# Status and prospects of Higgs Physics at the LHC

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# LHC luminosity delivered (per experiment)

| | | | |
|---|---|---|---|
| **Run 1** | **2010-2011** | **7 TeV** | **5 $fb^{-1}$** |
| | **2012** | **8 TeV** | **25 $fb^{-1}$** |
| **Run 2** | **2015** | **13 TeV** | **4 $fb^{-1}$** |
| | **2016** | | **40 $fb^{-1}$** |
| | **2017** | | **50 $fb^{-1}$** |
| | **2018** | | **65 $fb^{-1}$** |
| **Run 3** | **2021-2023** | **14 TeV** | **300 $fb^{-1}$** |
| **HL-LHC** | **2026-2038** | **14 TeV** | **3000 $fb^{-1}$** |

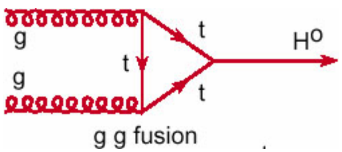
Integrated luminosities shown are approximate (small differences between ATLAS and CMS)

**In this short talk:**

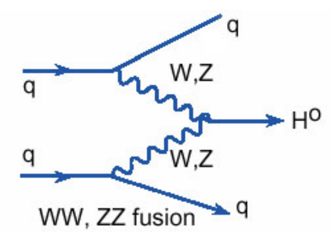
- Only a select set of recent results will be presented (many more interesting results are available and continue to come out)
- For simplicity, I will often select only either ATLAS or CMS results (results from ATLAS and CMS are always comparable)

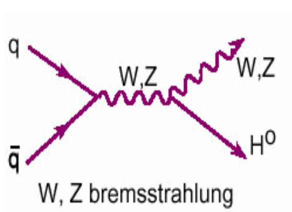
# h(125) production modes (pb)

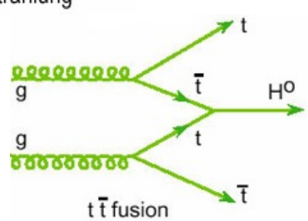
| | ggF | VBF | WH | ZH | bbH | ttH | tHq | tHW |
|---|---|---|---|---|---|---|---|---|
| 8 TeV | 19.5 | 1.60 | 0.70 | 0.42 | 0.20 | 0.13 | 0.019 | 0.0012 |
| 13 TeV | 44.1 | 3.78 | 1.37 | 0.88 | 0.49 | 0.51 | 0.074 | 0.0029 |
| ratio | 2.3 | 2.4 | 2.0 | 2.1 | 2.5 | 3.9 | 3.9 | 2.4 |

