Higgs to Fermion Decays at LHC (ATLAS and CMS)

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on behalf of the CMS and ATLAS Collaborations

XXVII Workshop on
Deep Inelastic Scattering 2019 - Torino

Outline

- Higgs couplings to fermions - general introduction
- Dominant decay mode H→bb *
  - Overview strategy for an VH(bb) analysis in CMS and ATLAS
  - Combination of H→bb results
  - STXS for H→bb and H→ττ
- Further decay modes of H to fermions – status
  - H→cc
  - H→ττ
  - H→μμ
  - H→ee
  - ttH (fermion coupling in the production) (→ see talks Cruz, Dimitriu)
- First limits on anomalous couplings in H→ bb vertex
- Outlook and conclusions

*note: H→ ll denotes H→ lepton + antilepton

Higgs couplings to fermions

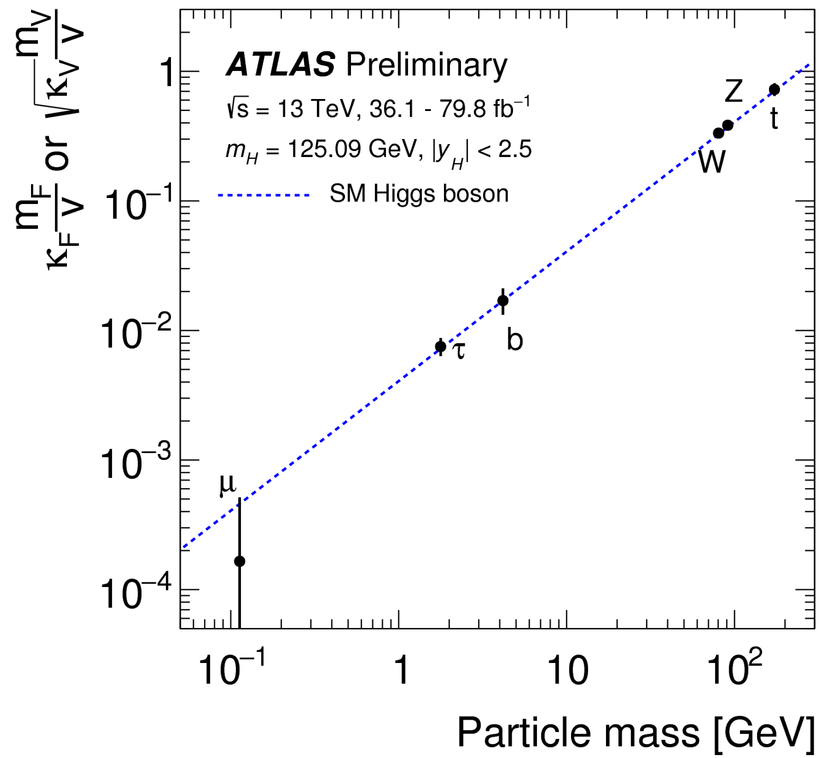
Higgs couplings to Fermions

- The Higgs field couples to fermions in SM through a Yukawa interaction, proportional to fermion mass m_f

$$L_{Yukawa} = \frac{1}{\sqrt{2}} g_f \left(\bar{f}_L f_R + \bar{f}_R f_L \right) v + \frac{1}{\sqrt{2}} g_f \left(\bar{f}_L f_R + \bar{f}_R f_L \right) h \qquad m_f = \frac{g_f v}{\sqrt{2}}$$

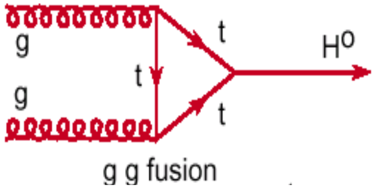
fermion mass term — Higgs coupling

- Still unresolved questions
  - **Do all fermion generations interact by Yukawa interaction?**
  - **Is there CP violation in the Yukawa coupling?**

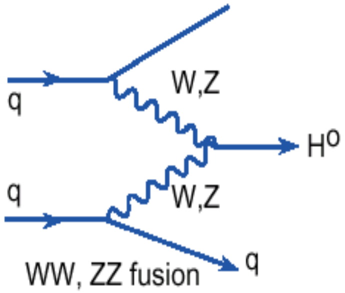


Higgs Production at the LHC

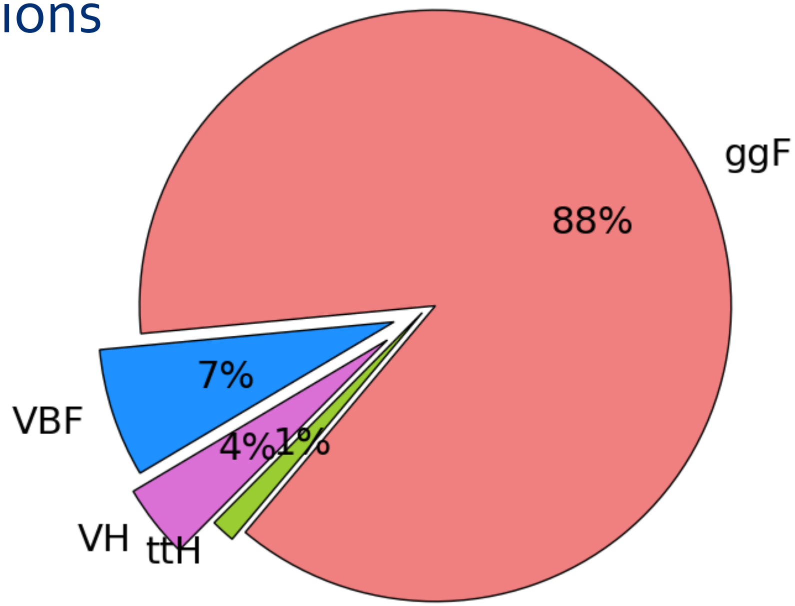
- Very large datasets at LHC give access to several production modes to search for H⟶ Fermions



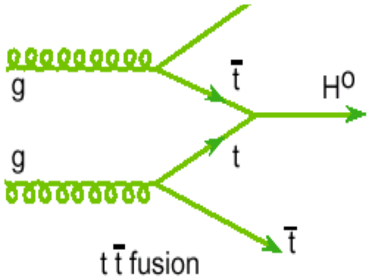
ggF: Gluon fusion (88%):
highest cross-section,
huge background



Vector-Boson Fusion VBF (7%):
large background,
but distinctive topology



H-Strahlung: associated production
with V (4%), and V→ leptons,
high pt-V topology to suppress background

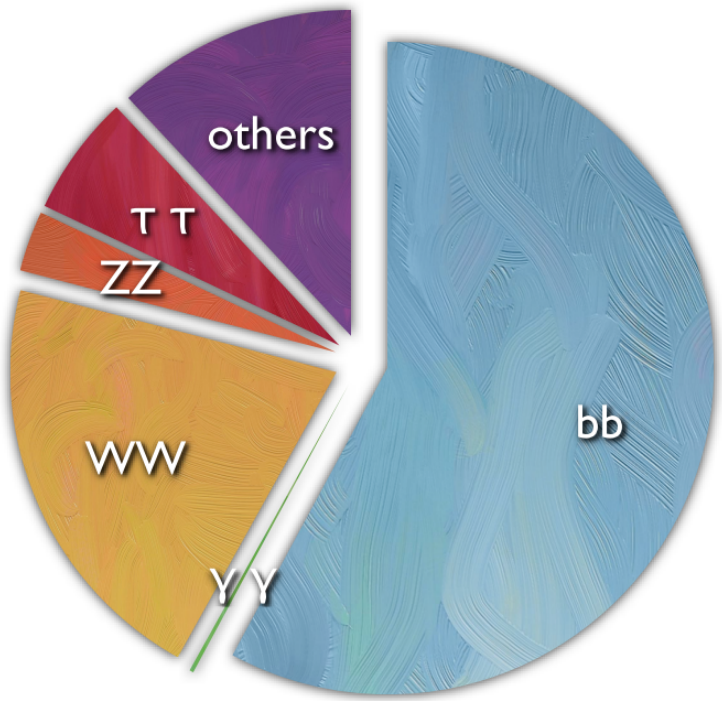


top fusion ttH (1%):
dominant tt +jets background

Higgs boson decays to fermions

Higgs boson BRs depend only on H mass m_H in SM; at m_H = 125 GeV:

- **bb ~ 58%**
  - Drives the uncertainty of the total Higgs boson width
  - Use additional objects to tag: VH (V = W, Z), VBF , and $t\bar{t}H$
  - Unique final state to measure coupling with down-type quarks
  - Limits the sensitivity to BSM contributions
- **ττ~ 6.3%**
  - missing energy from neutrinos,
  - advanced m(ττ) reconstruction
  - background from Z→ττ+jets, and jets faking τ
- **cc ~2 9%**
  - very large backgrounds from multijets
  - strong c -tagging needed
- **μμ ~ 0.022%**
  - very rare process, large background from D-Yan
- **ee ~ 5*10⁻⁹** : extremely suppressed (hopeless..?)



BR@125 GeV

Analysis Strategy –
Example: dominant H $\rightarrow$ bb Decay

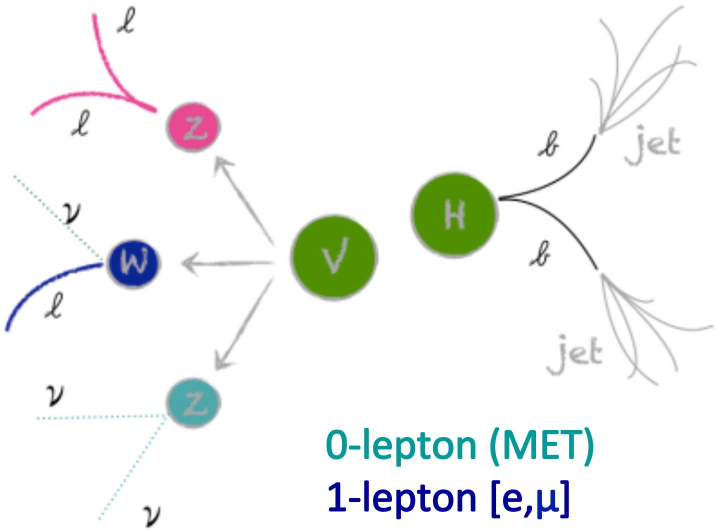
VH(bb): Analysis strategy

- **Analysis strategy :**

Exemplified with CMS-analysis,
similar in ATLAS.

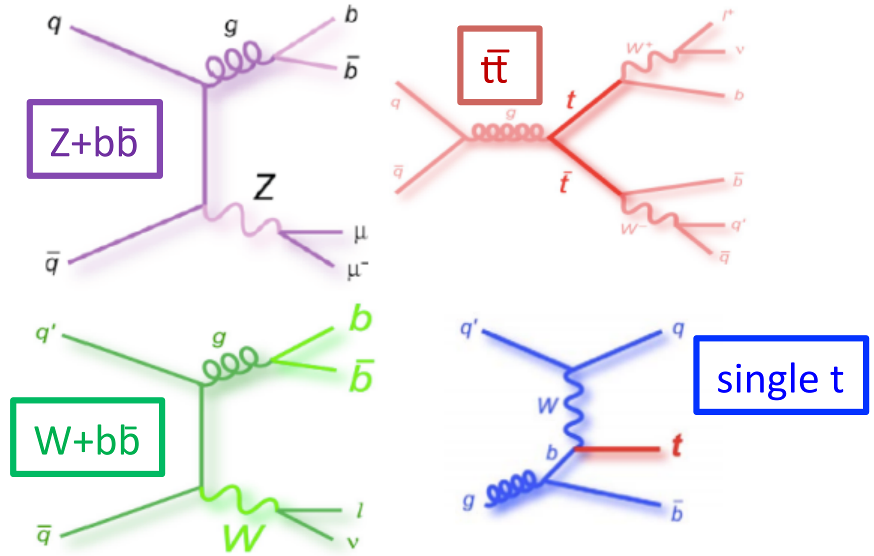
  - **Exploit associated V(Z/H) kinematics for BG reduction:**
  - **Use 3 channels** with 0, 1, and 2 leptons and 2 b-tagged jets for Z and W decays
  - **Signal region designed to increase S/B**
    - **Large boost** for vector boson
    - **Multivariate analysis** exploiting the most discriminating variables ($m_{b\bar{b}}$, $\Delta R_{b\bar{b}}$, b-tag)
  - **Control regions** to validate backgrounds and control/constrain normalizations
  - **Perform simultanous fit of signal and control regions**

