Higgs couplings to fermions at the ATLAS and CMS experiments

LHCP 2018, Bologna
June 4th 2018

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on behalf of the ATLAS and CMS collaborations

Higgs couplings to fermions

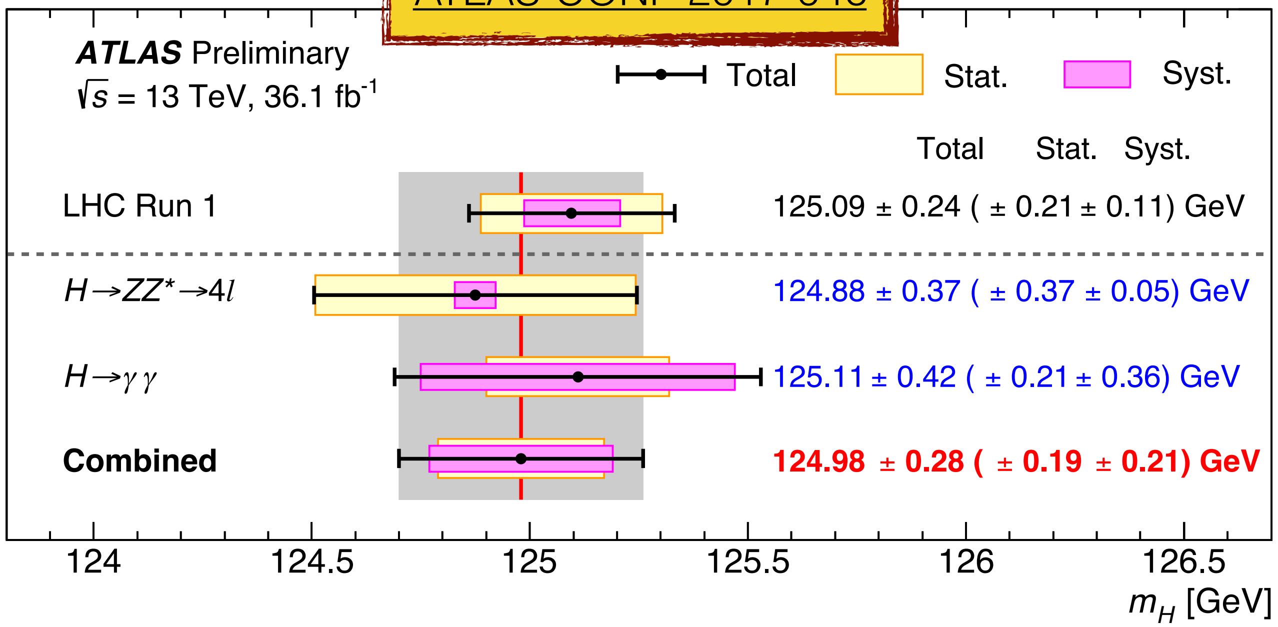
- Higgs boson mass and spin-CP well constrained by measurements using decays into bosons $H\to\gamma\gamma$, $H\to ZZ\to 4\ell$ and $H\to WW^*$
- Yukawa coupling in the SM: Higgs coupling to fermions proportional to fermion mass

mass term   Higgs coupling

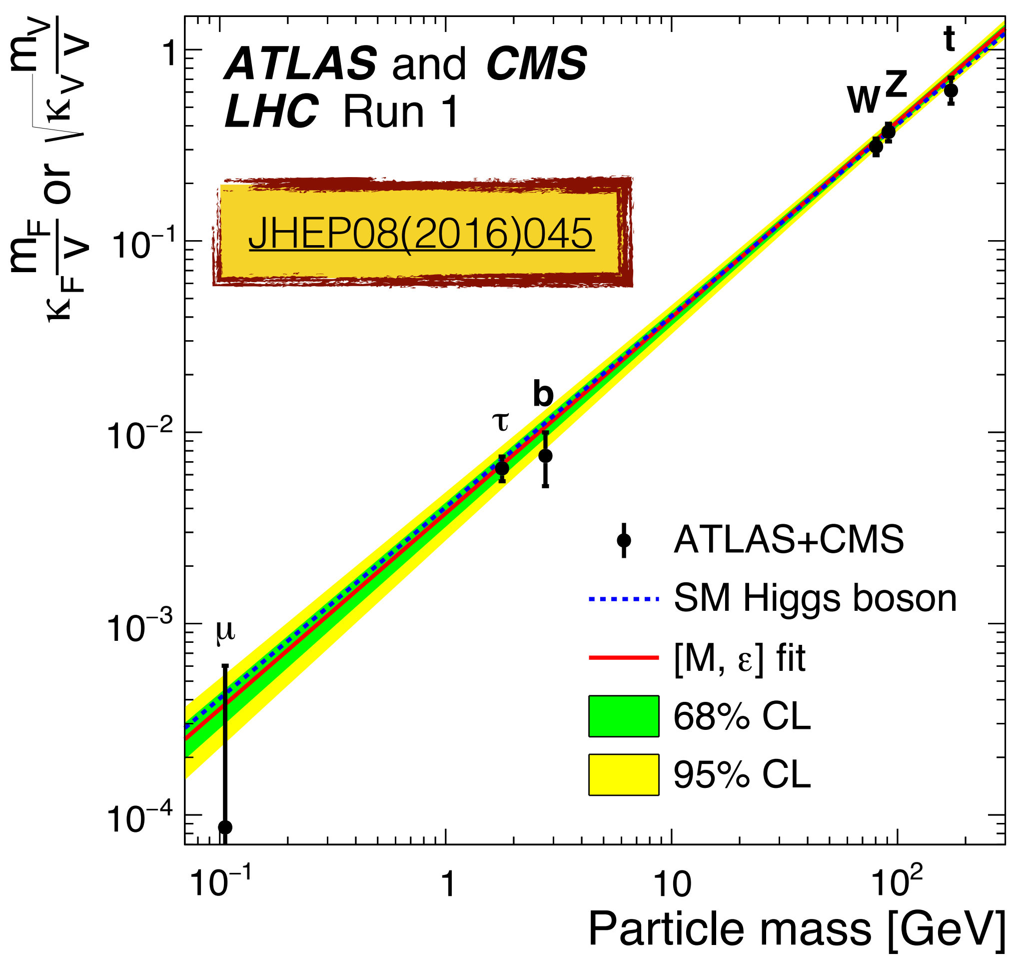
$$\mathscr{L}_{\text{Yukawa}} = -g_f\, v\, \overline{\psi}_f \psi_f - g_f\, h\, \overline{\psi}_f \psi_f$$

- Does the Yukawa interaction apply to all fermion generations?
- Is the $m_f \propto g_f$ relation correct?
- Is there CP violation in the Yukawa coupling?

ATLAS-CONF-2017-046



JHEP08(2016)045



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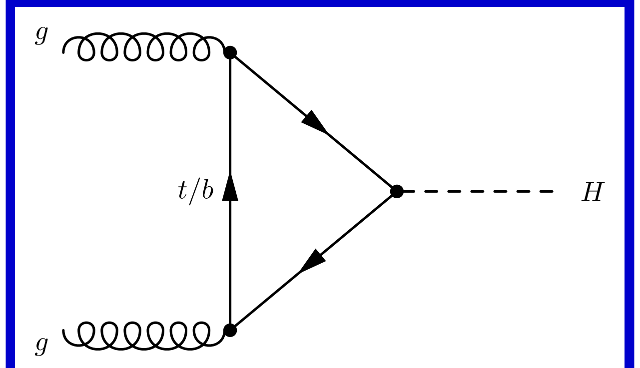
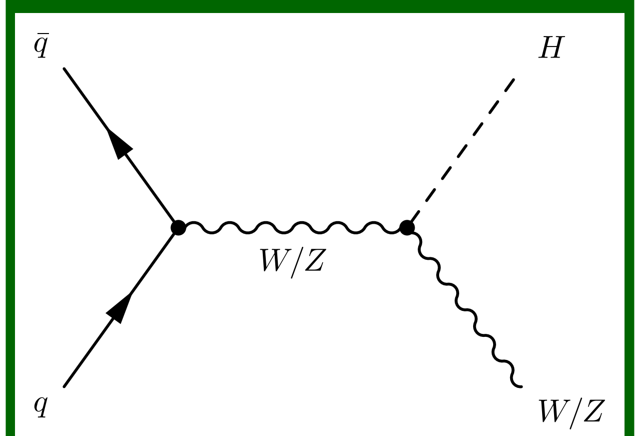
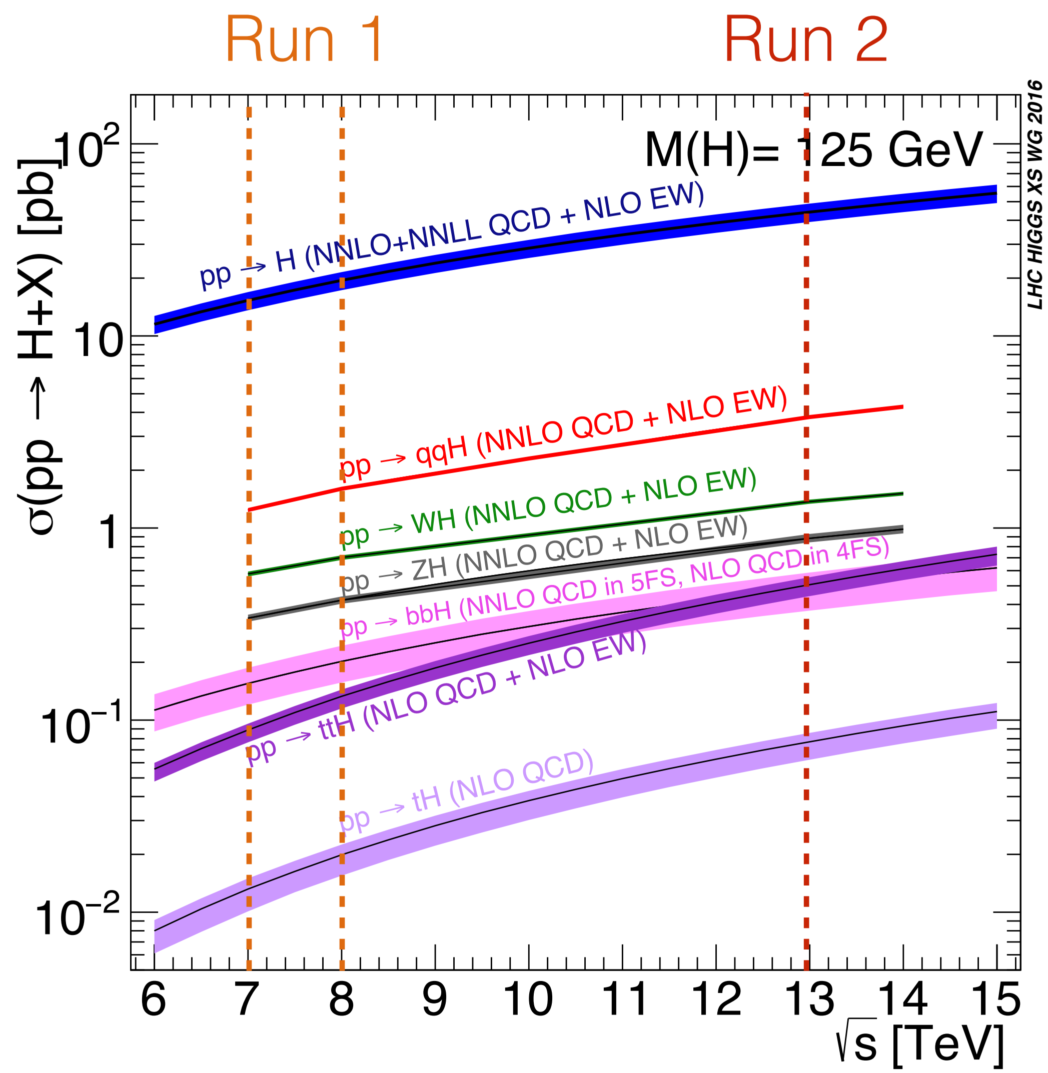
Higgs production at the LHC

gluon-gluon-fusion

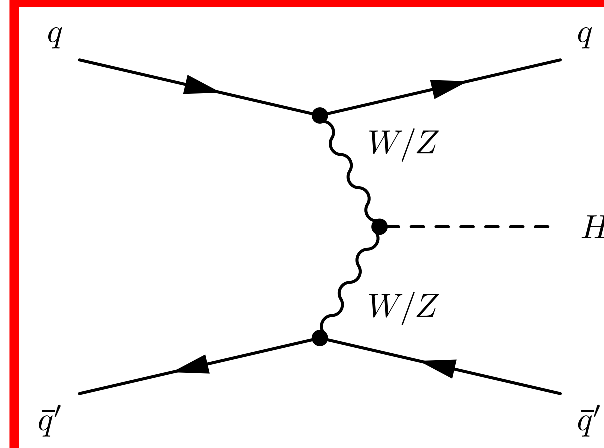


$W/Z + H$

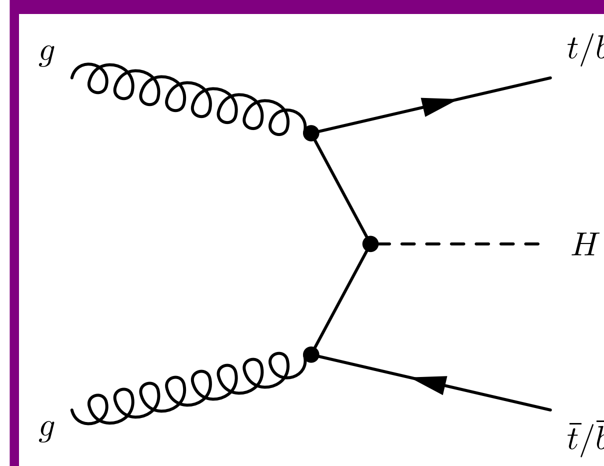




VBF



bbH / ttH



- ***gg*F** has the highest cross-section but suffers from large backgrounds
- ***ttH***, **VBF** and especially ***VH*** topologies can be used to **efficiently tag events**
- ***ttH*** and ***bbH*** production are **directly sensitive to *b*- and *t*-Yukawa** coupling

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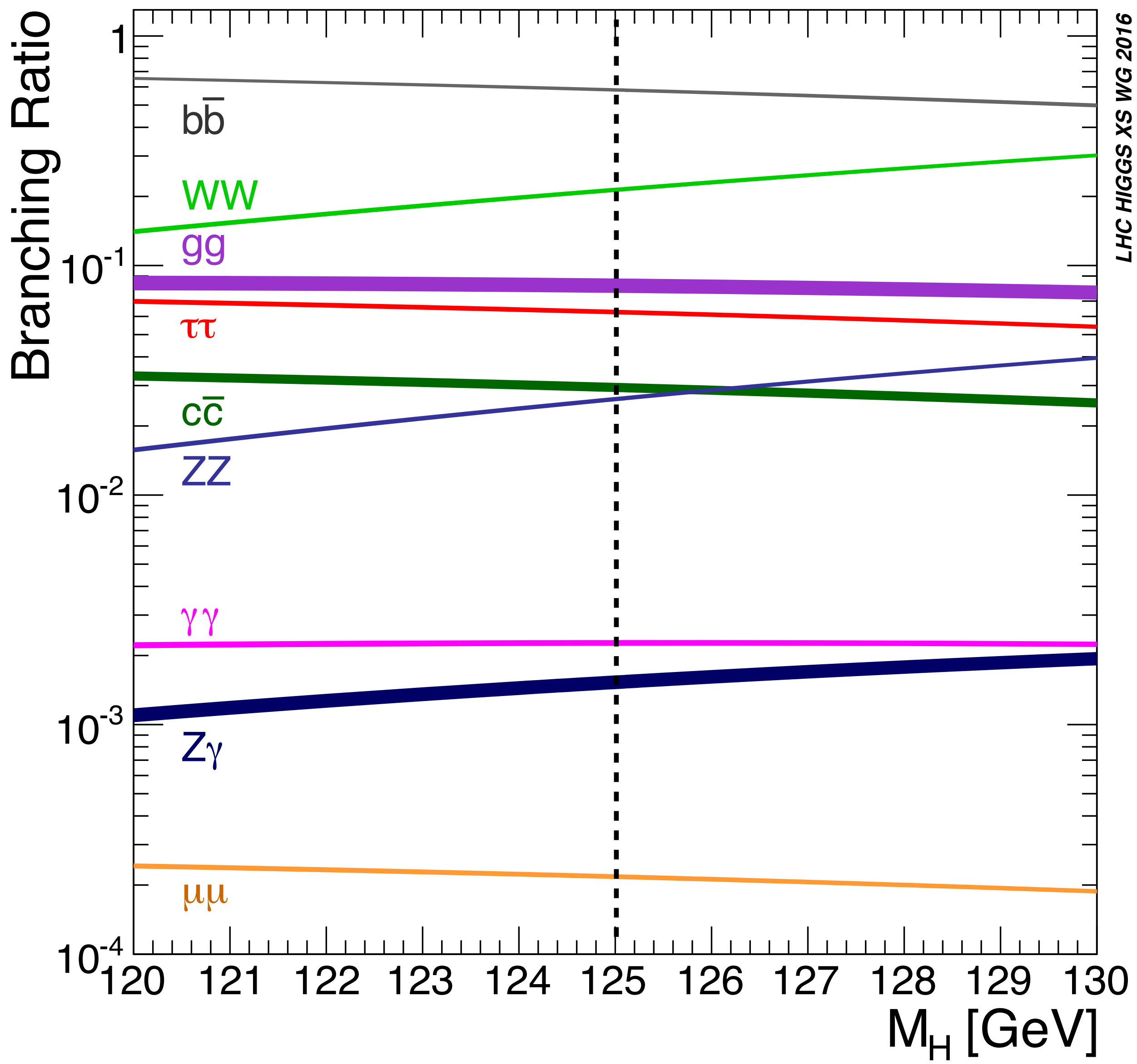
Higgs decays to fermions

