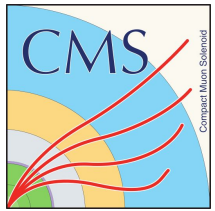



# Measurements with fermionic Higgs decays

## Couplings and searches

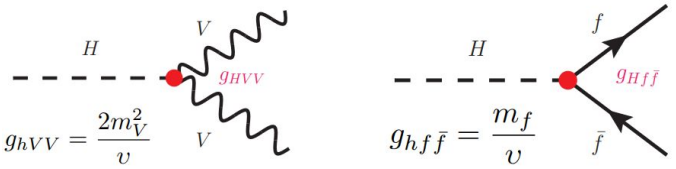
**Markus Spanring***

ON BEHALF OF ATLAS AND CMS

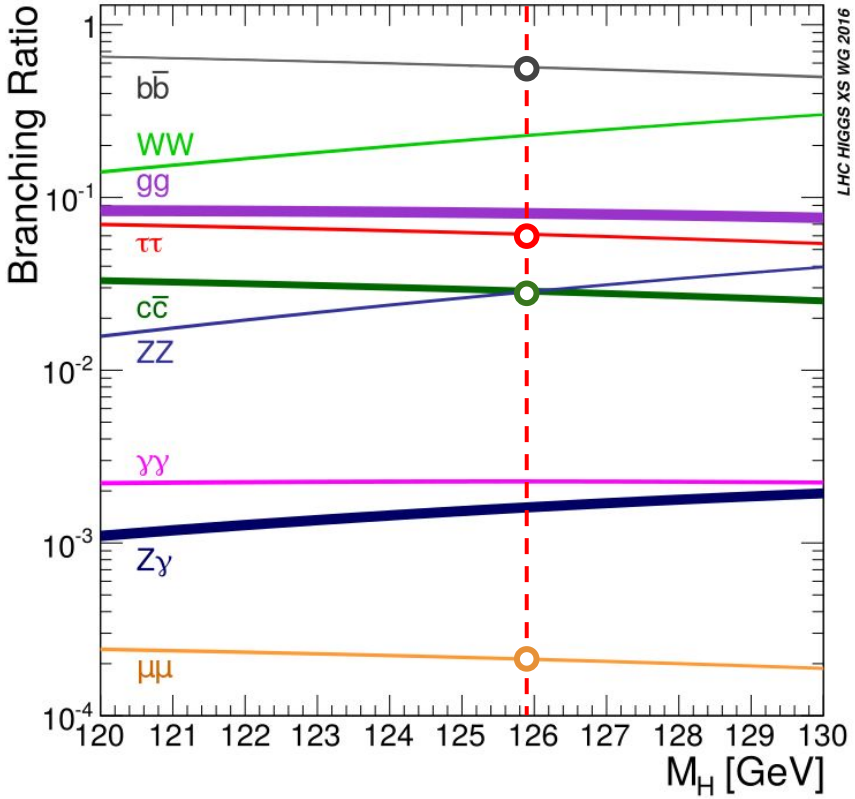
LHCP 2019 - Puebla

* supported by
Austrian Science Fund (FWF): 28857-N36

- Higgs coupling to **vector bosons** defined by **EWK symmetry breaking**.
- Higgs coupling to **fermions** via ad-hoc **Yukawa couplings** $\propto m_f$.
  - several BSM scenarios predict changes in Yukawa couplings.

