# Search and measurement of the SM Higgs boson

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*on behalf of the CMS and ATLAS collaborations*

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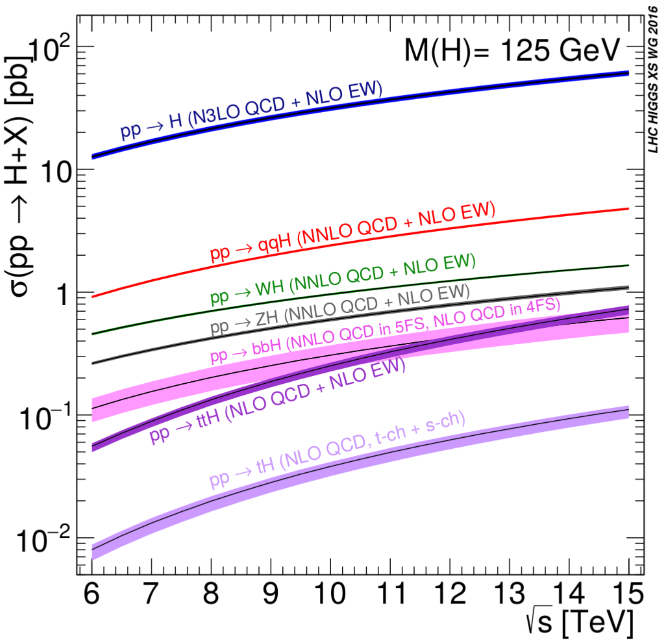
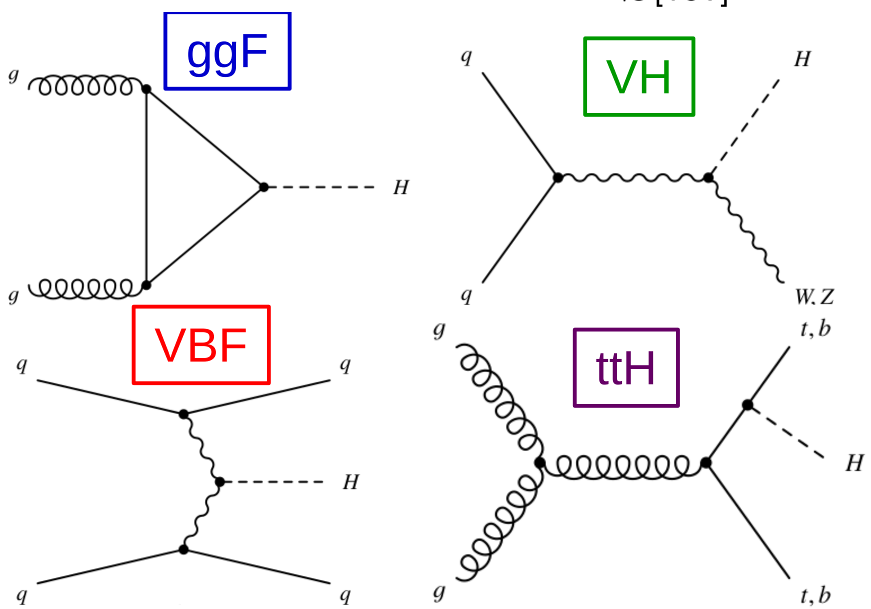
# Introduction

Higgs boson production cross sections

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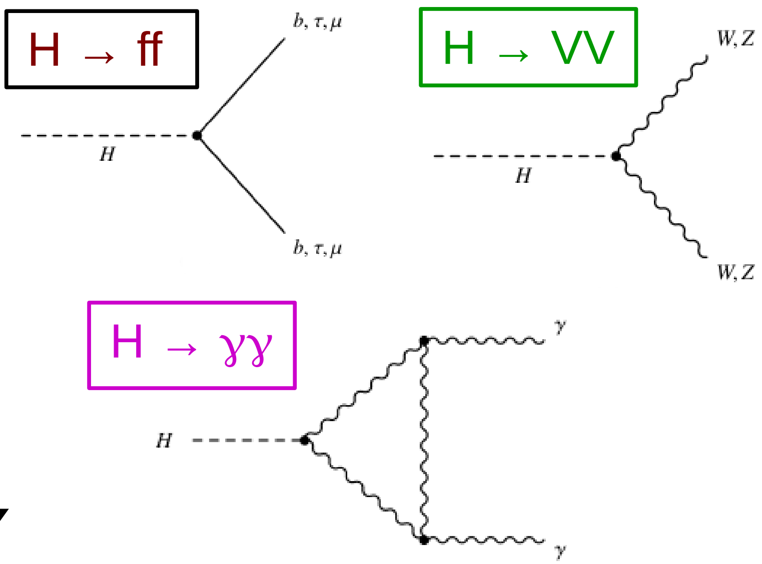
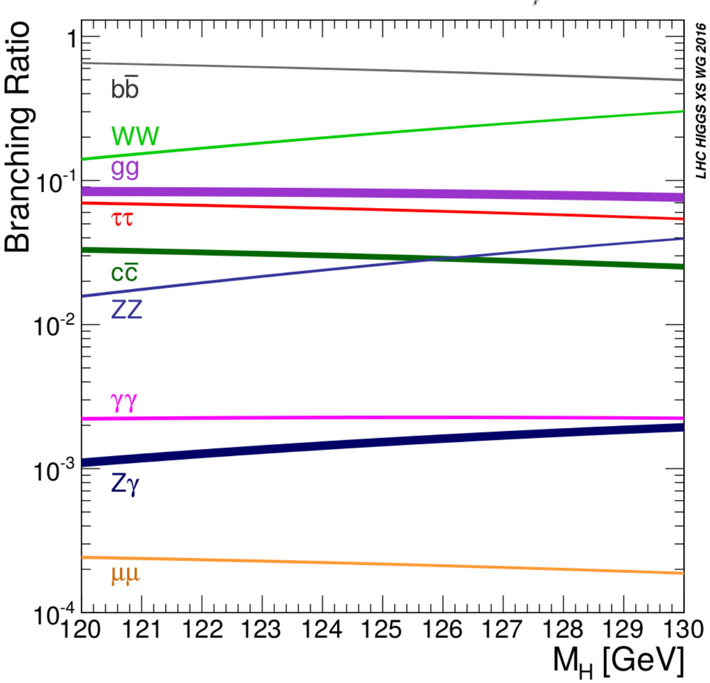
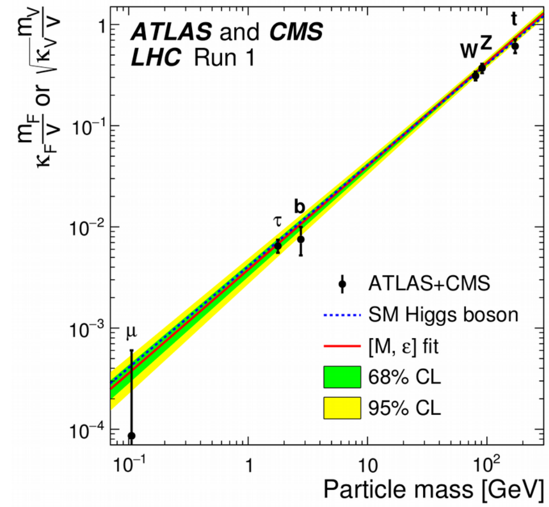


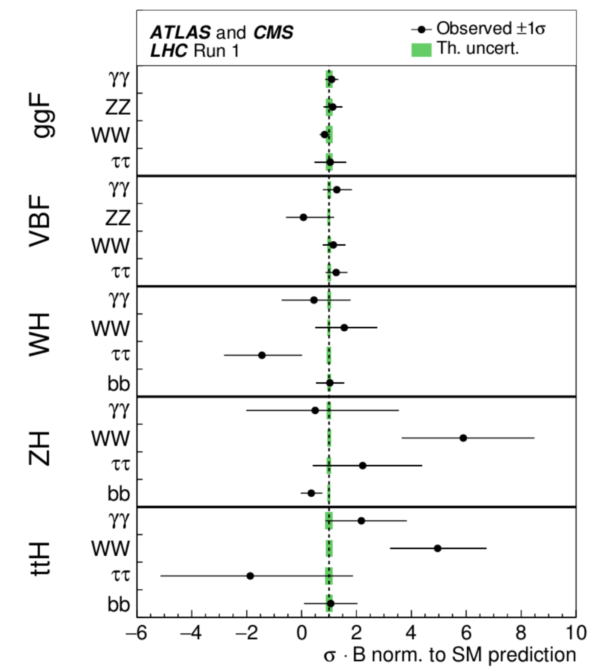

Higgs boson decay branching ratios

# Introduction

- The legacy of the LHC Run-1 has been a huge success with the discovery of the Higgs boson and the first measurement of its properties and couplings.
  - No significant deviation from the SM has been found so far.
- gg→H and VBF production, and ZZ, γγ, WW decays observed
  - many other channels to be observed.
- ATLAS and CMS collaborations obtained many new results with 36fb$^{-1}$ of 13 TeV data → they are summarized in this talk.




| Production process | Measured significance ($\sigma$) | Expected significance ($\sigma$) |
|---|---|---|
| VBF | 5.4 | 4.6 |
| $WH$ | 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 |




THE
Devil
IS IN THE
details
NEW PHYSICS

# Outline

- Introduction
- Big news:
  - Single experiment observation of $H \rightarrow \tau\tau$;
  - Evidence for ttH;
  - Evidence for $VH \rightarrow bb$.
- Other SM Higgs searches:
  - $VH \rightarrow cc$;
  - boosted $H \rightarrow bb$;
  - $H \rightarrow \mu\mu$;
  - $H \rightarrow Z\gamma$;
  - $H \rightarrow$ light quarks.
- Towards precision SM Higgs measurements with $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ$:
  - simplified template cross section;
  - differential cross section;
  - couplings;
- Conclusions.

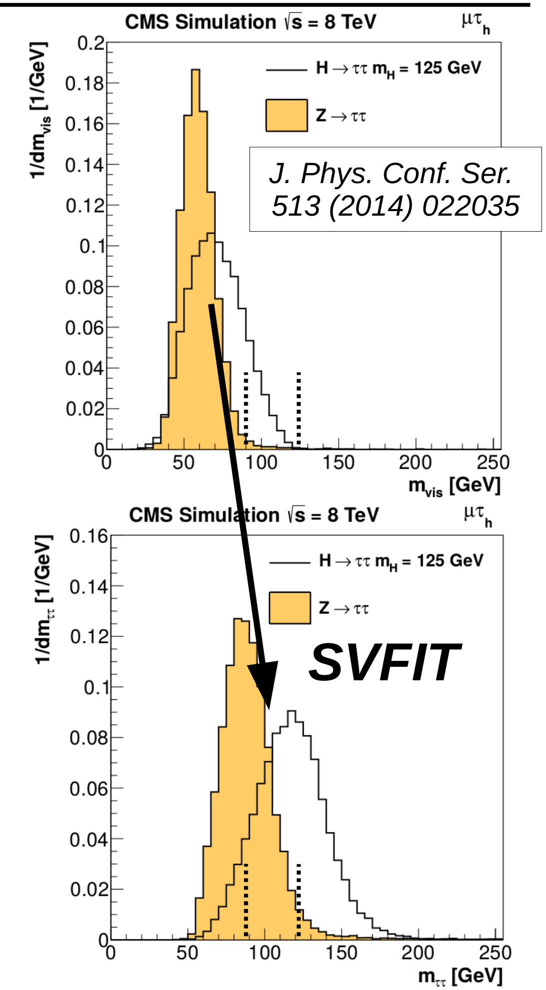
ONLY FRESH RESULTS
(<1 year)

# Big news

# $H \to \tau\tau$

arXiv:1708.00373 (sub. PLB)