- Higgs BRs only depend on m_H in the SM. For m_H = 125 GeV:
  - ***bb*** ≈ 58% - very large backgrounds from multijets, good *b*-tagging
  - ***ττ*** ≈ 6.3% - missing energy from neutrinos, $m_{\tau\tau}$ reconstruction, background from jets faking taus
  - ***cc*** ≈ 2.9% - very large backgrounds from multijets, good *c*-tagging
  - ***μμ*** ≈ 0.022% - rare process, large background from Drell-Yan



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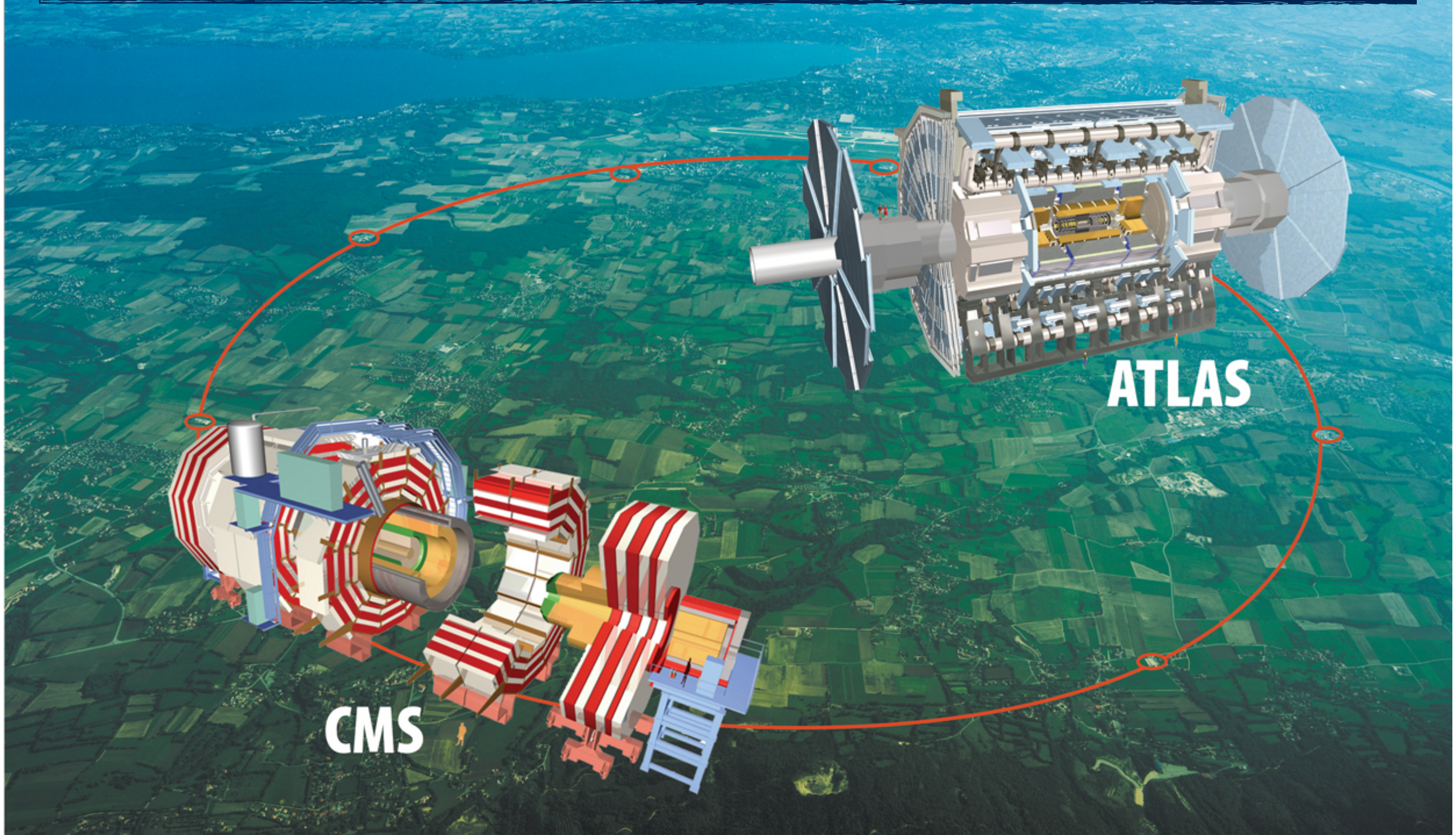
New Results!

Showing ATLAS and CMS results using LHC Run 2 data from 2015 and 2016: ~35fb^{-1} @ $\sqrt{s}$ = 13 TeV



… and some combinations with LHC Run 1 results : ~5fb^{-1} @ $\sqrt{s}$ = 7TeV + ~20fb^{-1} @ $\sqrt{s}$ = 8TeV

Yukawa couplings we have seen:

bottom, top and tau

Bottom-Yukawa coupling

How?

- Look for Higgs decays into two *b*-quarks
- Huge background from jet events ⟹ use production modes with additional objects to tag: **VBF, *VH* and *ttH***
- Complex final states ⟹ **multivariate analysis techniques** to assign jets to objects and to distinguish signal and background

Greatest challenges

- Good **flavour tagging** performance to identify *b*-jets
- Large backgrounds from ***tt*** and ***W/Z* + heavy flavour jets**

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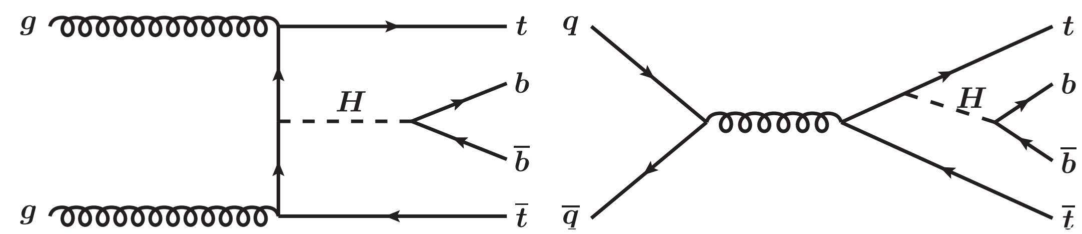
Search for *ttH*, *H*→*bb*

Phys. Rev. D 97 (2018) 072016

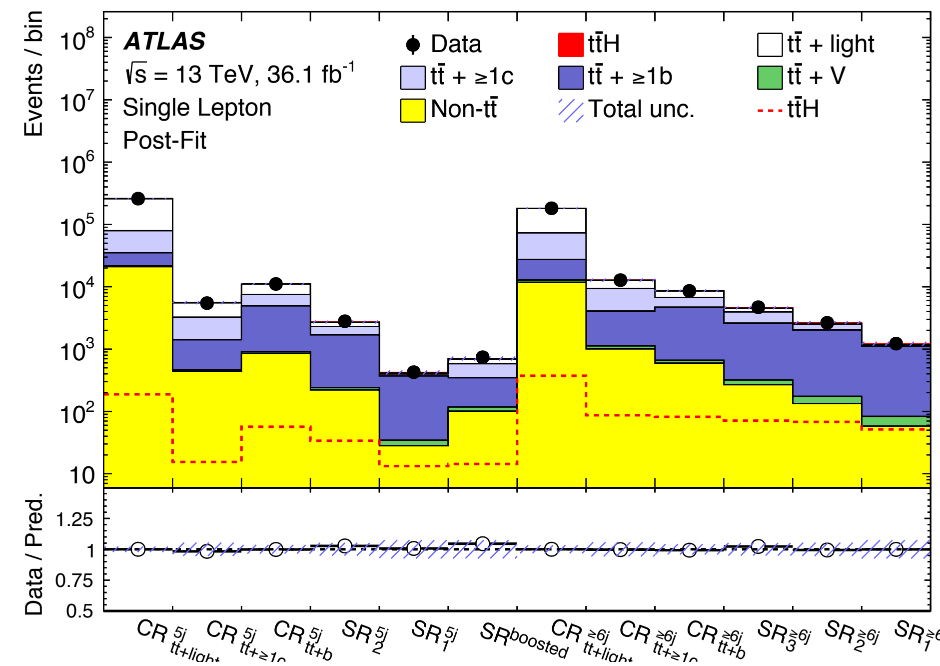
arXiv:1804.03682



- Target topologies with **1 or 2 leptons + 4 *b*-jets**
- Largest background from ***tt* + heavy flavour jets**
- Categorise events by N_ℓ, N_{jets} and *b*-tag score into multiple signal and control regions
- Use MVA for event reconstruction and classification
- Use matrix element method (MEM) as additional input to event classification

ATLAS

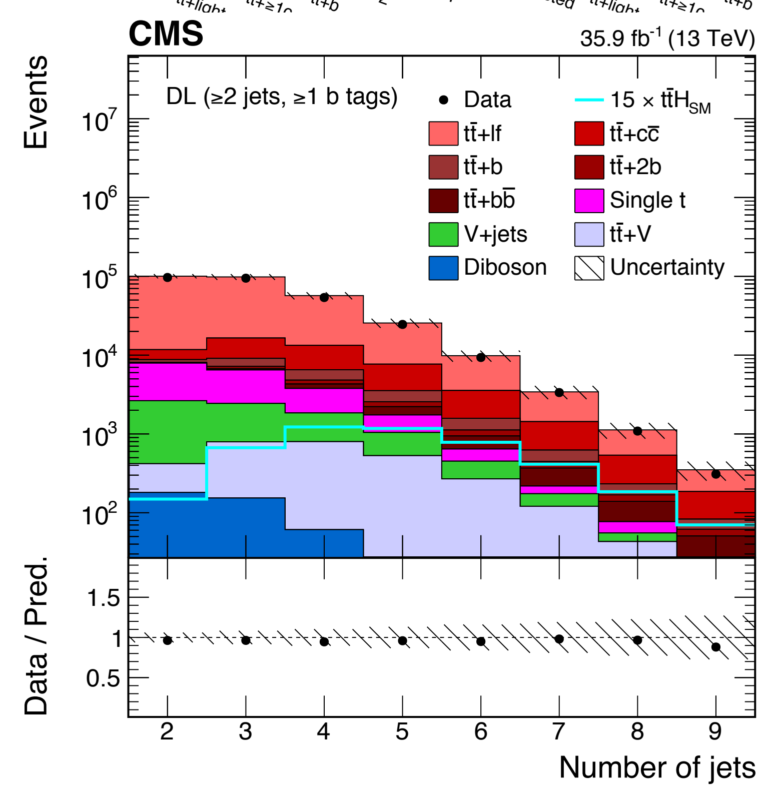
- use **BDT to associate jets to top quark and Higgs candidates** + dedicated **BDTs for each signal region** to classify signal and background events (using MEM)



- single-lepton: **deep neural network to identify most probable topology** and distinguish signal and background
- di-lepton: **use BDT + MEM** to distinguish signal and background

CMS

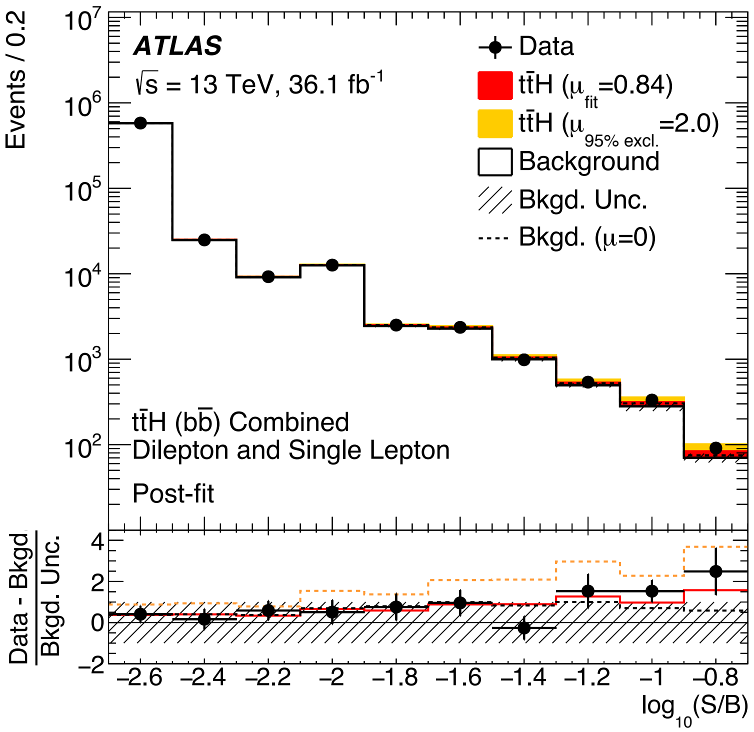
see also CMS *ttH*, *H*→*bb* + 0 leptons: arXiv:1803.06986

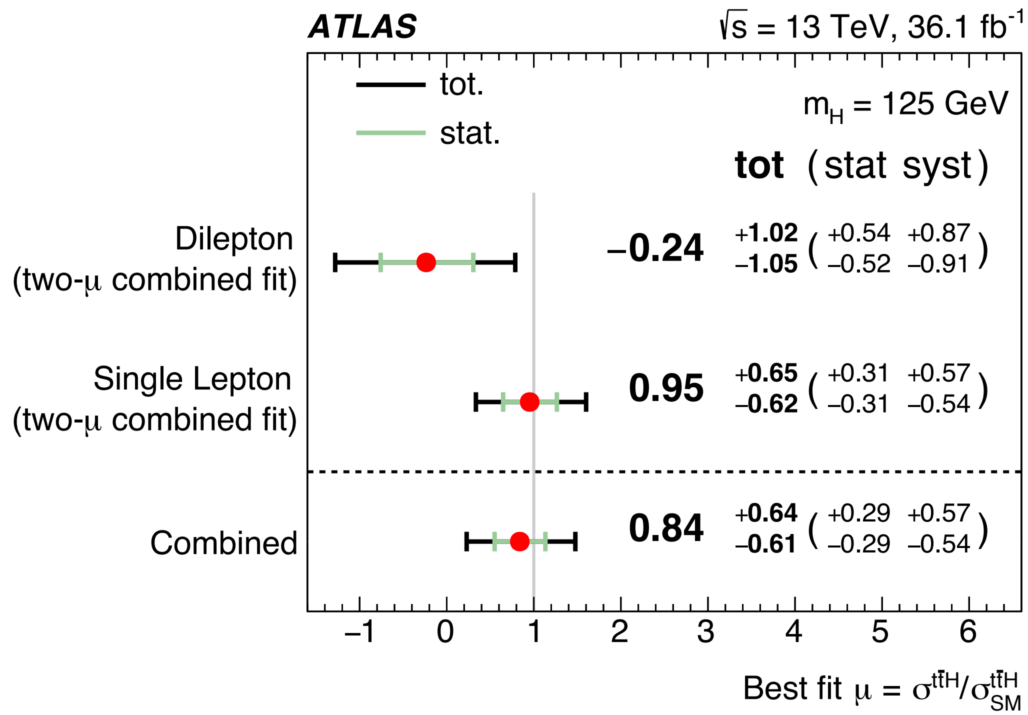


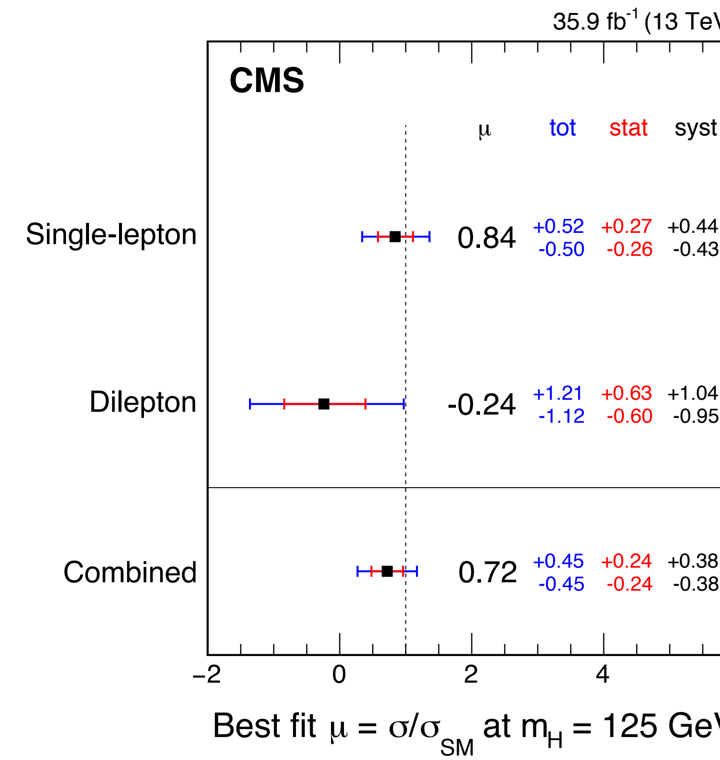
Search for *ttH, H→bb*

[Phys. Rev. D 97 (2018) 072016](#)

[arXiv:1804.03682](#)