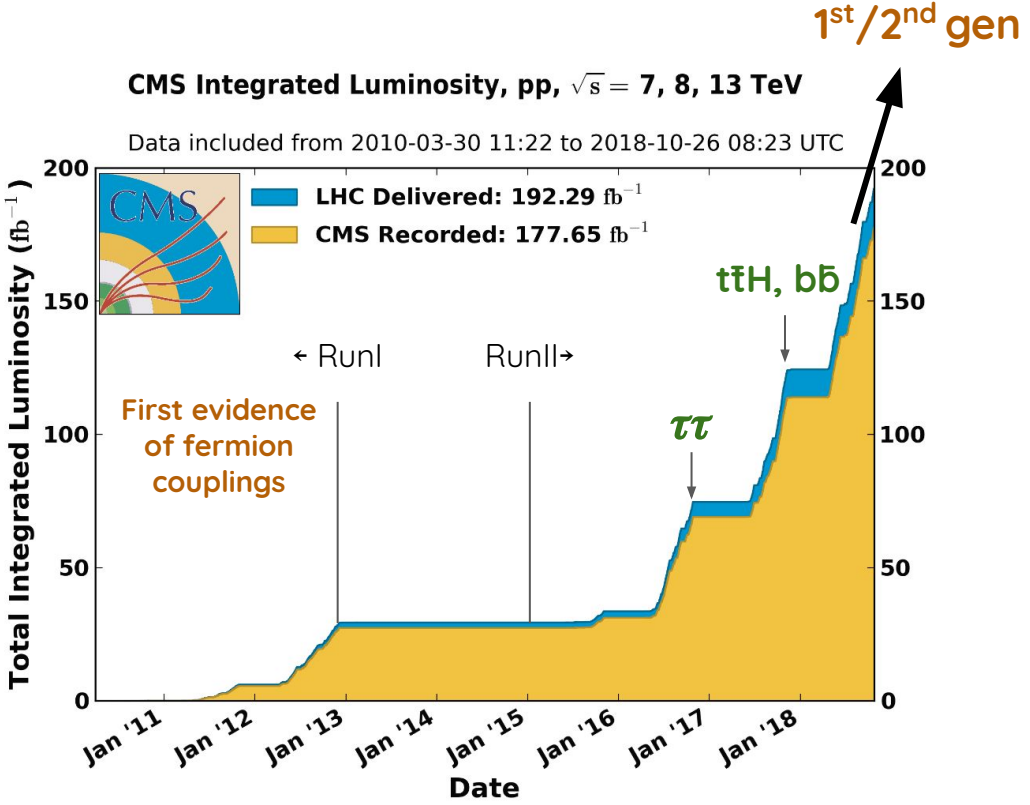



⇒ Information on Higgs couplings to fermions is essential.



# The fermion story so far

- 3rd generation fermions
  - Observed direct coupling to:
    - $\tau$-lepton (**A**TLAS/**C**MS)
    - b-quark (A/C)
    - top-quark (A/C via $t\bar{t}H$)
- 1st/2nd generation fermions
  - Upper limits set for:
    - $\mu$ (A/C)
    - charm-quark (A)
  - No measurements
    - electron
    - u/d/s-quark



# The fermion story so far

- 3rd generation fermions
  - Observed direct coupling to:
    - ➢
    - ➢
    - ➢
- 1st/2nd
  - U
    - ➢
    - ➢
  - N
    - ➢ e
    - ➢ u/d/s-quark