signal



0-lepton (MET)
1-lepton [e,μ]
2-leptons [ee,μμ]

reducible backgrounds



normalization from data, shapes from MC

VH(bb): Analysis strategy

- **Analysis strategy :**
  - **Exploit associated V(Z/H) kinematics for BG reduction:**
  - **Use 3 channels** with 0, 1, and 2 leptons and 2 b-tagged jets for Z and W decays
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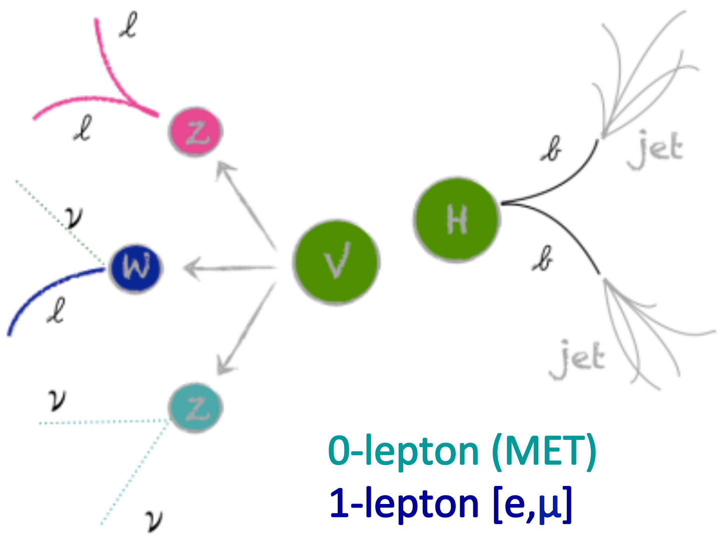
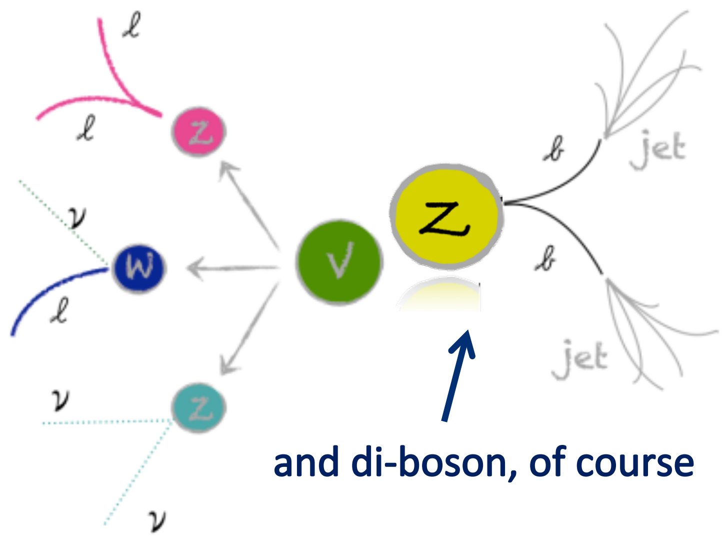
signal



0-lepton (MET)
1-lepton [e,μ]
2-leptons [ee,μμ]

irreducible backgrounds



and di-boson, of course

used to validate the analysis strategy

VH(bb) : main features

- **Strive to achieve high mass resolution from:**
  - strong **b-jet identification algorithms** (combination of tagging modes)
  - Exploit **b-jet energy regression**
  - Perform **Kinematic fits** (in 2-lepton channel)
  - Apply final state radiation (FSR) jet recovery

- Use of **MVA** (BDT, DNN, ...) to :
  - Discriminate signal from background, and background components from each other
  - Control large backgrounds from $t\bar{t}$, W/Z plus heavy/light flavor jets, + single top

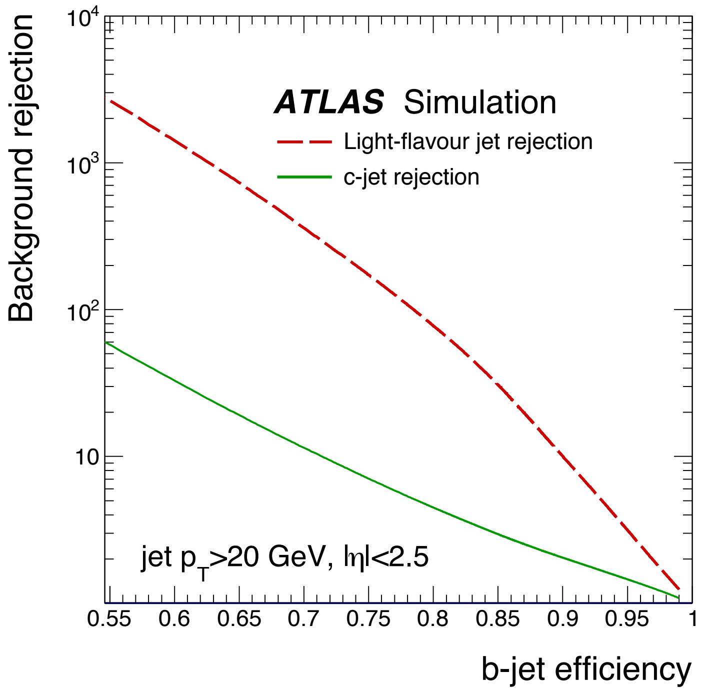
- Results quoted in terms of *Signal Strength Modifier* defined as:
  $\mu = (\sigma x BR)_{Obs} / (\sigma x BR)_{SM}$ ...and in terms of significance of observation "n σ".

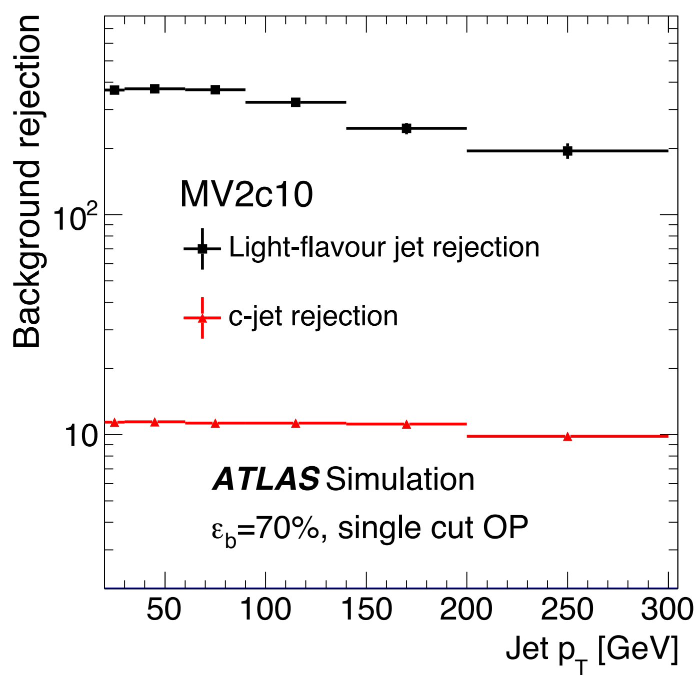
- **Datasets**: Run-1 (7, 8 TeV); CMS~5.1, 18.9 1/fb; ATLAS~4.7, 20.3 1/fb
  Run-2: 2015, 2016, 2017 sets (no 2018). CMS~ 77.2 1/fb; ATLAS~79.8 1/fb

b-jet identification

- **Continuous effort to improve b-tagging algorithms**
  - **ATLAS: BDT (MV2c10) algorithm on high-level input variables** such as SV, JetFit (excl. decay chain reco), IP-tag, (some versions also use $p_T^{rel}(\mu)$).
  - **CMS: DNN algorithm (DeepCSV) using low level input variables**, + per-track info
  - Achieve low contamination from light (q/g) < 1% for efficiency ~70%
  - Efficiencies derived from data with $t\bar{t}$ events by: combinatorial likelihood approach and a tag-and-probe (and muon in jets in CMS)
- Good agreement between data and MC verified in all analysis regions

ε_b vs BGND rejection





BGND rejection for ε_b = 70%

b-jet energy regression (CMS)

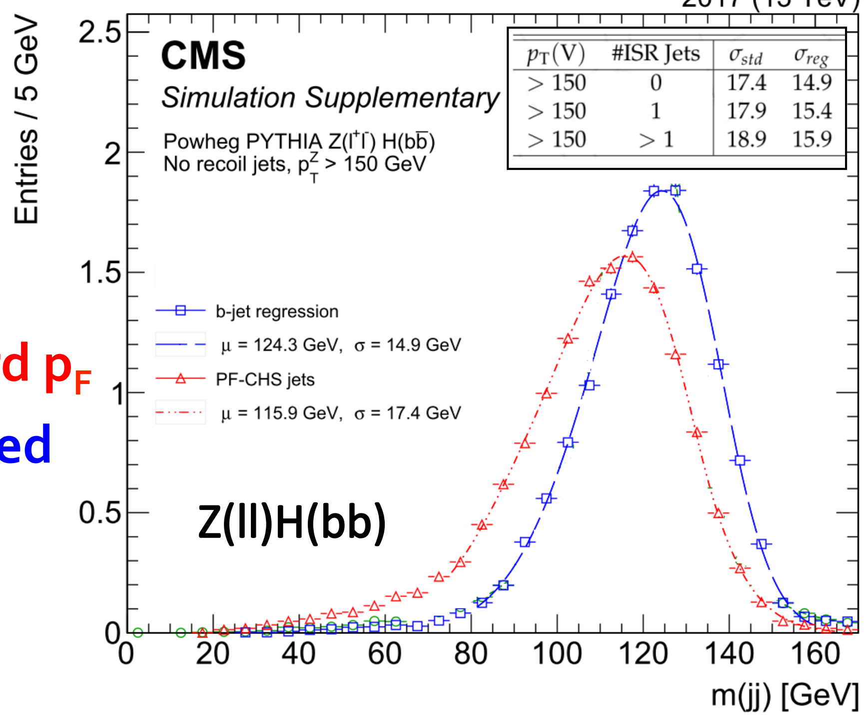
- **Regression mainly recovers missing energy in the jet due to neutrino**
  - Boosted Decision Trees in 2016 and DNN algorithm in 2017/18
- **Extended set of input variables** including lepton flavor (μ/e), jet mass, fragmentation-like variable, energy fractions in ΔR rings
- **Significant m(bb) resolution improvement without sculpting of background**
  - σ/peak down to 11.9% in 2017 wrt 13.2% in 2016