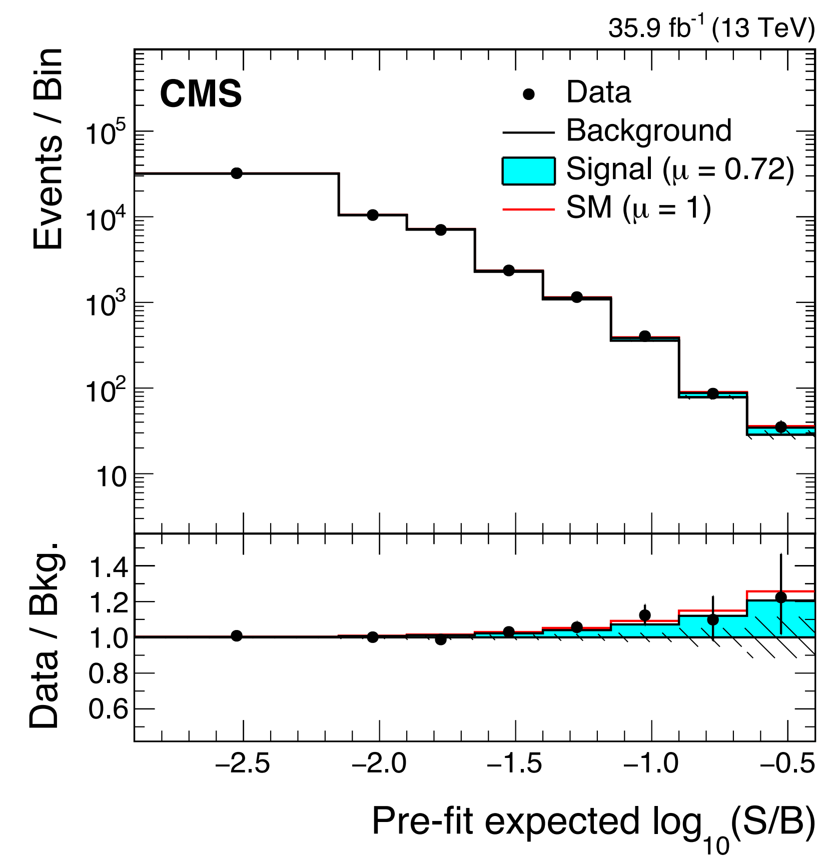






- Extract signal from combined likelihood fit to MVA distribution in all signal and control regions

- Largest uncertainties: *tt*+heavy flavour modelling, data and MC statistics, and flavour tagging



ATLAS

Obs. (exp.) excess of **1.4*σ* (1.6*σ*)** for $m_H = 125$ GeV

Obs. (exp.) 95% C.L. limit at **$\mu < 2.0$ (1.2)**

CMS

Obs. (exp.) excess of **1.6*σ* (2.2*σ*)** for $m_H = 125$ GeV

Obs. (exp.) 95% C.L. limit at **$\mu < 1.5$ (0.9)**

Signal strength: $\mu = \sigma \times B / (\sigma_{SM} \times B_{SM})$

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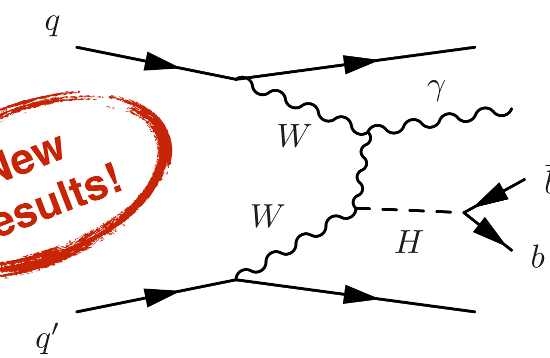
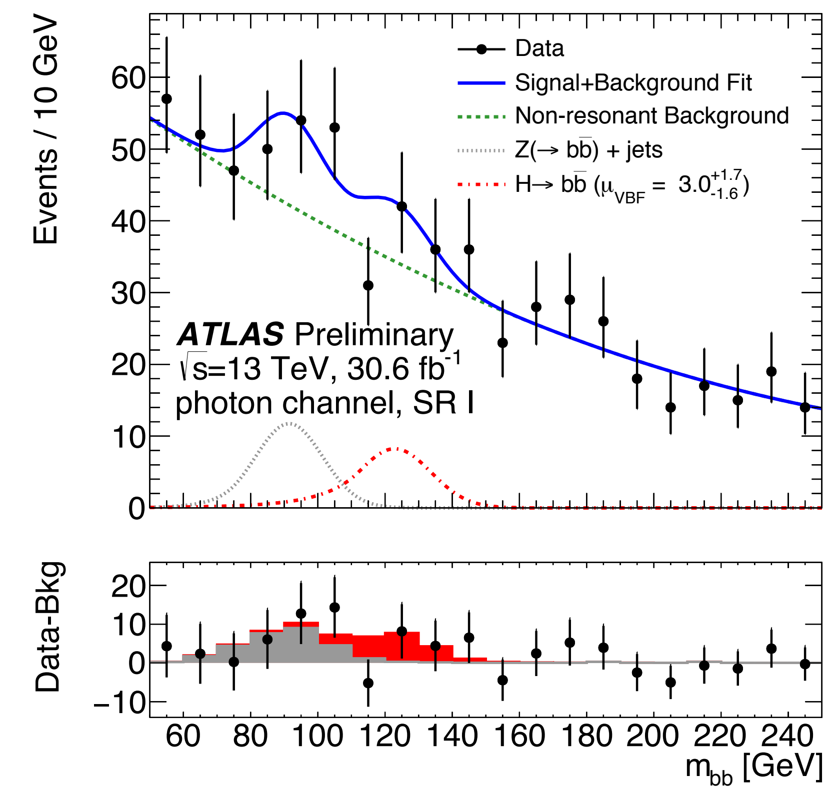
Search for VBF, $H \to bb$

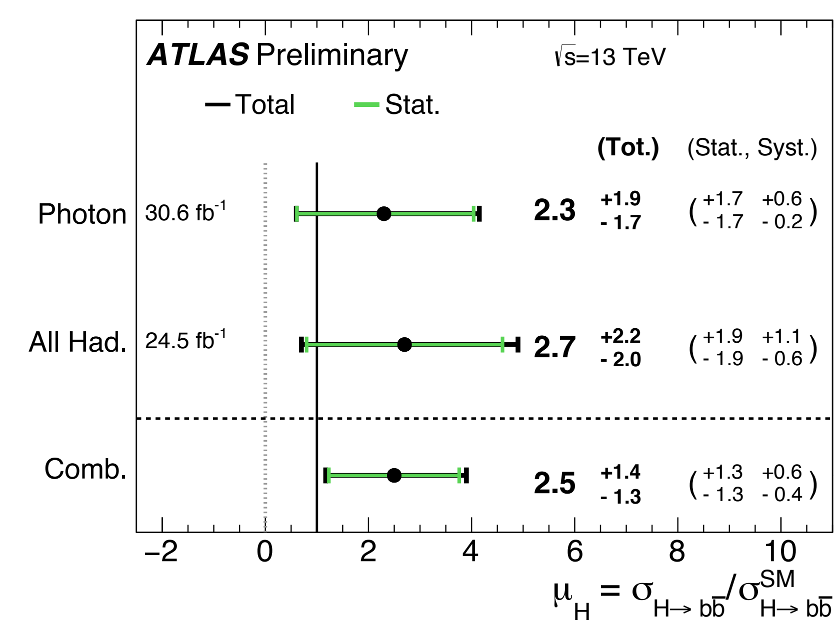
ATLAS-HIGG-2016-30

New Results!



- Require **2 VBF jets + 2 *b*-tagged jets (+ additional photon)**
- Use **dedicated VBF triggers** to record events (separate trigger for central and forward jets)
- Largest background from **non-resonant jet** production and ***Z*→*bb* + jets**
- Use BDT to classify events in each signal region based on jet kinematics (without m_{bb})
- Largest uncertainties: jet energy scale and resolution, signal modelling and flavour tagging
- Fit **analytical background function** to data in sidebands
- Obs. (exp.) significance of **1.9σ (0.9σ)**
- Obs. (exp.) limit of **μ_{Hbb} < 4.8 (2.5)** and for VBF production only **μ_{VBF} < 5.9 (3.0)** at 95% C.L.



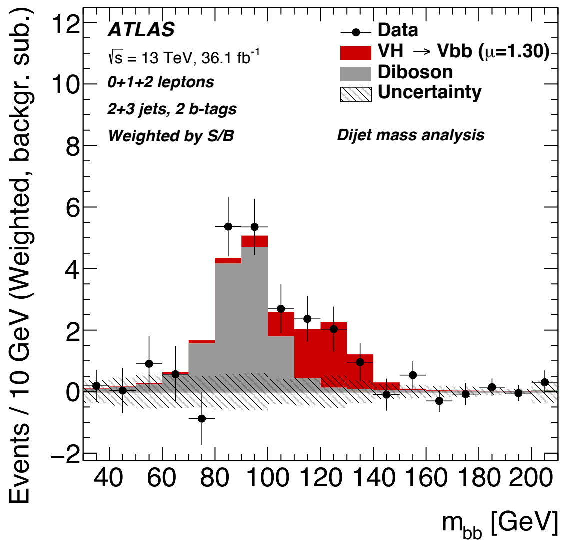


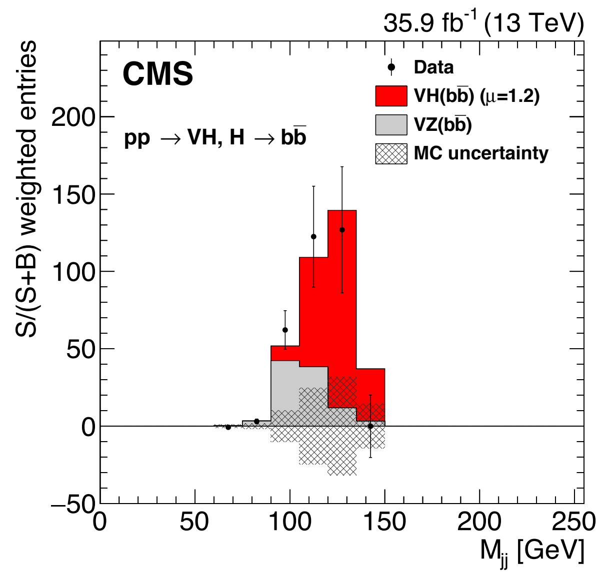
see also CMS-PAS-HIG-16-003

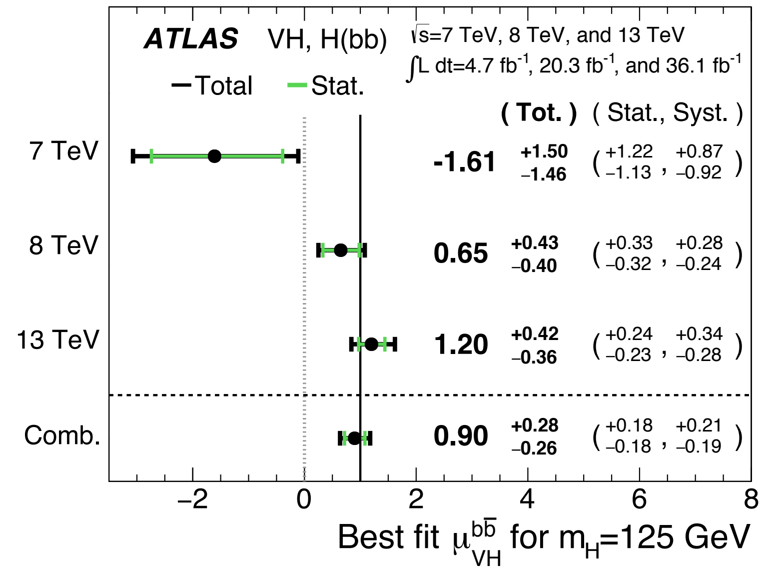
Evidence for VH, $H\rightarrow bb$

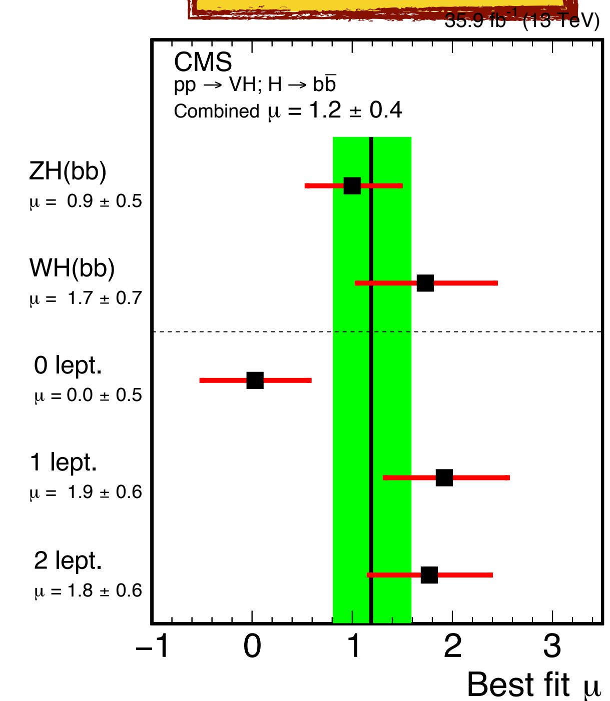
[JHEP 12 (2017) 024]

[arxiv:1709.07497]









- Require **2 *b*-tagged jets** + 0 ($Z\rightarrow\nu\nu$), 1 ($W\rightarrow\ell\nu$) or 2 ($Z\rightarrow\ell\ell$) **leptons**
- Largest background from ***Z*+heavy flavour** (0- and 2-lepton) and ***tt*** (1-lepton) and irreducible background from ***VZ*** with $Z\rightarrow bb$
- Requires good m_{bb} resolution
- Use BDT to classify events in all signal regions

ATLAS

- Obs. (exp.) sign. of **3.5σ (3.0σ)**
- Combination with Run 1: obs. (exp.) significance of **3.6σ (4.0σ)**

CMS

- Obs. (exp.) sign. of **3.3σ (2.8σ)**
- Combination with Run 1: obs. (exp.) significance of **3.8σ (3.8σ)**

Top-Yukawa coupling

How?

- For m_H = 125GeV no $H \to tt$ decays $\Longrightarrow$ **measure *ttH* production**
- Use all final states with large branching fraction or clean signatures: $H \to bb$, $H \to \gamma\gamma$ and leptonic decays ($H \to \tau\tau$, $H \to WW^*$ and $H \to ZZ^*$)

Greatest challenges

- Good **flavour tagging** performance to identify top decays
- Control backgrounds from ***tt* + *bb*, *tt* + *W/Z*** and **fake leptons**
- Many different topologies with **complex final states**

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ttH, H→multi-leptons

[Phys. Rev. D 97 (2018) 072003]

[arXiv:1803.05485]

- Target ***ttH* + all Higgs decays with leptons** in final state: $H\rightarrow\tau\tau$, $H\rightarrow WW^*$ and $H\rightarrow ZZ^*$
- Categorise events based on number of hadronic taus and light leptons
- Large backgrounds from ***ttV*, non-prompt leptons and jets faking taus** depending on region
- Dedicated BDTs to **reject non-prompt leptons**
- Largest uncertainties: signal modelling, jet energy scale and non-prompt lepton estimate