**Covered in today's talk**

$H \to \mu\mu$

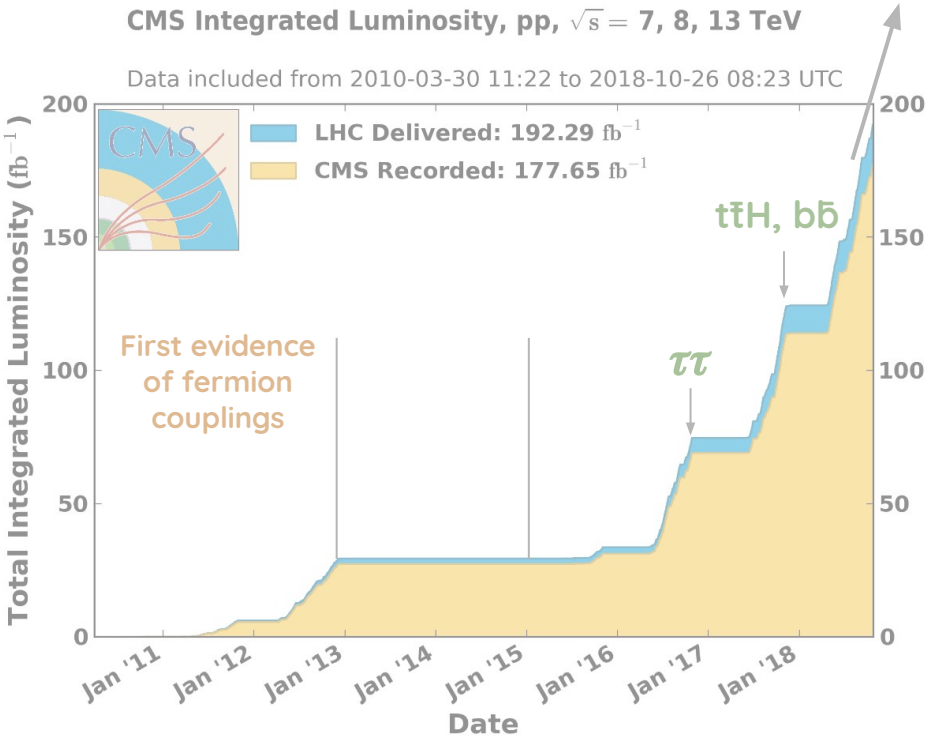
$H \to c\bar{c}$

$H \to b\bar{b}$

$H \to \tau\tau$

results on $t\bar{t}H$ shown in previous talk by John

1st/2nd gen



# H → $\mu\mu$ publications

## ATLAS

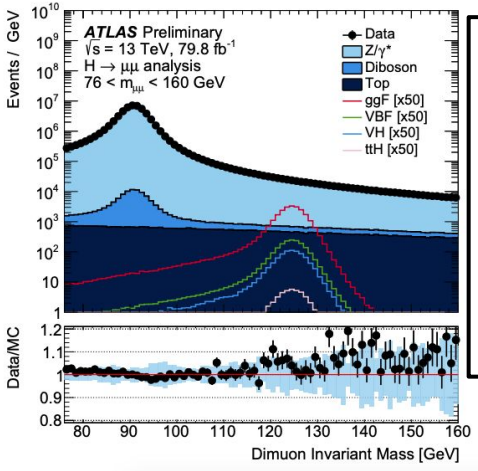
| | |
|---|---|
| Phys. Rev. Lett. 119, 051802 (2017) | Search using 7+8+13TeV(2015-2016) data |
| ATLAS-CONF-2018-026 | Search using 13TeV(2015-2017) data |

## CMS

| | |
|---|---|
| Phys. Rev. Lett. 122, 021801 (2019) | Search using 7+8+13TeV(2016) data |

# H → μμ analysis strategy

- Higgs boson decay to muons most sensitive channel to investigate couplings to 2nd generation fermions.
  - very rare process, but high di-muon mass resolution makes channel accessible
- Signal would appear as narrow resonance over smoothly falling background (primarily Drell-Yan and leptonic top decays.)



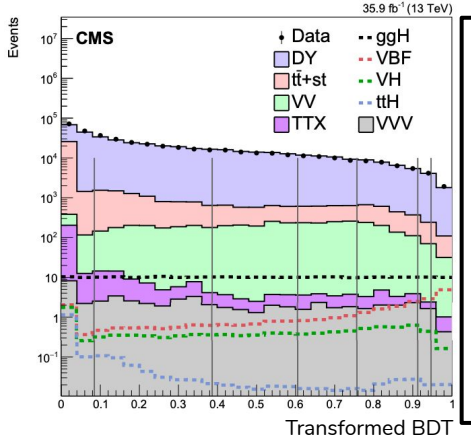

ATLAS-CONF-2018-026

## ATLAS

- Use BDT to select events in 2 VBF categories.
- All other events categorised in 6 ggF categories based on $p_T^{\mu\mu}$ and $\eta^{\mu}$

## CMS

- Separate signal from background using BDT.
- Define 15 signal regions based on BDT score and $\eta^{\mu}$.

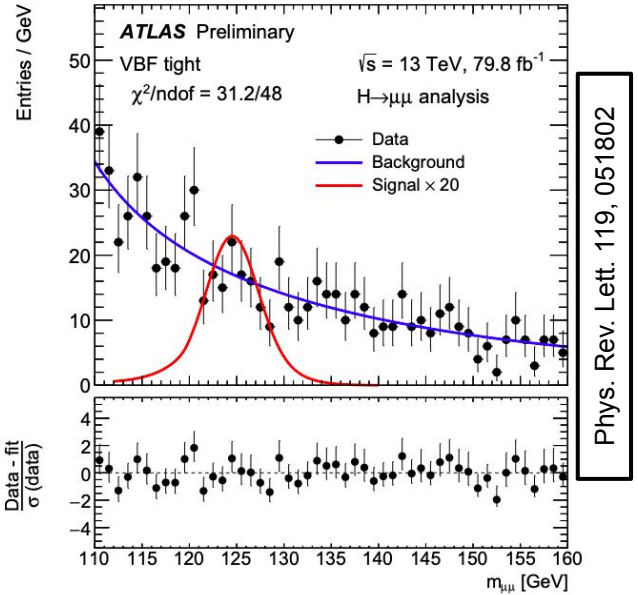



Phys. Rev. Lett. 122, 021801

- Use analytic functions to describe signal and background distributions

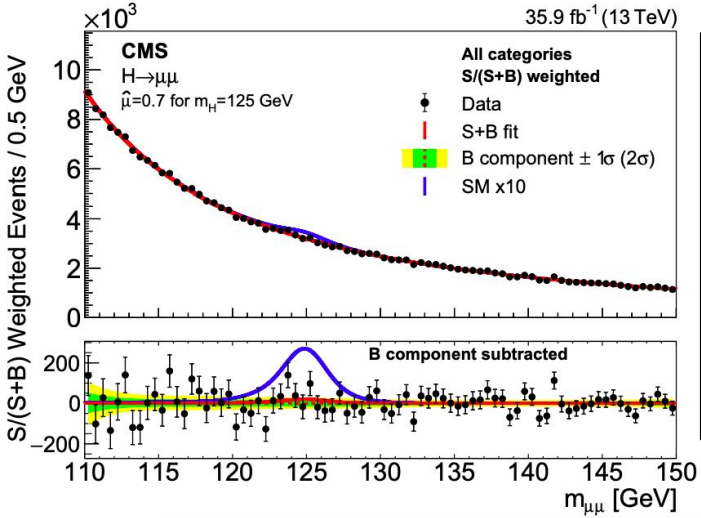
95% CL observed (background-only expected) upper limit on σx$\mathcal{B}$ is