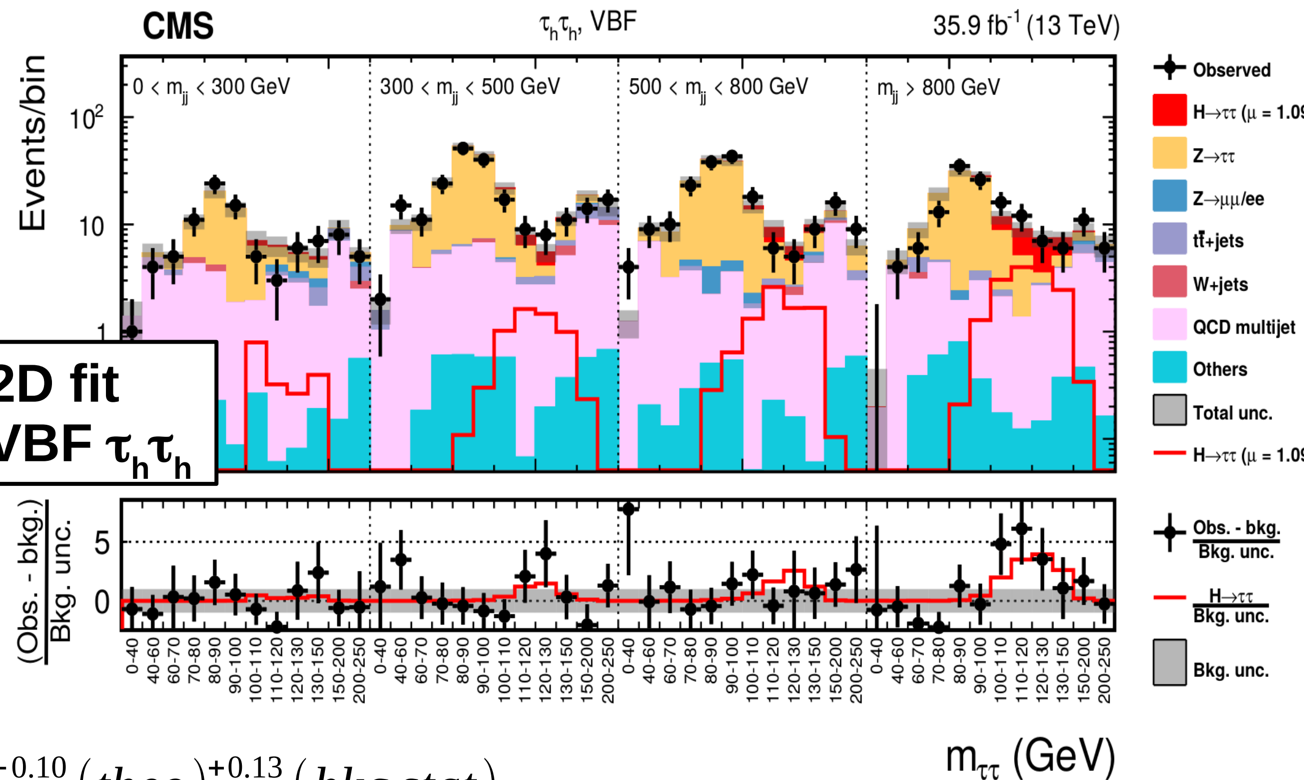
- The $H \to \tau\tau$ can decay into $e\mu$, $\mu\tau_h$, $e\tau_h$, $\tau_h\tau_h$ ($\tau_h$=$\tau\to$hadr.).
  - **All final states have been exploited.**
- Three categories with different purities: **0-jet, VBF, boosted**.
- $\tau_h$ identified by a MVA discriminant.
  - energy calibrated for different $\tau_h$ final states using $\mathbf{Z \to \tau\tau}$;
  - $m_{\tau\tau}$ reconstructed combining $\tau$ momenta with MET (**SVFIT**).
- Opposite **charge** and lepton **isolation** $\to$ **QCD** rejection.
- [$e\tau_h$, $\mu\tau_h$] **Transverse mass** $< 50$ GeV $\to$ **W+jets** rejection.
- [$e\mu$] **Large MET projected along di-tau axis** $\to$ $\mathbf{t\bar{t}}$ rejection.
- Main backgrounds:
  - $\mathbf{Z \to \tau\tau}$ simulation is corrected using $Z \to \mu\mu$ data;
  - **W+jets** and $\mathbf{t\bar{t}}$ simulations are normalized to data inverting rejection cuts;
  - **QCD** fully estimated from data $\to$ ABCD method inverting charge and isolation cuts.



# $H \to \tau\tau$

arXiv:1708.00373 (sub. PLB)

- Signal extraction:
  - 1D or **2D fit** of the most discriminating variables, eg. $(m_{jj}, m_{\tau\tau})$ for $\tau_h\tau_h$ VBF.




**2D fit VBF $\tau_h\tau_h$**

- **Results** [CMS]:
  - $\mu = 1.09^{+0.15}_{-0.15}(stat)^{+0.16}_{-0.15}(syst)^{+0.10}_{-0.08}(theo)^{+0.13}_{-0.12}(bkg\,stat)$
  - corresponding to a sign. of 4.9σ (exp. 4.7σ).

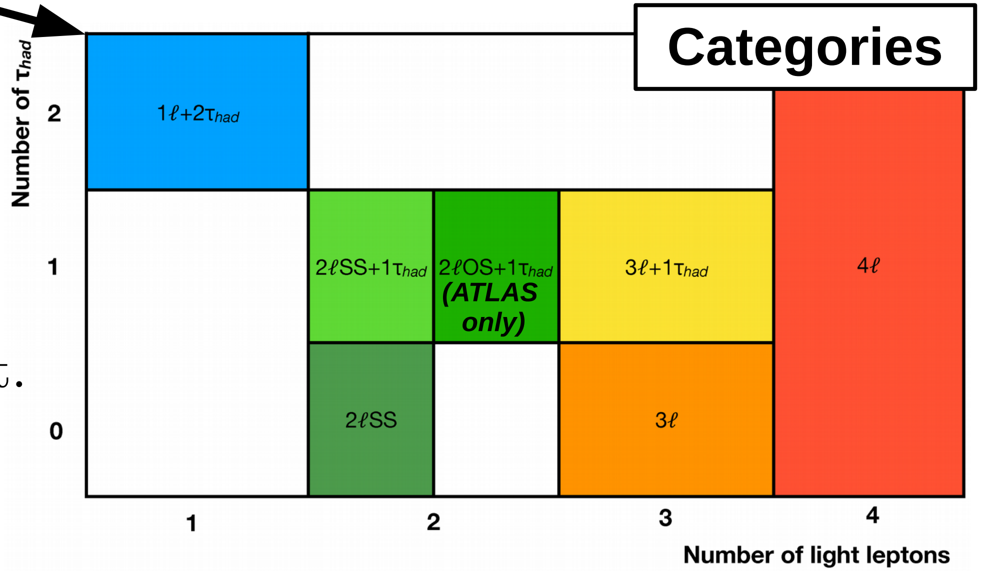
- **13 TeV + 8 TeV combination:**
  - $\mu = 0.98 \pm 0.18 \to$ sign. **5.9σ** (exp. **5.9σ**).

**First observation of $H \to \tau\tau$ by a single experiment**

CMS-PAS-HIG-17-003
CMS-PAS-HIG-17-004
arXiv:1712.08891 (sub. PRD)

# ttH multilepton

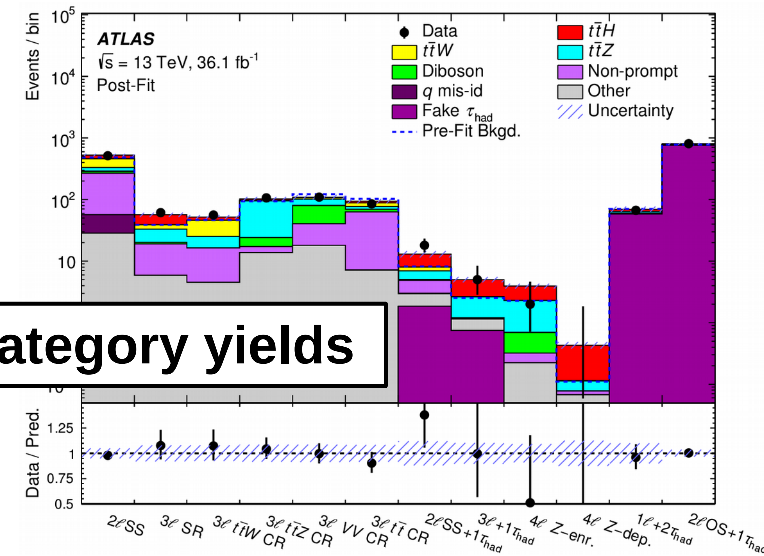
- In **ttH**, the Higgs boson can decay into leptons (e, μ, τ) through the decay H → WW, ZZ, ττ
  - up to two other leptons can be originated from the top decays in ttH
- The presence of at least two **same-sign leptons** can be used to eliminate the large Z/W+jets and $t\bar{t}$ background.
- Many final states considered.
- **Main backgrounds**:
  - ttV and VV
    → estimated by **simulations**;
  - charge mis-id, fake $\tau_h$, non-prompt lept.
    → **data-driven** estimate.



# ttH multilepton

CMS-PAS-HIG-17-003
CMS-PAS-HIG-17-004
arXiv:1712.08891 (sub. PRD)

- Fit is performed combining most discriminating variables using a BDT.
  - In several cases, a **multinomial BDT** is trained to reject the different backgrounds → combined into a 1D discriminant.

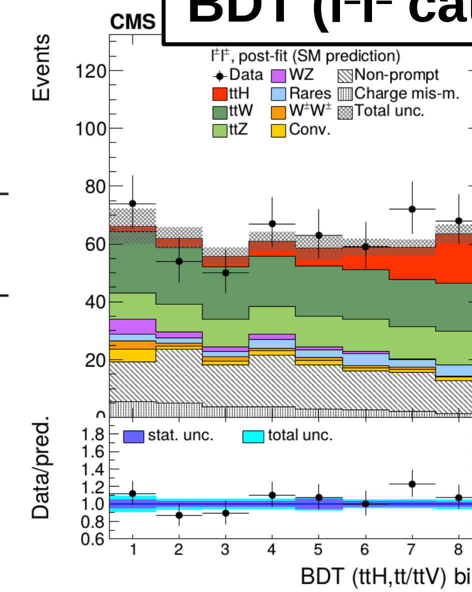



**Category yields**

- **Results:**

| | Final state | Signal strength | Sign.(exp.) |
|---|---|---|---|
| ATLAS | inclusive | $\mu = 1.6^{+0.3}_{-0.3}(\text{stat})^{+0.4}_{-0.3}(\text{syst})$ | $4.1\sigma(2.8\sigma)$ |
| CMS | $N(\tau_h) = 0$ | $\mu = 1.5^{+0.3}_{-0.3}(\text{stat})^{+0.4}_{-0.4}(\text{syst})$ | $3.3\sigma(2.4\sigma)$ |
| | $N(\tau_h) > 0$ | $\mu = 0.76^{+0.62}_{-0.53}$ | $1.4\sigma(1.8\sigma)$ |

**BDT (l±l± cat.)**

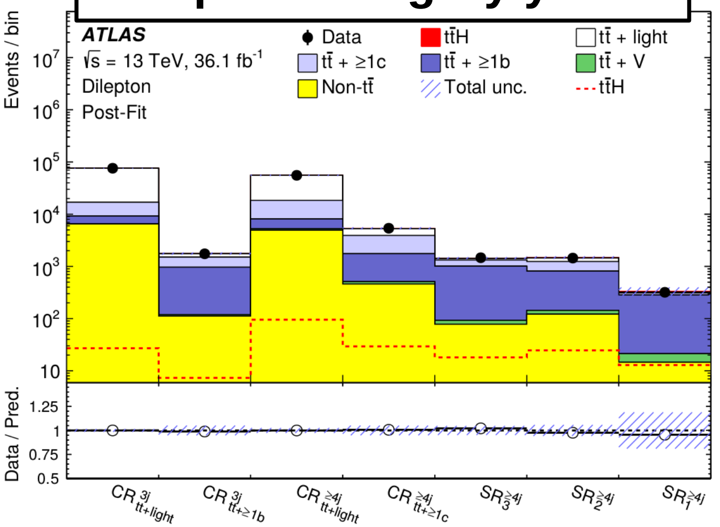


# ttH → bb

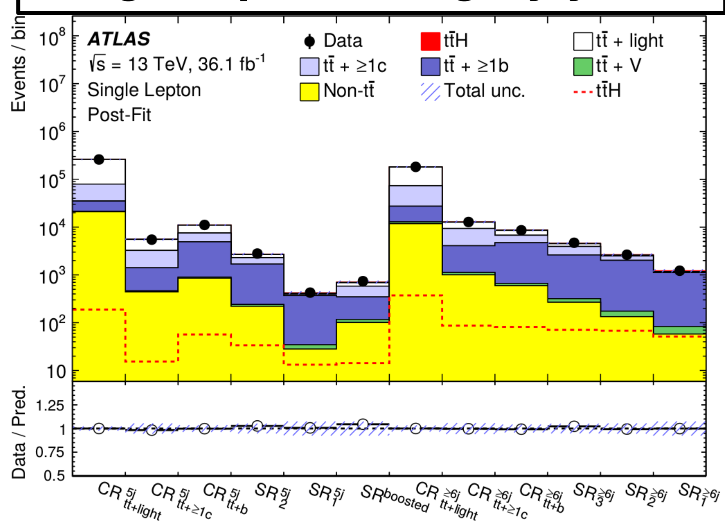
arXiv:1712.08895 (sub. PRD)

- In ttH(bb), **4 b-jets** are expected from the top and Higgs decays plus:
  - 2 leptons + MET (**Dilepton** decay);
  - 2 jets + 1 lepton + MET (**Single lept.** decay).
- Main background is **tt + b/c/light jets**.
- Events are **categorized** depending on the number of jets and leptons, and **b-tagging** discriminant, into:
  - 9 signal regions, to select different purities;
  - 10 control regions, to constrain the different background components.