Higgs mass in 2-lep SR

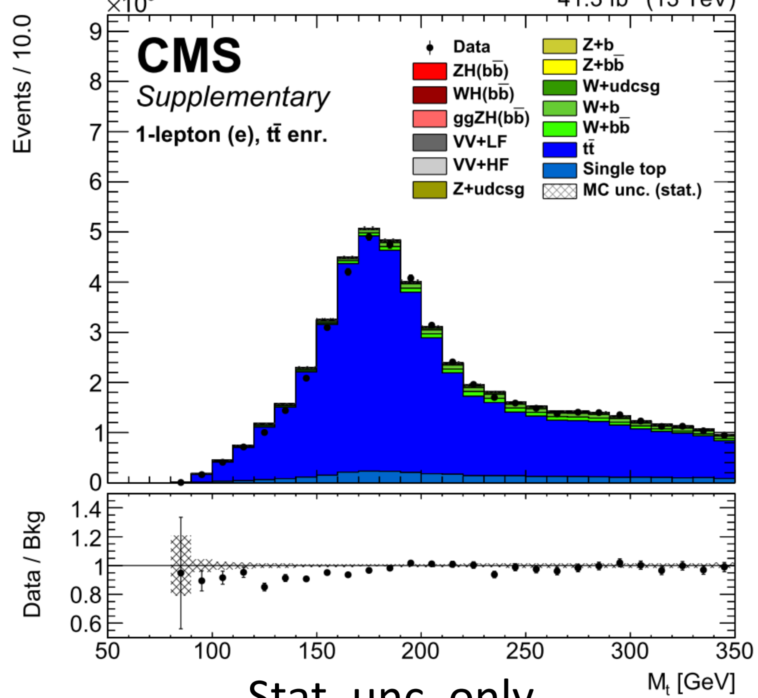
b-jets:

standard p_F

regressed



Top mass in 1-lep tt CR

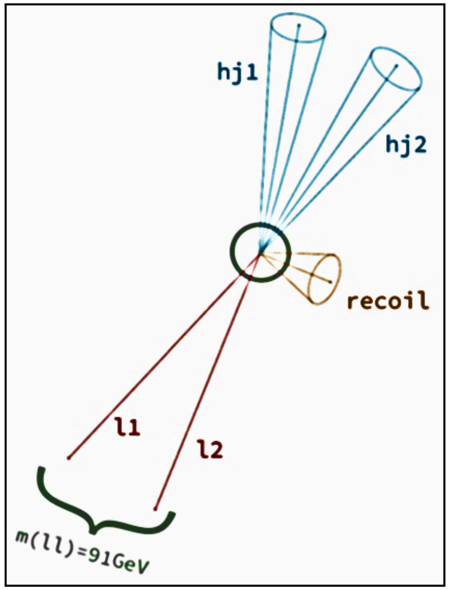


Stat. unc. only

CMS: Kinematic fit in 2-lepton channel

- **No intrinsic missing energy in the Z(ll)H($b\bar{b}$) process**
- Improve jet p_T measurement through kinematic fit
  - ➢ Constrain dilepton system to Z mass
  - ➢ Balance the ll+bb+j system in the (p_x, p_y) plane
  - ➢ Z+b, Z+bb treated identically
- **Improvement up to 36% on m($b\bar{b}$) resolution**

VH topology

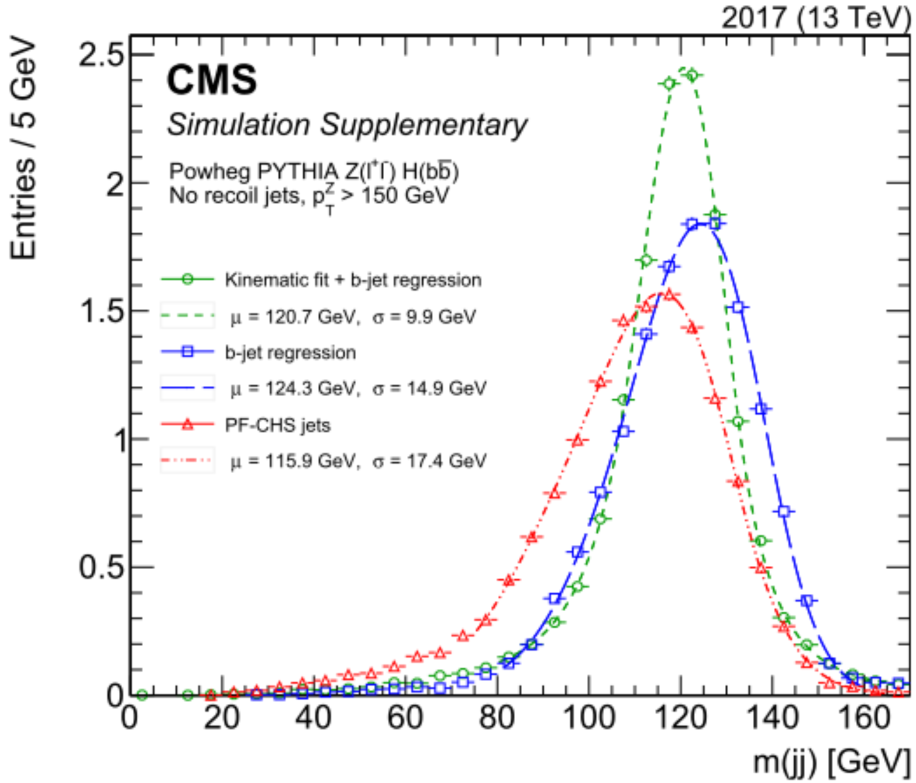


b-jets:

standard p_F

regressed

kinem. fit



Systematics of VH(bb) results

Systematic uncertainties dominated by:

- b-tagging
- Simulation MC size
- Modelling of background and signal

CMS: Run1 + Run2 combined

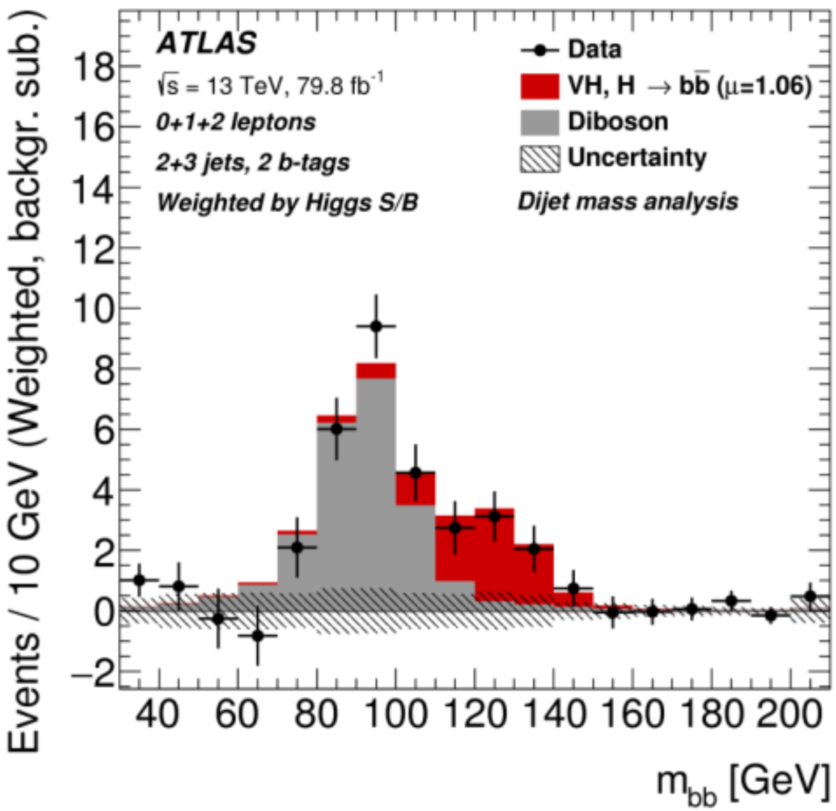
Uncertainty source	$\Delta\mu$	
Statistical	+0.26	−0.26
Normalization of backgrounds	+0.12	−0.12
Experimental	+0.16	−0.15
b-tagging efficiency and misid	+0.09	−0.08
V + jets modeling	+0.08	−0.07
Jet energy scale and resolution	+0.05	−0.05
Lepton identification	+0.02	−0.01
Luminosity	+0.03	−0.03
Other experimental uncertainties	+0.06	−0.05
MC sample size	+0.12	−0.12
Theory	+0.11	−0.09
Background modeling	+0.08	−0.08
Signal modeling	+0.07	−0.04
Total	+0.35	−0.33

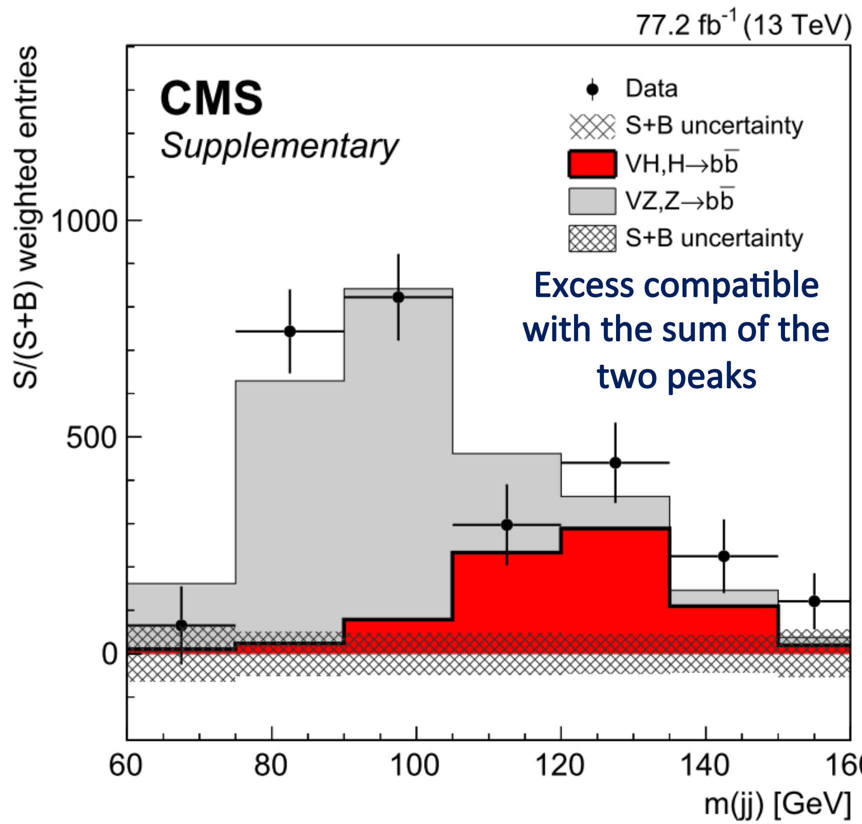
ATLAS: 2015-2017 combined

Source of uncertainty		σ_μ
Total		0.259
Statistical		0.161
Systematic		0.203
Experimental uncertainties		
Jets		0.035
E_T^{miss}		0.014
Leptons		0.009
b-tagging	b-jets	0.061
	c-jets	0.042
	light-flavour jets	0.009
	extrapolation	0.008
Pile-up		0.007
Luminosity		0.023
Theoretical and modelling uncertainties		
Signal		0.094
Floating normalisations		0.035
Z + jets		0.055
W + jets		0.060
$t\bar{t}$		0.050
Single top quark		0.028
Diboson		0.054
Multi-jet		0.005
MC statistical		0.070

Visualizing the excess: m(jj) analysis

- **Fit dijet mass m(jj)**: lower sensitivity but direct visualization of Higgs signal
- **a) ATLAS: event preselection tighter than MVA**
  b) CMS: categorized in DNN sensitivity after removing correlations with m(jj)
- m(jj) distributions combined and weighted by S/(S + B)
- **Signal strengths compatible with main analysis**





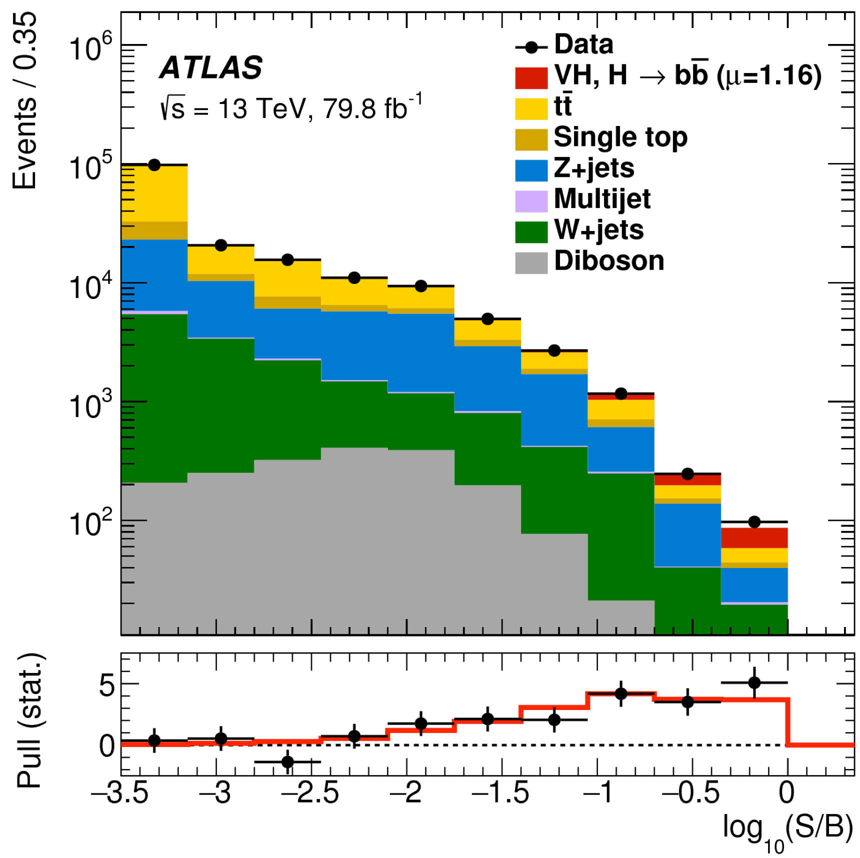
Run2 (13 TeV)