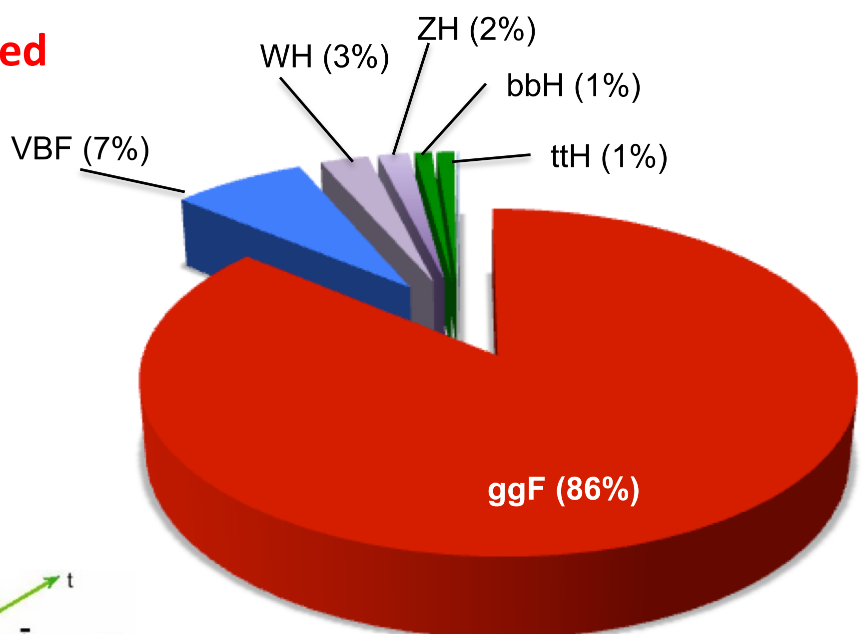


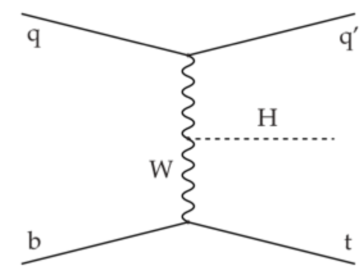

loop induced

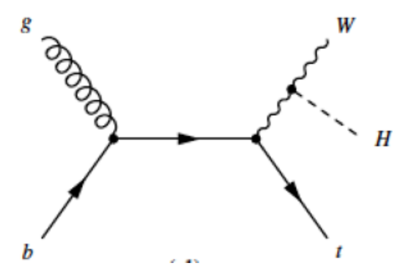


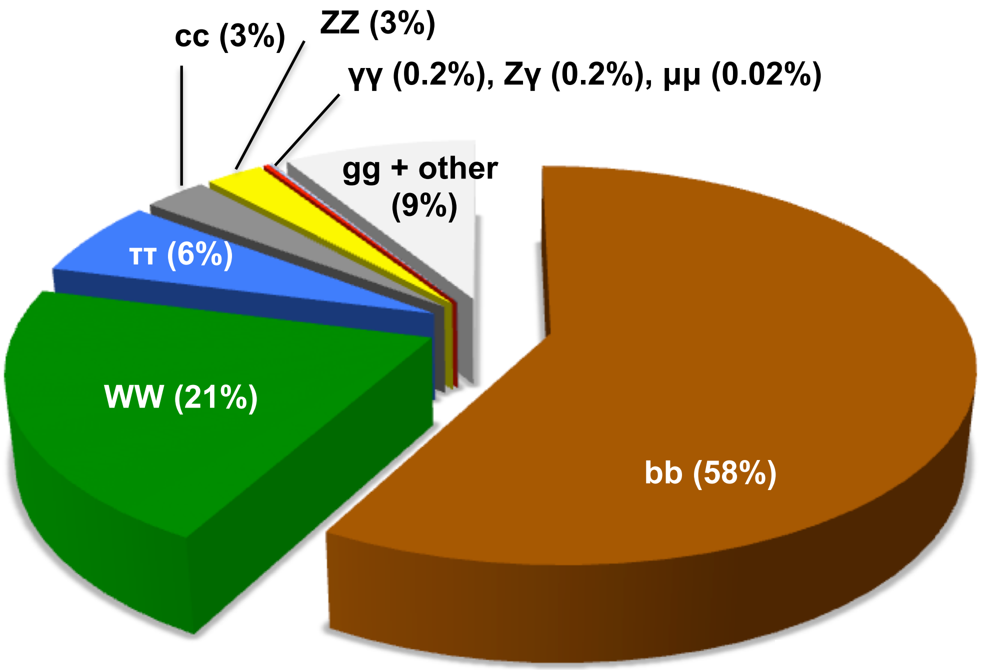



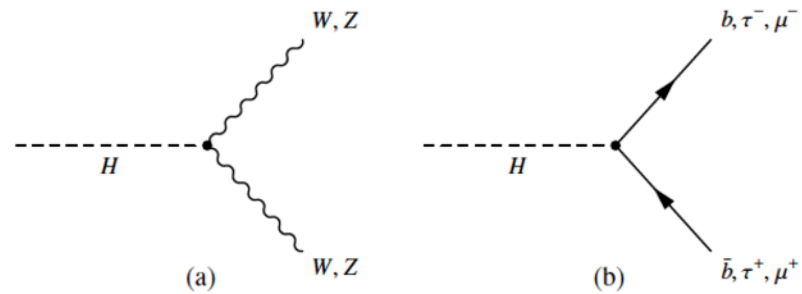



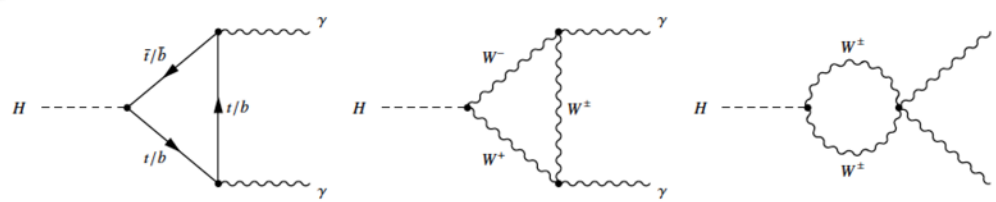
# h(125) production-decay modes

| | bb | WW | ττ | cc | ZZ | γγ | Zγ | μμ | gg + … |
|---|---|---|---|---|---|---|---|---|---|
| **all** | **58%** | **21%** | **6.3%** | **2.9%** | **2.6%** | **0.23%** | **0.15%** | **0.022%** | **9%** |
| leptonic | | 1.0% | | | 0.012% | | 0.010% | | |




**loop induced**



# Event categorization

**All analyses use event categorization, based on**

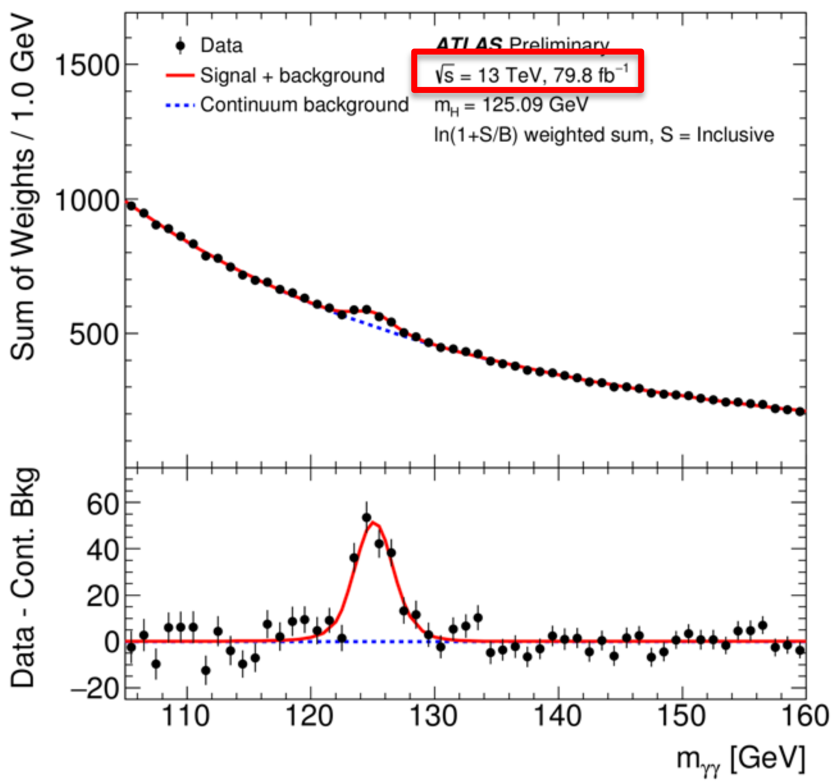
- **decay final states** (e.g. H->ZZ->4l: 4e, 4$\mu$, 2e2$\mu$; H->$\tau\tau$: …, etc)
- **quality of particles in the decay** (e.g. photons)
- **production mode tags** (e.g. VBF-like jet pair, Z(ll) for ZH, etc)

**Different categories have different S/B ratios, which helps improve search sensitivities and measurement accuracies**

**Production mode tags help disentangle contributions of different production mechanisms**

# $H \rightarrow \gamma\gamma$

ATLAS-CONF-2018-028




## Event Selection Strategy

- 2 "tight" high-$p_T$ photons
- vertex: use recoiling charged particles, "pointing" of photons
- key observable: di-photon mass
- split events into exclusive categories:
  - di-jet/MET/e/μ tagged (VBF and VH like)
  - untagged events are further sorted into a number of classes based on the quality of photons

## Backgrounds

- *entire background = fit of the $m_{\gamma\gamma}$-distribution*

## Analysis features to note

- fairly high event yield
- bad "effective" S/B-ratio: 1:10
- good mass resolution (instrumental): 1-2%