**Dilepton category yields**




**Single lepton category yields**



# ttH → bb

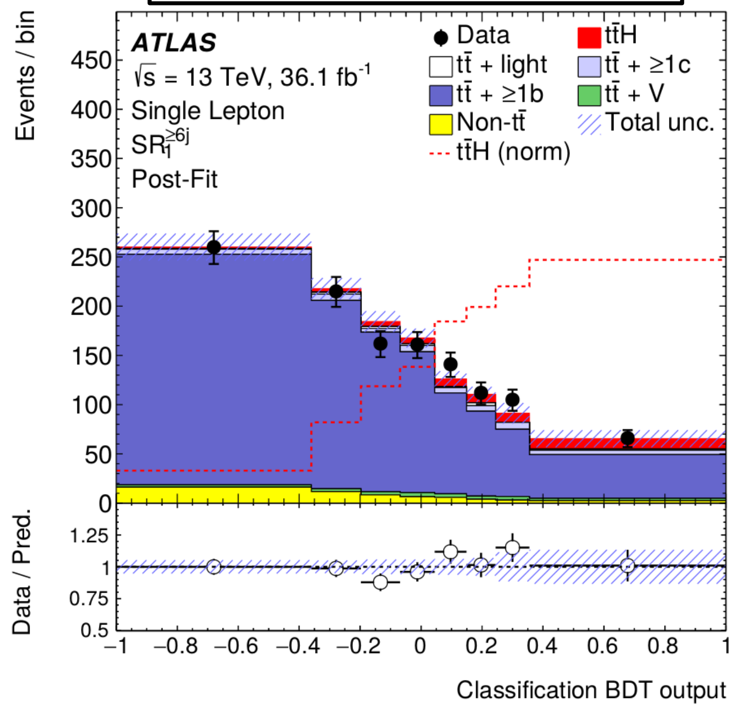
arXiv:1712.08895 (sub. PRD)

- Signal is extracted fitting simultaneously all signal and control regions
  - BDTs are used to enhance the S/B separation.
- ATLAS **results** and ttH **combination**:

| Channel | Best-fit $\mu$ Observed | Best-fit $\mu$ Expected | Significance Observed | Significance Expected |
|---|---|---|---|---|
| Multilepton | $1.6\,^{+0.5}_{-0.4}$ | $1.0\,^{+0.4}_{-0.4}$ | $4.1\sigma$ | $2.8\sigma$ |
| $H \rightarrow b\bar{b}$ | $0.8\,^{+0.6}_{-0.6}$ | $1.0\,^{+0.6}_{-0.6}$ | $1.4\sigma$ | $1.6\sigma$ |
| $H \rightarrow \gamma\gamma$ | $0.6\,^{+0.7}_{-0.6}$ | $1.0\,^{+0.8}_{-0.6}$ | $0.9\sigma$ | $1.7\sigma$ |
| $H \rightarrow 4\ell$ | $< 1.9$ | $1.0\,^{+3.2}_{-1.0}$ | — | $0.6\sigma$ |
| Combined | $1.2\,^{+0.3}_{-0.3}$ | $1.0\,^{+0.3}_{-0.3}$ | $4.2\sigma$ | $3.8\sigma$ |

**Evidence for ttH by a single experiment**

**BDT distribution in the highest-purity SR**




- CMS results (ICHEP2016, ~**13 fb**$^{-1}$): $\mu = -0.19^{+0.45}_{-0.44}(stat)^{+0.66}_{-0.68}(syst)$

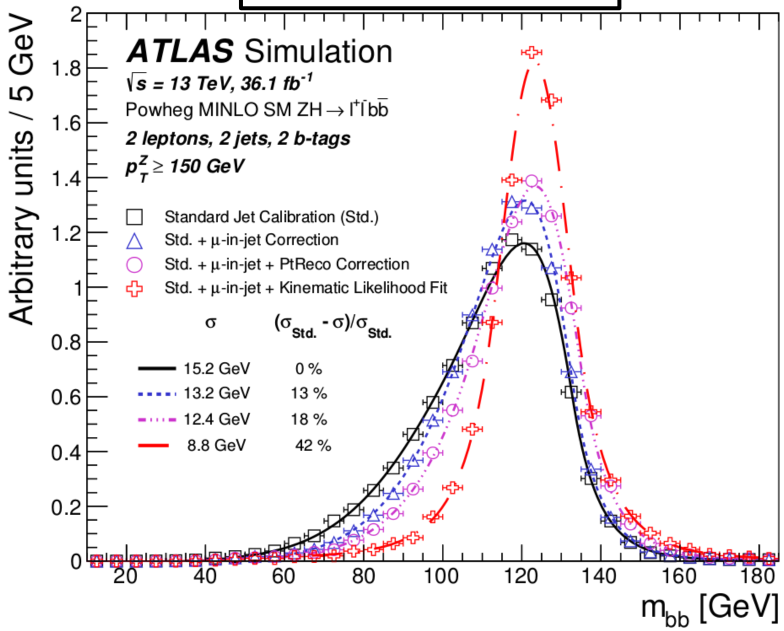
See YSF talk by Changqiao LI

JHEP 12 (2017) 024
arXiv:1709.05543 (acc. PRL)

# VH → bb

- Most sensible H → bb channel is **VH(bb)**, with a leptonic decay ($Z\to\ell\ell$, $W\to\ell\nu$, $Z\to\nu\nu$) to suppress the QCD multijet background.
  - H(bb) is also the most sensible VH channel.
- **Four channels** (0-lepton, 1-lepton, low and high boosted 2-lepton).
  - ATLAS split signal regions depending also on the number of jets (2 or 3).
- Main backgrounds are Z+(b)jets, W+(b)jets, tt:
  - bkg **shape** modeled using simulations;
  - yields are **free parameters** of the final fit;
    - control regions added into the final fit to constrain background yields.
- Special calibration of **b-jet energy** in order to improve $m_{bb}$ resolution.

**$M_{bb}$ resolution**



See YSF talk by Changqiao LI

JHEP 12 (2017) 024
arXiv:1709.05543 (acc. PRL)

# $VH \rightarrow bb$

- **BDT** trained against all bkg in each SR, combining discriminating variables (eg. $m_{bb}$, b-tag)
- A **simultaneous fit** of all SR and CR is performed for the signal extraction.
- [ATLAS] Cross-check analysis w/o BDT

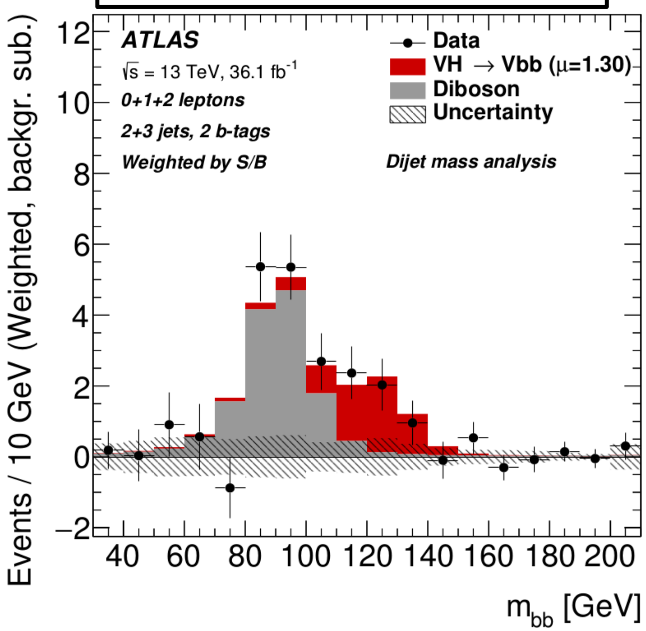
**ATLAS**

| Channel | SR/CR | Categories | |
|---|---|---|---|
| | | 2 jets | 3 jets |
| 0-lepton | SR | BDT | BDT |
| 1-lepton | SR | BDT | BDT |
| 2-lepton | SR (high $p_T^V$) | BDT | BDT |
| 2-lepton | SR (low $p_T^V$) | BDT | BDT |
| 1-lepton | $W$ + HF CR | Yield | Yield |
| 2-l.(high $p_T^V$) | $t\bar{t}(e\mu)$ CR | Yield | $m_{bb}$ |
| 2-l.(low $p_T^V$) | $t\bar{t}(e\mu)$ CR | $m_{bb}$ | $m_{bb}$ |

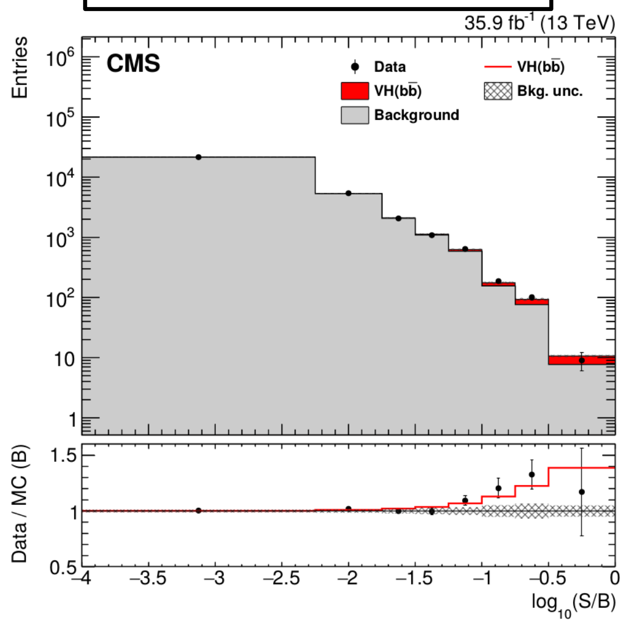
**CMS**

| Channel | SR/CR | Categories |
|---|---|---|
| 0-lepton | SR | BDT |
| 1-lepton | SR | BDT |
| 2-l.(high $p_T^V$) | SR | BDT |
| 2-l.(low $p_T^V$) | SR | BDT |
| 0-lepton | $t\bar{t}$ CR | $CSV_2$ |
| 0-lepton | $Z$ + LF CR | $CSV_2$ |
| 0-lepton | $Z$ + HF CR | $CSV_2$ |
| 1-lepton | $t\bar{t}$ CR | $CSV_2$ |
| 1-lepton | $W$ + LF CR | $CSV_2$ |
| 1-lepton | $W$ + HF CR | $CSV_2$ |
| 2-l.(high $p_T^V$) | $t\bar{t}$ CR | $CSV_2$ |
| 2-l.(high $p_T^V$) | $Z$ + LF CR | $CSV_2$ |
| 2-l.(high $p_T^V$) | $Z$ + HF CR | $CSV_2$ |
| 2-l.(low $p_T^V$) | $t\bar{t}$ CR | $CSV_2$ |
| 2-l.(low $p_T^V$) | $Z$ + LF CR | $CSV_2$ |
| 2-l.(low $p_T^V$) | $Z$ + HF CR | $CSV_2$ |

**$M_{bb}$ (bkg subtracted)**




**Purity distribution**



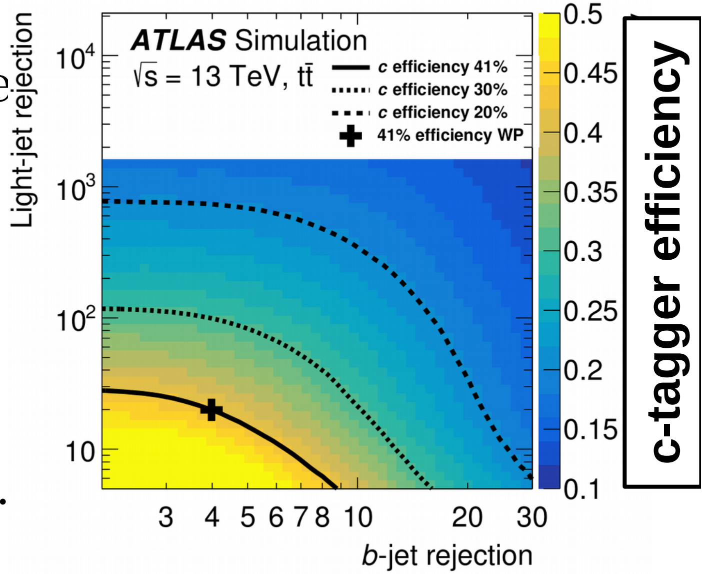

- VZ(bb) measurement:
  - CMS: $\mu = 1.02 \pm 0.22$
  - ATLAS: $\mu = 1.11 \pm 0.23$
- Results (Run1+Run2):
  - CMS: **3.8σ (exp. 3.8σ)** $\mu = 1.06^{+0.31}_{-0.29}$
  - ATLAS: **3.6σ(exp. 4.0σ)** $\mu = 0.90 \pm 0.18(stat)^{+0.21}_{-0.19}(syst)$