Results on $H \rightarrow bb$

Signal in VH, H→bb in CMS and ATLAS

Observed significant signal in terms of $\log_{10}$(S/B) , here for VH mode alone

Run-2 ('15,'16,'17) results



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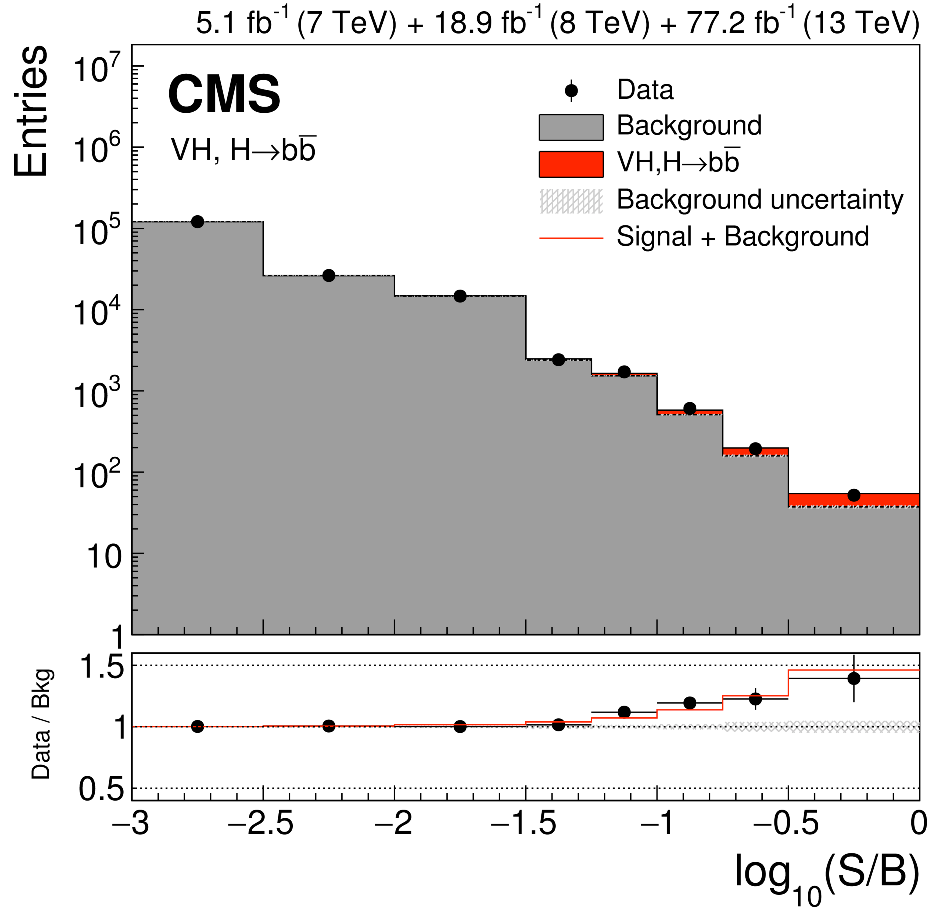
Run-1 and Run-2 ('15,'16,'17) results

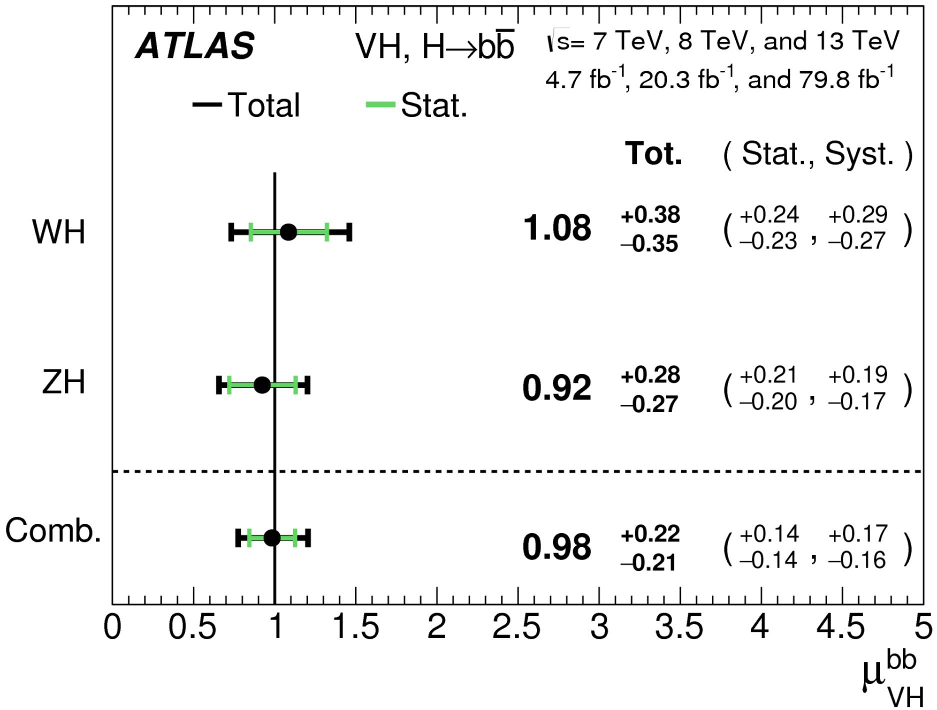


Phys. Rev. Lett. 121 (2018) 121801

Evidence for VH, H→bb in CMS and ATLAS

Run-1 and Run-2 ('15,'16,'17) combined **results based on VH mode alone**

Phys. Lett. B 786 (2018) 59



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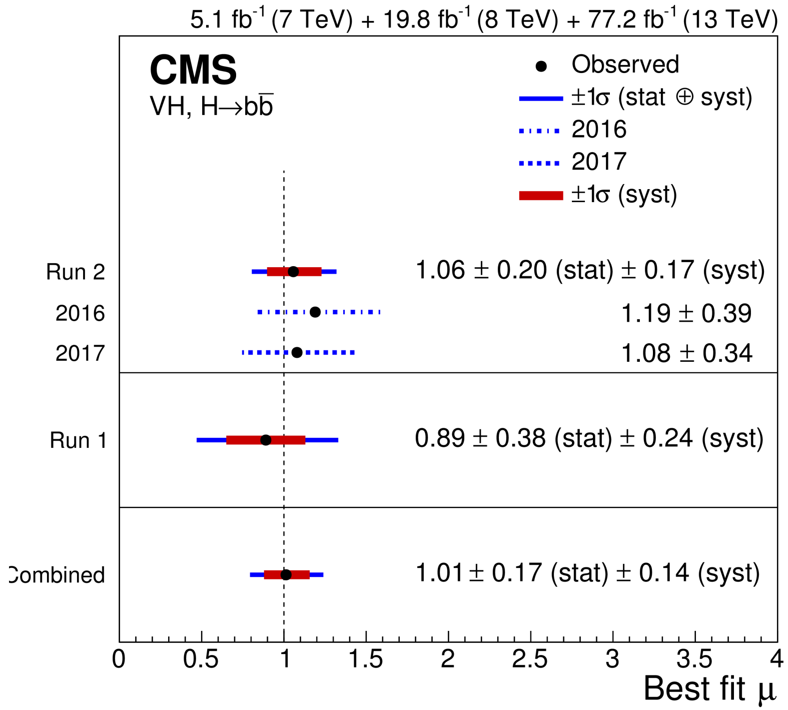

Run 1+2	Obs (exp) significance	μ(H→bb)
ATLAS	4.9 (5.1) σ	$0.98 \pm 0.14(stat.)\ {}^{+0.17}_{-0.16}(syst.)$
CMS	4.8 (4.9) σ	$1.01 \pm 0.17(stat.) \pm 0.14(syst.)$

Observation of H→bb in CMS and ATLAS

- Run-1 and Run-2 (15,16,17) **combined: all production modes - VBF, ggF, ttH, VH**
- Most sources of systematic uncertainty are treated as uncorrelated
- Theory uncertainties are correlated between all processes and data sets

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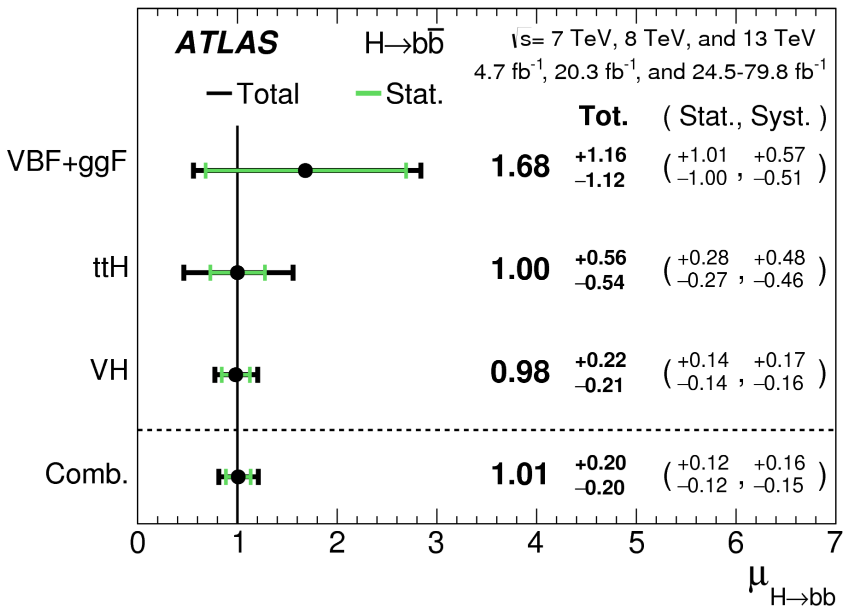

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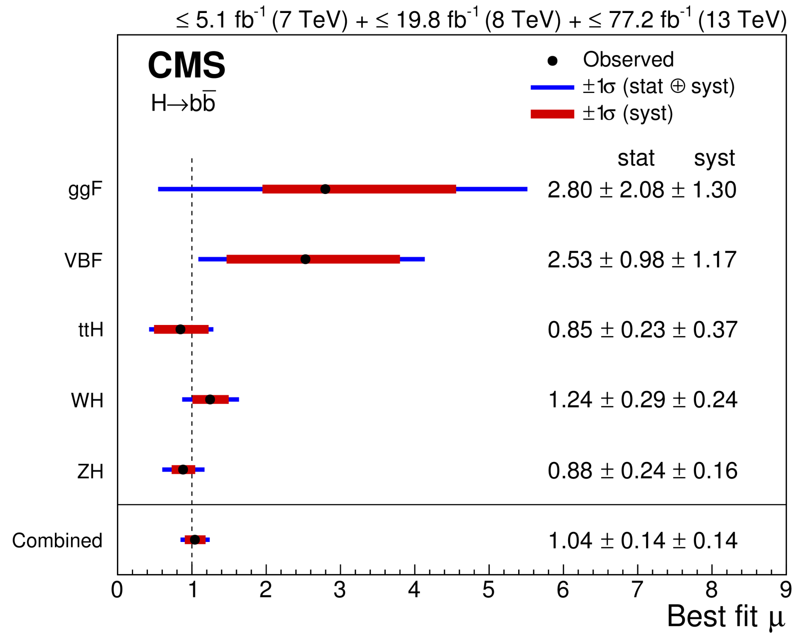