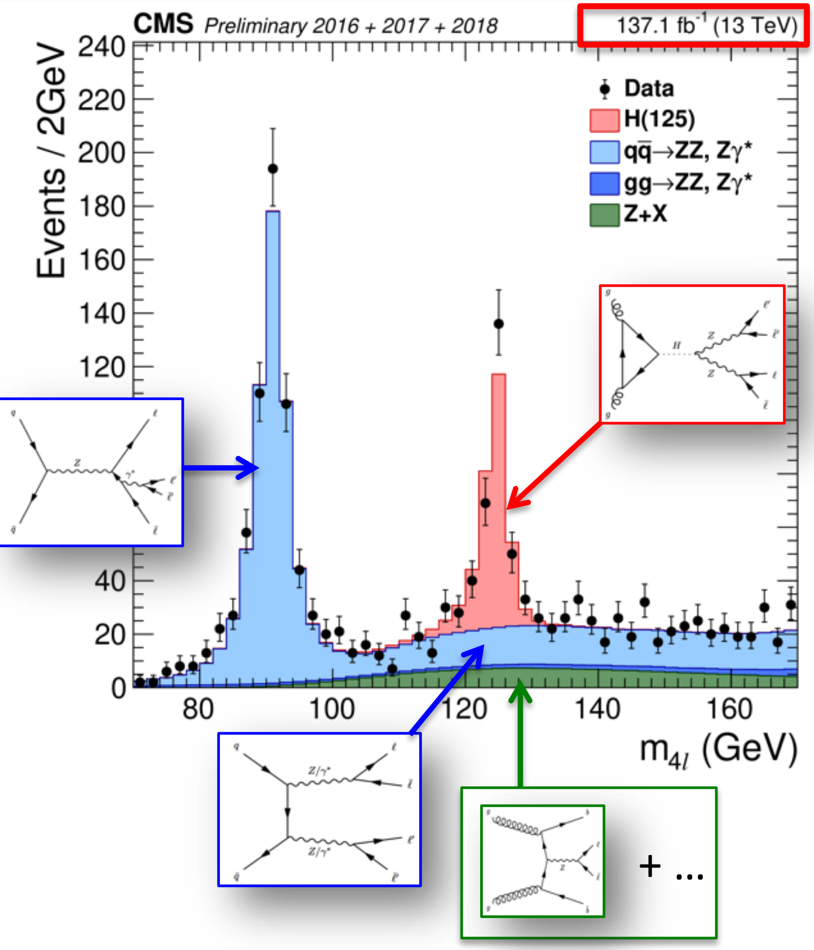
Signal strength

$$\mu = 1.06\,^{+0.14}_{-0.12} = 1.06\ \pm 0.08\,(\text{stat.})\,^{+0.08}_{-0.07}\,(\text{exp.})\,^{+0.07}_{-0.06}\,(\text{theo.})$$

**Note:** statistical, experimental syst, and theoretical syst uncertainties are already of the same scale!

# H → ZZ → 4l

CMS HIG-19-001




## Event Selection Strategy

- **4 "tight" leptons** (4e, 4μ, 2e2μ)
- **final key observables:**
  - **four-lepton mass is the key observable**
  - **ME-kinematic discriminant** (+20% sensitivity)

## Backgrounds

- **ZZ (dominant):** *well calculable process (MC)*
- **reducible (WZ+jets, Z+jets, tt, WW+jets, …):** *data-driven*

## Analysis features to note

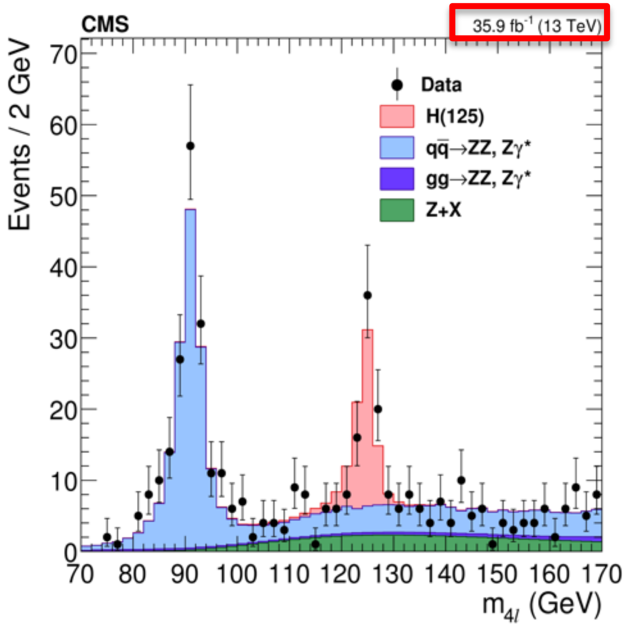
- **small event yield**
- **high S/B-ratio: >2:1** (best among all)
- **most sensitive channel for H observation**
- **good mass resolution: 1-2%**
- **four-body decay, fully reconstructed: spin-parity**
- **on/off-shell production: indirect width**

Signal strength = $0.94^{+0.07}_{-0.07}(\mathrm{stat.})^{+0.08}_{-0.07}(\mathrm{syst.})$

(with respect to SM)

# Mass

JHEP 11 (2017) 047




**H->ZZ->4l channel provides the most accurate measurement**

- m(4l) distribution forms a narrow peak:
  - good muon/electron $p_T$ resolution (detector design)
  - small systematics thanks to the tag-and-probe calibration technique
- per-event four-lepton invariant mass uncertainties are taken into account:
  - Events with well measured four-lepton mass get higher weight in the fit
- one lepton pair comes from mostly on-shell Z boson:
  - Z-boson mass constraint allows one to improve $p_T$ measurements for two leptons in individual events
- Four-lepton configurations have different probabilities for ZZ and H->ZZ
  - ME-based discriminant reduces weight of ZZ background like events

**Run 1**
**ATLAS+CMS**
**ZZ+$\gamma\gamma$ combo**
125.09 $\pm$ 0.24 GeV

PRL 114 (2015) 191803

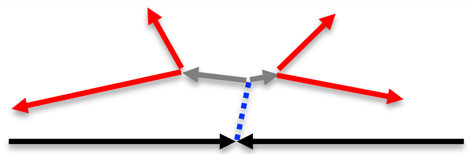
| 2016 dataset | H->ZZ->4l | H->$\gamma\gamma$ | Combination |
|---|---|---|---|
| ATLAS | 124.79 $\pm$ 0.37 | 124.93 $\pm$ 0.40 | 124.97 $\pm$ 0.24 |
| CMS | **125.26 $\pm$ 0.21** | 125.4 $\pm$ 0.3 | |

$\pm$ 0.20 (stat) $\pm$ 0.08 (syst)

**HL-LHC:** stat error will improve by a factor of 10: ~20 MeV
need to improve systematics proportionally to about 0.01% – challenge!

# Spin-parity from H->ZZ->4l

CMS HIG-18-002



Relative kinematics of four leptons are sensitive to **$J^P$ properties of H**
(parity of $\pi^0$ was assessed similarly from $\pi^0 \rightarrow \gamma*\gamma* \rightarrow$4l decays)

**Observation of H $\rightarrow \gamma\gamma$ excludes J=1 by the Yang-Landau theorem**
**Pure J=2 states and pure non-SM J=0 states were excluded with Run 1 data**

## Studies of possible non-SM-like admixtures continue:

Most generic amplitude of spin 0 decay to two vector (V) particles:

$$A(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_1^2 + \kappa_2^{\mathrm{VV}} q_2^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2}\right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu},$$

$a_1$=2 describes SM Higgs tree-level decays to ZZ (zero for H$\rightarrow \gamma\gamma$)
$a_2$ is **CP-even** term; in SM, it is O($10^{-2}$) for H$\rightarrow$ ZZ due to loop-induced decays (lead term for H$\rightarrow \gamma\gamma$)
$a_3$ is **CP-odd and hence CP-violating term**, present but unmeasurably tiny in SM (three-loop decays)