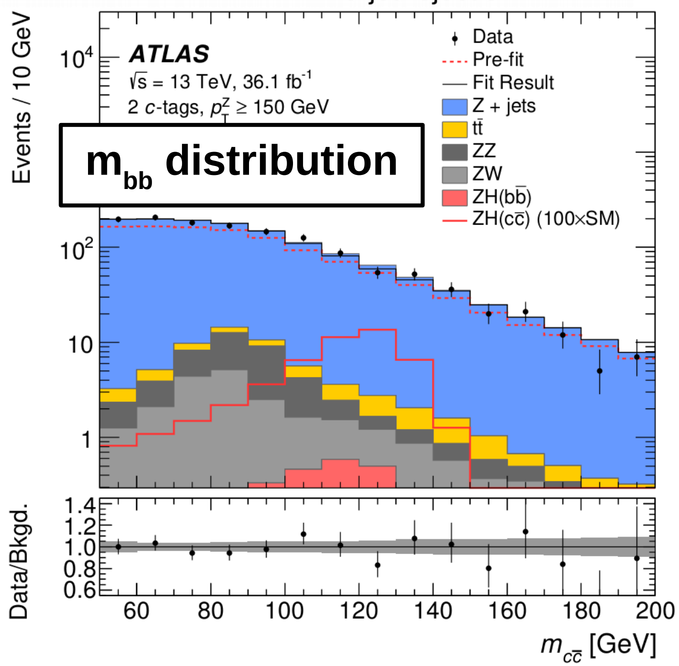
# Other SM Higgs boson searches

# VH → cc

arXiv:1802.04329 (sub. PRL)

- As for H → bb, H → cc has been searched in the Z(ℓℓ)H(cc) channel.
- Two **c-tagger** discriminators have been trained against b-jets and light-jets:
  - calibrated in data using t → Wb and W → cs/cd.
- **Challenges**: c-tagger, BR(H→cc)~2.9%, Z+cc bkg.
- A validation analysis has been performed looking for Z(ℓℓ)W(cs) and Z(ℓℓ)Z(cc).
  - $\mu = 0.6^{+0.5}_{-0.4} \rightarrow 1.4\sigma$ (exp. 2.2σ)
- Results: $\mu = -69 \pm 101$
  - upper limit $\mu < 100$ (exp. 150).

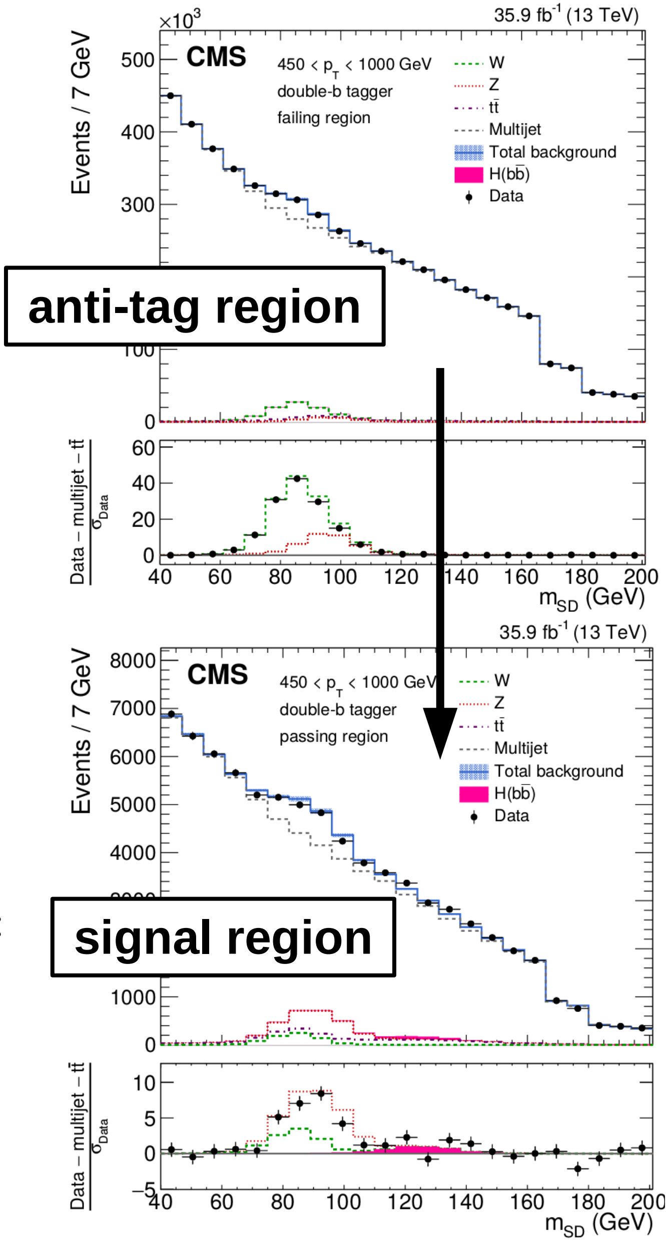


# Boosted H → bb

arXiv:1709.05543 (acc. PRL)

- Brand new analysis: boosted gg → H → bb.
- Large QCD multijet background.
- **AK8 jet** with $p_T$>450GeV:
  - pileup per particle identification (PUPPI);
  - soft drop grooming and two subjets ($N_2^1$ variable);
  - **double b-tagger** specifically designed for H(bb).
- **QCD** estimated inverting b-tag cut and propagated to SR with a transfer function $R_{p/f} = f(\log(m_{SD}/p_T), p_T)$.
- Other backgrounds estimated by simulations → b-tag fake rate and efficiency constrained from data.
- Challenging signal cross-section computation in boosted gg→H:
  - approximate NLO H+0,1,2 jet merged with finite $m_t$;
  - k-factor ~ 1.3, systematic unc. ~30% on normalization and slope.
- **Results**: $\mu = 2.3 \pm 1.5(stat)^{+1.0}_{-0.4}(syst)$ → 1.5σ (exp. 0.7σ)

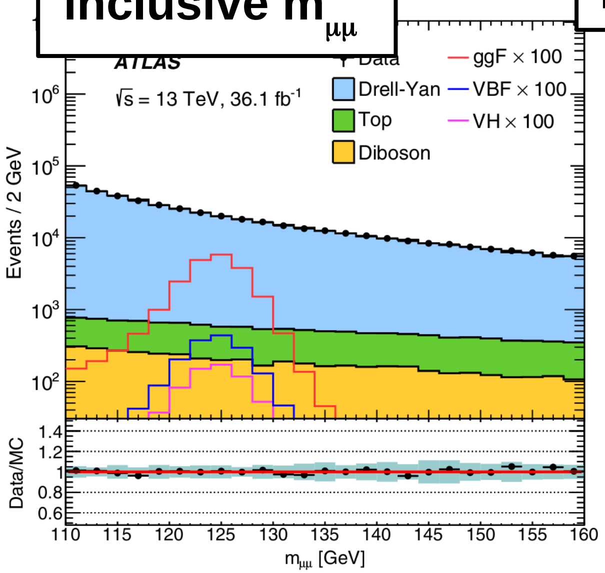


Phys. Rev. Lett. 119 (2017) 051802
CMS-PAS-HIG-17-019

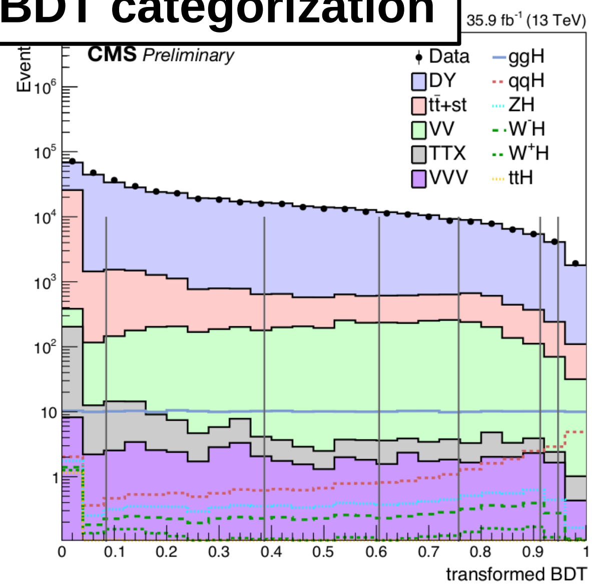
# $H \rightarrow \mu\mu$

- $H \rightarrow \mu\mu$ can be found as a peak in a **smoothly falling background**.
- The analysis is split in categories with different di-muon mass **resolution** and signal **purity** → a **BDT** is used to enhance S/B separation.
  - VBF-enriched categories have the largest purity and sensitivity.
- **Results**. CMS: $\mu=0.9^{+1.0}_{-0.9} \rightarrow 0.98\sigma(1.09\sigma)$; ATLAS: $\mu=-0.1\pm1.4$

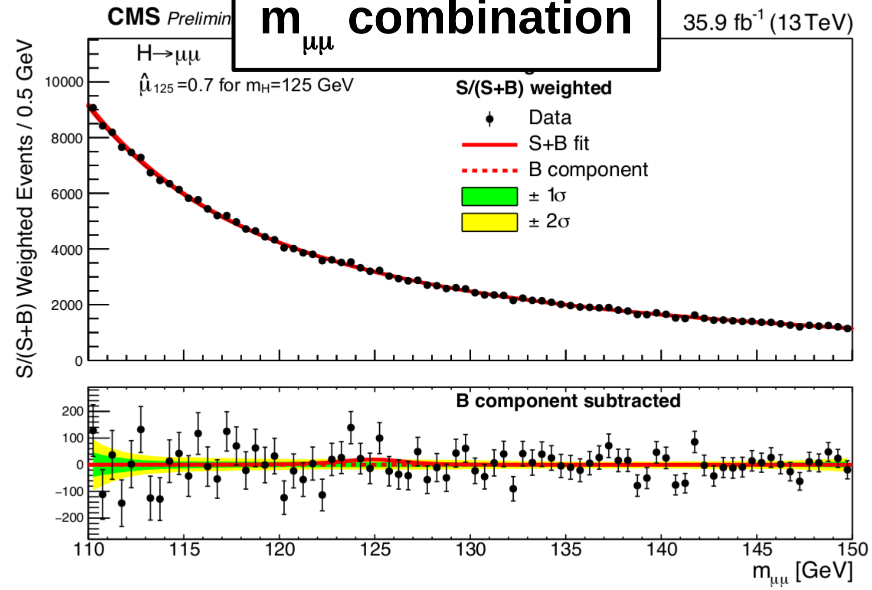
**inclusive $m_{\mu\mu}$**




**BDT categorization**



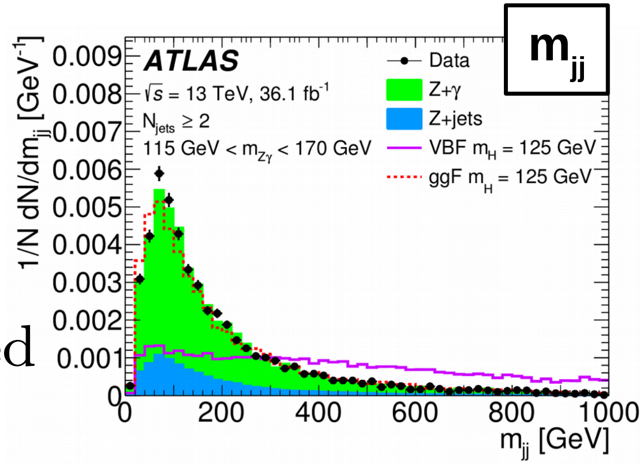

**$m_{\mu\mu}$ combination**

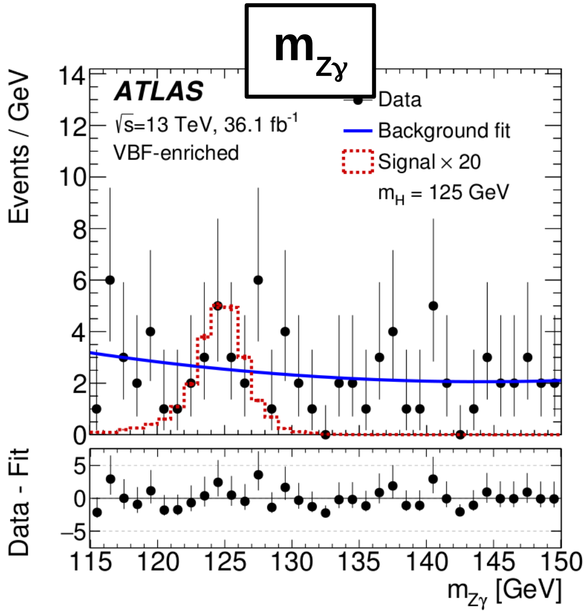


JHEP 10 (2017) 112

# $H \rightarrow Z\gamma$

- Higgs boson decays into $Z\gamma$ through loops.
  - BR similar to $H \rightarrow \gamma\gamma$, but only 6.6% $Z \rightarrow \mu\mu/ee$.
- $m_{Z\gamma}$ resolution improved recovering the FSR emitted close to the lepton and with a **kinematic fit**.
- Analysis divided in several categories with different purities
  - **VBF** category has the largest purity and sensitivity.
- **Result**: Upper limit 6.6 times the SM (exp. 5.2).