2.1 (2.0) x SM




Phys. Rev. Lett. 119, 051802

2.9 (2.2)* x SM




Phys. Rev. Lett. 122, 021801

* Combination with data recorded at 7 and 8 TeV

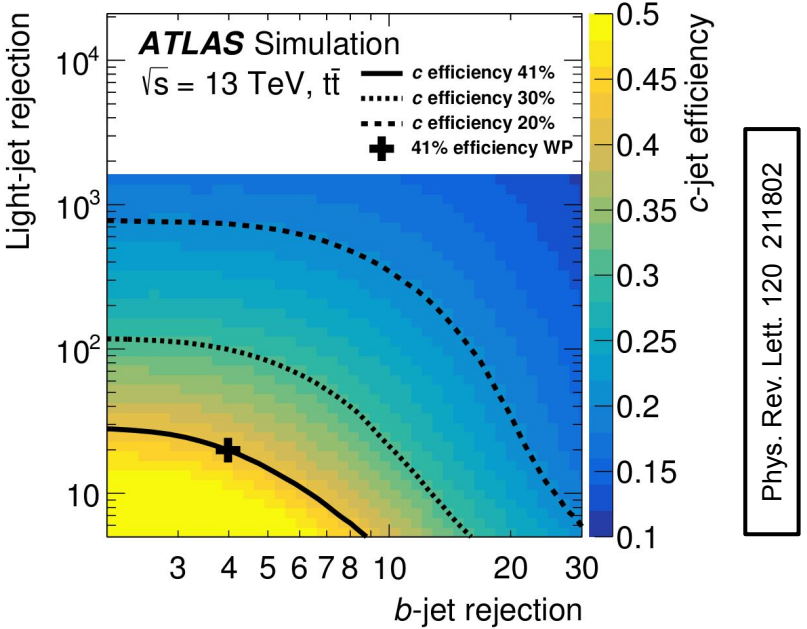
## ATLAS

| | |
|---|---|
| Phys. Rev. Lett. 120 (2018) 211802 | Search using 13TeV(2015+2016) data |
| Phys. Lett. B 786 (2018) 134 | h(125)/Z->J/psi gamma |
| ATL-PHYS-PUB-2018-016 | HL-LHC prospects |

## CMS

| |
|---|
| No searches published yet |

- Challenging due to small BR, trigger strategy and difficult jet flavor identification.
  - Two other approaches:
    - ➢ Searches for charmonium decay.
    - ➢ (e.g. Phys. Lett. B 786 (2018) 134)
    - ➢ Extract constraints from kinematics (e.g. Phys. Lett. B 792 (2019) 369 )
- Tagging of c-jet challenging:
  - Shorter lifetime and decay to fewer charged particles than b-hadrons.
  - Trade-off between rejection of light-jets and rejection of b-jets.

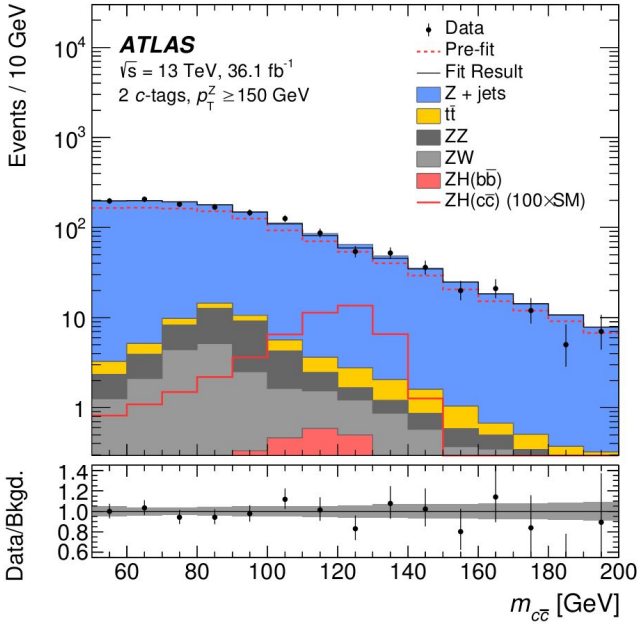



- Data analyzed for ZH → ℓℓcc̄ process in four categories:
  - Categories defined using $p_T^Z$ and number of c-tags.
  - Requirement on angular separation of dijet system to suppress background events.
  - Dijet invariant mass $m_{c\bar{c}}$ used as discriminating variable.