**Experimental limits:** 5.1 fb$^{-1}$ (7 TeV) + 19.7 fb$^{-1}$ (8 TeV) + 80.2 fb$^{-1}$ (13 TeV)

$$-0.14 < a_2/a_1 < 0.29$$

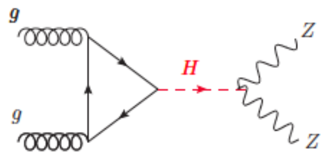
$$-0.18 < a_3/a_1 < 0.21$$

# $\Gamma_H$ from off-shell to on-shell production

CMS HIG-18-002

**Breit-Wigner production gg→H→ZZ:**

$$\boxed{\frac{d\sigma}{dm^2} \sim g_g^2 g_Z^2 \frac{F(m)}{(m^2 - m_H^2)^2 + m_H^2 \Gamma_H^2}}$$




**On-peak and off-peak cross sections:**

$$\boxed{\sigma^{\text{on-shell}} = \int_{|m-m_H|\leq n\Gamma_H} \frac{d\sigma}{dm} \cdot dm \sim \frac{g_g^2 g_Z^2}{m_H \Gamma_H}}$$

$$\boxed{\sigma^{\text{off-shell}} = \int_{m-m_H \gg \Gamma_H} \frac{d\sigma}{dm} \cdot dm \sim g_g^2 g_Z^2}$$

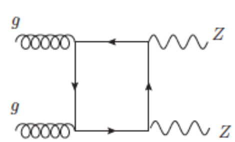
**Off-peak to on-peak ratio**

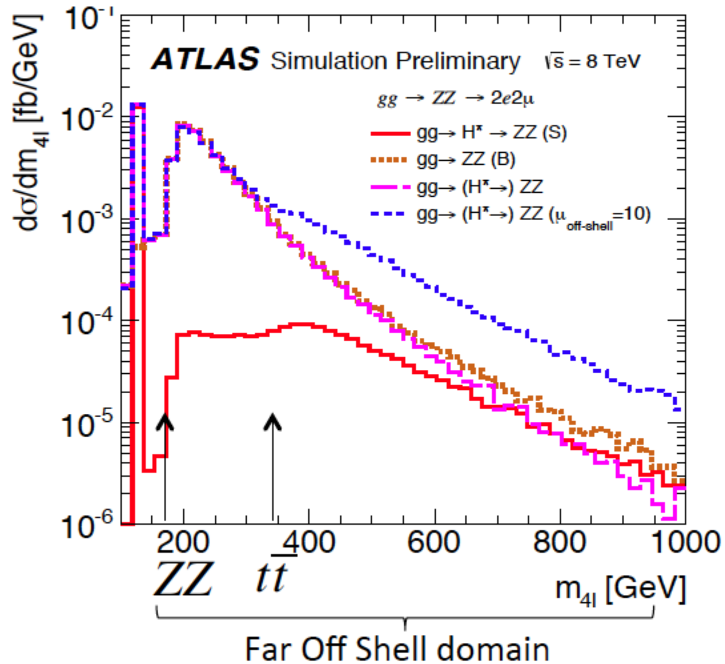
$$\boxed{\frac{\sigma^{\text{off-shell}}}{\sigma^{\text{on-shell}}} \sim \Gamma_H}$$

**F(m) depends on:**

- phase space for H→ZZ
- partonic gg-luminosity
- Hgg coupling evolution with $m_{H*}$
- tensor structure Hgg coupling

**The picture gets more complicated due to interference with non-resonant gg→ZZ**




**H→ZZ → 4l and H → ZZ → 2l2v**

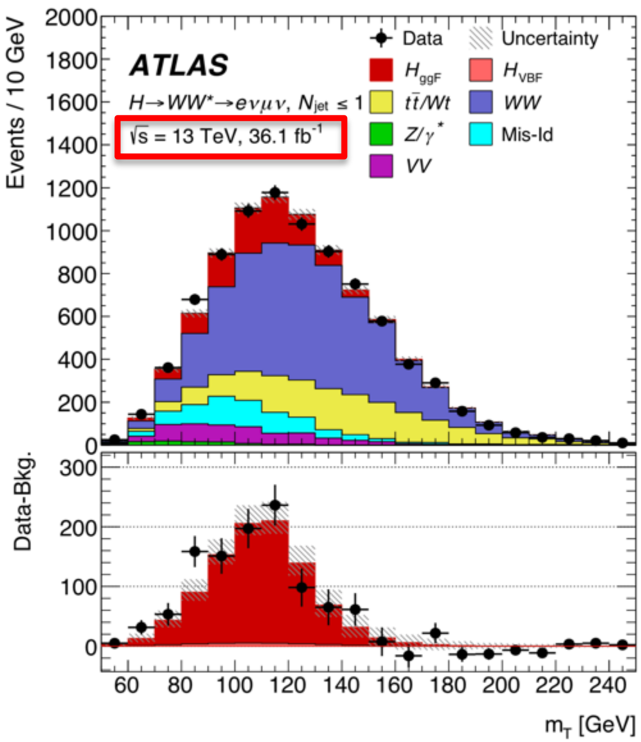
| |
|---|
| 5.1 fb$^{-1}$ (7 TeV) + 19.7 fb$^{-1}$ (8 TeV) + 77.5 fb$^{-1}$ (13 TeV) |
| $\Gamma_H$ (MeV) $\quad 3.2^{+2.8}_{-2.2}$ $\quad [0.08, 9.16]$ |

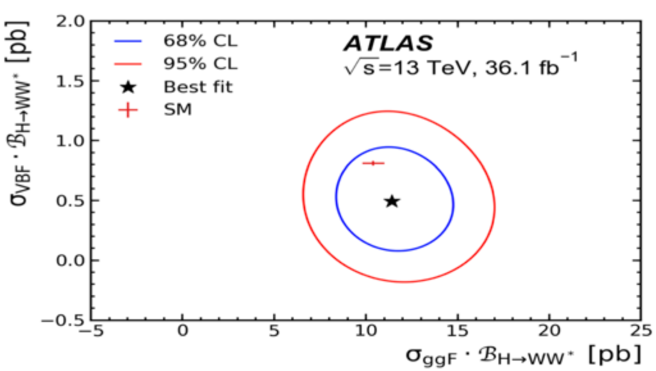
[95% Conf. Interval]

**SM Higgs $\Gamma_H$ = 4.0 MeV**

# H → WW → lνlν

PLB 789 (2019) 508

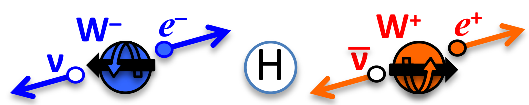



## Event Selection Strategy

- two "tight" leptons (ee, μμ, eμ) + MET
- main discriminating observables:
  - $m_T$ - transverse mass
  - $m_{ll}$ - di-lepton mass (tends to be small for H→WW)
  - $p_T$ of sub-leading lepton (tends to be small for H→WW*)

$$m_T = \text{inv. mass of } \left(m_{\ell\ell}, \vec{p}_T^{\,\ell\ell}\right) \text{ and } \left(0, \vec{p}_T^{\,\text{miss}}\right)$$