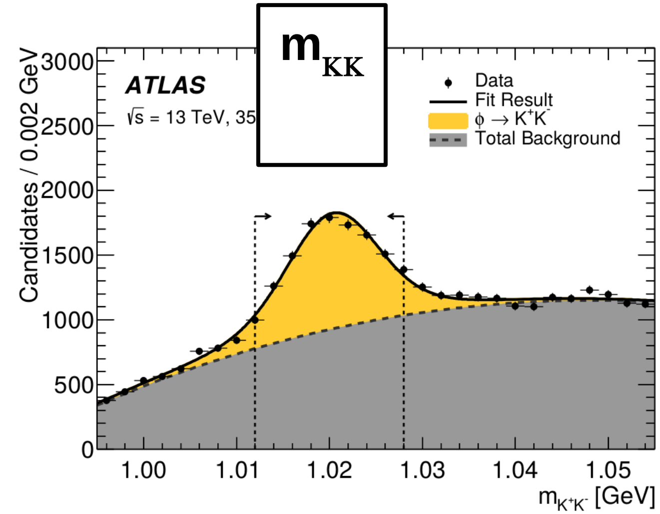


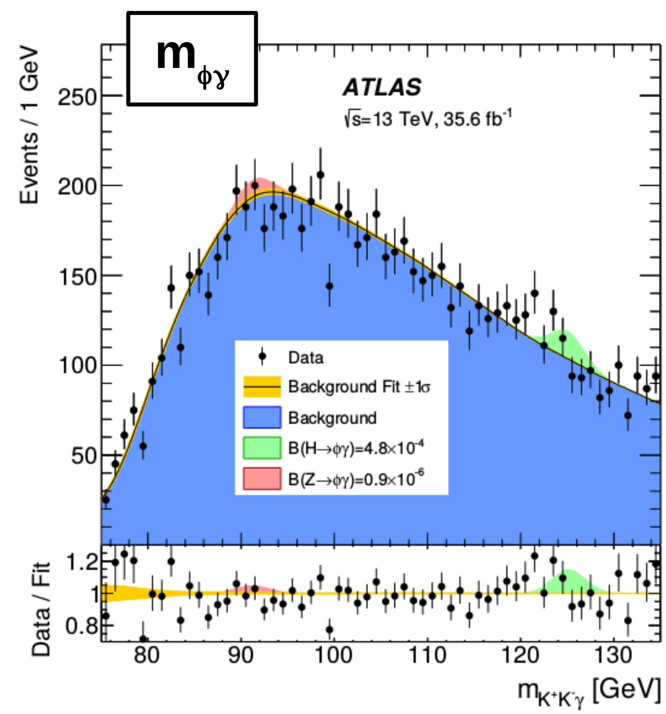



# $H \rightarrow$ light quarks

arXiv:1712.02758 (sub. JHEP)

- $\mathbf{H \rightarrow \phi\gamma}$ and $\mathbf{H \rightarrow \rho(770)\gamma}$ have been proposed as channel to probe the Higgs coupling with the s quark and u/d quarks, respectively.
- The expected SM BR are $2.3 \cdot 10^{-6}$ and $1.7 \cdot 10^{-5}$.
- They have been searched in the $\phi \rightarrow K^+K^-$ and $\rho \rightarrow \pi^+\pi^-$ decays.
- One isolated photon with $p_T > 35$ GeV.
- Two isolated tracks with $p_T > 15$ GeV and mass compatible to $\rho$ or $\phi$.
- **Data driven background estimate**:
  - validated in $\rho$ and $\phi$ side bands.
- **Results**:
  - upper limit BR($\phi\gamma$) $4.8(4.2) \cdot 10^{-4} \rightarrow \mu < 208(182)$;
  - upper limit BR($\rho\gamma$) $8.8(8.4) \cdot 10^{-4} \rightarrow \mu < 52(50)$.



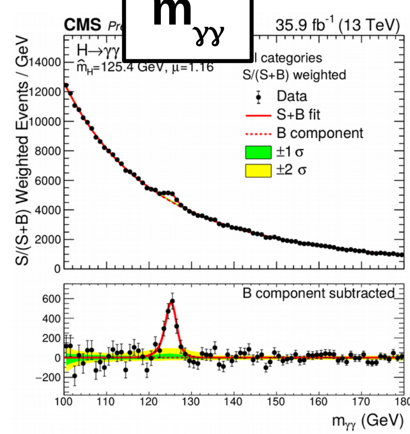
# Precision SM Higgs boson measurements

ATLAS-CONF-2017-047
CMS-PAS-HIG-17-015
JHEP 11 (2017) 047
JHEP 10 (2017) 1327
arXiv:1802.04146 (sub. JHEP)

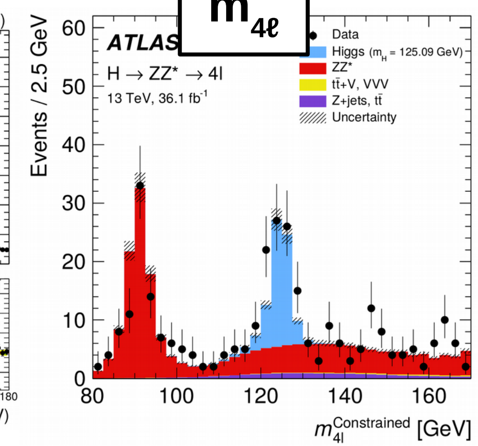
# $H \rightarrow 4\ell$ and $H \rightarrow \gamma\gamma$

- The $H \rightarrow \gamma\gamma$ and $H \rightarrow 4\ell$ are the most sensitive channel to provide precision measurement of the Higgs boson.
  - ATLAS has already provided the **combination** $H\rightarrow 4\ell$ + $H\rightarrow\gamma\gamma$.
- 13 TeV analyses confirm SM expectation:
  $\rightarrow$ measurement cross-section vs $\sqrt{s}$.

