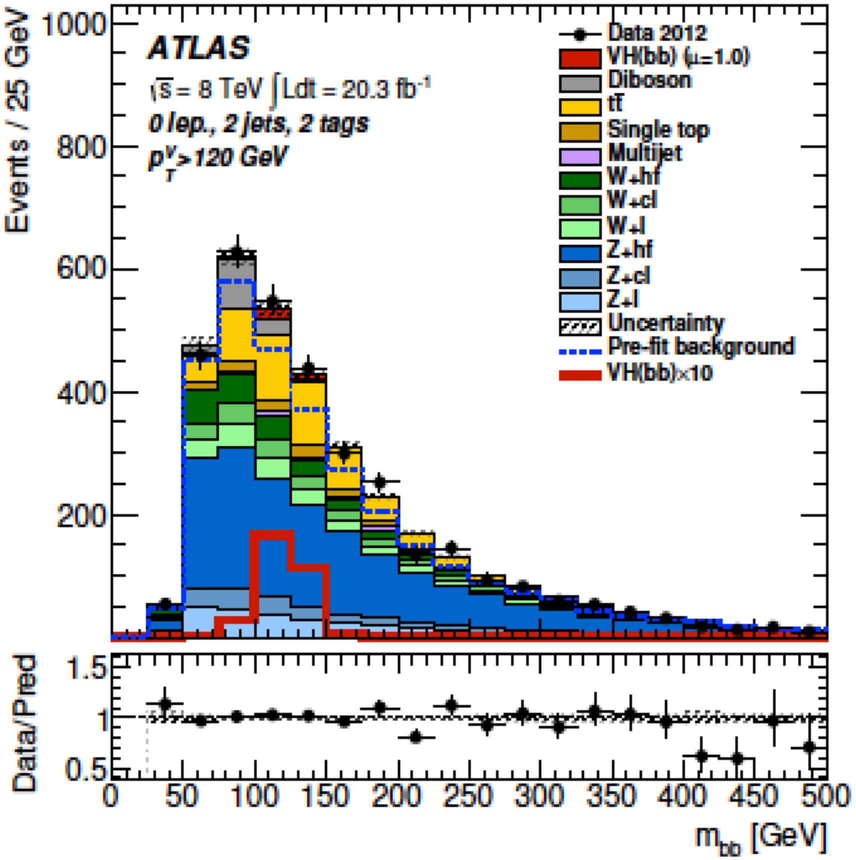
VH with H → bb

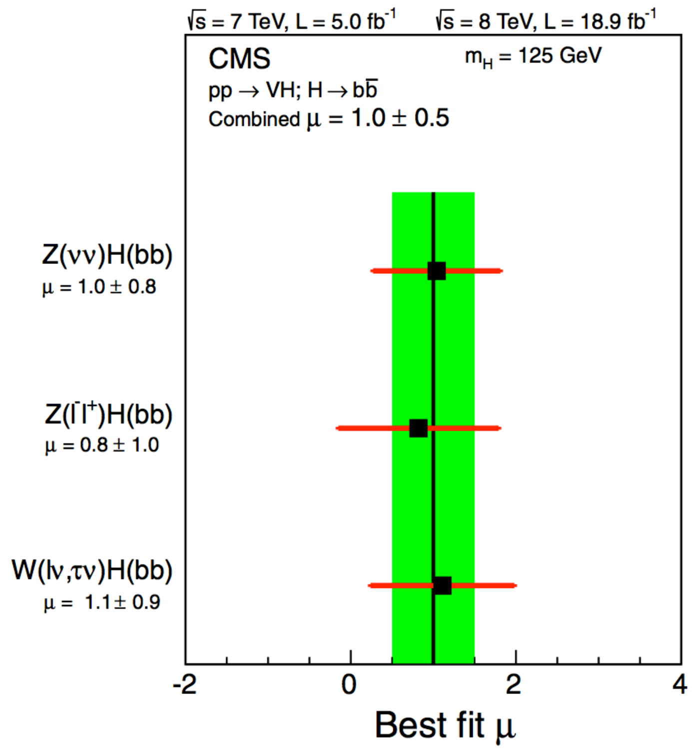
ATLAS: JHEP 01 (2015) 069
CMS: PRD 89 (2014) 012003

BR = 0.58

- mass resolution : 10%
- two b-tagged jets (very challenging)
- look into VH (VBF and ttH)
- both experiments use boosted decision trees

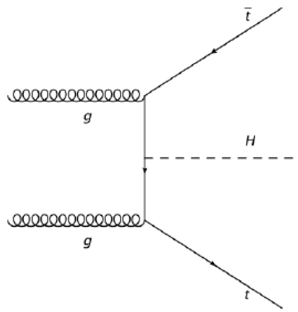
	best-fit $\mu = \sigma/\sigma_{SM}$	Obs. (exp.) significance
ATLAS (7+8 TeV)	0.5 ± 0.4	1.4σ (2.6σ)
CMS (7+8 TeV)	1.0 ± 0.5	2.1σ (2.1σ)