Higgs (spin=0) ==> small dilepton mass

## Backgrounds (many!)

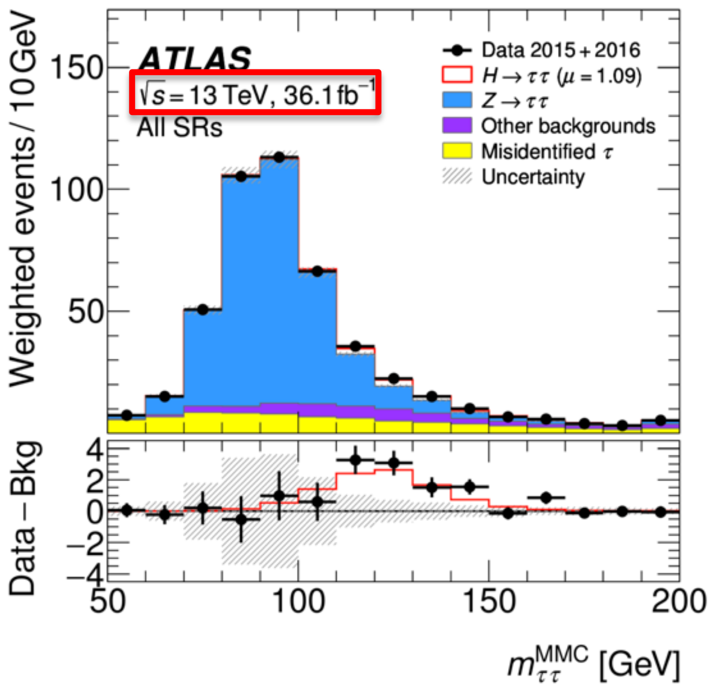
- WW, tt, DY+jets, W+jets, Wγ: *data-driven*
- ZW, ZZ: *from simulation*

## Analysis features to note

- fair signal event yield
- not-too-good "effective" S/B-ratio: **1:5**
- poor mass resolution (neutrinos!): **15%**

# H → ττ: observed!

ATLAS: PRD 99 (2019) 072001
CMS: PLB 779 (2018) 283



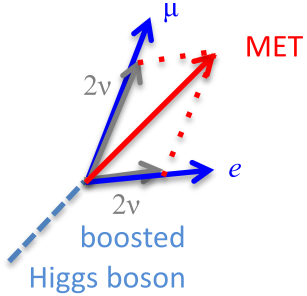

**Run 1 + Run 2 (2016)**

**ATLAS:** Significance = 6.4$\sigma$
Signal strength* $1.09^{+0.27}_{-0.26}$

**CMS:** 5.9$\sigma$ and $0.98 \pm 0.18$

## Event Selection Strategy

- **di-tau candidates ($e\tau_h$, $\mu\tau_h$, $e\mu$, $ee$, $\mu\mu$, $\tau_h\tau_h$) + MET**
- **key observable: di-tau mass**
- **most-important event categories:**
  - **2-jets (VBF-tag):** usual reasons
  - **Boosted (high $p_T(\tau\tau)$)**
    - *better di-tau mass resolution*
    - *better S/B for gg→H vs qq→Z*




## Backgrounds (many!)

- **Z→ττ, Z→ee, tt, W-jets, QCD:** *from control regions*
- **di-bosons:** *from simulation*

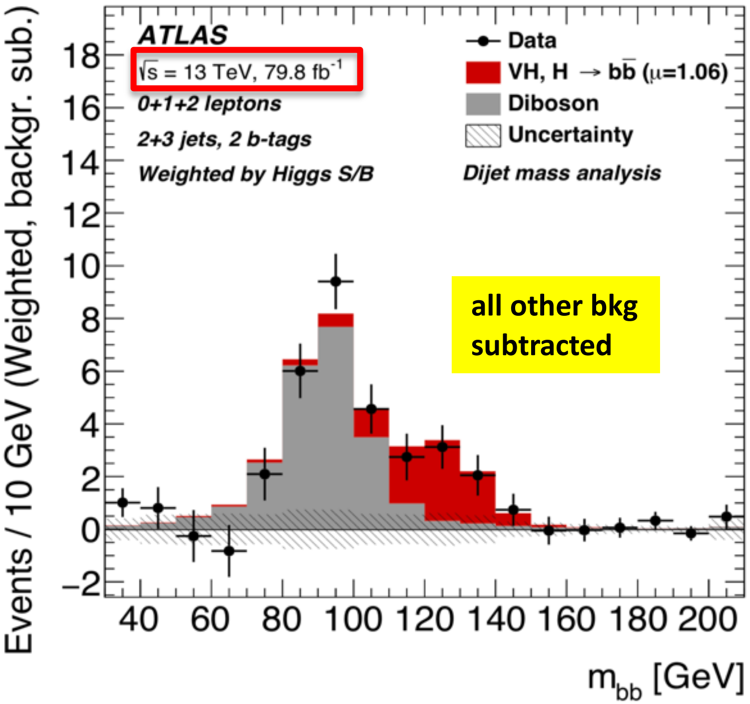
## Analysis features to note

- **small signal event yield**
- **poor "effective" S/B-ratio: 1:50**
- **Higgs boson "blip" is on the falling slope of the Z peak**
- **mass resolution (neutrinos!): 10% ($\tau_h\tau_h$) -- 20% (*ll*)**

* ATLAS signal strength is for the 2016 data alone
CMS – for Run 1 + Run 2 combination

# H → bb: observed!

ATLAS: PLB 786 (2018) 59
CMS: PRL 121 (2018) 121801




**With Run 1 data included:**

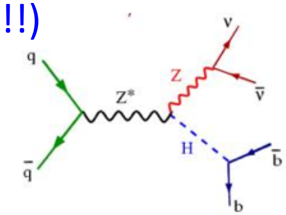
**ATLAS:** Significance = $5.4\sigma$

$$\mu = 1.01 \pm 0.12(\text{stat.})^{+0.16}_{-0.15}(\text{syst.})$$

**CMS:** $5.6\sigma$ and $1.04^{+0.20}_{-0.19}$

## Event Selection Strategy

- **Two b-tagged jets** (QCD bkg is huge!!!)
- **Target VH production**
- **split event further by $p_T(V)$**
  - **higher $p_T(V)$: better S:B, better $\delta m_{bb}$**
- **key observable:**
  - **MVA of many observables** ($m_{jj}$ is the most important)




## Main backgrounds (many!)

- **Vbb, V+jets, ttbar, single-top:** *from control regions*
- **di-boson:** *from simulation*