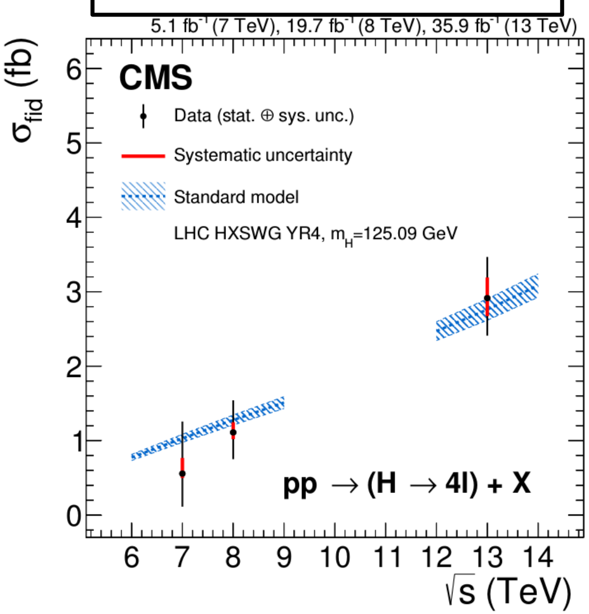
**$m_{\gamma\gamma}$**



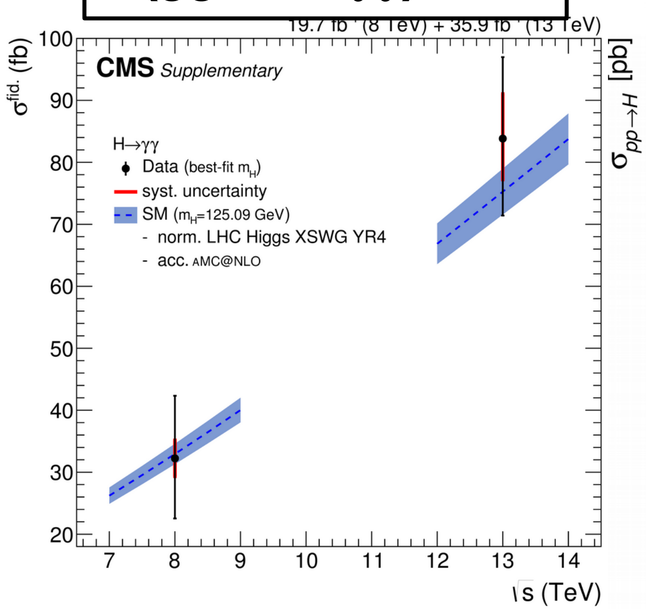

**$m_{4\ell}$**



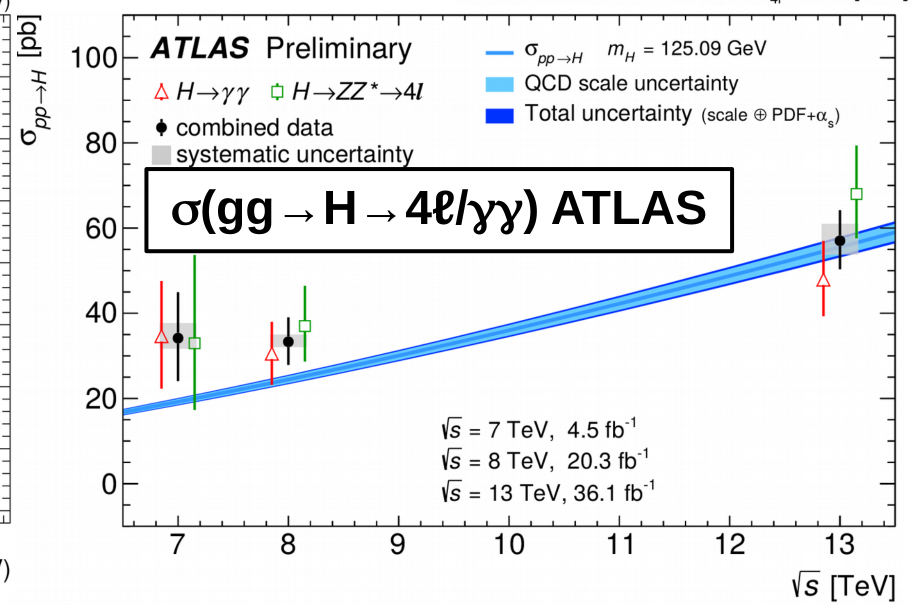

**σ(gg→H→4ℓ) CMS**




**σ(gg→H→γγ) CMS**



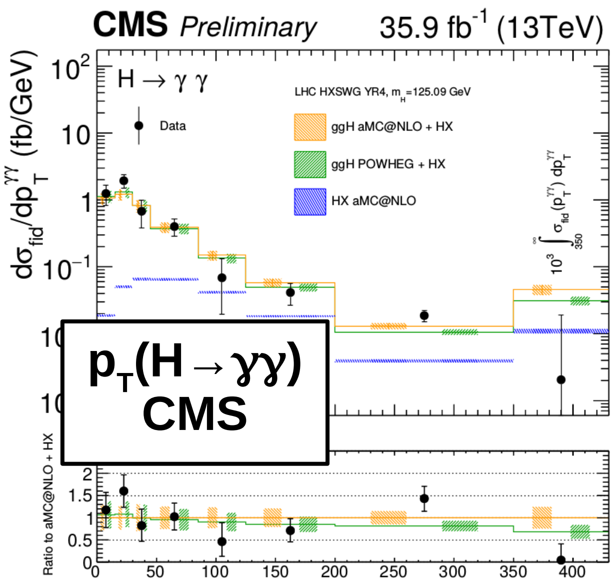

**σ(gg→H→4ℓ/γγ) ATLAS**

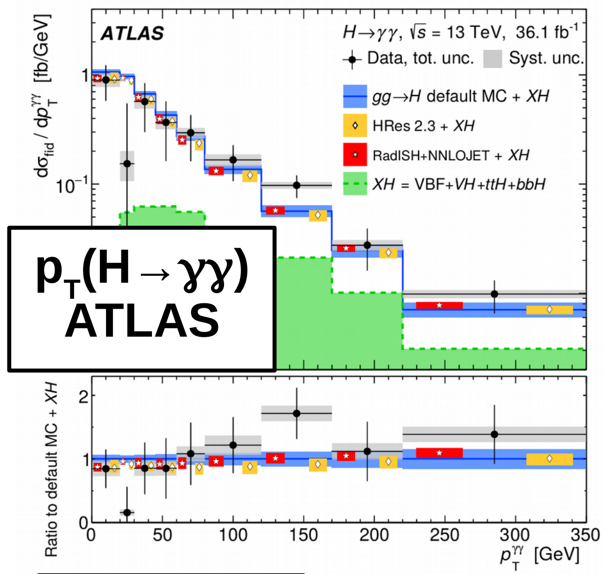


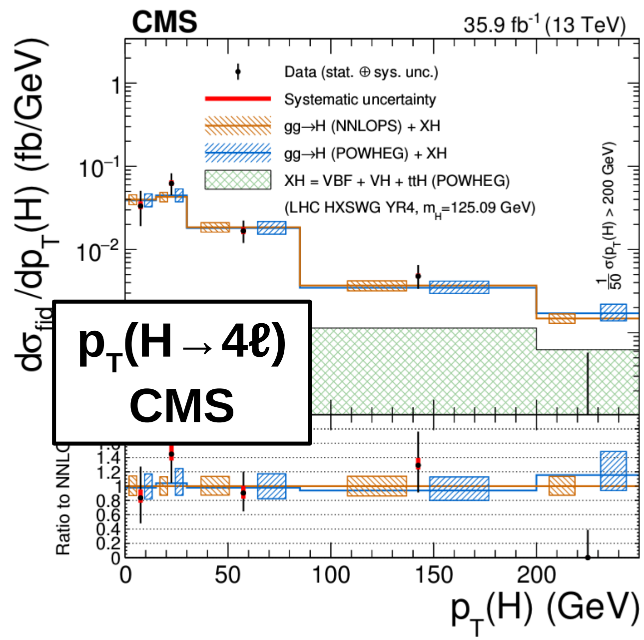
CMS-PAS-HIG-17-015
JHEP 11 (2017) 047
JHEP 10 (2017) 1327
arXiv:1802.04146 (sub. JHEP)

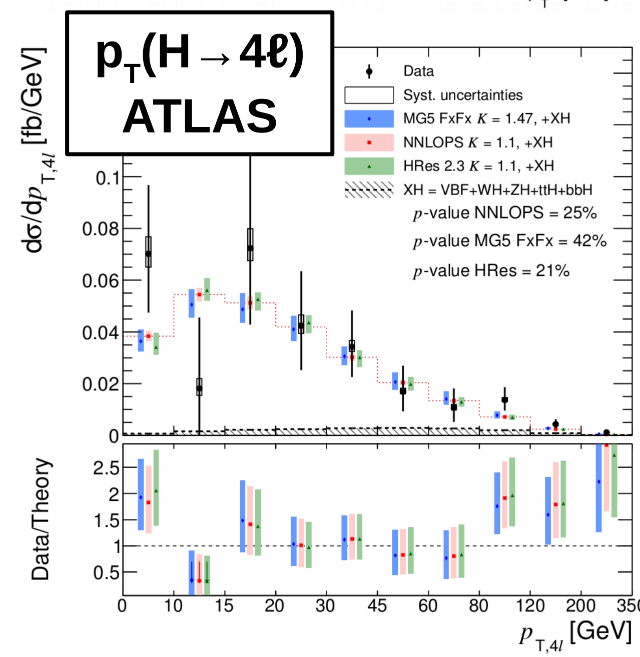
# $H \to 4\ell$ and $H \to \gamma\gamma$

- The growing signal allows to measure the **differential** cross section as a function of variable eg. $p_T(H)$, $N_{jet}$, $\eta(H)$, ...
- Here the measurement of $p_T(H)$ in $H \to 4\ell$ and $H \to \gamma\gamma$.
- The cross section is measured in a **fiducial** phase space in order to allow a good comparison with theory.

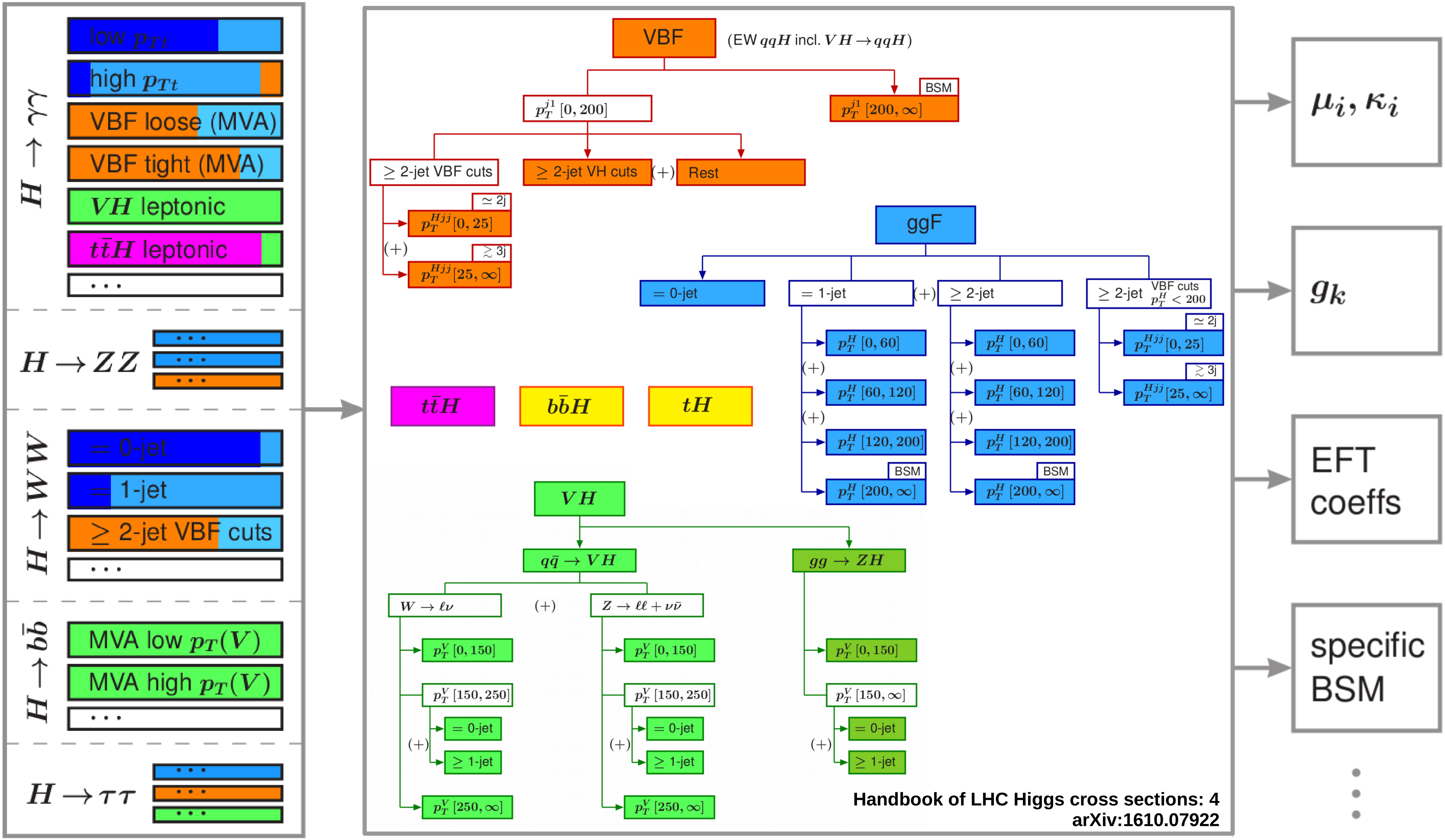


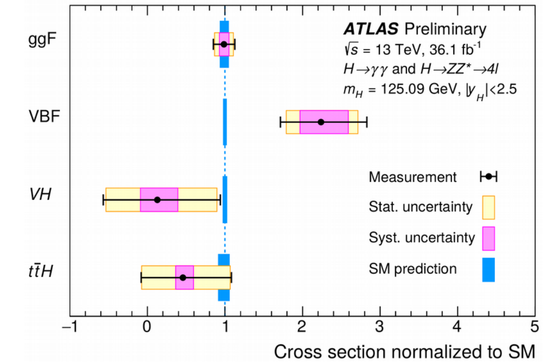
# Simplified Template Cross Section (STXC)

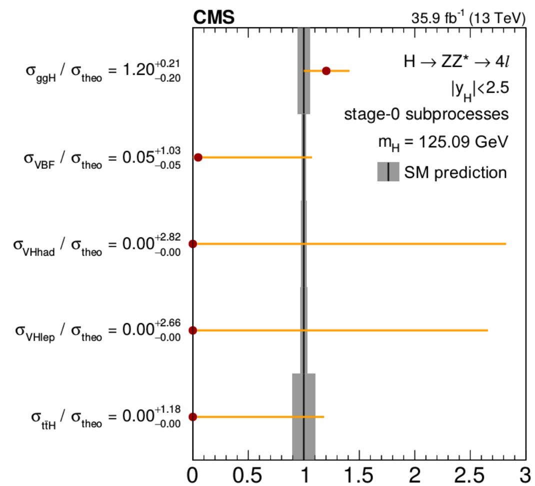


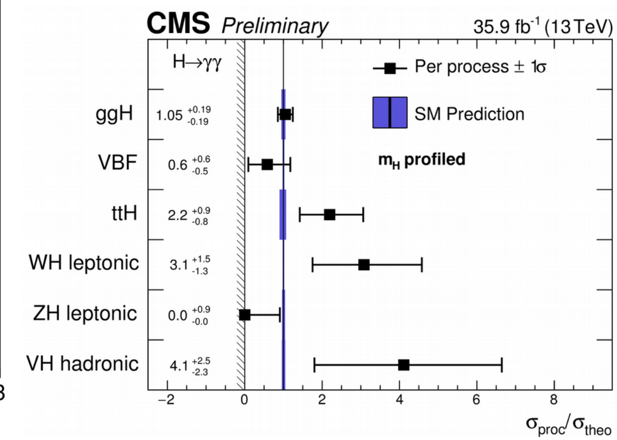
# Simplified Template Cross Section (STXC)

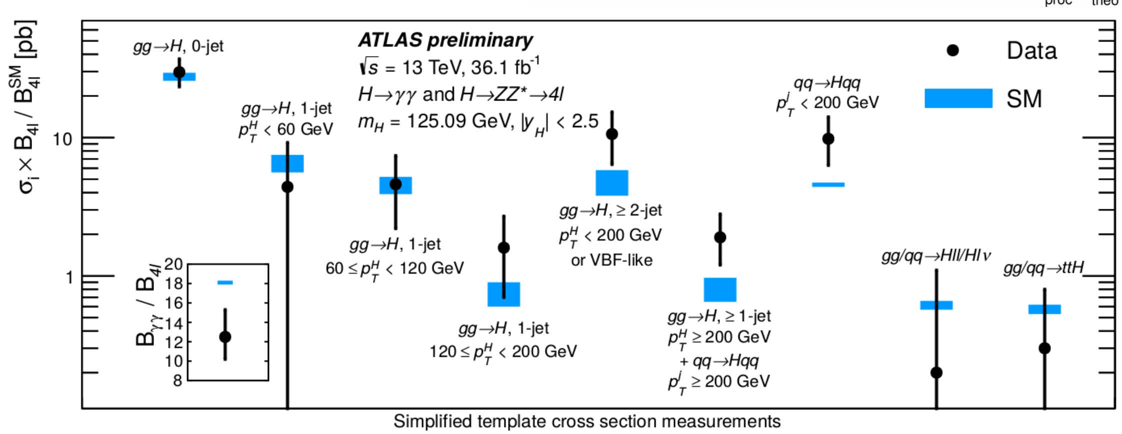
ATLAS-CONF-2017-047
CMS-PAS-HIG-17-015
JHEP 11 (2017) 047
JHEP 10 (2017) 1327
arXiv:1802.04146 (sub. JHEP)

- We are going towards the measurement of the Higgs boson cross-section using stage-1 STXC.
- The first step (stage-0) is the measurement of the cross-section per production channel (ggH, VBF, VH, ttH)
- ATLAS already provided a reduced stage-1 set of measurements with the combination of $H \to 4\ell$ and $H \to \gamma\gamma$.