Observed (expected) upper limit on σx$\mathcal{B}$ is

$$2.7\ \left(3.9^{+2.1}_{-1.1}\right)\ \text{pb}$$

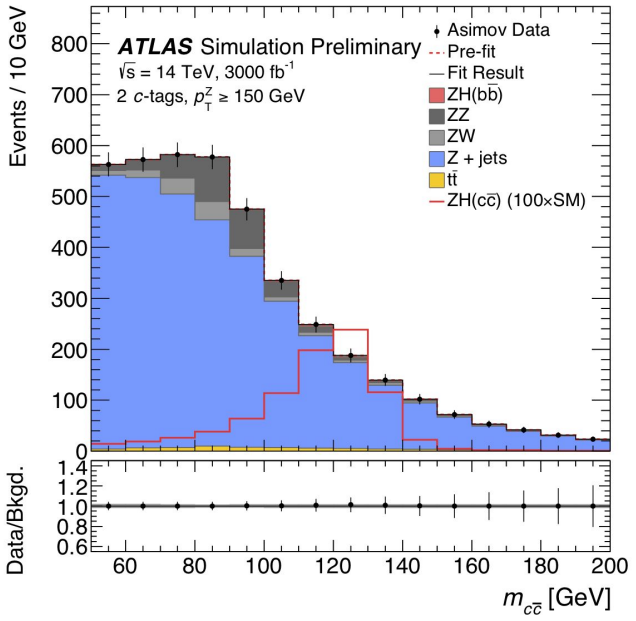
Corresponds to 110x the SM expectation.




Phys. Rev. Lett. 120 211802

HL-LHC prospect for VH, H→cc̄ with 3000 fb$^{-1}$ at 14 TeV assuming stat. uncertainties only and improvement of light-flavour rejection of factor 2

$$\mu_{ZH(c\bar{c})} < 6.3$$




ATL-PHYS-PUB-2018-016

See previous talk by Luca

## ATLAS

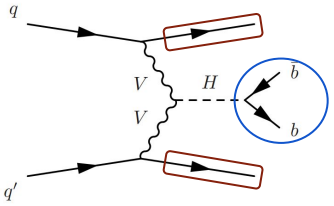
| | |
|---|---|
| Phys. Rev. D 98, 052003 | Search for VBF H→bb̄ 13TeV(partial 2015-2016) |
| Phys. Lett. B 786 (2018) 59 | Observation using 7+8+13TeV(2015-2017) data |
| 1903.04618 (submitted to JHEP) | STXS* measurement using 13TeV(2015-2017) data |

## CMS

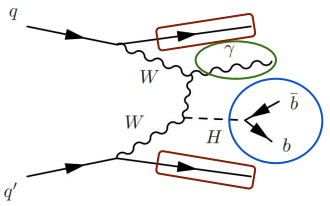
| | |
|---|---|
| Phys. Rev. Lett. 121, 121801 (2018) | Observation using 7+8+13TeV(2016-2017) data |

*simplified template cross sections (STXS)
For details see talk by Chikuma on Tuesday

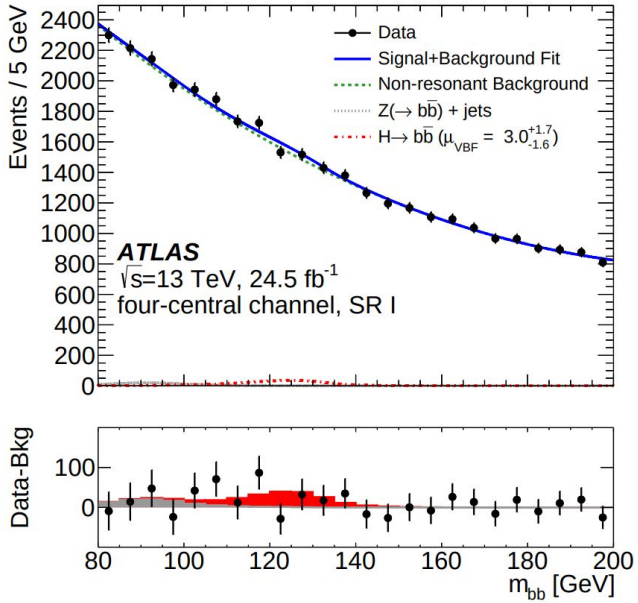
- Dominant decay of SM Higgs boson is into pair of b-quarks: BR(H→bb̄) ~ 58%
  - Similar challenges like in H→cc̄ due to large jet backgrounds and difficult to trigger.
- Event characterized by two central b-jets and two light-quark jets with large η gap + high momentum $\gamma$ in photon channel.
  - 3 categories: extra photon, 4 central jets, 2 forward 2 central jets
- BDT trained to separate signal/background in each channel.
- BDT response used to define several categories in which $m_{b\bar{b}}$ is finally fit to data.