## Analysis features to note

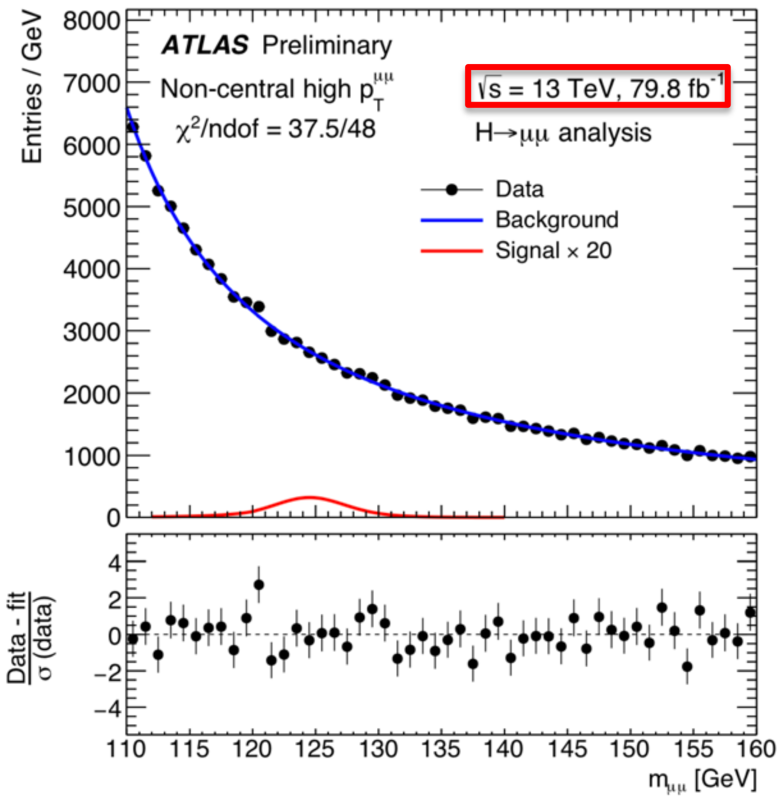
- **fair signal event yield: O(1000) events**
- **poor "effective" S/B-ratio = 1:20**
- **not-too-good mass resolution (jets): 10%**

**Note:** the analysis becomes systematic-error dominant

# Search for H → μμ

ATLAS-CONF-2018-026

Most sensitive event category




**Event Selection Strategy**

- 2 high-$p_T$ muons
- key observable: **di-muon mass**

**Backgrounds:** *mostly DY, fit of the dimuon mass distribution*

## Analysis features to note

Very small signal

very bad "effective" S/B-ratio: ~**1:150**

good mass resolution: **1-2%**

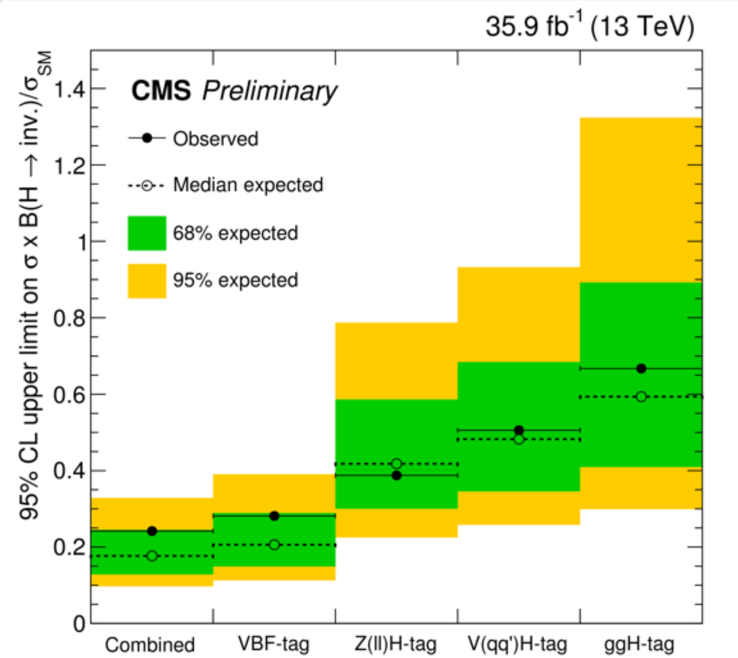
**Upper limit on signal strength 2.1**

**Signal strength** $\mu = 0.1^{+1.0}_{-1.1}$

**Optimistically, expect 3$\sigma$ evidence in Run 3 (need further analysis optimization)**

# H → invisible search

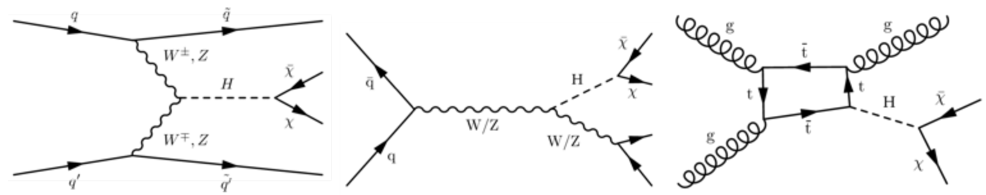
CMS HIG-17-023 (PLB)