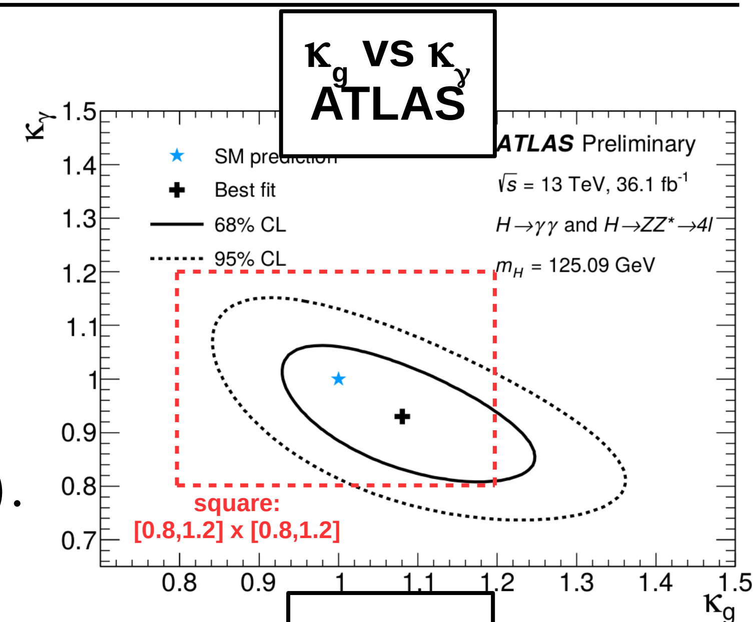



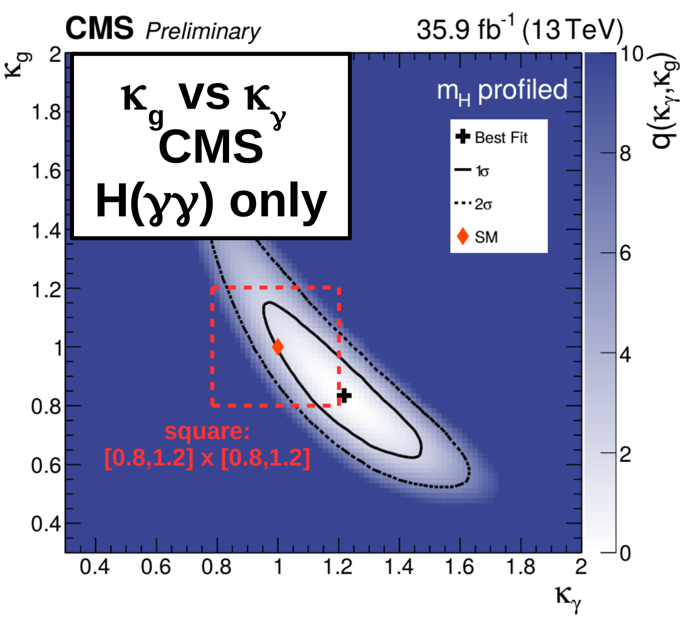



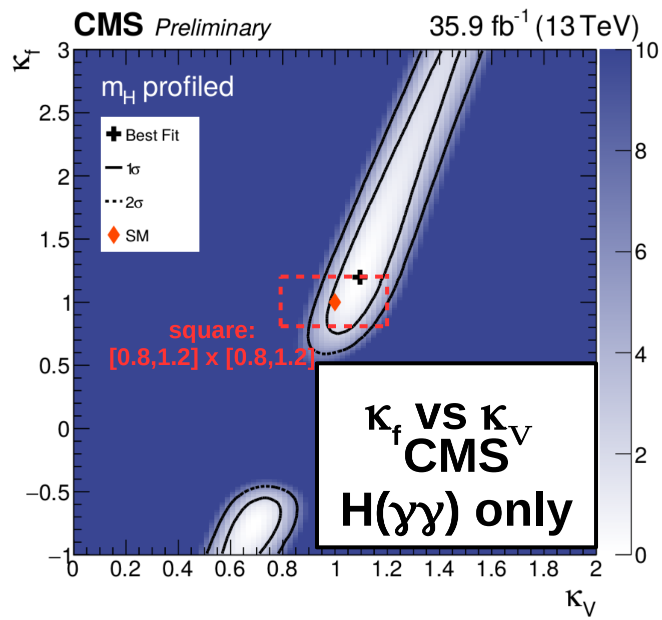
# Couplings

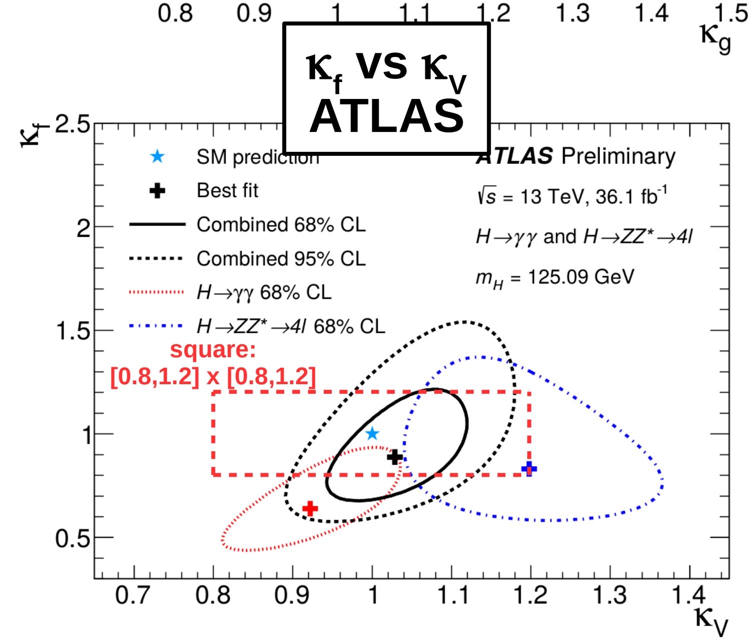
CMS-PAS-HIG-17-015
ATLAS-CONF-2017-047

- The first measurements of the **coupling modifiers** κ at 13 TeV are available.
- Example:
  - fermionic vs bosonic couplings ($k_f$ vs $k_V$);
  - loop couplings: photons vs gluons ($k_\gamma$ vs $k_g$).
- Compatible with SM within 1σ.



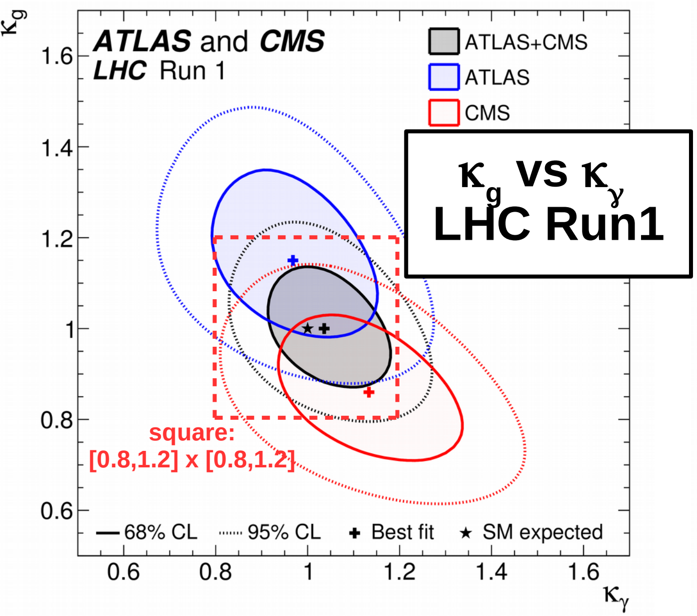



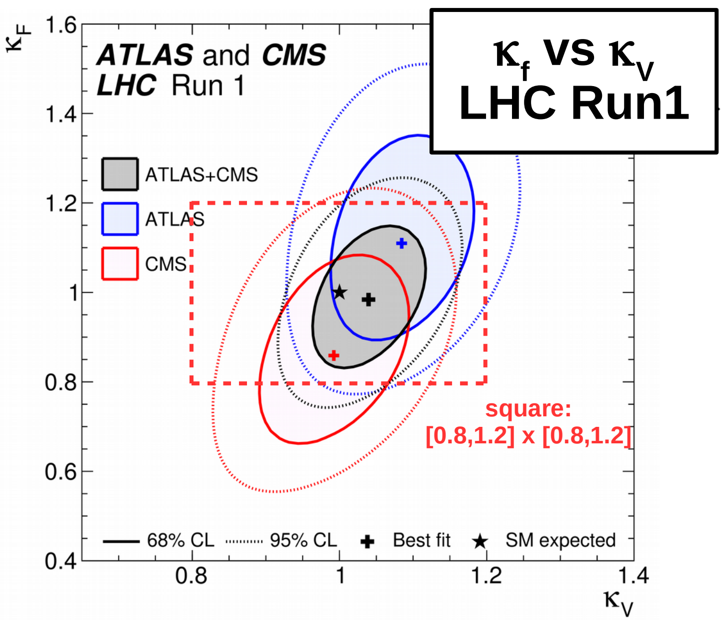



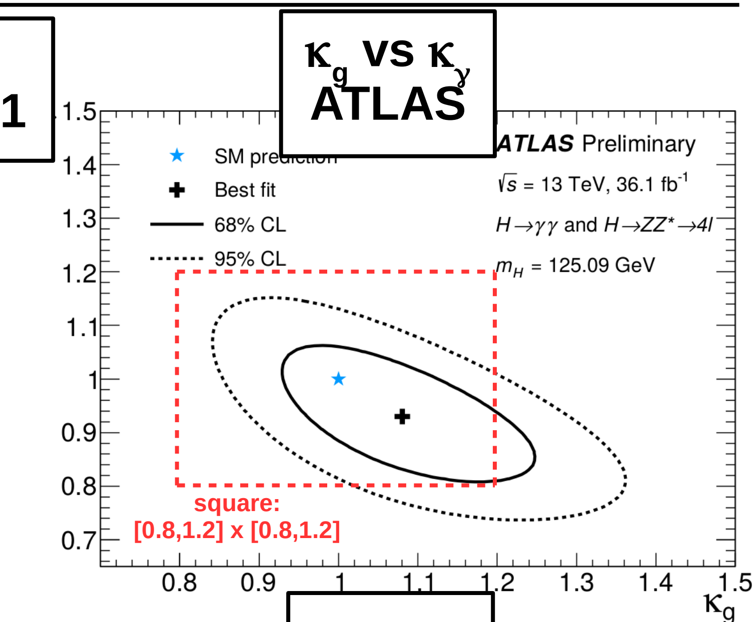



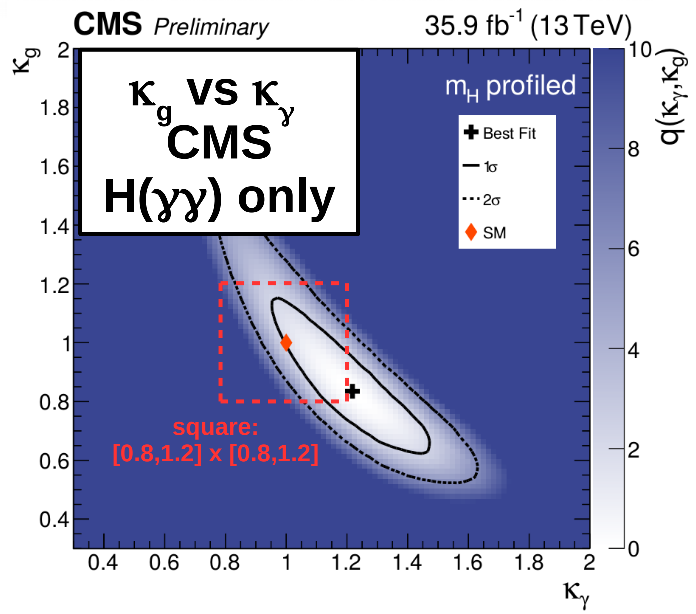
# Couplings

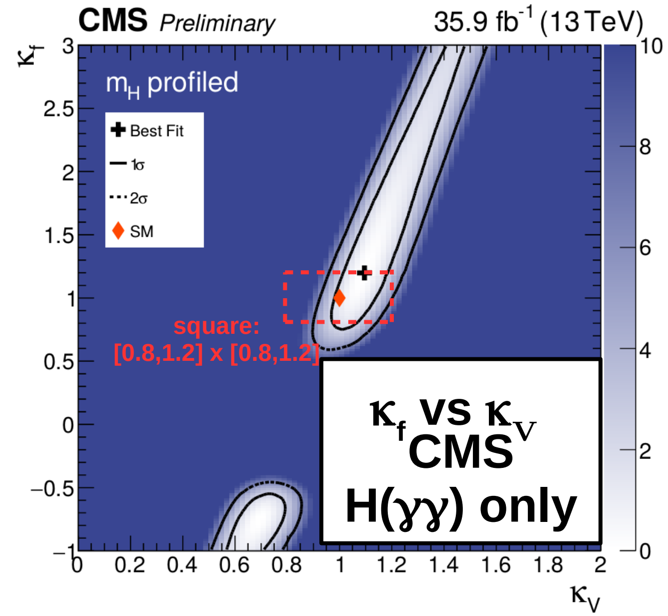
CMS-PAS-HIG-17-015
ATLAS-CONF-2017-047
J. High Energy Phys. 08 (2016) 045