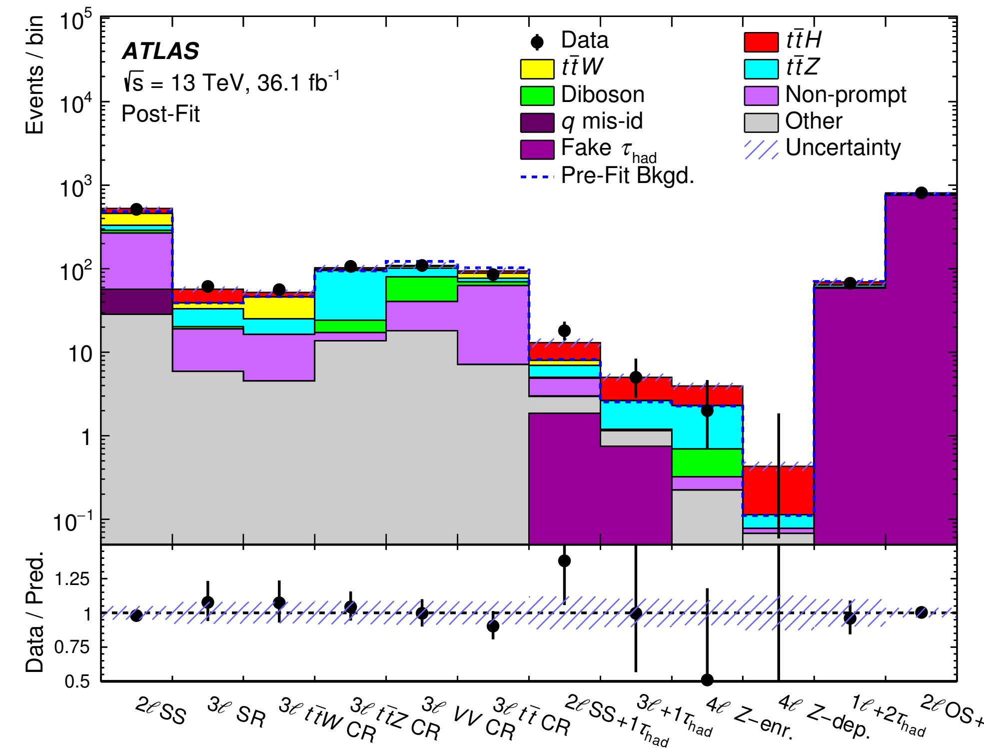
ATLAS

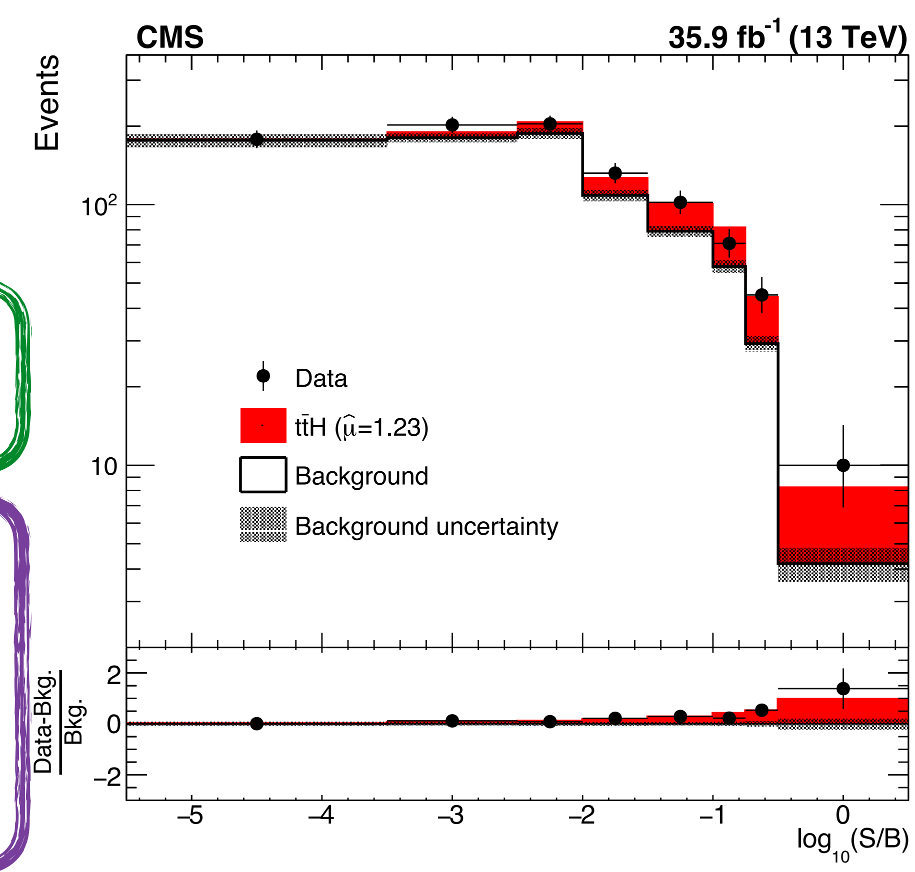
Obs. (exp.) excess of **4.1σ (2.8σ)** for m_H = 125 GeV

- Use BDT in each signal region to classify signal and background (jet and lepton kinematics)

CMS

Obs. (exp.) excess of **3.2σ (2.8σ)** for m_H = 125 GeV

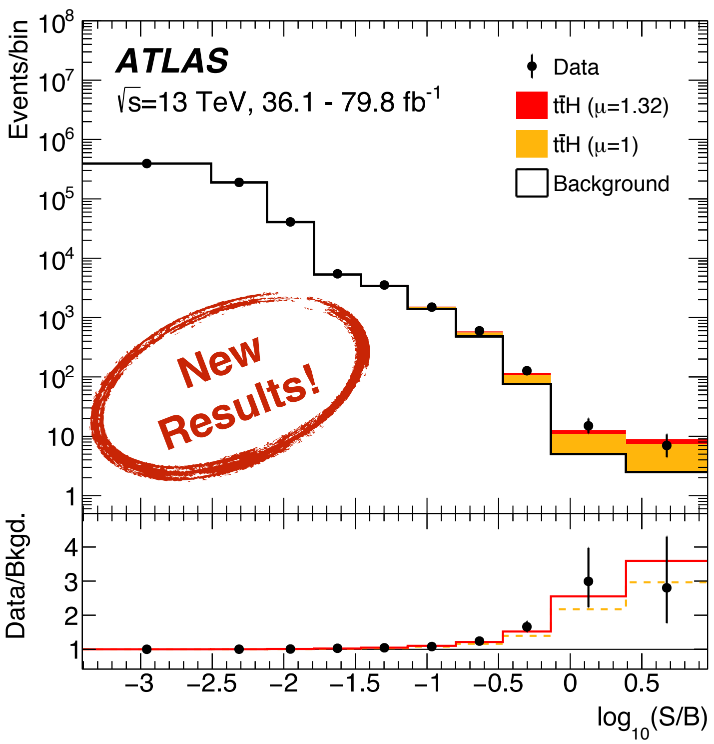


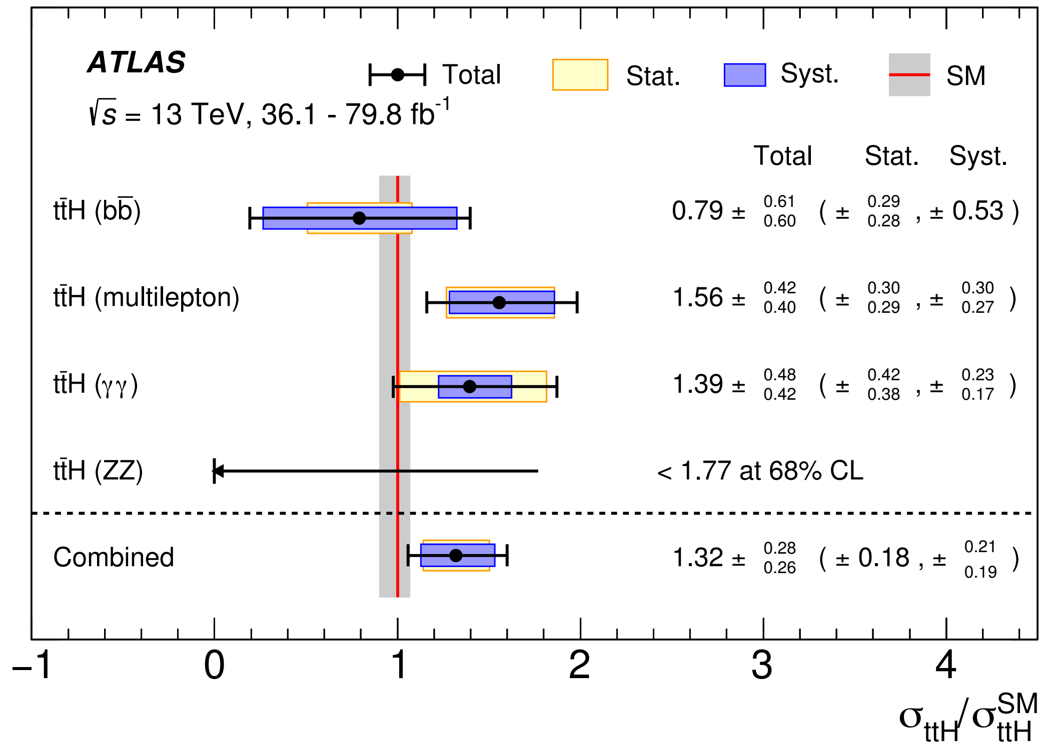


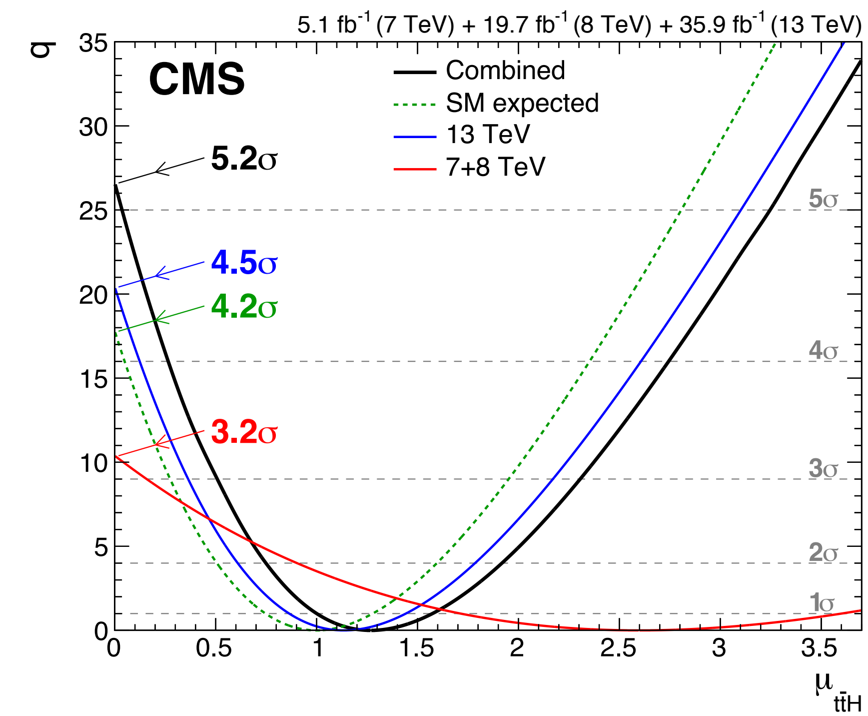
Observation of *ttH*

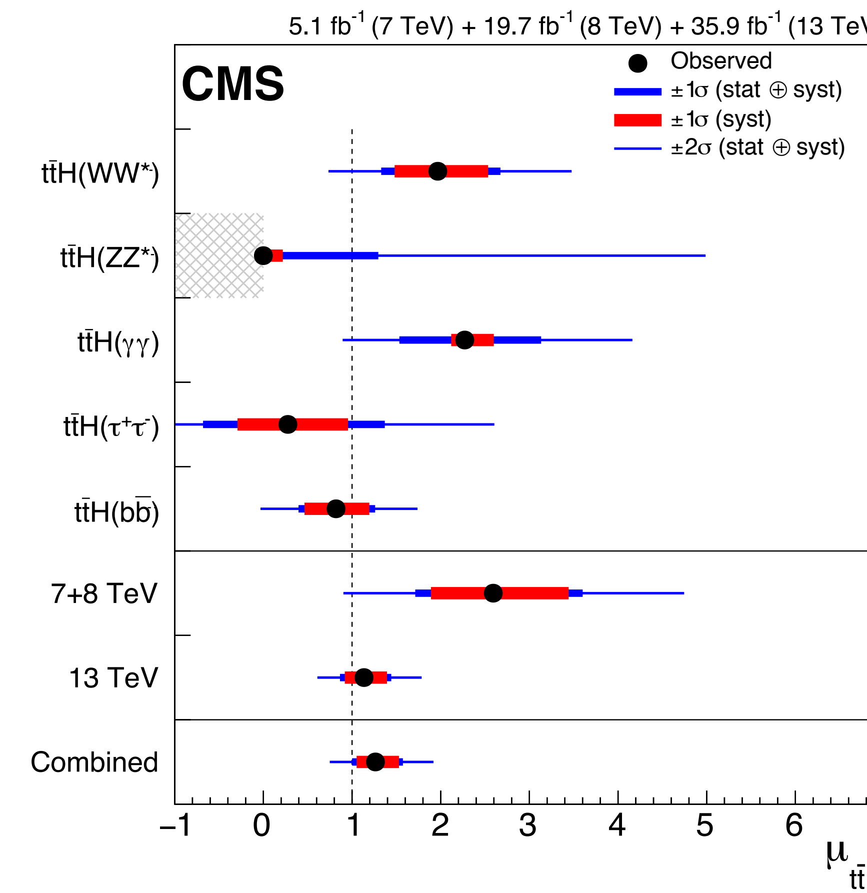
ATLAS-HIGG-2018-13

arXiv:1804.02610









- Combine measurements of all final states sensitive to *ttH: H→bb, H→ττ, H→WW*, H→ZZ* and H→γγ*

- Uses latest 80 fb^{-1} results for *H→γγ* and *H→ZZ*→4ℓ*

Obs. (exp.) excess of **5.8σ (4.9σ)** for m_H = 125 GeV

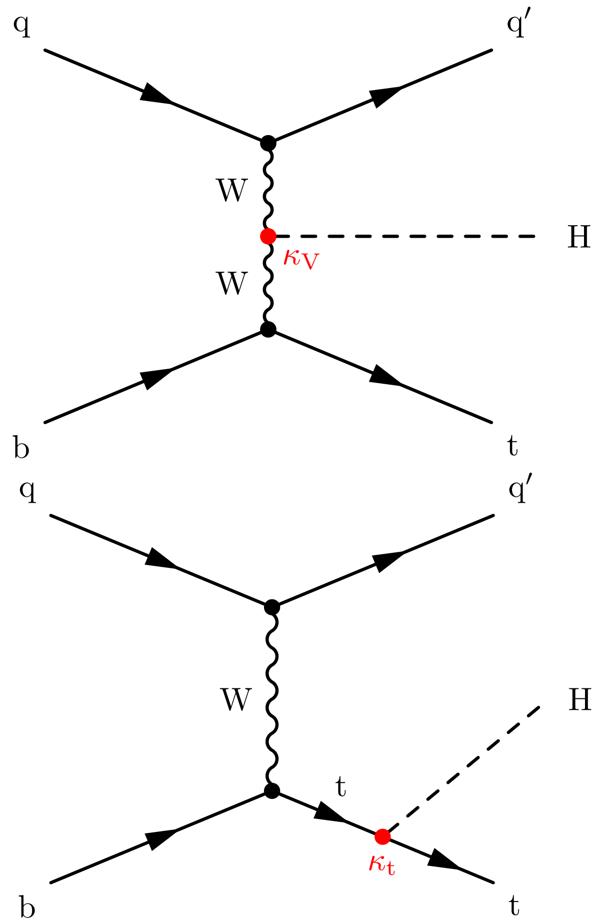
ATLAS Combined with Run 1: **6.3σ (5.1σ)**

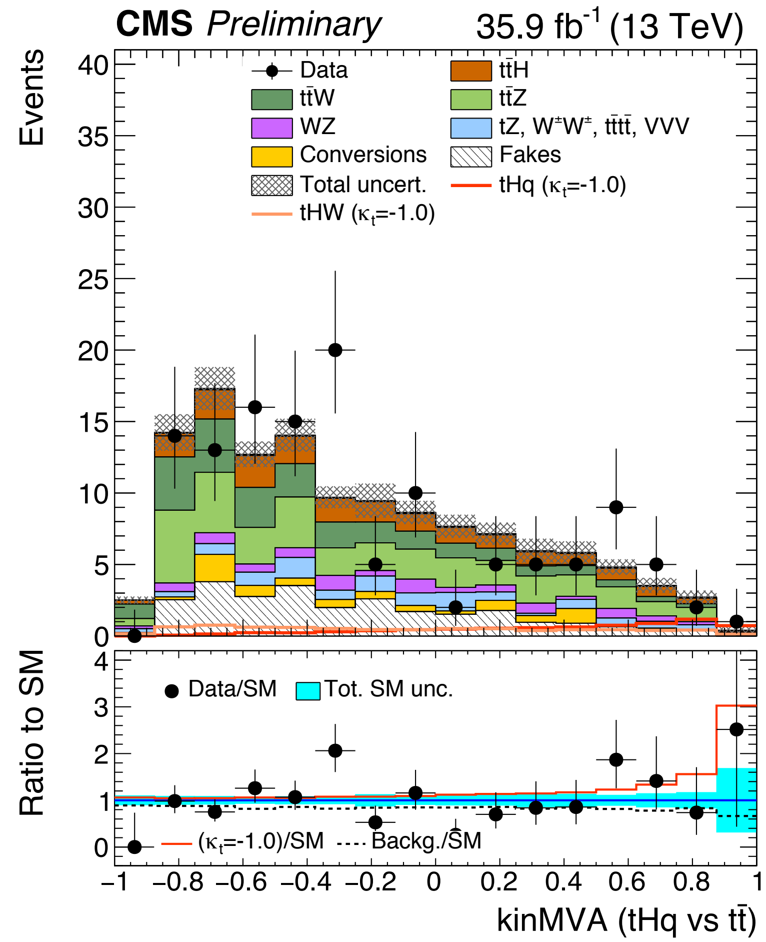
Obs. (exp.) significance of **5.2σ (4.2σ)** for a combination Run 1 and Run 2 data