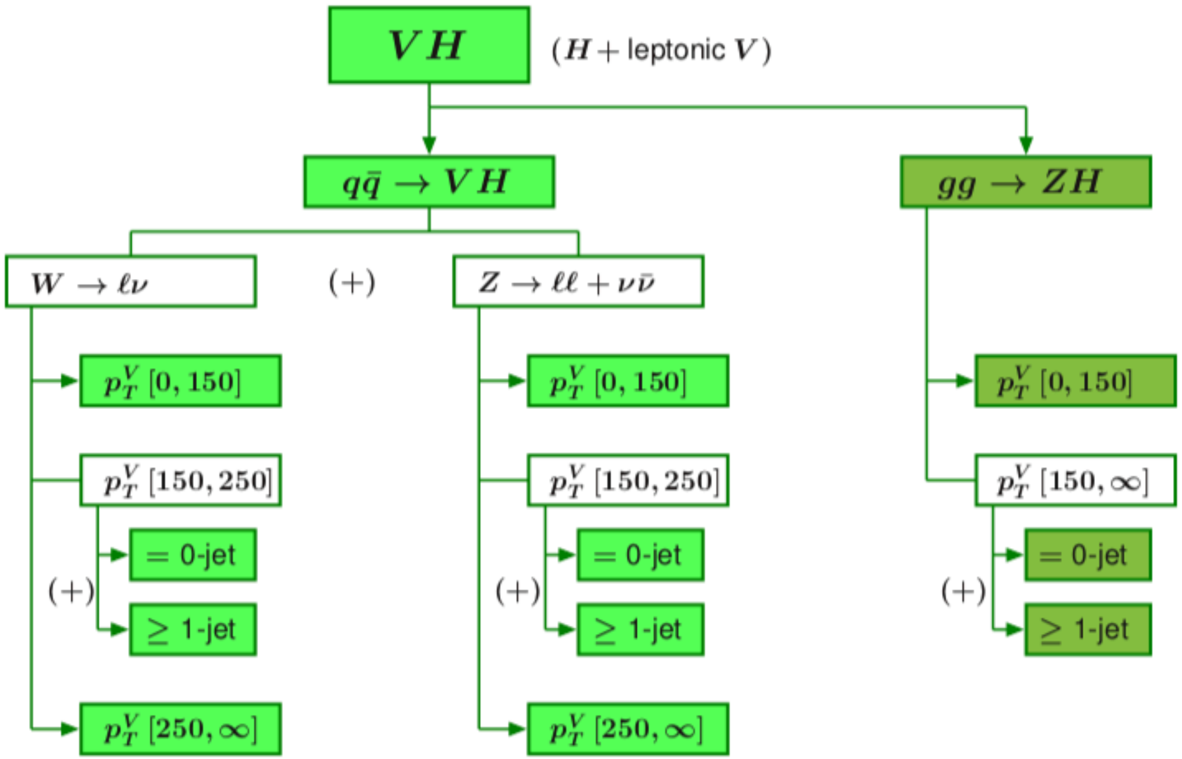
Run 1+2	Obs (exp) significance	μ(H→bb)
ATLAS	5.4 (5.5) σ	$1.01 \pm 0.12(stat.)\,^{+0.16}_{-0.15}(syst.)$
CMS	5.6 (5.5) σ	$1.04 \pm 0.14(stat.) \pm 0.14(syst.)$

ETH zürich

ATLAS H⟶bb
Simplified Template Cross sections

STXS in VHbb – in short

- STXS is a combination of fully fiducial cross sections and direct fits (a la Run 1)
- **Maintain sensitivity while reducing dominant theory dependence**
- **Phase space divided up into several generator-level bins (p_T(V),#jets) -> get σ/σ_{SM}**
- **Optimized for analysis sensitivity (here VH), driven by analysis categories**;
  ATLAS paper (ATL-PHYS-PUB-2018-035) used 5 bins due to limited sensitivity.



Inclusions:
- qq→V(qq)H as part of "VBF" bins
- gg→Z(qq)H as part of "ggF" bins
- "VH" includes leptonic VH(undecayed H)

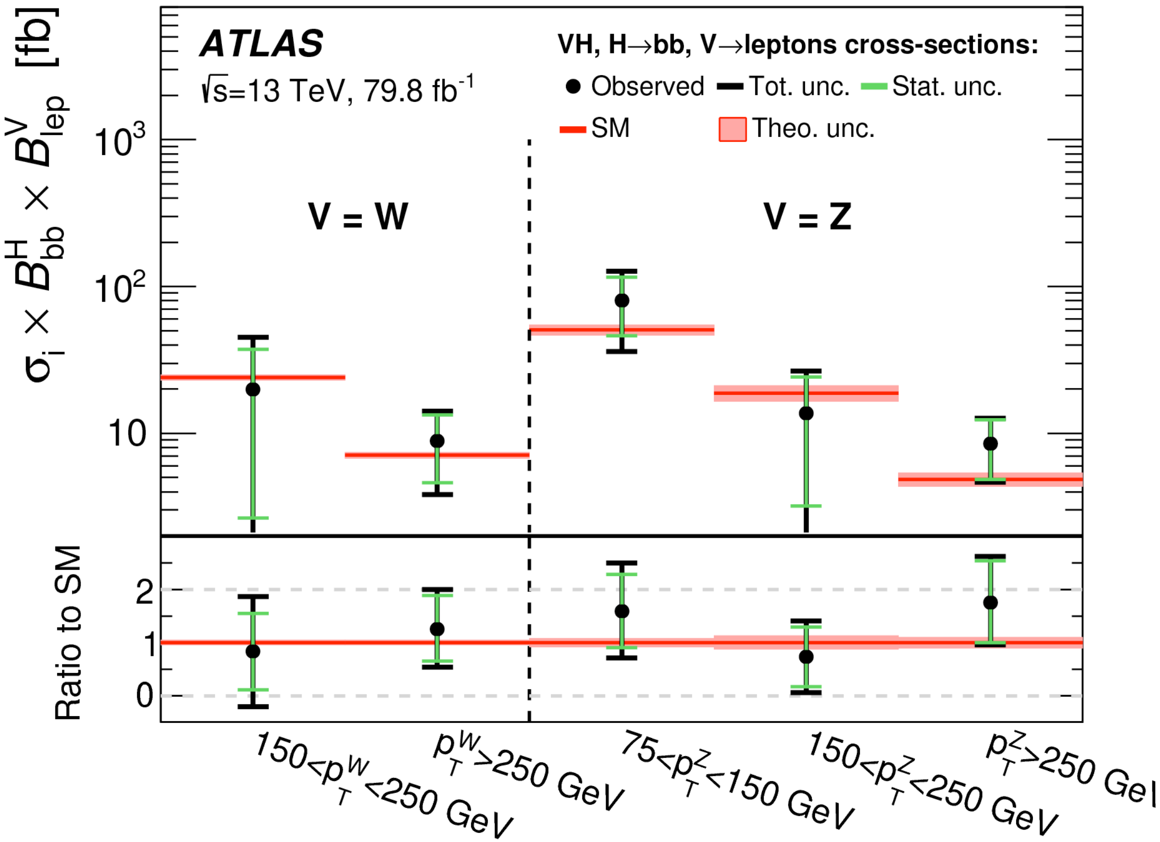
- see also ATLAS paper ATL-PHYS-PUB-2018-035

ATLAS: STXS in H→bb

ATLAS: H→bb (80 1/fb)

- Event classification identical to VHbb inclusive case
- Use BDT to discriminate between pt(V)-regions
- Fit σ*B by unbinned ML-fit (BDT_{VH}, m_{bb} or N_{ev}) per region; MC shape or data templates for SR and CR

- Systematics limited by BGND modelling and MC-stat
- Highest sensitivity in pt(V)>250GeV
- **Good agreement with SM predictions**



Sub. to JHEP_119P_0319
ATLAS-Conf-2018-053

ATLAS H→bb Anomalous Coupling

ATLAS: Anom. Hbb coupling in VHbb

- Assume a **strongly interacting sector with a light composite Higgs, that causes EW symmetry breaking.**
- Consider an effective Langrangian with additional dimension-6 operators.
- STXS results used to extract constraints on anomalous Higgs boson interactions in HEL (Higgs effective Lagrangian) formulation.
- 5 operators (CP-even: O_{HW}, O_{HB}, O_{W}, O_{B}, O_{d}) directly affect the VH xsec and B(H⟶bb), recast in dimensionless coefficients C_{xx}:

$$\bar{c}_{HW} = \frac{m_W^2}{g}\frac{c_{HW}}{\Lambda^2}, \quad \bar{c}_{HB} = \frac{m_W^2}{g'}\frac{c_{HB}}{\Lambda^2}, \quad \bar{c}_{W} = \frac{m_W^2}{g}\frac{c_{W}}{\Lambda^2}, \quad \bar{c}_{B} = \frac{m_W^2}{g'}\frac{c_{B}}{\Lambda^2}, \quad \bar{c}_{d} = v^2\frac{c_{d}}{\Lambda^2},$$

$$O_{HW} = i\,(D^\mu H)^\dagger\,\sigma^a\,(D^\nu H)\,W^a_{\mu\nu},$$

$$O_{HB} = i\,(D^\mu H)^\dagger\,(D^\nu H)\,B_{\mu\nu},$$

$$O_W = \frac{i}{2}\left(H^\dagger\sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu},$$

$$O_B = \frac{i}{2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right)\partial^\nu B_{\mu\nu}.$$

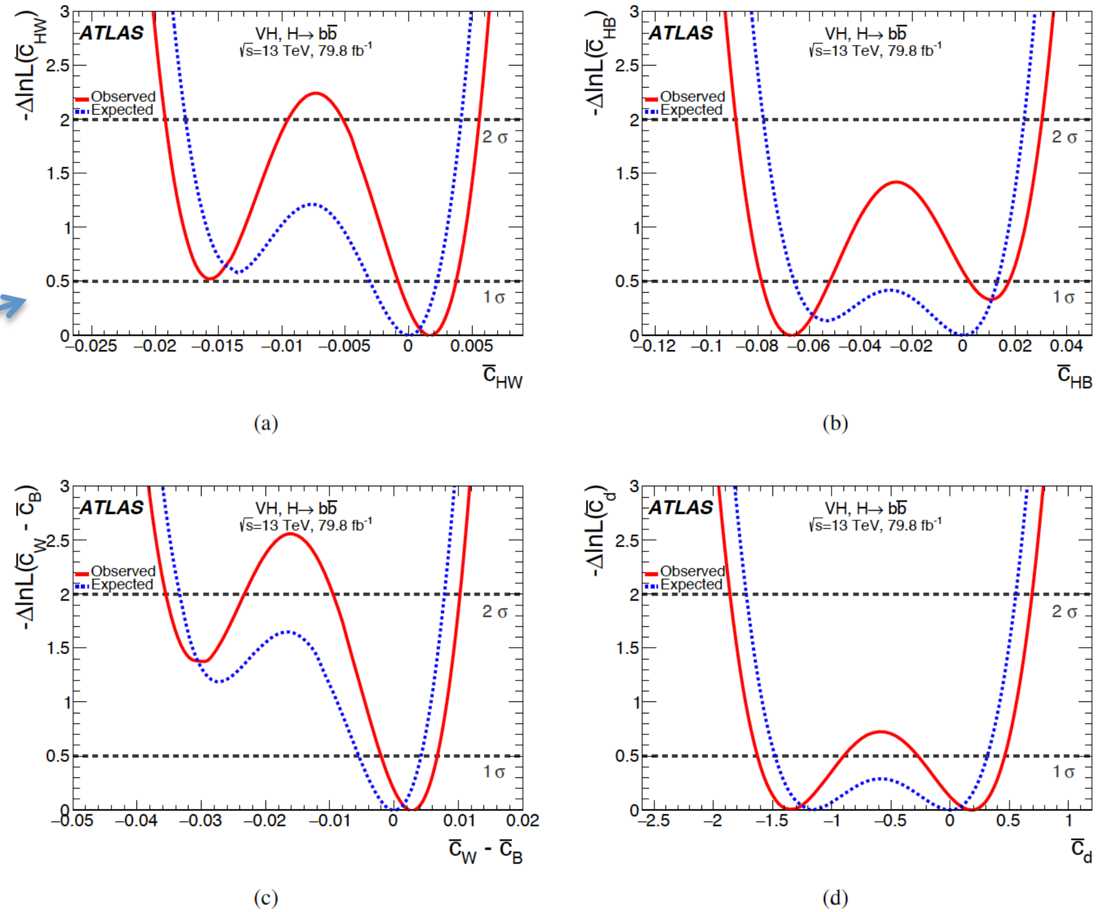
$$O_d = y_d|H|^2\bar{Q}_L H d_R$$

- Extract constraints on these coefficients C_{xx} by simultanous ML-fit of all 5-POI STXS
- Highest sensitivity from pt(V)>250GeV
- Sensitiv to CP-violation