all-hadronic




photon

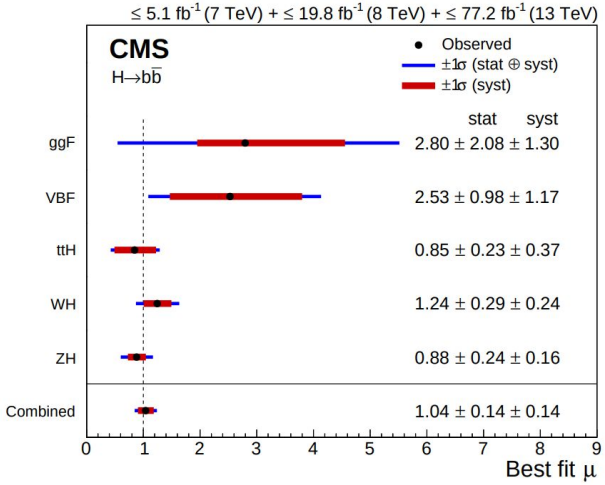



Phys. Rev. D 98, 052003

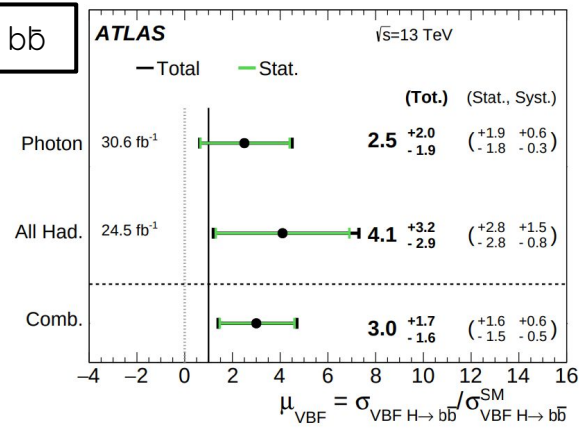
Observation announced by both experiments with observed (expected) significance:

| | |
|---|---|
| ATLAS | **5.4** (5.5)σ |
| CMS | **5.6** (5.5)σ |

Phys. Rev. Lett. 121, 121801

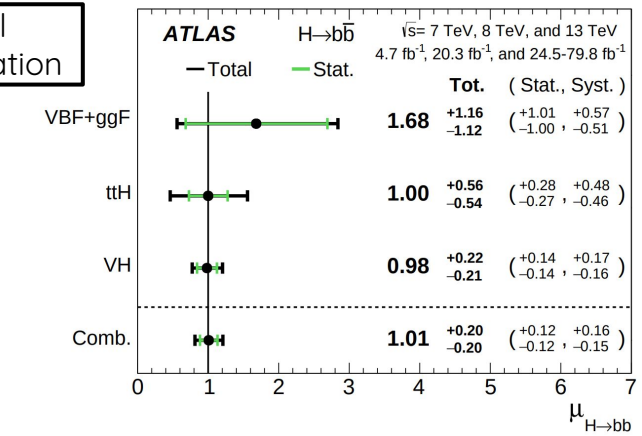



VBF H → bb̄




Phys. Rev. D 98, 052003

Total combination




Phys. Lett. B 786 (2018) 59

# H → $\tau\tau$ publications

## ATLAS

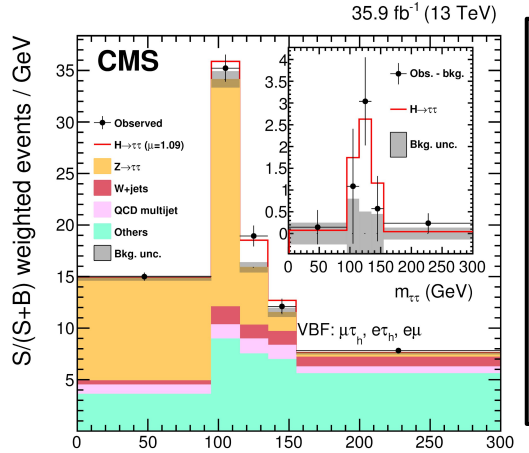
| | |
|---|---|
| Phys. Rev. D 99, 072001 (2019) | Observation and STXS measurement using 7+8+13TeV(2015-2016) data |