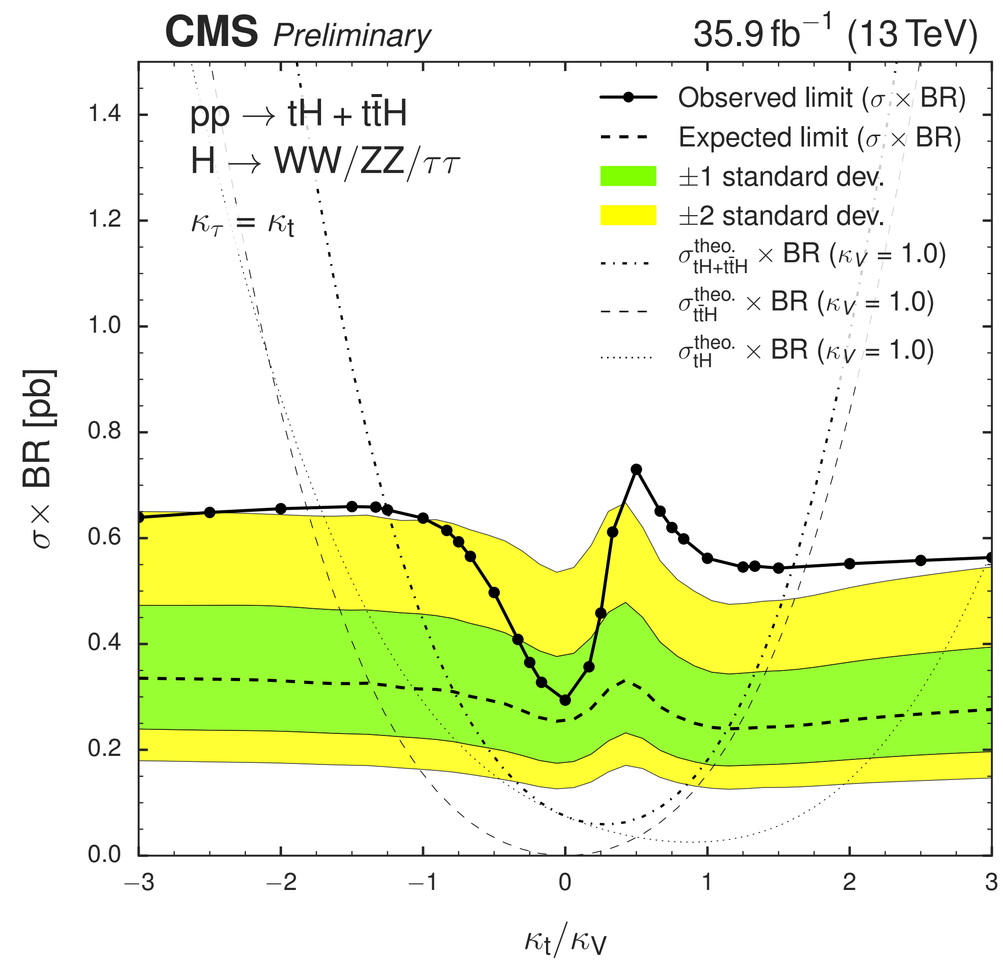
CMS

CMS-PAS-HIG-17-005

Search for *tHq*, *H*→multi-leptons







- Target ***tHq* with all Higgs decays into leptons** in final state: $H\to\tau\tau$, $H\to WW^*$ and $H\to ZZ^*$
- Sensitive to contributions from boson and fermion couplings, allows to resolve sign in κ_t: +1 destructive / -1 constructive interference
- Select events with **2 same-sign leptons or 3 leptons + *b*-tagged jet** and use **BDT to separate signal and background** for each signal region
- Large backgrounds from ***ttV*, non-prompt leptons and jets faking taus** and ***ttH***

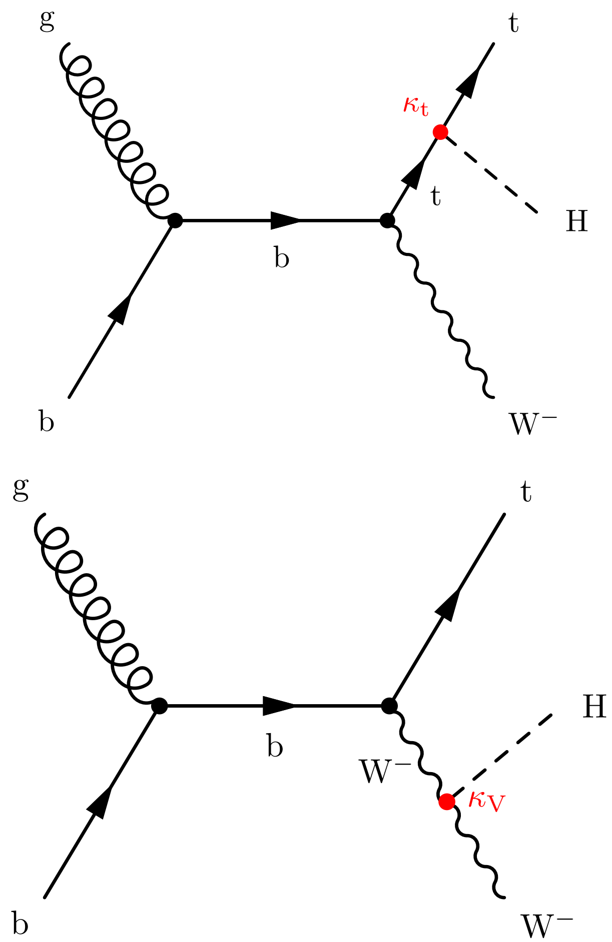
Obs. (exp.) limit of σ_{tH+ttH} **< 0.56 (0.24) pb** at 95% C.L.

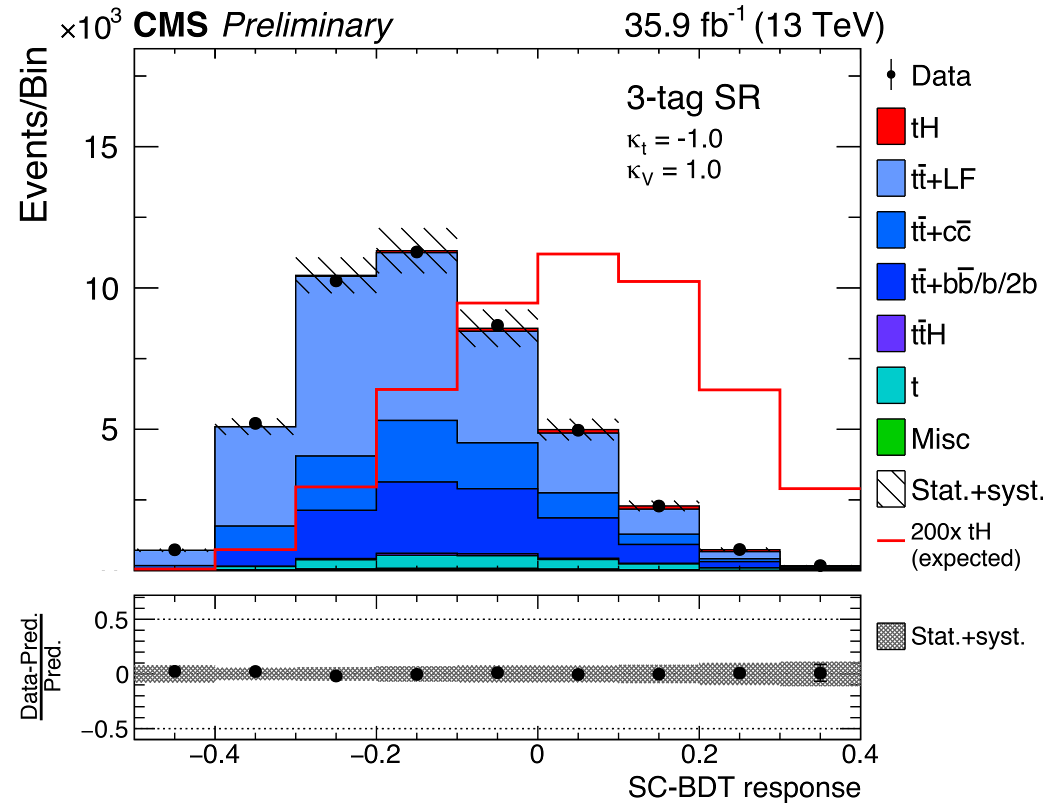
Limit of **$-1.25 < \kappa_t / \kappa_V < +1.6$** at 95% C.L.

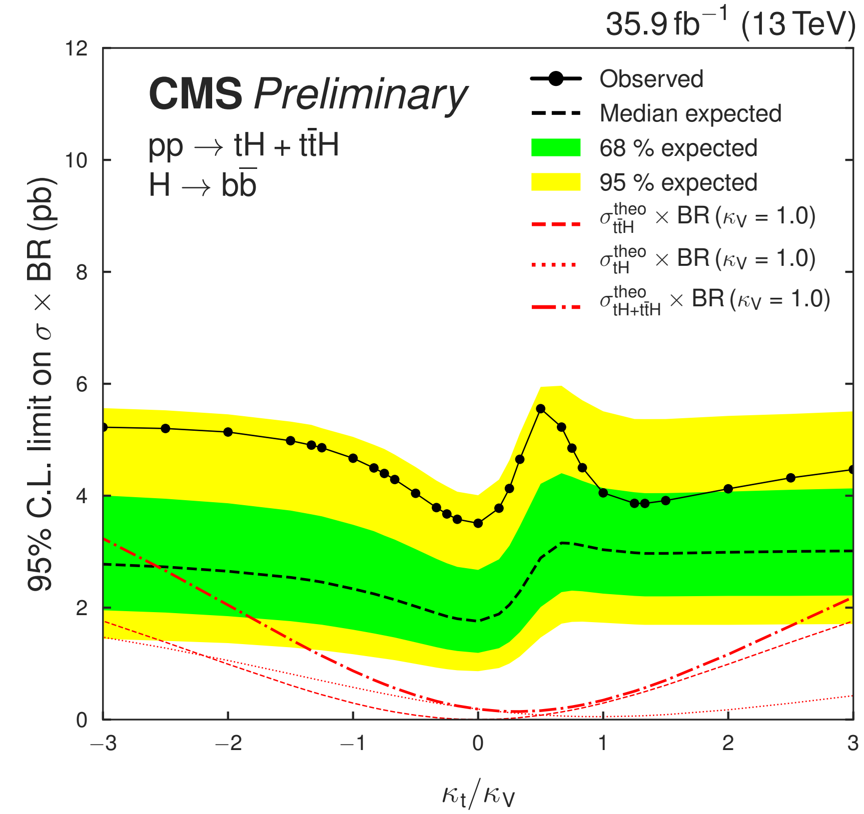
Search for *tH, H→bb*

New Results!

CMS PAS HIG-17-016







- Target ***tHq* and *tHW* with *H→bb***
- Select events with **3 *b*-tagged jets + lepton** (*tHq*), **3 *b*-tagged jets + 2 leptons** (*tHW*) and **4 *b*-tagged jets + lepton** to control *tt* background
- Large backgrounds from ***tt*+HF** and ***tt*+LF**

- Use one **BDT to assign jets to objects** in all categories, second **BDT to separate signal and background** for each signal region, third **BDT to separate *tt*+HF from *tt*+LF** in di-lepton category
- Obs. (exp.) limit of σ_{tH+ttH} **< 89 (41)*** σ_{SM} at 95% C.L.
- Obs. (exp.) limit of σ_{tH+ttH} **< 5.8 (2.9)*** σ_{SM} at 95% C.L. for inverted coupling scenario

Tau-Yukawa coupling

How?

- Search for **di-tau events with additional jets** (boosted *gg*F and VBF production) or additional leptons (*VH*)
- Make use of all tau decay modes $\Longrightarrow$ leptonic and hadronic tau decays

Greatest challenges

- Efficient trigger for hadronic taus and light leptons at low p_T
- Dominant backgrounds from $\boldsymbol{Z\rightarrow\tau\tau}$ and **jets faking taus**
$\Longrightarrow$ good **hadronic tau identification** to reject fakes
- Neutrinos in the final state require advanced techniques for best **di-tau mass reconstruction**

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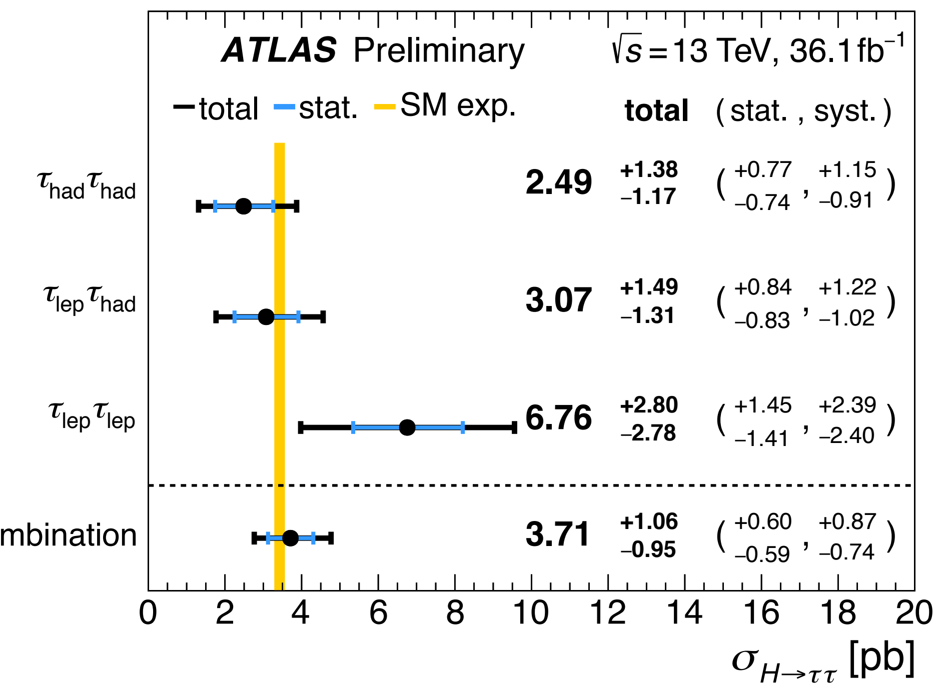
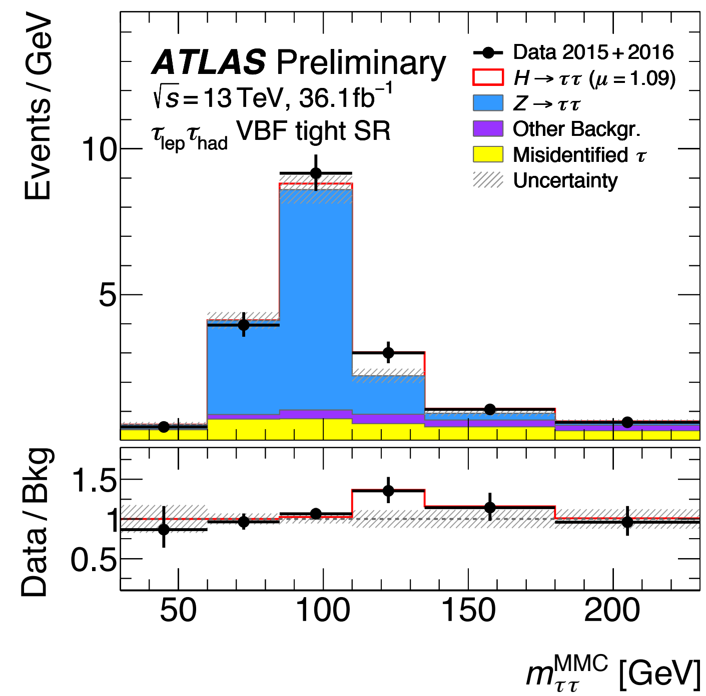
ATLAS EXPERIMENT

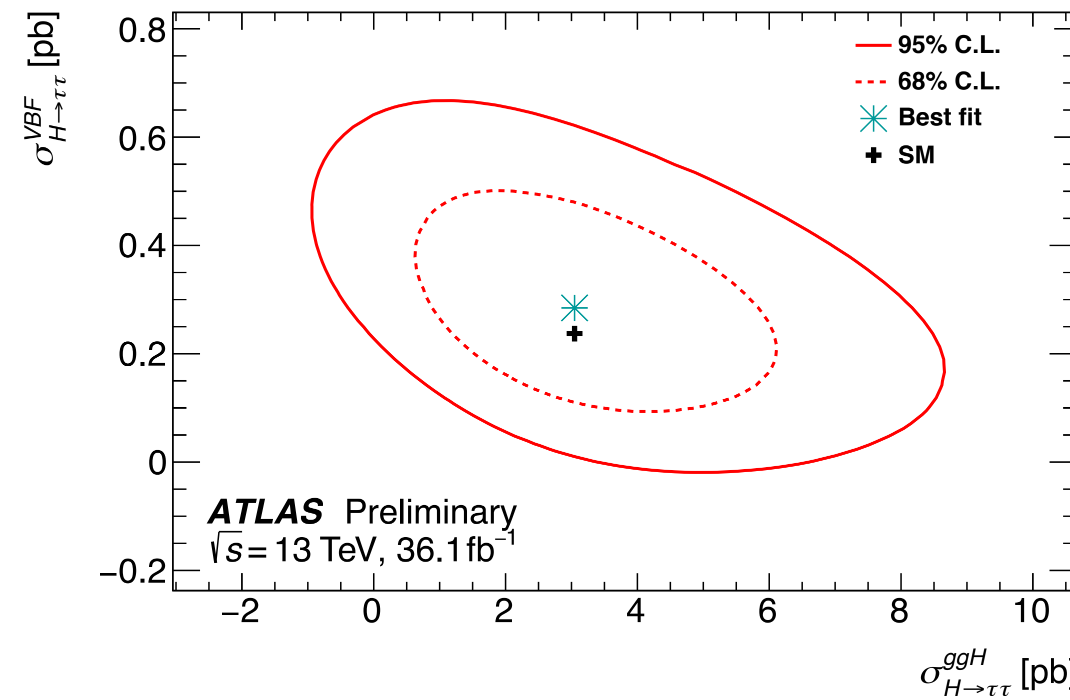
New Results!