ATLAS: Sub. to JHEP_119P_0319

ATLAS: Anom. Hbb coupling in VHbb

- Results on constraints on coefficients C_{xx} by simultaneous ML-fit (lin. and quad term) of all 5-POI STXS; in fit all but ONE coefficient set := 0.
- Observed and expected profiled neg.LL in one-dimensional projections
- Highest sensitivity stems from pt(V)>250GeV (see STXS above)
- **parameters $\bar{C}_{HW}$ and $\bar{C}_W - \bar{C}_B$ are constrained at 95% CL to < few percent.**
- Expect coefficients C_{xx} =0 in SM



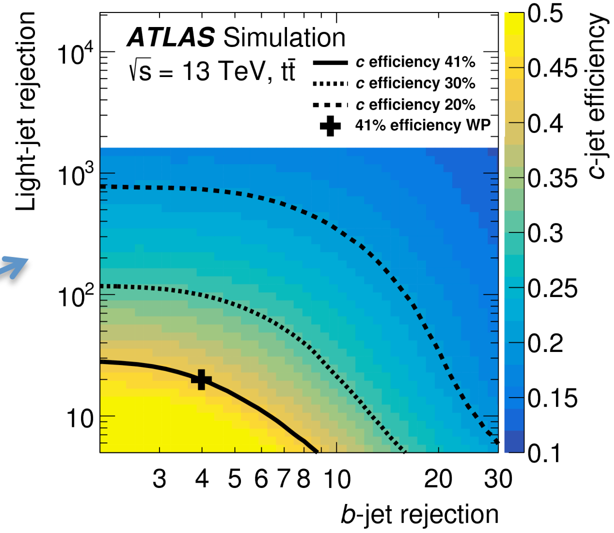
ATLAS: Sub. to JHEP_119P_0319

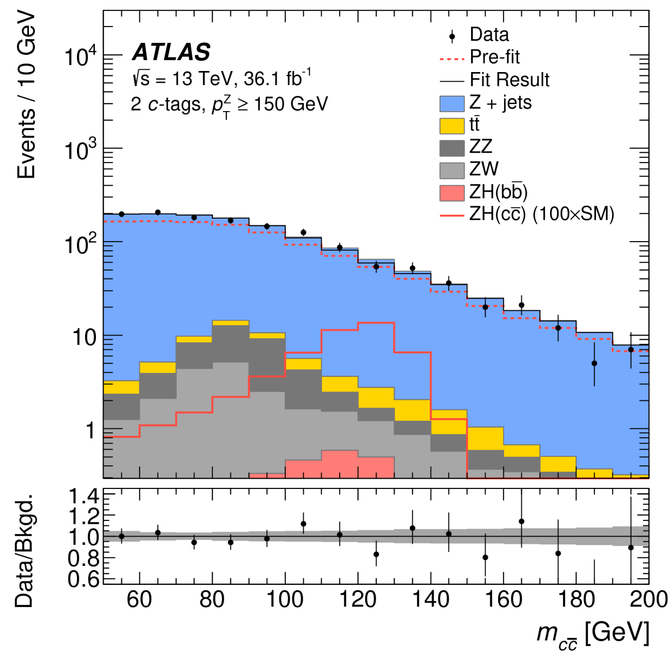
$H \longrightarrow cc$ Decays

ATLAS: Search for H→cc

ATLAS PRL 120 (2018) 211802

- Run2: 36 1/fb
- Use ZH, H→ cc category
- Charmed hadron-tagging with BDT using lifetime and jet-structure;
  using MV2c10, optimized for charm tag
- Efficiencies from data in tt and W-decays
- Validation by ZV production
- Profile likelihood fits of M(cc) in four categories in terms of $p_T(Z)$ and # c-tag





Run 2	UL. obs (exp) at 95% CL
ATLAS	$\sigma(pp \to ZH)\cdot\sigma(H \to cc) < 2.7\ (3.9^{+2.1}_{-1.1})$ pb $\mu(H \to cc) < 110\ \ (150^{+80}_{-40})$

$H \longrightarrow \tau\tau$ Decays

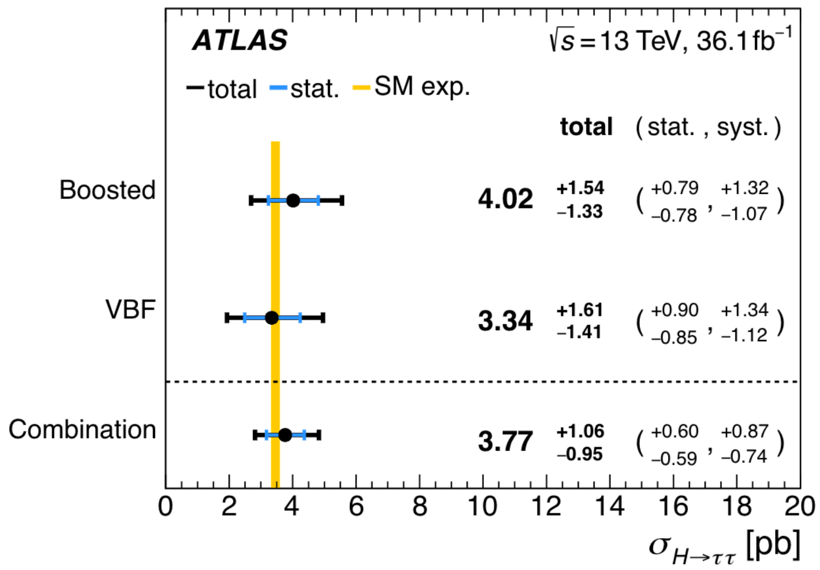
Observation of H→ττ in CMS and ATLAS

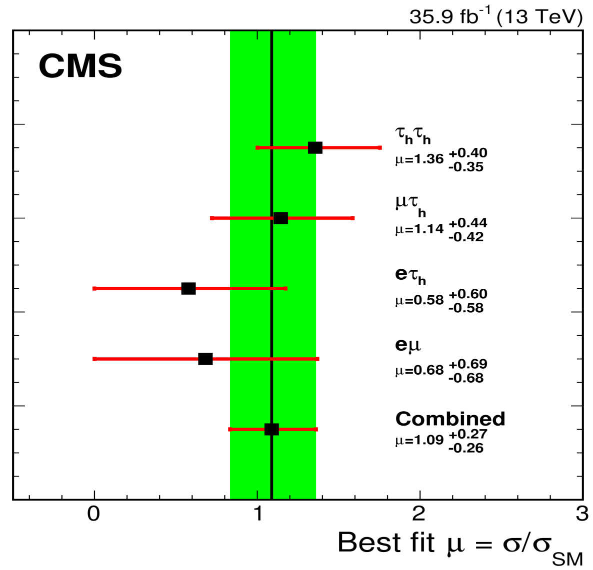
ATLAS ATLAS-CONF-2018-21

- 2 categories: VBF and boosted
- Cut-based analysis using fit to m distribution in 13 signal regions
- Run2:Obs. (exp.) sig. of 4.4 (4.1)

CMS PLB 779 (2018) 283

- 3 categories: 0-jet, VBF and boosted
- Extracting the signal in 2D likelihood fit
- Dominant backgrounds : di-boson +fake τ
- 2016: Obs. (exp.) signific. of 4.9 (4.7)

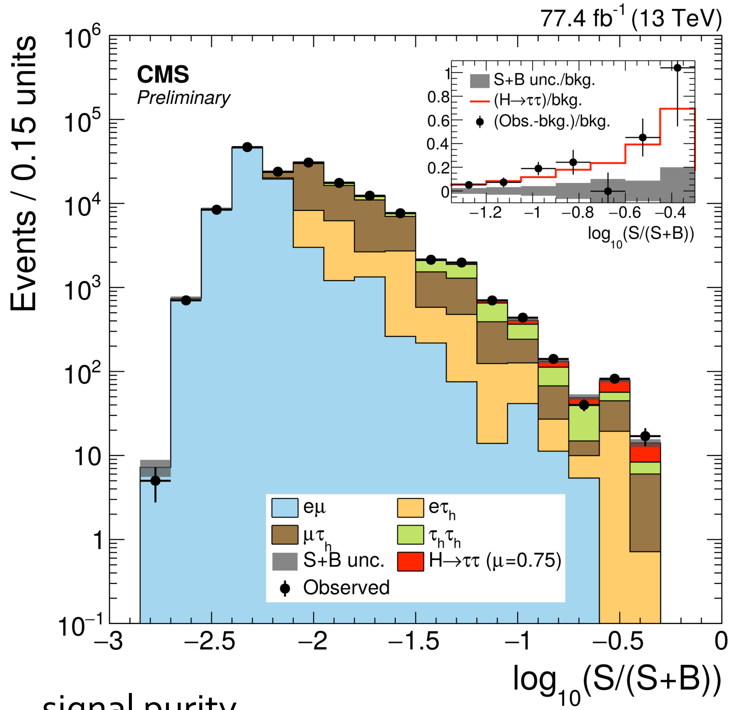




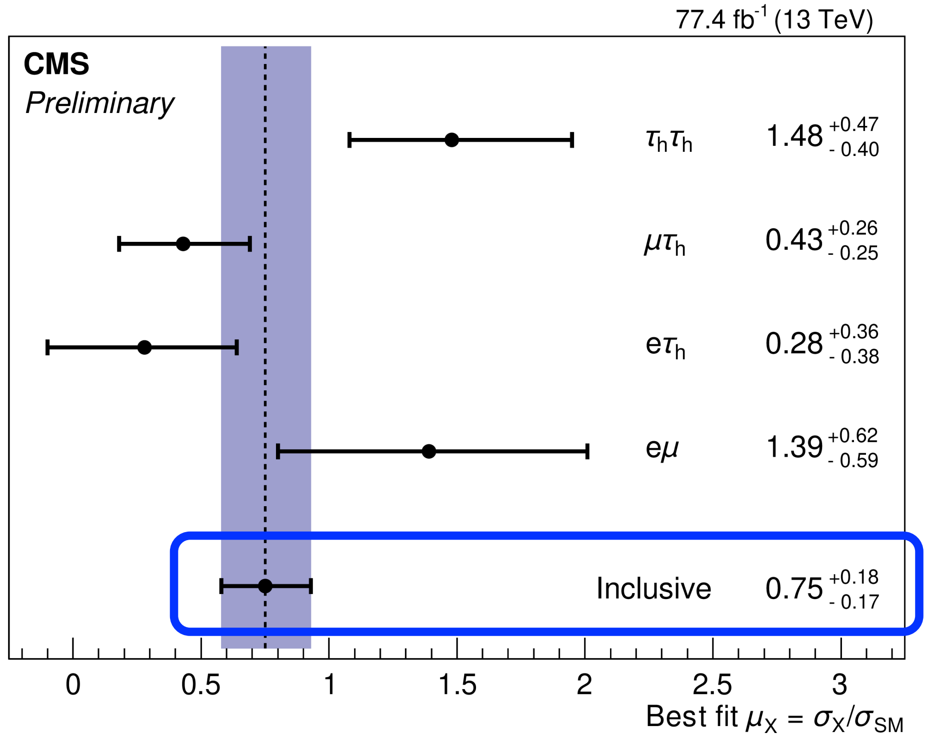
Run 1+2	Obs (exp) significance	μ(H→ττ)
ATLAS	6.4 (5.4) σ	$1.09^{+0.18}_{-0.17}(stat)\ ^{+0.26}_{-0.22}(syst)\ ^{+0.16}_{-0.11}(the)$ (VBF, boosted)
CMS	5.9 (5.9) σ	0.98 ± 0.18 (VH, ggF, VBF)