## CMS

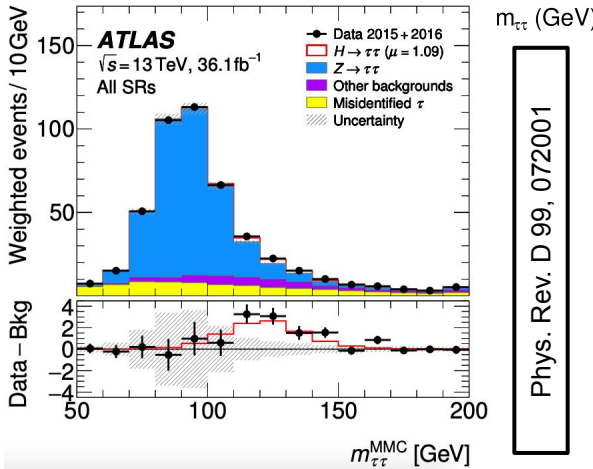
See previous talk by Luca →

| | |
|---|---|
| Phys. Lett. B 779 (2018) 283 | Observation using 7+8+13TeV(2016) data |
| 1903.06973 (Submitted to Phys. Rev. D) | anomalous HVV coupling using 13TeV(2016) data |
| 1809.03590 (Submitted to JHEP) | VH, H→$\tau\tau$ using 13TeV(2016) data |
| CMS-PAS-HIG-18-032 | STXS measurement using 13TeV(2016-2017) data |

- Higgs boson decay to pair of $\tau$-leptons is most promising channel to explore Yukawa-couplings to fermions.
  - Smaller BR than H→bb̄ but better experimental accessibility.
- In CMS most sensitive ditau final states are considered (eμ, e$\tau$, μ$\tau$, $\tau\tau$) in ATLAS all final states (+ ee, μμ).
  - CMS categories: 0-jet, boosted, vbf
  - ATLAS categories: boosted, vbf
- Major backgrounds from Drell-Yan, W+jets, QCD and top production.
- Both collaborations able to observe H→$\tau\tau$ signal with more than 5σ by combining data collected at 7, 8 and 13 TeV.