Observation of $H\rightarrow\tau\tau$

ATLAS-CONF-2018-21







- Use **all combinations** of hadronic and leptonic τ **decays** in 2 categories: **VBF** and **boosted** (mostly *gg*F)
- Cut-based analysis using fit to $m_{\tau\tau}$ distribution in 13 signal regions
- Largest backgrounds from ***Z*+jets** and from **jets faking taus** (*W*+jets and multi-jet)
- Estimate of $Z\rightarrow\tau\tau$ using Sherpa NLO
- Largest uncertainties: data and MC statistics, signal modelling and jets

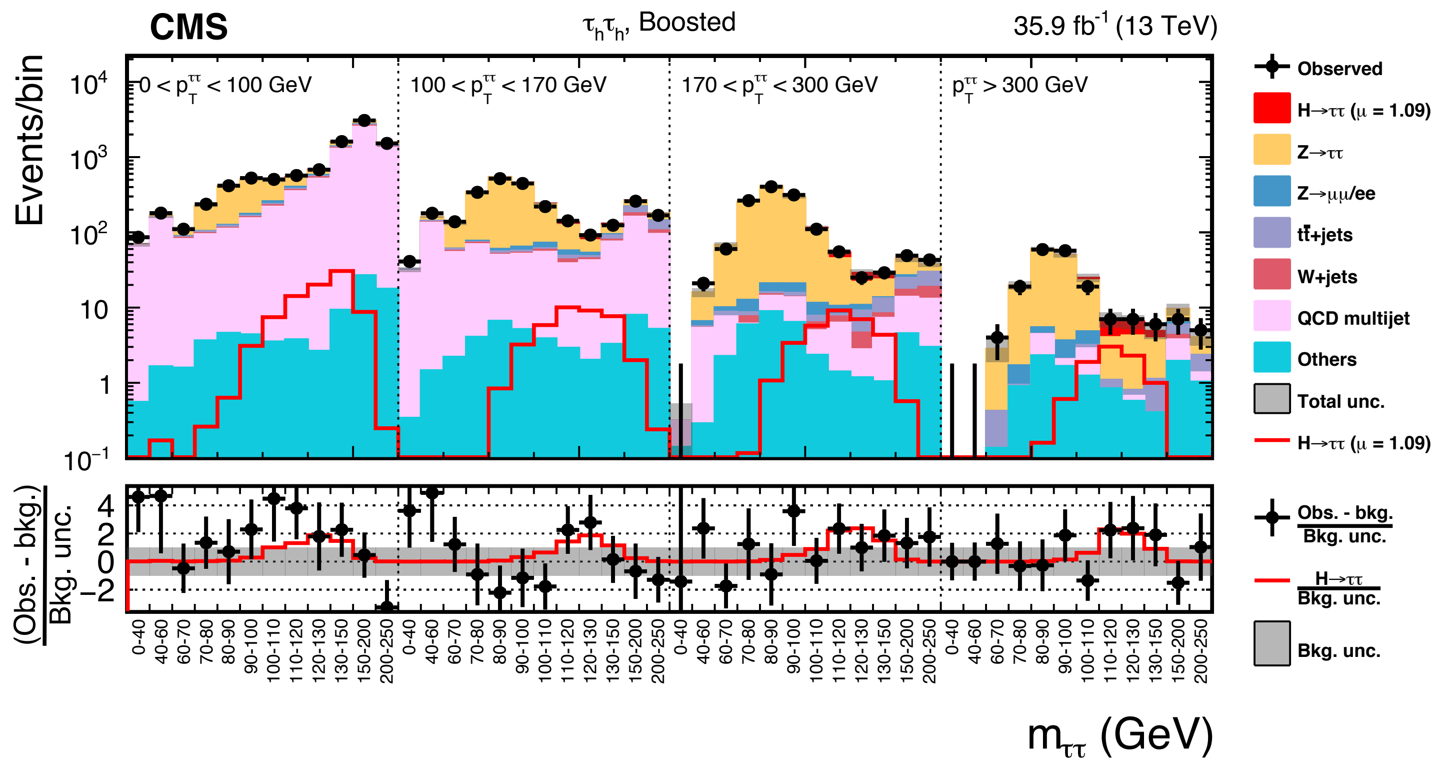
- Obs. (exp.) significance of **4.4σ (4.1σ)**
- Combination with Run 1: obs. (exp.) sign. of **6.4σ (5.4σ)**
- Combined measurement of cross sections for VBF and *gg*F production:

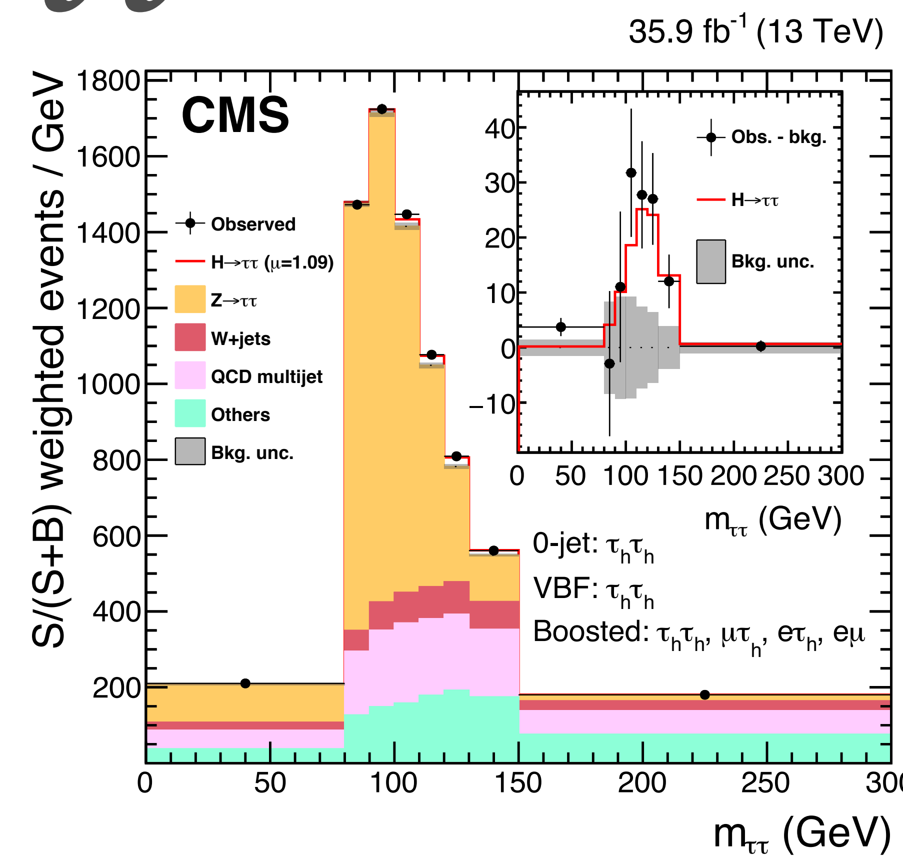
$$\sigma_{ggF} = 3.0 \pm 1.0\ (\text{stat.})\ {}^{+1.6}_{-1.2}\ (\text{syst.})\ \text{pb}$$

$$\sigma_{VBF} = 0.28 \pm 0.09\ (\text{stat.}) \pm 0.10\ (\text{syst.})\ \text{pb}$$

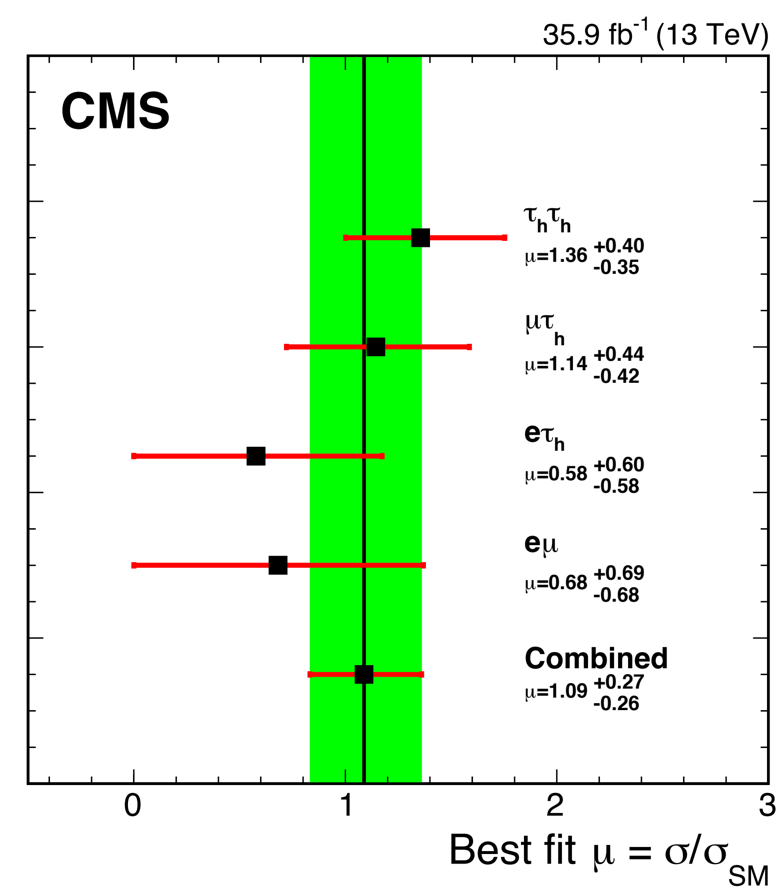
Observation of $H \to \tau\tau$

[Phys. Lett. B 779 (2018) 283]





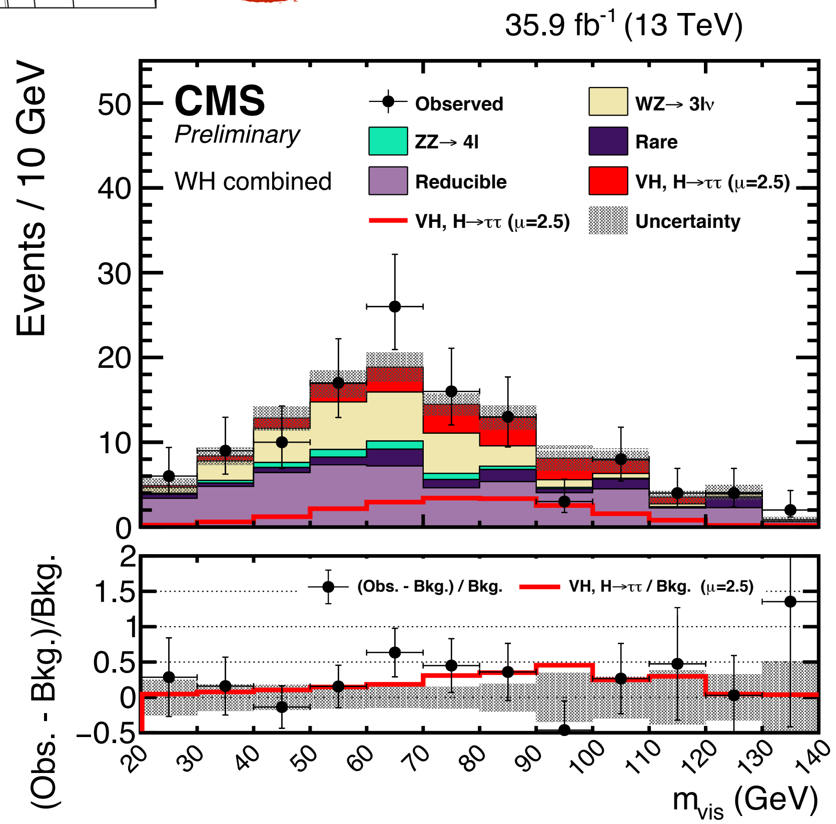
- **All combinations** of hadronic and leptonic ***τ* decays** (except same flavour leptons) in 3 categories: **0-jet**, **VBF** and **boosted** (mostly *gg*F)
- Use $m_{\tau\tau}$ + τ decay mode, m_{jj} or $p_T^{\tau\tau}$ in **2D likelihood fit**
- Obs. (exp.) significance of **4.9*σ* (4.7*σ*)**
- Combination with Run 1: ***μ* = 0.98 ± 0.18**, obs. significance of **5.7*σ***

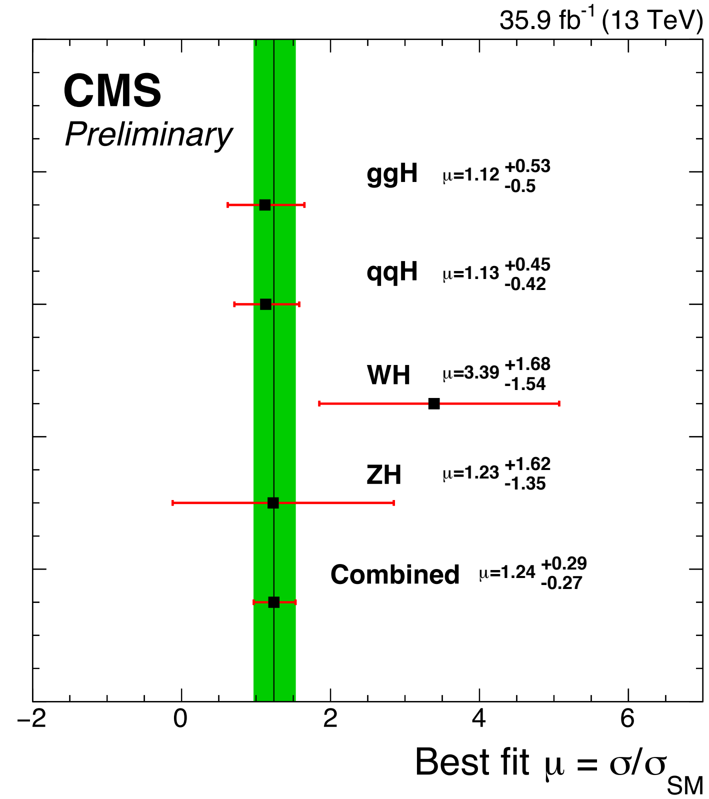


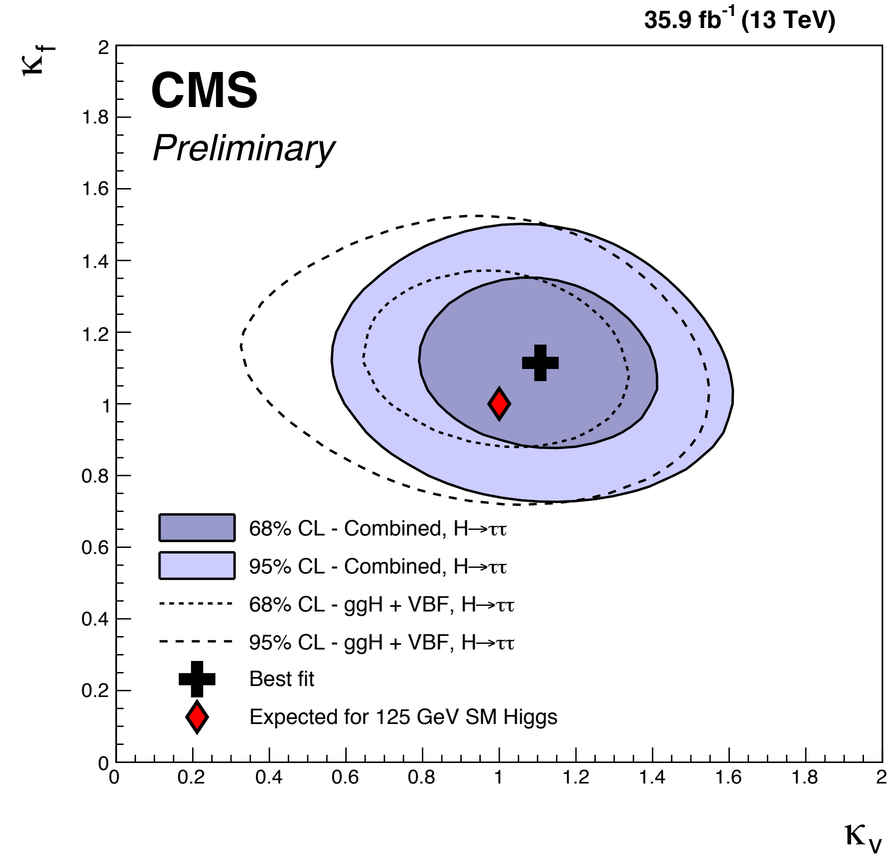
New Results!

Search for *VH*, $H\to\tau\tau$

CMS PAS HIG-18-007







- Target **leptonic W and Z decays +** $\boldsymbol{H\to\tau\tau}$
- Require **2 OS leptons** + any combination of **2 τ decays** (*ZH*) or **2 SS leptons + hadronic τ** (*WH*)
- Likelihood fit to reconstructed $m_{\tau\tau}$ in *ZH* and m_{vis} in *WH*
- Largest backgrounds from di-boson and fake taus

- Measurement of $\boldsymbol{\mu_{VH} = 2.5 \pm 1.3}$, with obs. (exp) significance of **2.3σ (1.0σ)**
- Combination with ggF and VBF: $\boldsymbol{\mu_{H\tau\tau} = 1.2 \pm 0.3}$, with obs. (exp) significance of **5.5σ (4.8σ)**
- **Improved 2D scan of κ_f vs. κ_V**

Yukawa couplings we are searching for:

muon, charm and exotica

Muon-Yukawa coupling

How?