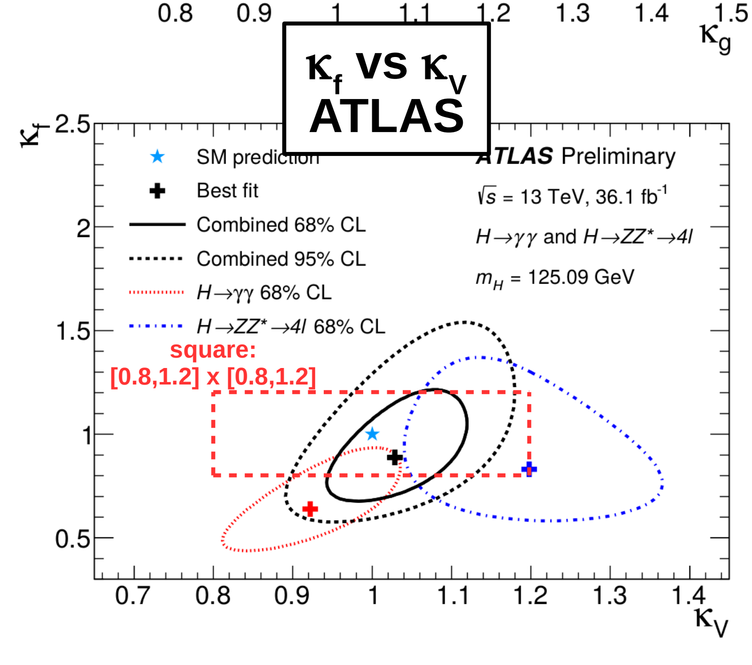


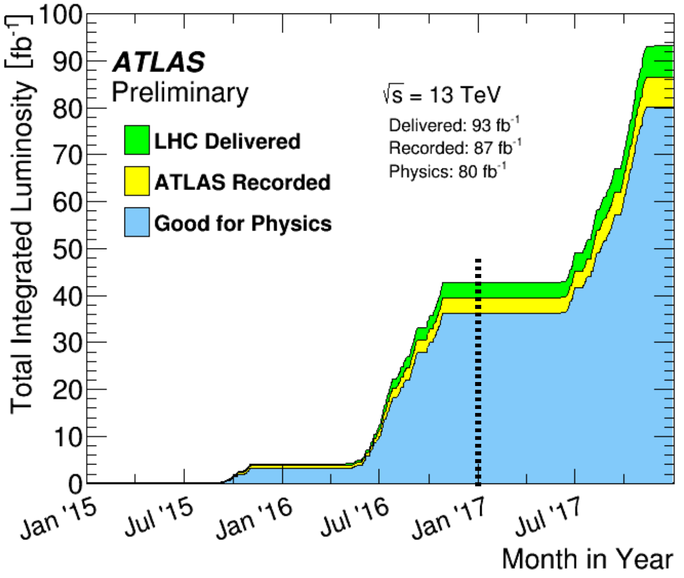



# Conclusions

# Conclusions

- CMS and ATLAS collaborations published many important Higgs results in the last year.
  - single-experiment observation of $H \to \tau\tau$;
  - evidence for $H \to bb$ and ttH;
  - new Higgs channel (eg. boosted $H \to bb$);
  - large improvement in $H \to \mu\mu$.



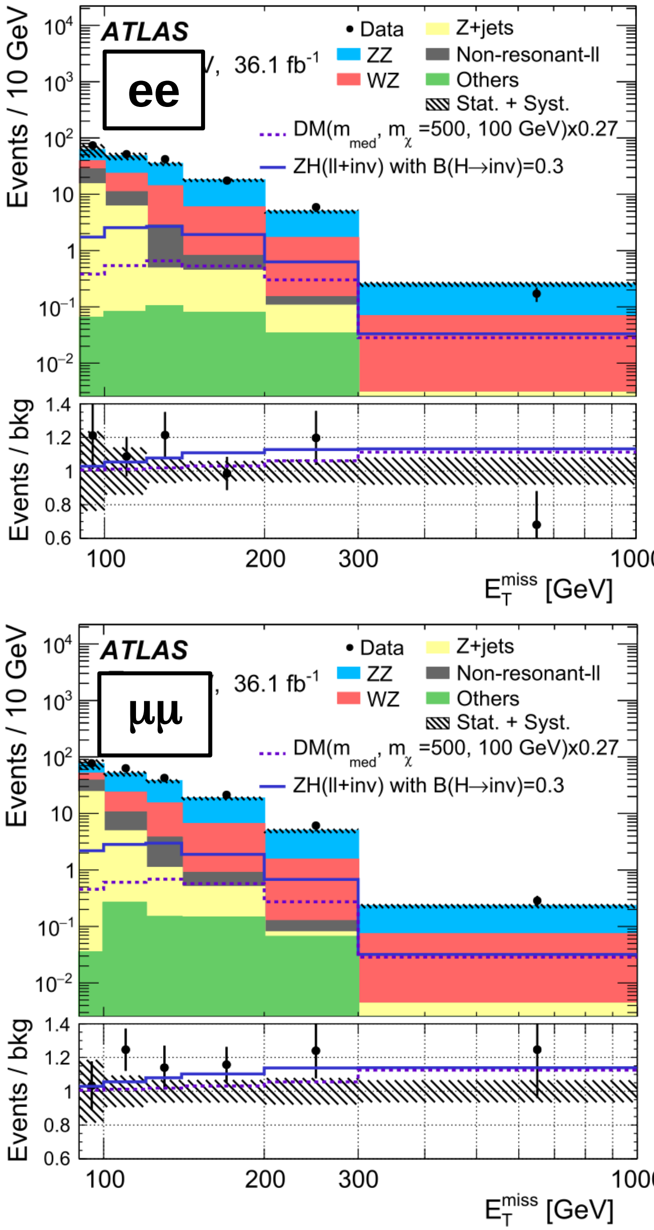

- $H \to 4\ell$ and $H \to \gamma\gamma$ are now channels for precision measurements
  - differential cross sections, and couplings.
- All results have been obtained using 2015-16 data (36 $fb^{-1}$):
  - LHC doubled the integrated luminosity in 2017 and even more luminosity is expected in 2018.
- Many more results are expected in the next months/years!

**Thank you for your attention!**

# Backup

# ZH → invisible

- H → invisible decay can be enhanced by New Physics (eg. **dark matter**).
  - SM prediction BR(H→ZZ→inv.)~$10^{-3}$
- Analysis performed in **Z(ℓℓ)H(inv.)** channel.
- Main backgrounds :
  - **Diboson**: estimated by simulation and scaled by a data-driven scale factor
  - **Z+jets**, non-resonant(ll) : estimated by data.
- **Results** on BR(H→inv.):
  - upper limit 67% (exp. 39%).



JHEP 11 (2017) 047
ATLAS-CONF-2017-046

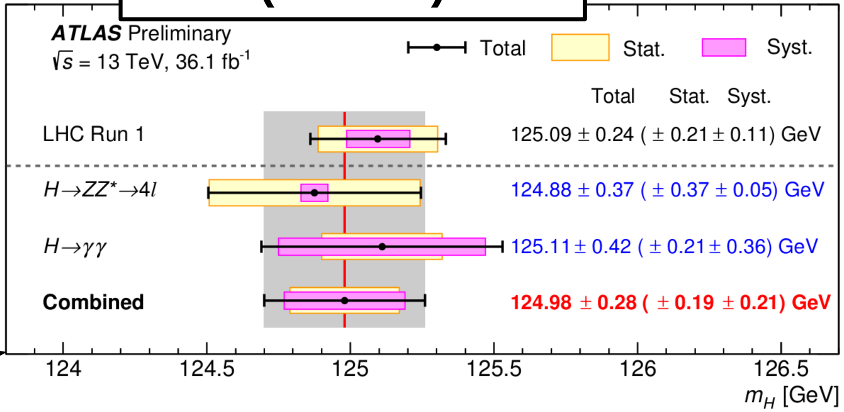
# Mass

- Measurement of the Higgs mass and width.
- ATLAS:
  - combination H(γγ) with H(4ℓ);
  - combination with LHC Run-1.
- CMS:
  - only H(4ℓ) available:

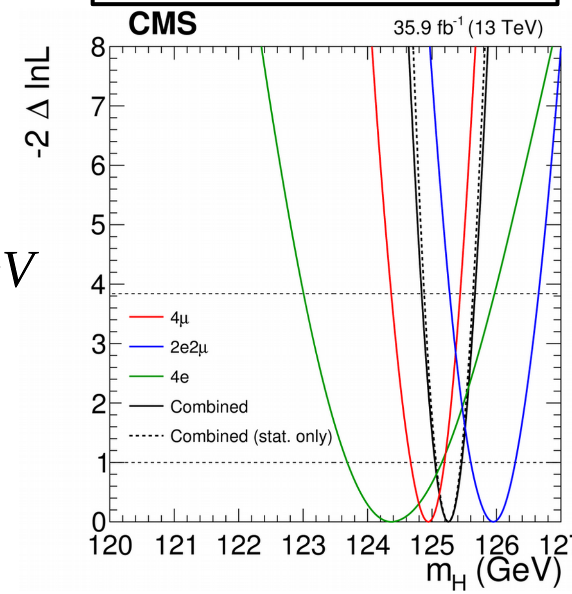
$$m_H = 125.26 \pm 0.20(stat) \pm 0.08(syst)\,GeV$$

$$\Gamma_H < 1.10\,GeV\,(95\%\,CL)$$

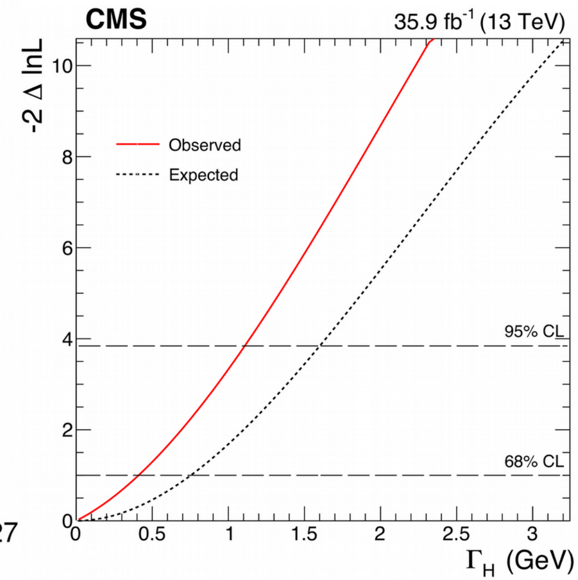
**Mass combination (ATLAS)**




**Mass H(γγ) (CMS)**




**Mass H(4ℓ) (CMS)**



# H → bb (History)

PLB 776 (2017) 318

- Significance @125 GeV (expected):
  - CDF: ~2.8σ (~1.5σ)
  - ATLAS: 1.7σ (2.7σ) – Run-1

    3.5σ (3.0σ) – Run-2

    3.6σ (4.0σ) – Run-1+Run-2
  - ATLAS: 2.0σ (2.5σ) – Run-1

    3.3σ (2.8σ) – Run-2

    3.8σ (3.8σ) – Run-1+Run-2