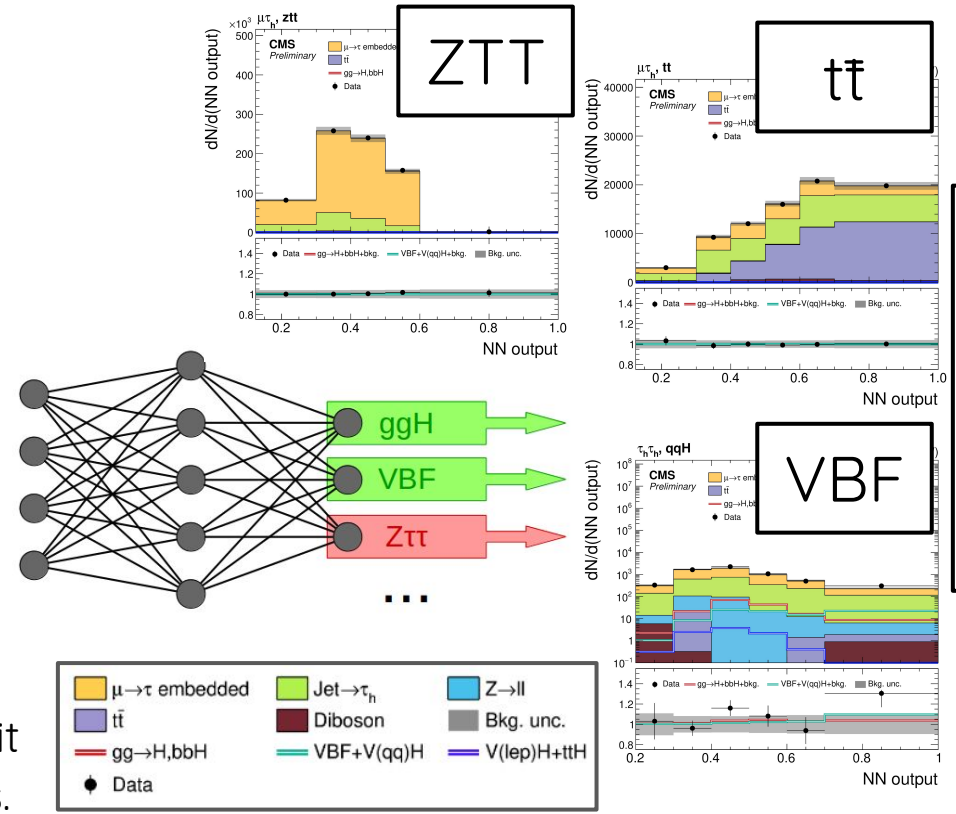

Phys. Lett. B 779 283




Phys. Rev. D 99, 072001

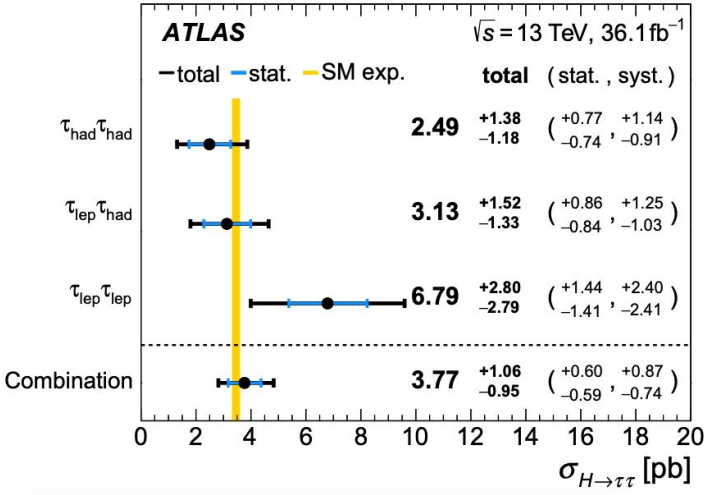
# H → $\tau\tau$ strategy with ML approach

- Result from CMS in context of simplified template cross sections (STXS)
- 90% of backgrounds are estimated with fully data-driven methods.
  - Tau embedding (Z → $\boldsymbol{\tau\tau}$)
  - Fake factor method (jet → $\boldsymbol{\tau}_h$)
- Output nodes of Multiclass NN used to define several signal and background categories.
- Cut-based approach used to further split signal categories according to STXS bins.
  - ATLAS STXS result uses fully cut based approach.



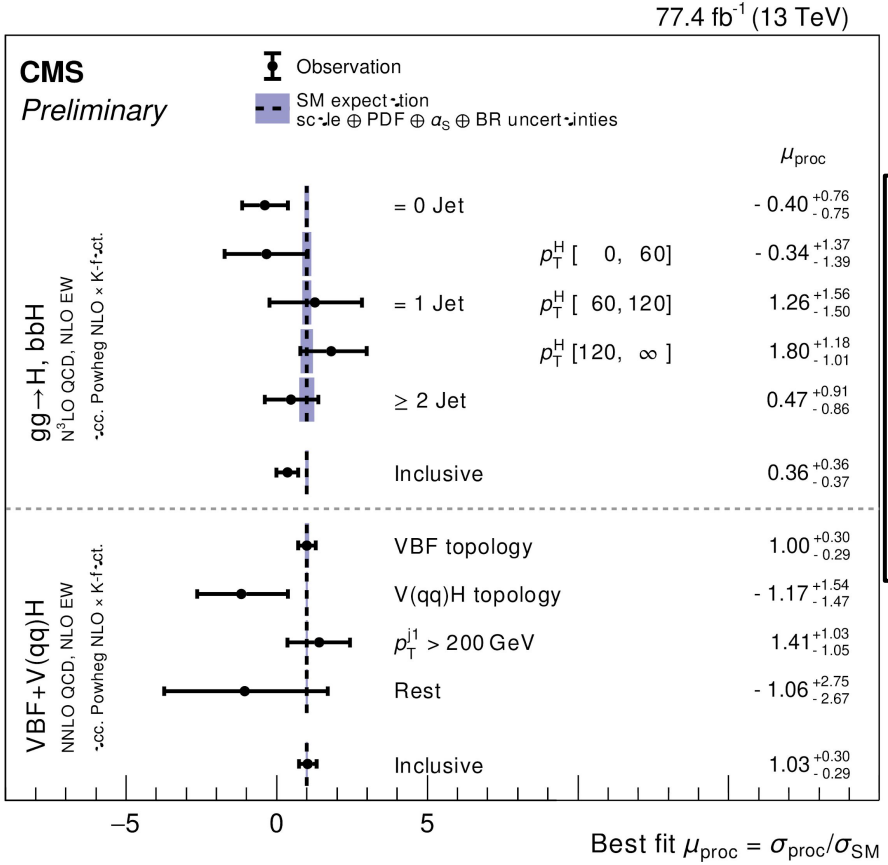
# H → ττ results on STXS

Phys. Rev. D 99, 072001




ATLAS $\sqrt{s} = 13\ TeV,\ 36.1 fb^{-1}$

| Process | Particle-level selection | signal strength μ |
|---|---|---|
| ggF | $N_{jets} \geq 1,\ 60 < p_T^H < 120\ GeV,\ \lvert y_H \rvert < 2.5$ | $4.48 \pm 2.28$ |
| ggF | $N_{jets} \geq 1,\ p_T^H > 120\ GeV,\ \lvert y_H \rvert < 2.5$ | $0.86 \pm 0.55$ |
| VBF | $\lvert y_H \rvert < 2.5$ | $1.14 \pm 0.52$ |




CMS-PAS-HIG-18-032

# Summary

- Presented most recent results on fermionic Higgs decays from ATLAS and CMS.
- Established couplings to **3rd generation** fermions.
- **H → μμ** in reach with full Run II and Run III data.
- First search for **H → cc̄** at the LHC.
- So far no deviation from the SM prediction observed.