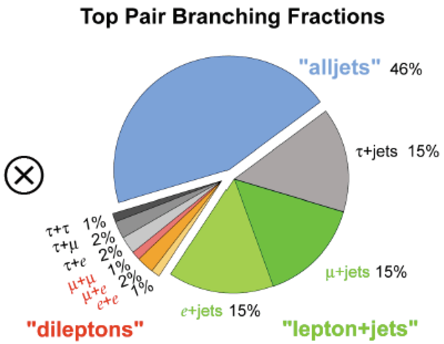


Direct searches for ttH production

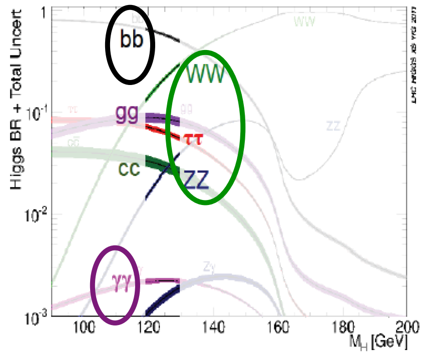
ATLAS:
ttH(γγ): PLB 740 (2015) 222
ttH(bb): Eur. Phys. J. C (2015) 75:349
ttH(multileptons): arXiv:1506.05988
CMS: JHEP 09 (2014) 087
Eur. Phys. J. C 75 (2015) 251



⊗



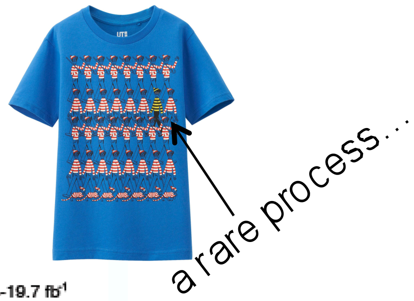
⊗

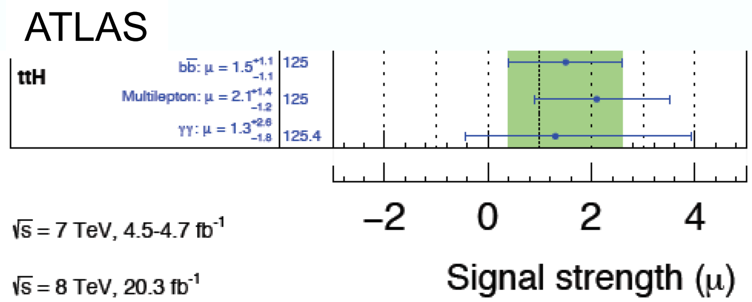


Virtues:

Many possible final states
→Several channels are defined depending on the final signature

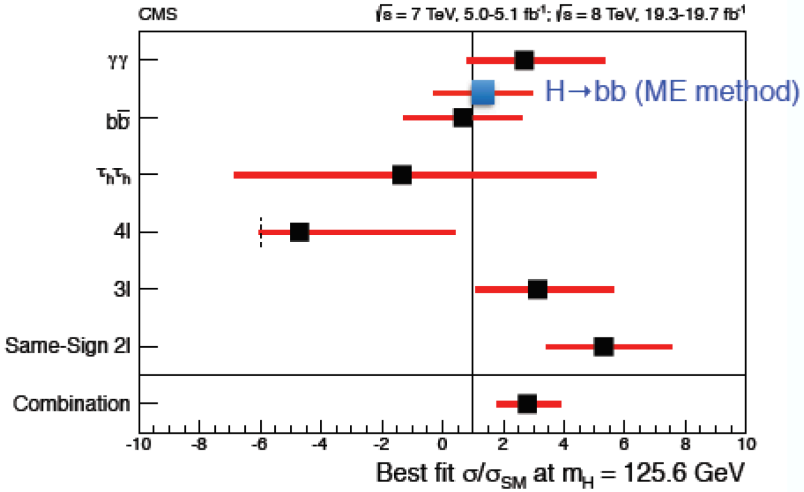
H→bb: dominant mode but large background
H→ WW, ZZ, ττ: multilepton final state
H→γγ : tiny but clean signature





Challenges:

- low production cross section
- large tt background (ttH:tt ~ 1:20



	best-fit $\mu = \sigma/\sigma_{SM}$	Obs. (exp.) significance
ATLAS (H→bb)	1.5 ± 1.1 @ 125.0 GeV	2.4σ (?)
CMS (7+8 TeV)	2.8 ± 1.0 @ 125.6 GeV	3.4σ (1.2σ)