- Clean final state with two isolated muons ⟹ search for ***gg*F and VBF**
- Search for bump over falling background shape
  ⟹ **fit background shape to data** in sidebands
- **Multivariate analysis to separate signal from background** in events with additional jets

Greatest challenges

- Large background from Drell-Yan
  ⟹ requires **excellent di-muon mass resolution**, categorise events by muon p_T resolution for optimal performance

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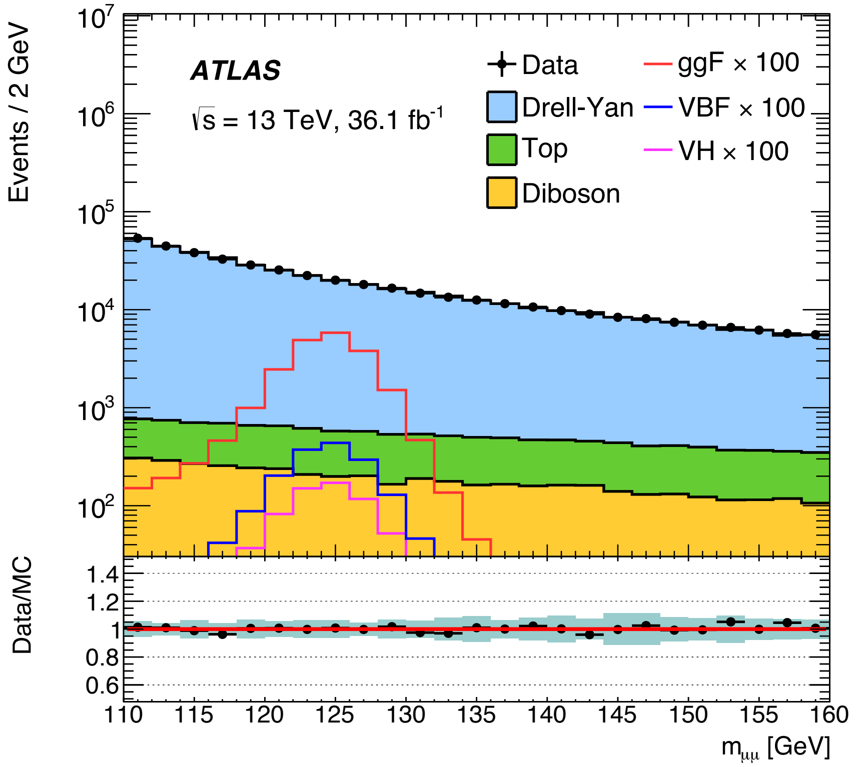
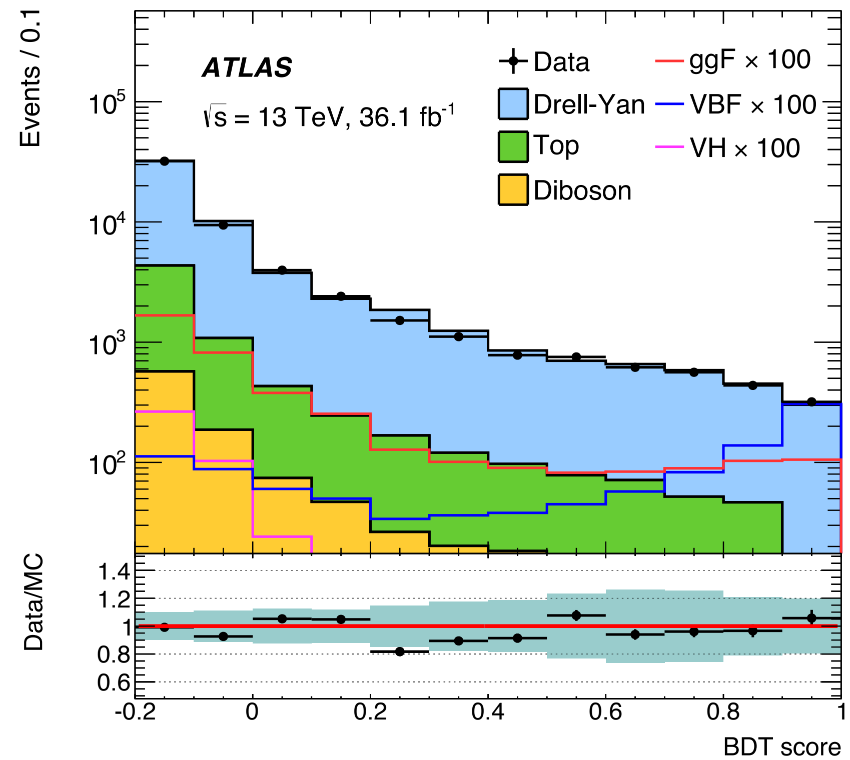
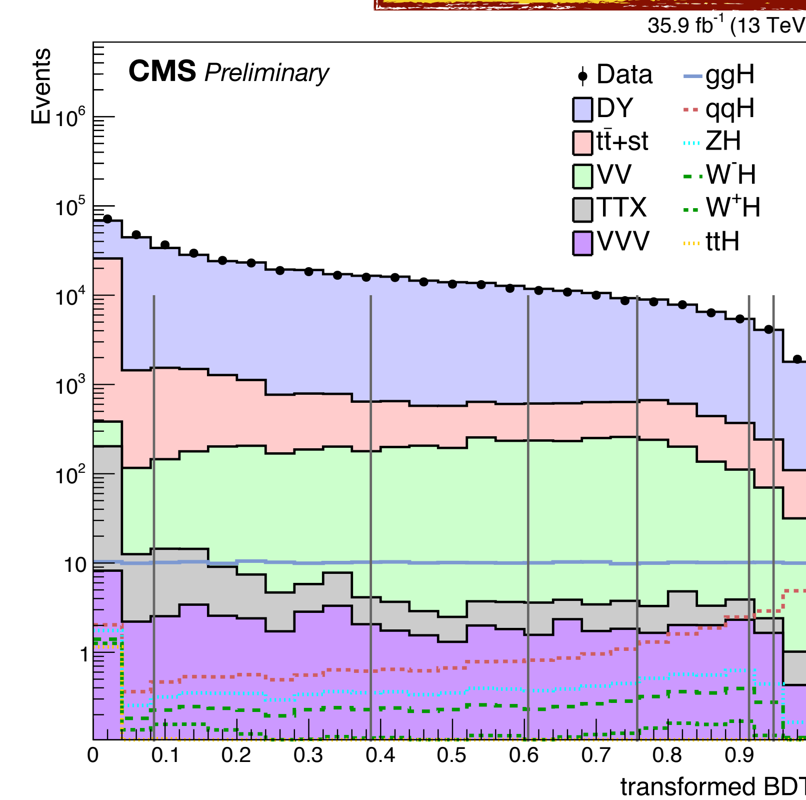
Search for $H \rightarrow \mu\mu$

Phys. Rev. Lett. 119 (2017) 051802

CMS-PAS-HIG-17-019







- Loose event selection **requiring two isolated OS muons** and veto *b*-jets
- Large background from Drell-Yan and smaller background from top quarks
- Signal and background described by analytical functions; fit to di-muon mass distribution in all signal regions

ATLAS

- Use **BDT to select events in 2 VBF** categories (m_{jj}, $p_T^{\mu\mu}$, $|\Delta\eta_{jj}|$, ΔR_{jj}, etc.)
- All other events categorised in 6 *gg*F categories based on $p_T^{\mu\mu}$ and $|\Delta\eta_{\mu}|$

CMS

- Separate signal from background using BDT ($p_T^{\mu\mu}$, $\eta_{\mu\mu}$, m_{jj}, $|\Delta\eta_{jj}|$, $N_{b\text{-jets}}$ etc.)
- Define 15 signal regions in **slices of BDT score** and $|\Delta\eta_{\mu}|$

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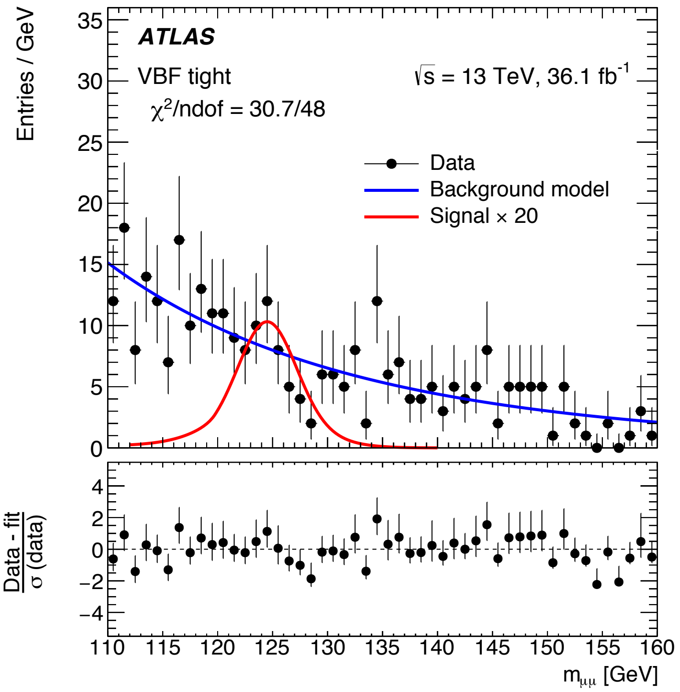
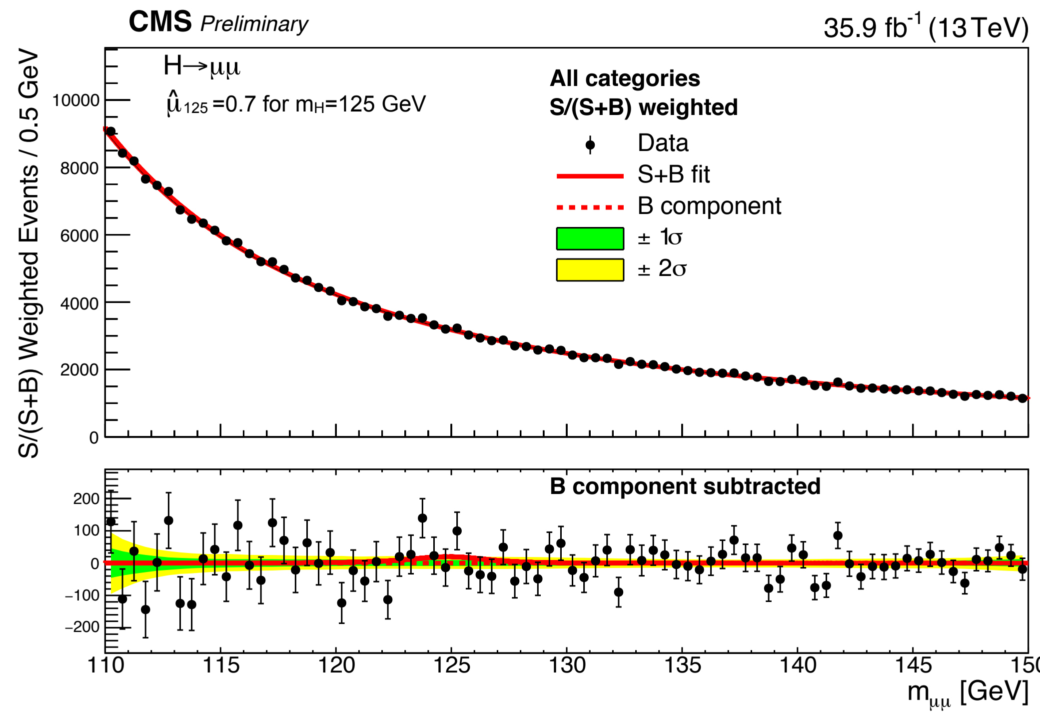
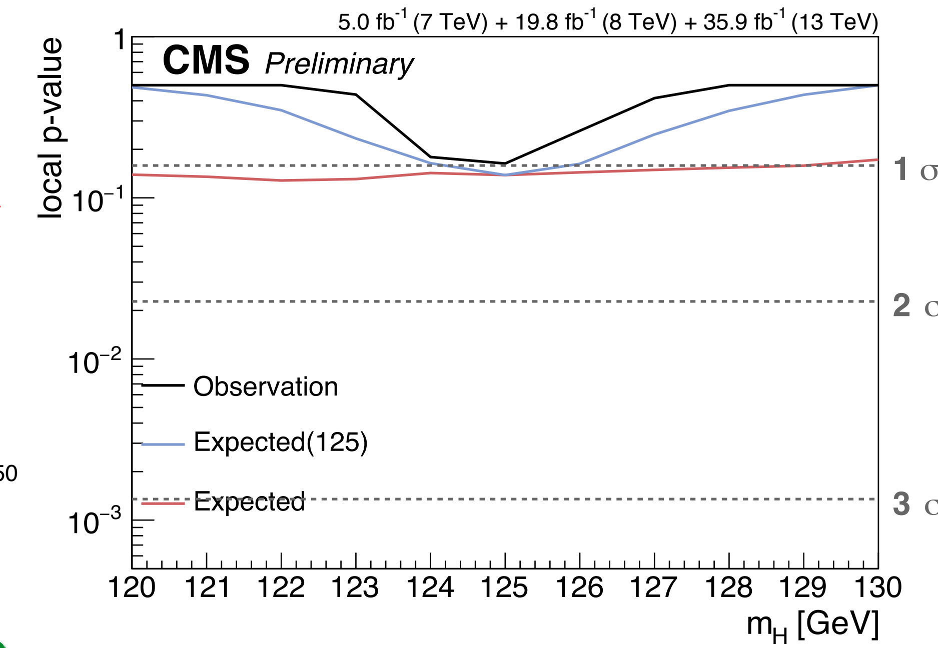
Search for $H \to \mu\mu$

[Phys. Rev. Lett. 119 (2017) 051802]

[CMS-PAS-HIG-17-019]







ATLAS

Obs. (exp.) upper limit on ***μ* < 3.0 (3.1)** at 95% C.L.

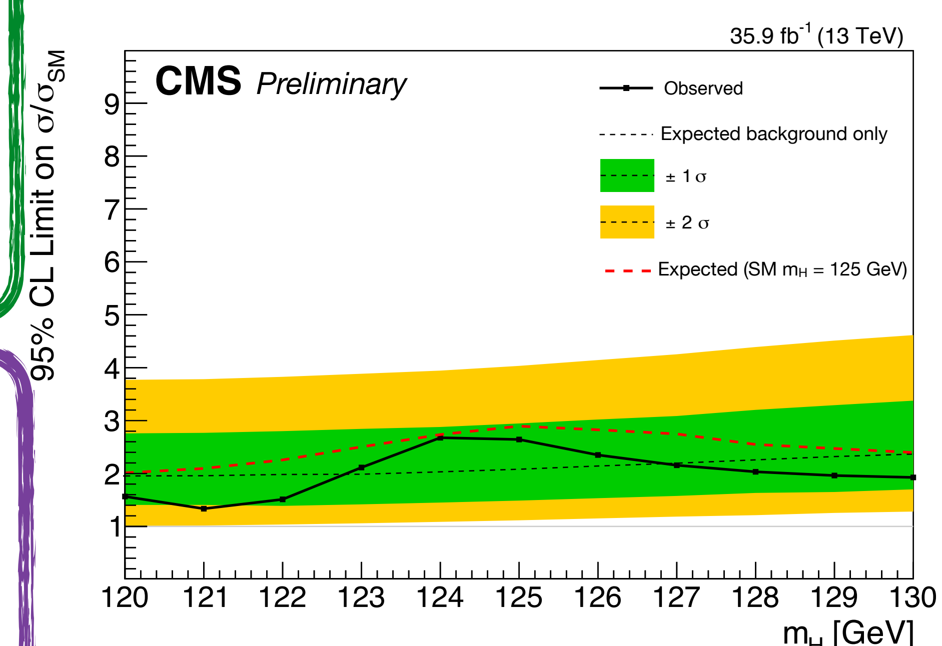
Combined with Run 1 data: ***μ* < 2.8 (2.9)** at 95% C.L.

CMS

Best fit: ***μ* = 0.7 ± 1.0** for m_H = 125 GeV

Obs. (exp.) upper limit on ***μ* < 2.6 (2.1)** at 95% C.L.

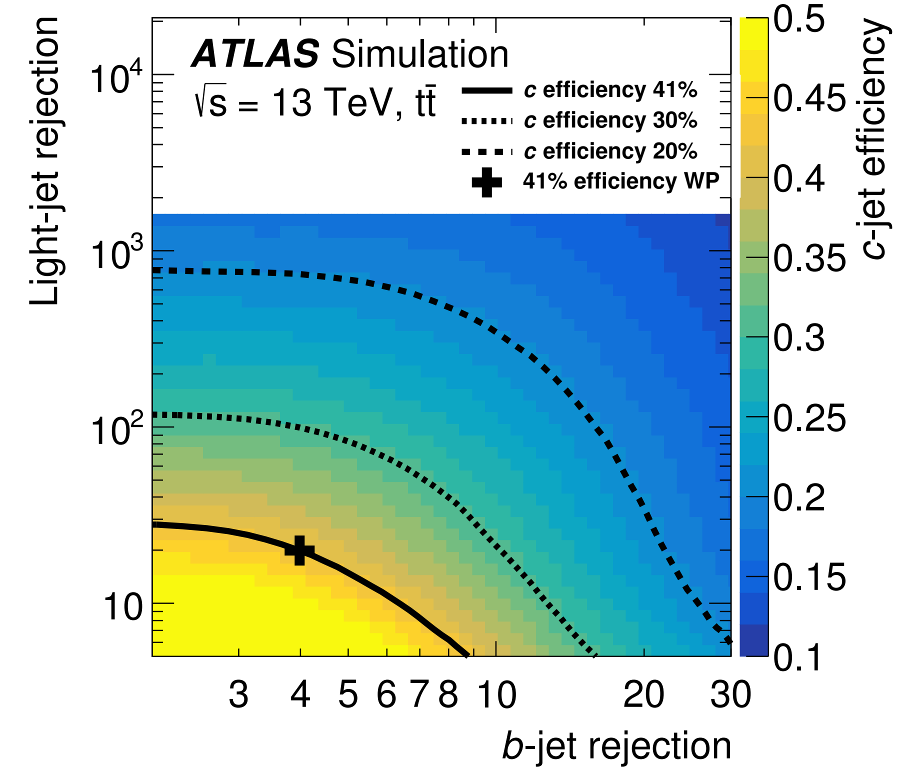
Combined with Run 1 data: ***μ* < 2.6 (1.9)** at 95% C.L.