CMS: Cross section σ_{incl}*B(H→ττ) New

- Inclusive production xsec σ*B(H→ττ) in ggH & VBF production modes, Run-2 (16+17)
- S/B discrimination by Neural Network multi-classifier → pure categories (ggH, VBF, BGN)
- MC for NN training; for signal extraction some 90% of backgrounds are estimated from data (by τ-embedding for genuine taus, and fake rate method for reducible background)
- Tau-pair selection by eμ, $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$ channels



signal purity



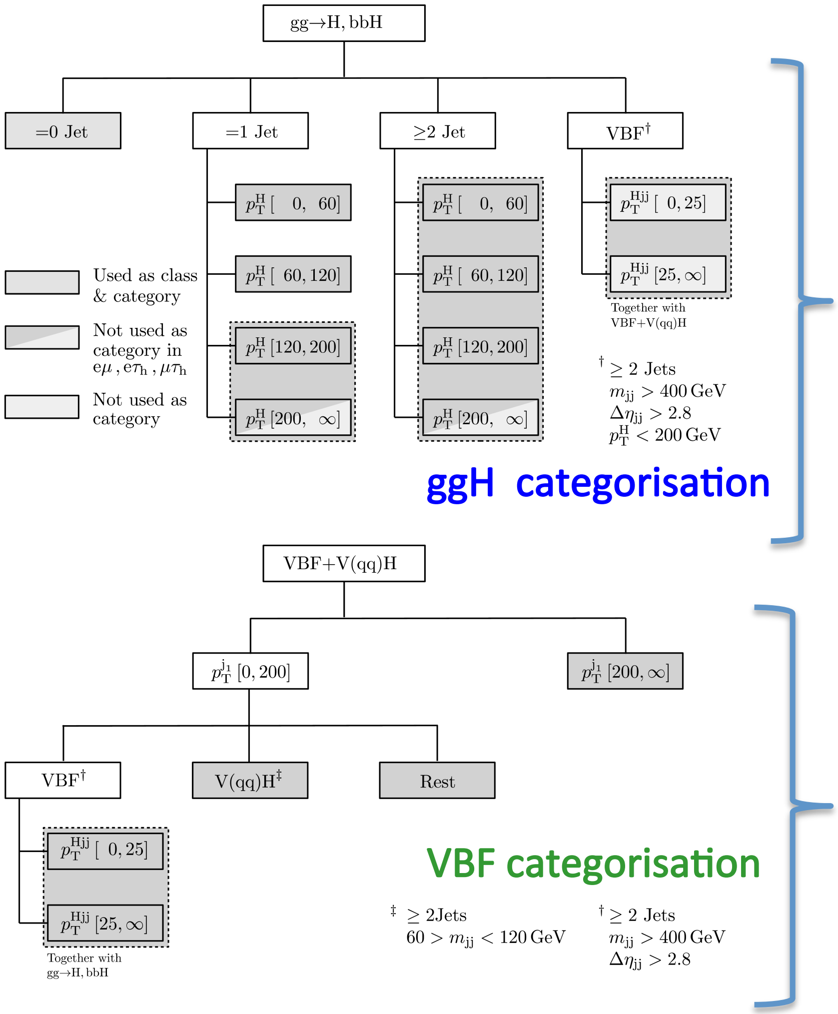
$$\sigma_{incl} \cdot B(H \to \tau\bar{\tau}) = 2.56 \pm 0.48(stat) \pm 0.34(syst)\,\text{pb}$$

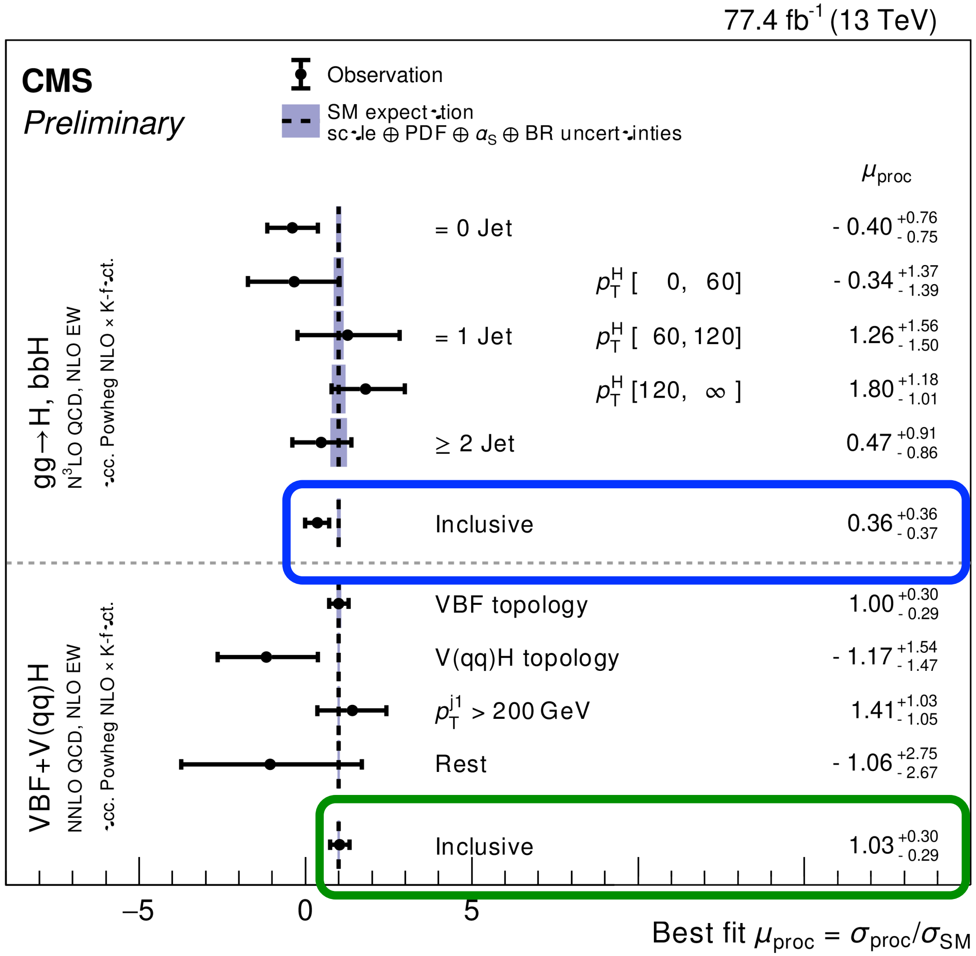
CMS PAS HIG-18-032

CMS: STXS σ_{incl}*B(H⟶ττ)

- First stage-1 categorisation for tau-tau in many ggF+VBF bins, AND inclusive fit result
- STXS from MLL-fit for 9 categories, extracting signal strength parameters.

CMS PAS HIG-18-032





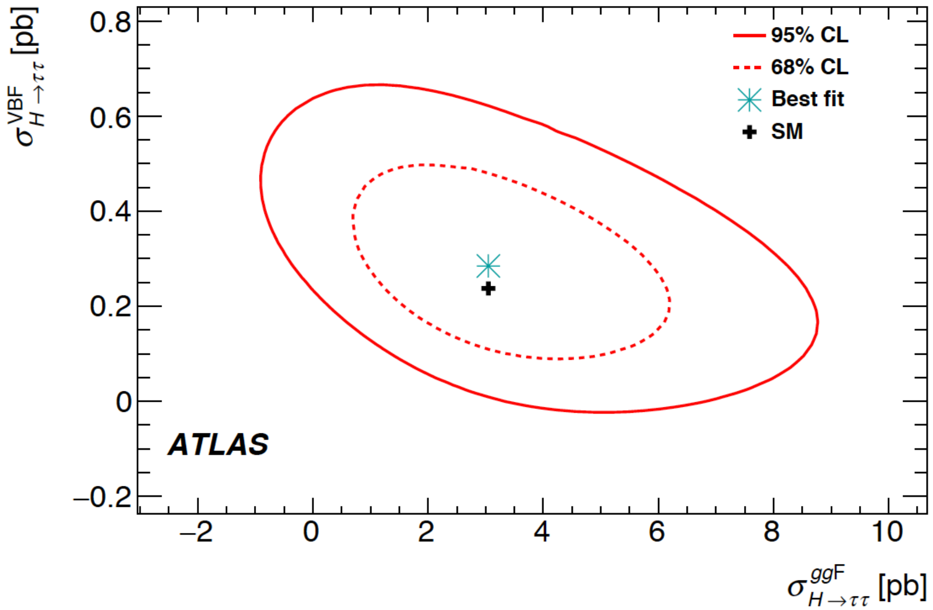
ATLAS: STXS in H→ττ

ATLAS arXiV:1811.08856

ATLAS: H→ττ (36 1/fb)

- Analysis identical to inclusive analysis; use 3D fit to measure STXS
  - ggF and VBF production cross sections set to measured values, if outside particle-level range..
  - Cross sections of other H-production processe set to SM values
- **Good agreement with SM predictions**

2D fit for ggF vs VBF



Process	Particle-level selection	σ [pb]	σ^{SM} [pb]
ggF	$N_{jets} \geq 1, 60 < p_T^H < 120$ GeV, $\lvert y_H \rvert < 2.5$	1.79 ± 0.53 (stat.) ± 0.74 (syst.)	0.40 ± 0.05
ggF	$N_{jets} \geq 1, p_T^H > 120$ GeV, $\lvert y_H \rvert < 2.5$	0.12 ± 0.05 (stat.) ± 0.05 (syst.)	0.14 ± 0.03
VBF	$\lvert y_H \rvert < 2.5$	0.25 ± 0.08 (stat.) ± 0.08 (syst.)	0.22 ± 0.01

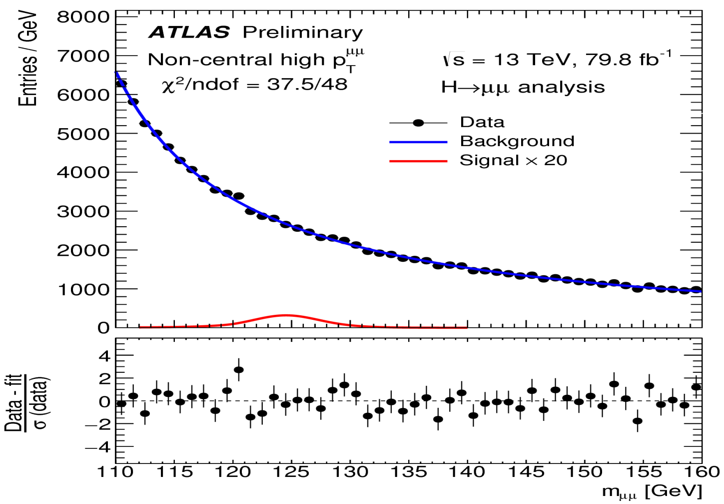
CMS: VVH (H→ττ) : Anomalous couplings on the VVH vertex, not H-->ττ (see CMS-HIG-17-034)
(see talk Donszelmann)

$H \longrightarrow \mu\mu$ Decays

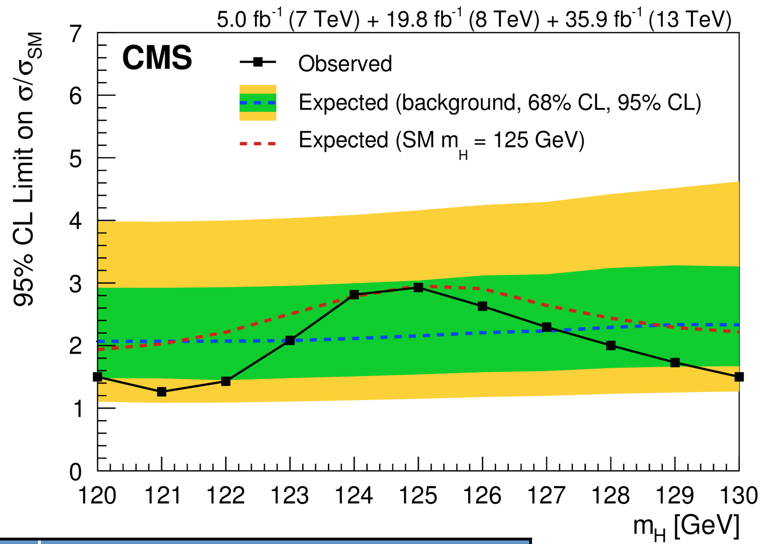
Search for H→μμ in CMS and ATLAS

- Isolated muons provide **clean final state** in search for ggH and VBF: **but small BR** !
- Peak search on smooth background; background shape extracted from sidebands in data
- Good m(μμ) resolution needed for rejection of DY and leptonic tt_{bar} backgrounds
- Use MVA techniques to categorize VBF and ggF enriched regions [in p_T (μ) resolution]