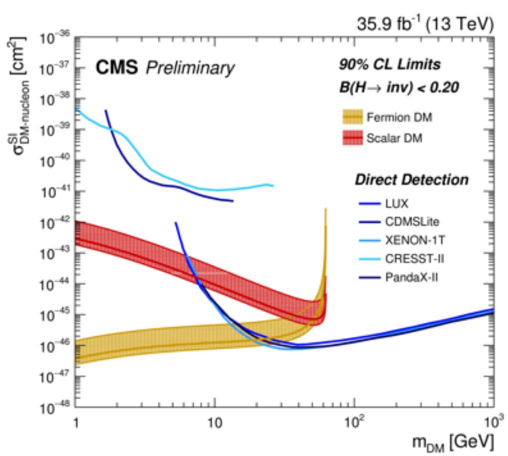

**In SM:** B(H→inv) ~ 0.1%

**Searches for H→inv probe BSM possibilities, e.g., Higgs boson decaying to DM particles**

**Production modes exploited are:**




**Run 2 (2016) limit:** B(H→inv) < 0.20 at 90% CL

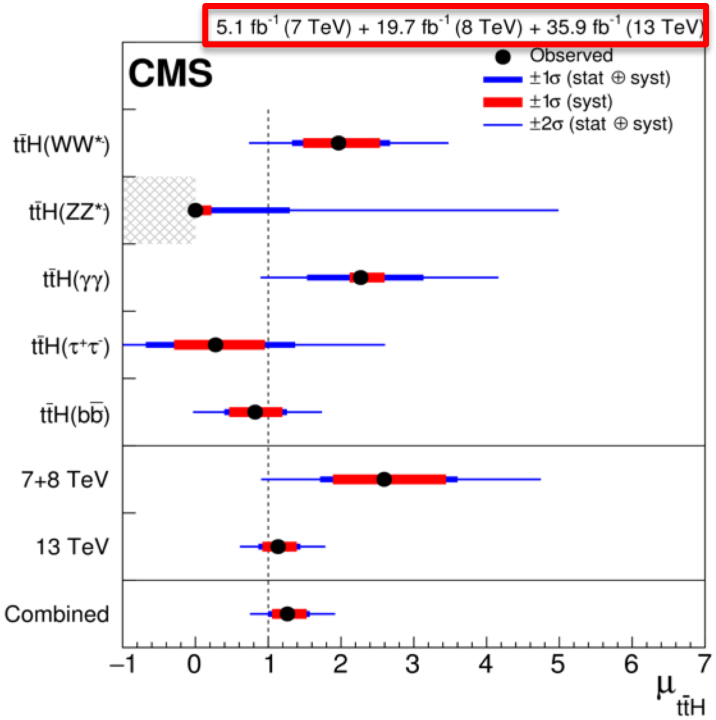



**This allows one to set limits in the space of (DM mass, DM-nucleon cross section) for $m_{DM} < m_H/2$**

**Results are complementary to direct DM searches**

# pp → ttH: observed!

CMS: PRL 120 (2018) 231801
ATLAS: PLB 784 (2018) 173




**Very challenging search**

- very few events are expected
- tt background is BAD: ttH : tt ≈ 1 : 2,000
- all other Higgs production mechanisms (99%) must be suppressed as well

**Search strategy:**

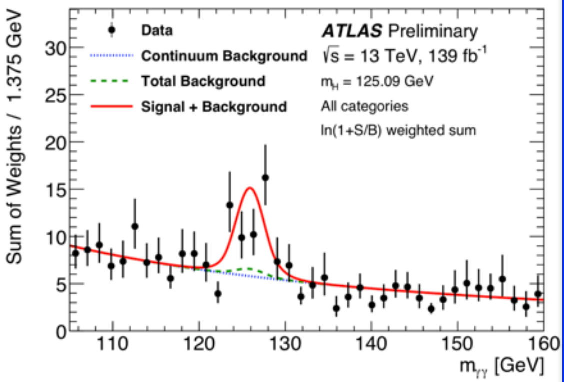
- Make use of all main five Higgs decay modes
- Take into account b-jets from t->Wb
- Consider tt decays with 0, 1, 2 leptons in the final state
- Extensive use of MVA techniques

**Run 1 + Run 2 (2016)**

**CMS:** Significance = $5.2\sigma$
Signal strength = $1.26^{+0.31}_{-0.26}$

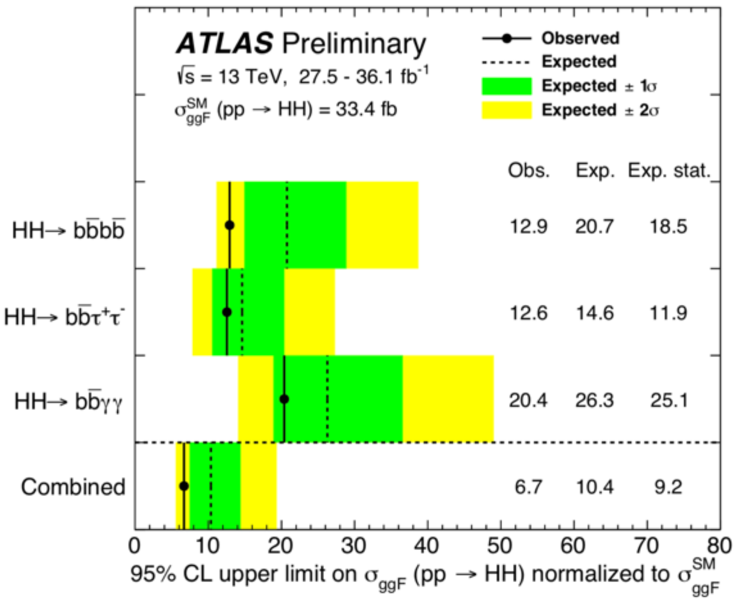
**ATLAS:** $6.3\sigma$ and $1.32 \pm {}^{0.28}_{0.26}$

Fresh out of press:
**ATLAS, full Run 2 dataset**
ttH, H→ $\gamma\gamma$
Significance $4.9\sigma$
Signal strength $1.38\ ^{+0.41}_{-0.36}$

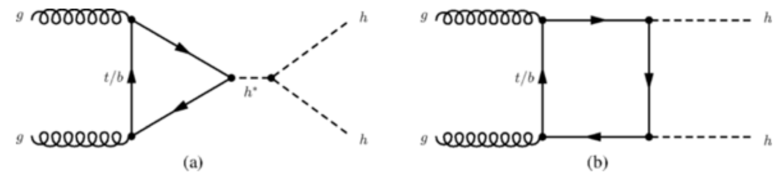


# Search for pp→HH

ATLAS-CONF-2018-043

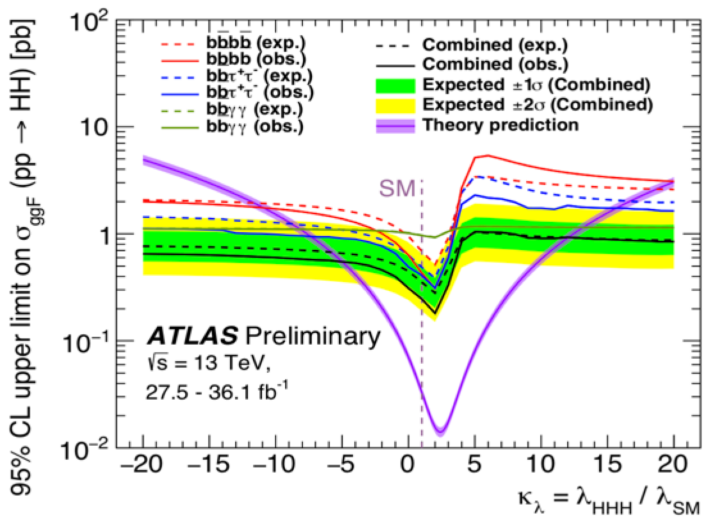



**SM:**

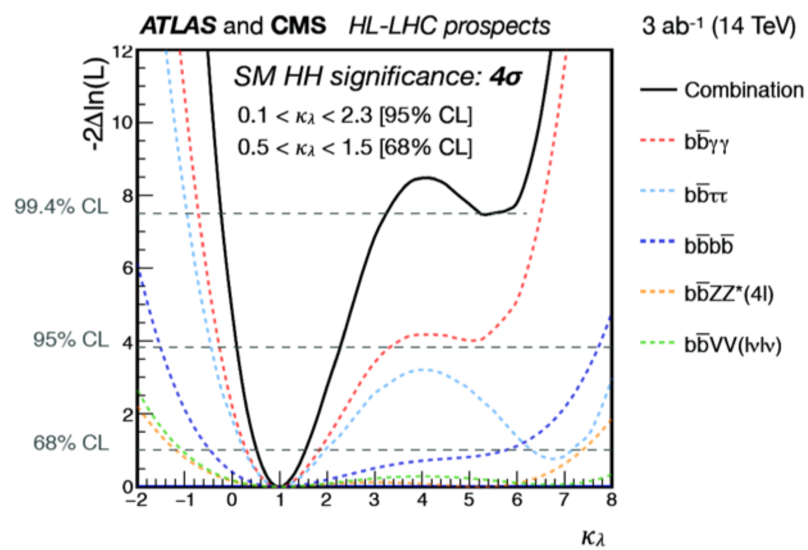



**Current result:**

- **Di-Higgs cross section:** **$\sigma$(HH) < 6.7 x SM**
- **Higgs trilinear coupling:** **$-5 < \kappa_\lambda < 12.1$**