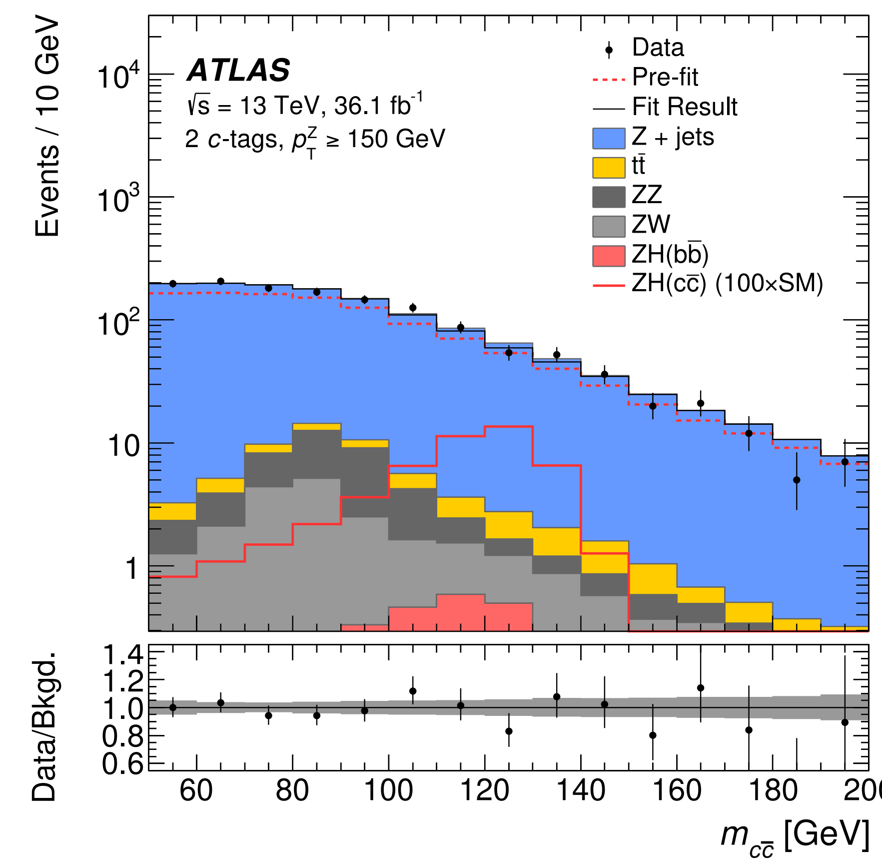


Search for *ZH*, *H*→*cc*

arXiv:1802.04329

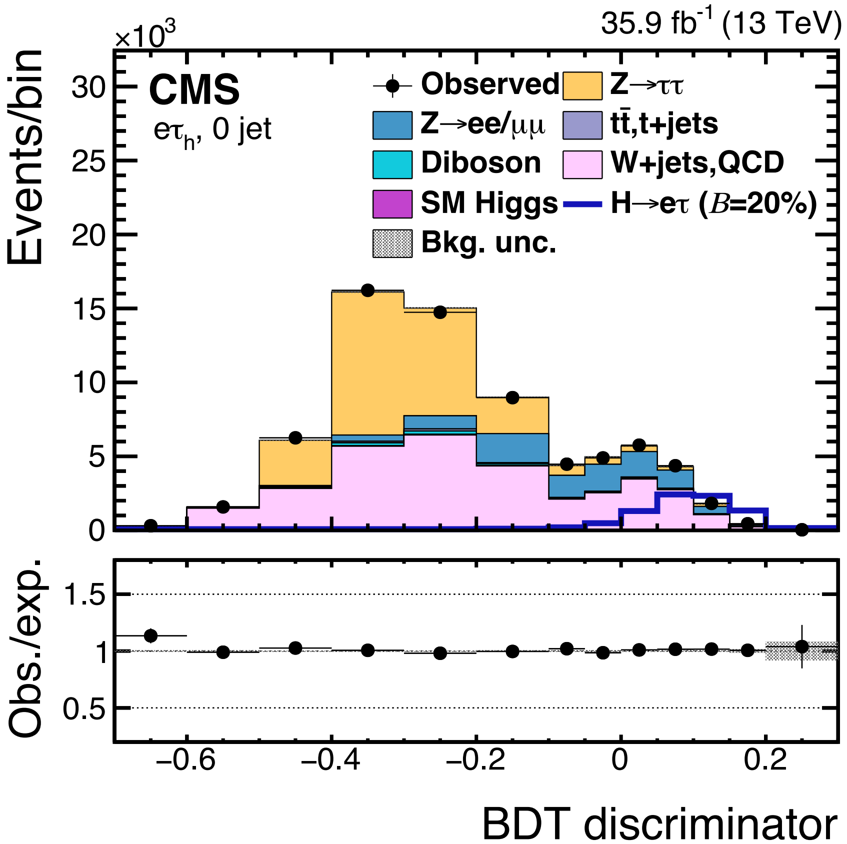
- Similar approach as search for *VH*, *H*→*bb*
- **1 or 2 *c*-tagged jets and 2 leptons** with $81<m_{\ell\ell}<101$GeV
- Recent **major improvements in charm tagging** allow this measurement
- Largest background from ***Z* + heavy flavour jets**, other backgrounds from *tt* and di-boson
- Maximum likelihood fit to m_{cc} distribution in 4 signal regions based on $N_{c\text{-jets}}$ and p_T^V
- Largest uncertainties: flavour tagging and data statistics
- **Measurement of** irreducible background from ***ZV*** with a significance of 1.4σ (2.2σ): $\mu_{ZV} = 0.6^{+0.5}_{-0.4}$
- Obs. (exp.) upper limit on μ_{Hcc} **< 110 (150)** at 95% C.L.

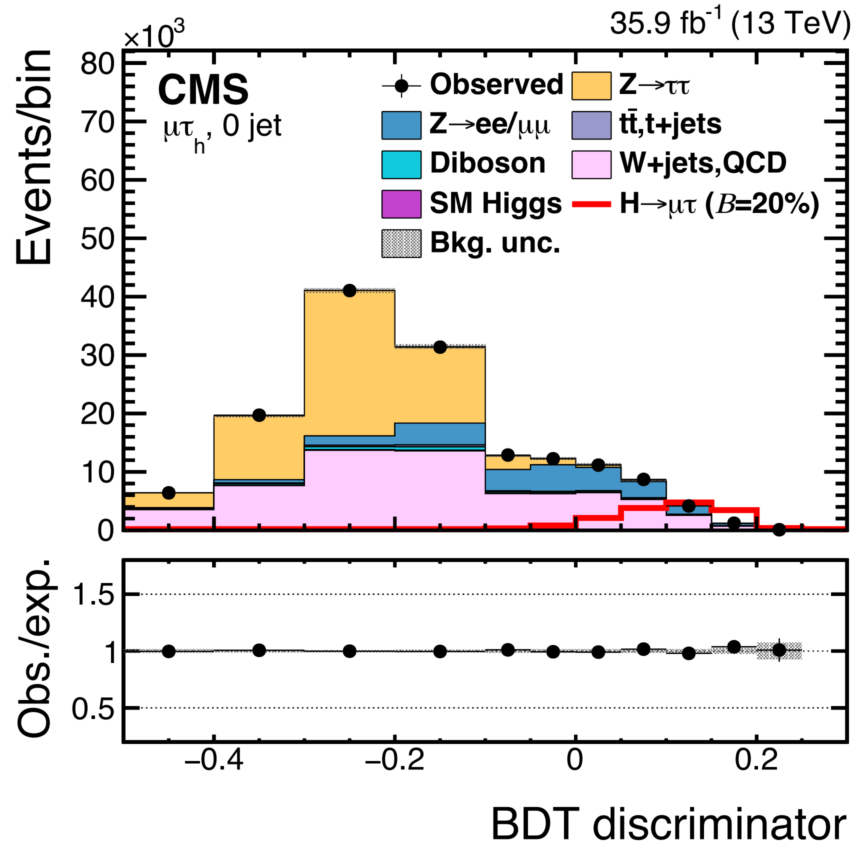


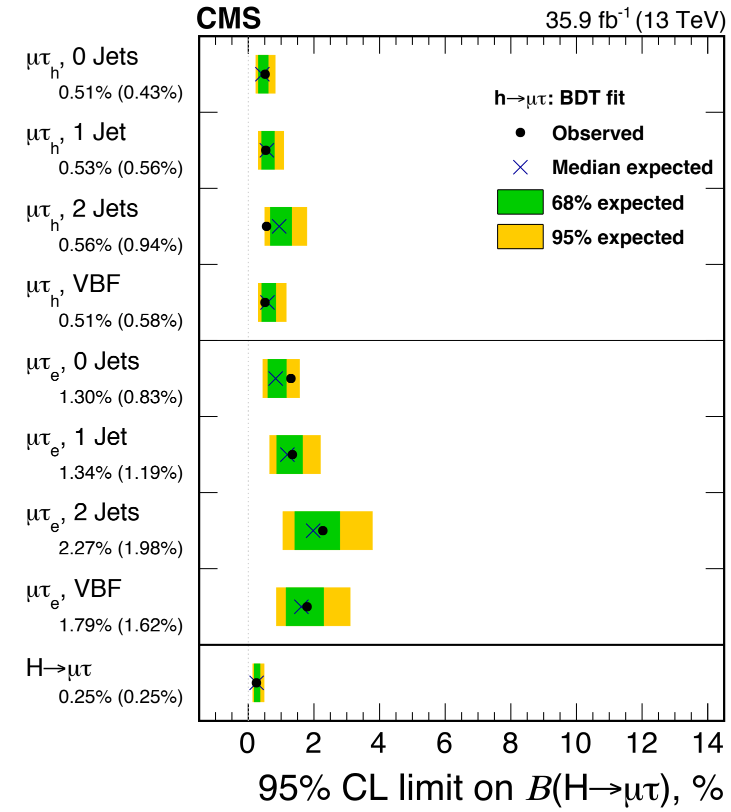


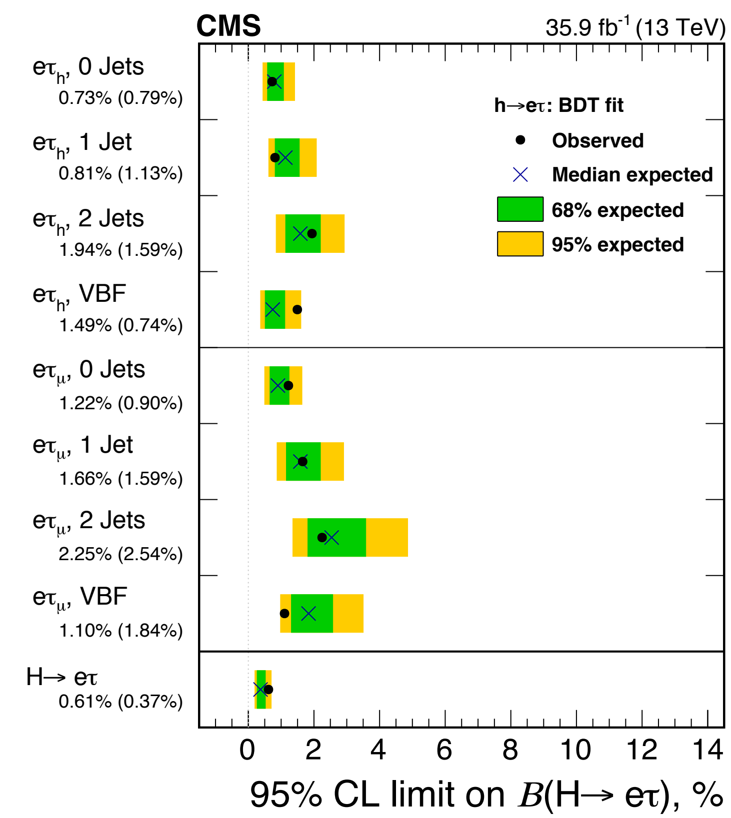
Search for LFV decays

arXiv:1712.07173







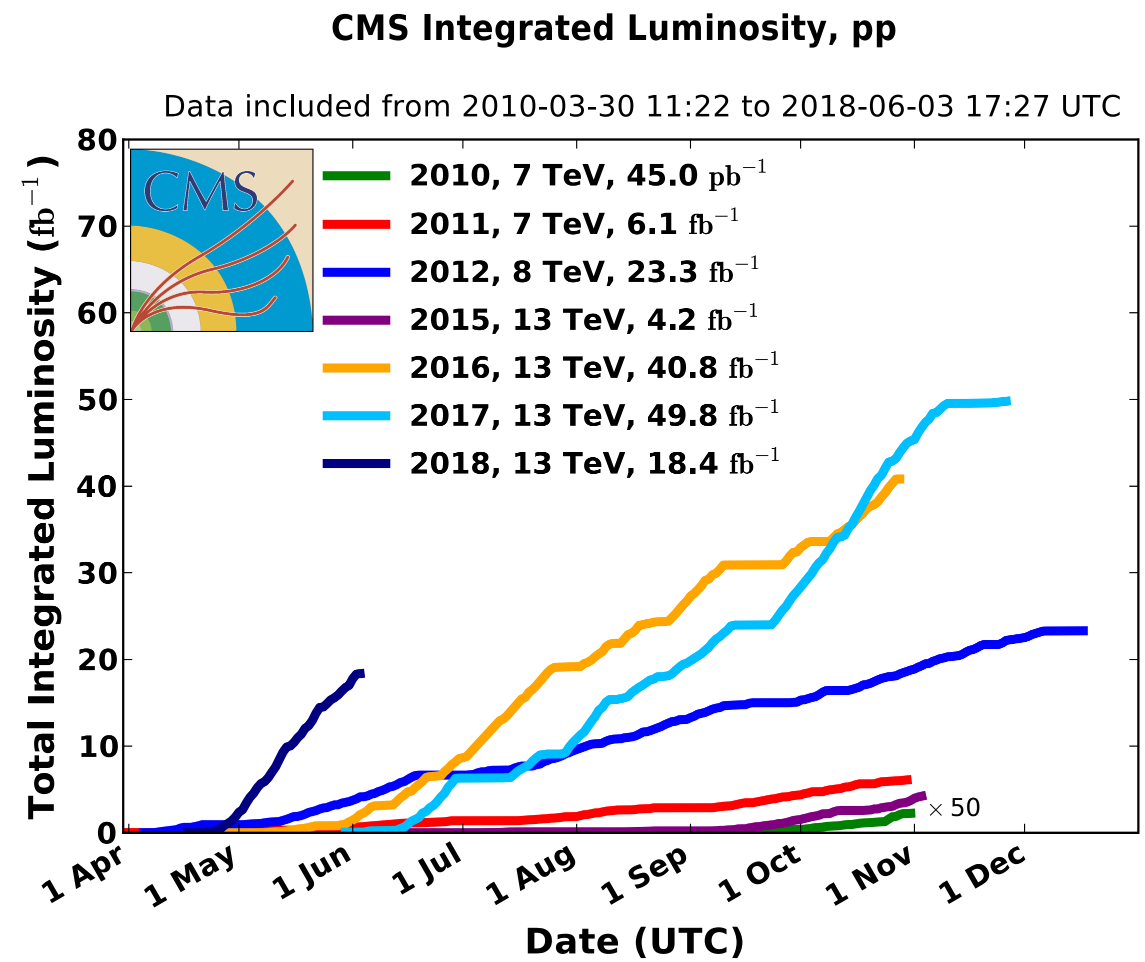


- LFV Higgs decays not allowed in the SM, strong limits on $H\to e\mu$ from low energy experiments
- Similar final states as in $H\to\tau\tau$: search for $H\to e\tau$ and $H\to\mu\tau$ using leptonic and hadronic **tau decays + prompt lepton**
- Background from ***Z*+jets and jets faking taus** (*W*+jets and multi-jet)
- Use BDTs to classify signal and background in 8 signal regions per final state, depending on N_{jets}
- 95% C.L. limits from likelihood fit are $\boldsymbol{B_{He\tau} < 0.61\%}$ and $\boldsymbol{B_{H\mu\tau} < 0.25\%}$

Summary

u	***c***	***t***
d	*s*	***b***
e	***μ***	***τ***

- Observed ***ttH*** production and ***H→ττ***, evidence for ***H→bb***
- So far no deviations from the SM observed!
- ***H→μμ*** seems in reach with full Run 2 and Run 3 data
- New searches for ***tH*** production and ***H→cc*** decays



Thanks to the LHC for the fantastic performance!

Looking forward to precision measurements with more data

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Related talks at this conference

- June 4th
  - 15:30 - ***Recent ATLAS results of the Higgs produced in association with top quarks*** - Jelena Jovicevic
  - 15:45 - ***Recent CMS results of the Higgs produced in association with top quarks*** - Karim El Morabit
- June 5th
  - 11:30 - ***Experimental results of the decay of the Higgs to b-quarks (ATLAS + CMS)*** - Andrew Stuart Bell
  - 11:50 - ***Experimental results using the decay of the Higgs to taus and muons (ATLAS + CMS)*** - Mareike Meyer
  - 12:05 - ***Higgs couplings, mass + width measurements (ATLAS + CMS)*** - Yanping Huang
- June 6th
  - 12:00 - ***Searches for exotic and rare Higgs decays (ATLAS+CMS)*** - Andrew Haas
  - 12:30 - ***Future projections in Higgs physics (ATLAS + CMS)*** - Eric Feng