**HL-LHC projections** (arXiv:1902.00134)



# Combination of all Higgs analyses

$$\sigma(xx \to H) \cdot BR(H \to yy) \;\propto\; \frac{\Gamma_{xx} \cdot \Gamma_{yy}}{\Gamma_{\mathrm{TOT}}}$$

One needs **9 independent parameters** to describe all currently relevant production & decay mechanisms

| | gg->H | VBF | VH | ttH |
|---|---|---|---|---|
| WW | ■ | ■ | ■ | ■ |
| ZZ | ■ | ■ | ■ | ■ |
| bb | ■ | ■ | ■ | ■ |
| ττ | ■ | ■ | ■ | ■ |
| γγ | ■ | ■ | ■ | ■ |
| μμ | ■ | ■ | | |
| invisible | | ■ | ■ | |

$\Gamma_{WW}$

$\Gamma_{ZZ}$

$\Gamma_{bb}$

$\Gamma_{\tau\tau}$

$\Gamma_{\gamma\gamma}$ **(loop induced; W and t)**

$\Gamma_{\mu\mu}$

$\Gamma_{gg}$ **(loop induced; t and some b)**

$\Gamma_{tt}$

$\Gamma_{TOT}$ (or $\Gamma_{TOT} = \Gamma_{WW} + \Gamma_{ZZ} + \Gamma_{bb} + \ldots + \Gamma_{inv/undetectable}$)

# Combo: couplings

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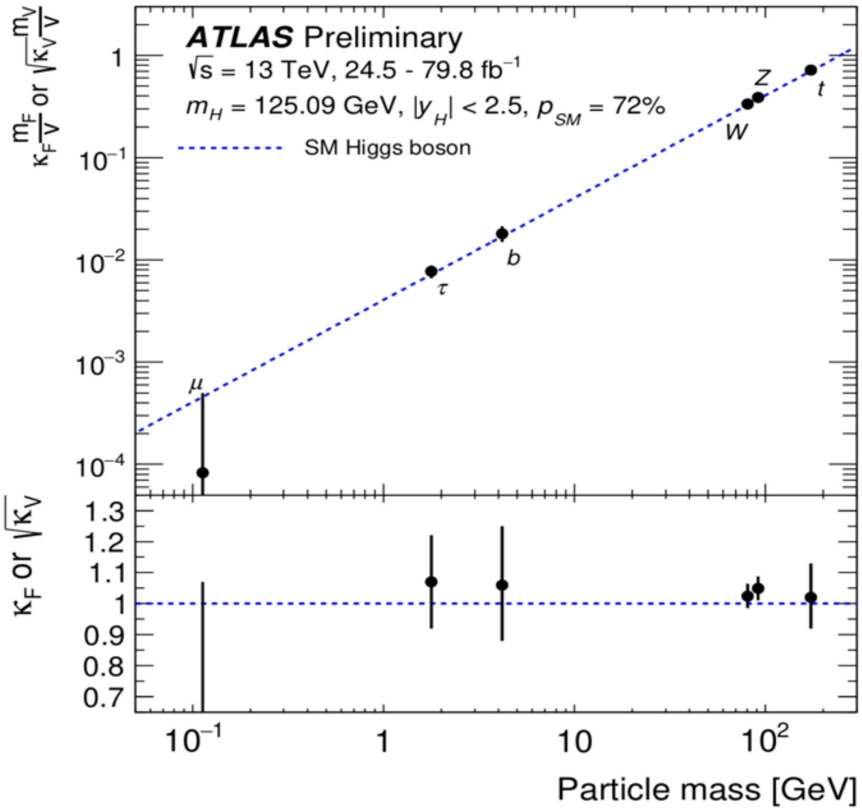


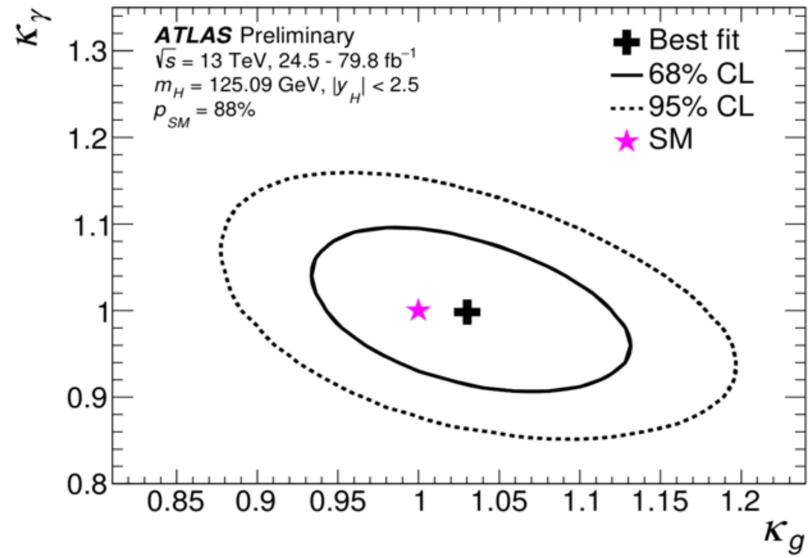


**Assuming SM-like tree-level couplings,**

**measured effective couplings to two loop-induced couplings (Hgg, H$\gamma\gamma$) are consistent with the SM predictions**

**Assuming no new particles/interactions,**

- **six relevant Higgs boson couplings to the SM particles are right on mark**
- **W, Z, t couplings are already constrained with an accuracy of 5-10%**

# Summary

- **Higgs boson mass is measured with better than 2 ppm accuracy**
- **Five Higgs decay modes are established: ZZ, WW, $\gamma\gamma$, $\tau\tau$, bb**
- **Four main production modes are established: ggF, VBF, VH, ttH**
- **No deviations from SM have been observed, but the search is on**
  - **Higgs boson is the most recent fundamental (?) particle discovered**
  - **It has a very special role in the SM**
  - **It is the only scalar particle in SM, and scalars are not particularly friendly entities in the quantum field theory**