ATLAS ATLAS-CONF-2018-026



CMS **PRL 122 (2019), 021801**



Run 1+2	upper limits on obs. (exp.) production rate at 95% C.L.	Data periods
ATLAS	< 2.1 (2.0) x SM prediction	Run 2 (79.8 1/fb)
CMS	< 2.9 (2.2) x SM prediction	Run 1+2 (24.8+35.9 1/fb)

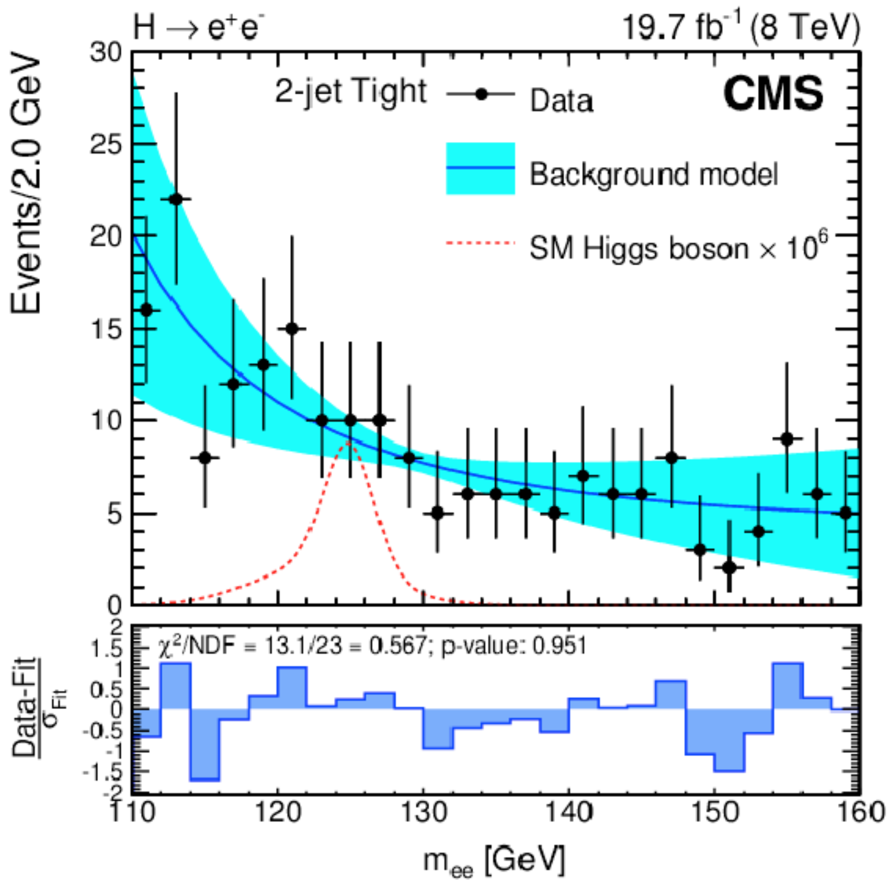
$H \longrightarrow ee$ Decays

Search for H→ee in CMS

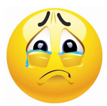
CMS PLB 744 (2015) 184

- **Nearly hopeless** : B_{SM}(H->ee)=5*10^{-9}
- Run1: 8 TeV , 19.7 1/fb
- Search for narrow peak in m(ee) in four categories (0, 1 and 2 jets)
- Setting upper limit (95% cl)on BF (H→ee) <0.00019

Signal enhanced by 10^6 !



Run 1	UL. on B(H→ee) / B_{SM}
CMS	$< 3.7 \cdot 10^5$ (95% CL)



Outlook and Conclusions

Extrapolation for HL-LHC for H→fermions

arXiv: 1902-00134v2

- Assume various scenarios on treatment of systematics uncertainties

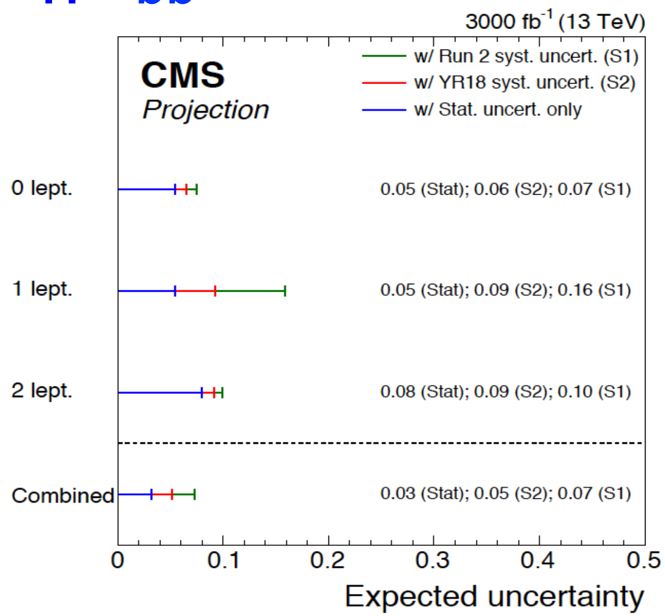
  - **H→bb** – uncertainties dominated by theoretical modelling of signal production xsec. experimentally by b-tagging
    expect precision on μ ~5-7 % (here CMS)

  - **H→ττ** - precision reached similar to theory predict. uncertainties dominated by theoretical errors on signal acceptance and background modelling
    expect precision on μ ~10 % (here ATLAS)

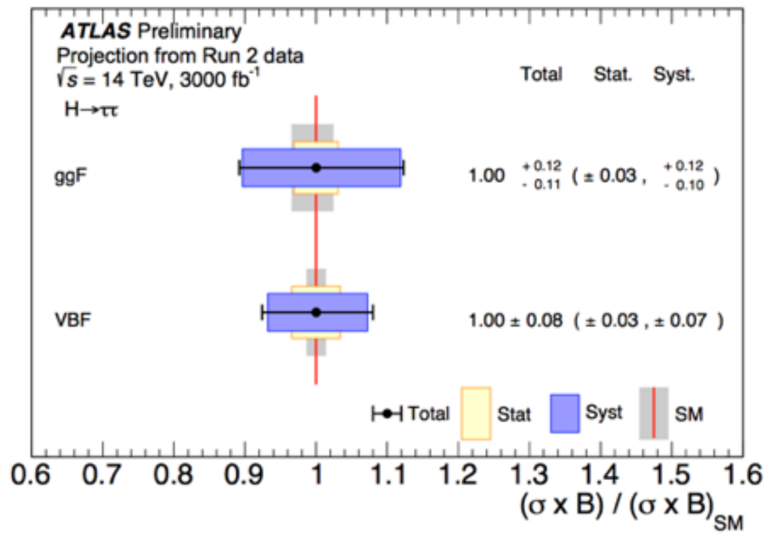
  - **H→μμ** - analysis limited by stat uncertainty; leading systematics is bias of dimuon fit function.
    expect unc. on μ ~ 15% for ATLAS/CMS
    observation in reach at HL-LHC

  - **ttH** : Yukawa couplings - mostly dominated by tt+bb Xsec uncertainty in ttH→bb final state - relative precision on μ ~14% (11%) for ATLAS (CMS)

H→bb



H→ττ



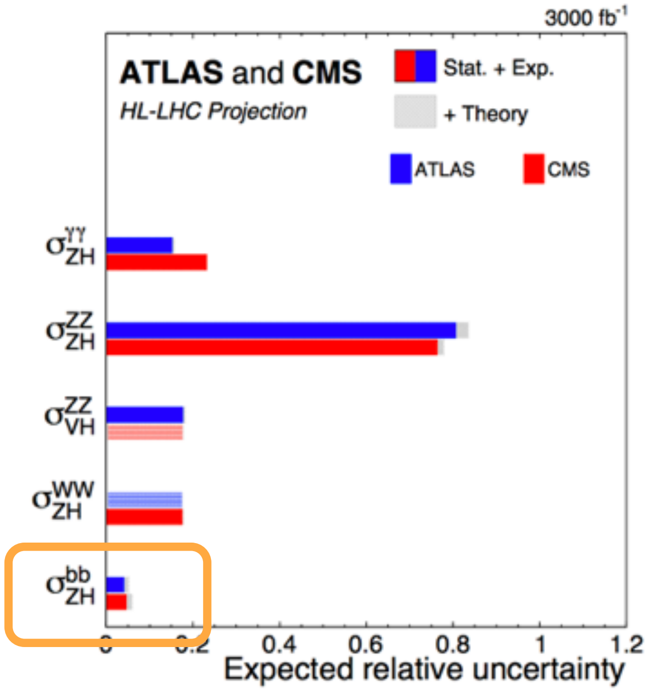
Full coupling combination at HL-LHC

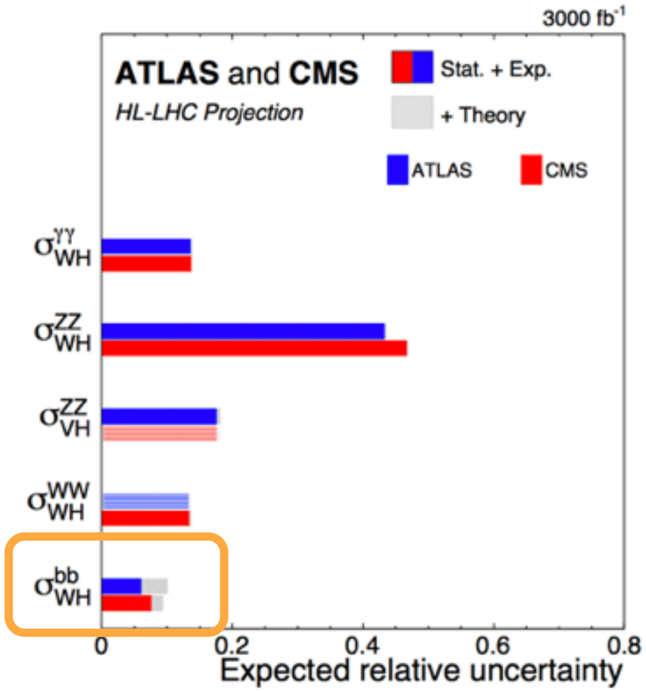
- Coupling combination in ATLAS and CMS for productions and decays in Higgs to fermion decays
  - Assume dedicated scenarios for treatment of systematics uncertainties

Extensive doc in arXiv: 1902-00134v2

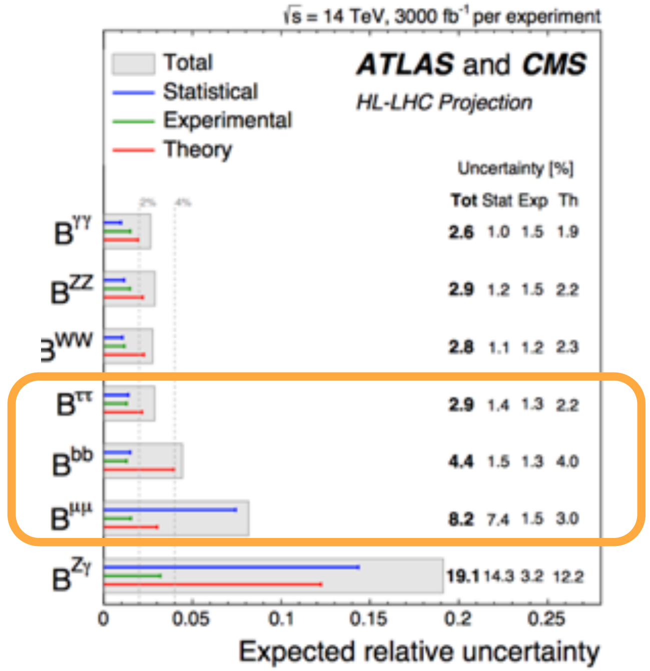
Expected relative uncertainty on:

production cross sections





branching ratios



Conclusions for H$\longrightarrow$ fermions

- **Standard Model** assumption on **Yukawa coupling was confirmed** within the present **O(20%)** uncertainty in the
  - **decays of Higgs to b-quarks and tau-leptons,**
  - **production process ttH, with H$\rightarrow$** bb/$\tau\tau$/ZZ*/WW*/$\gamma\gamma$

- **CMS and ATLAS have independently reached clear observations beyond >5σ level for combinations of different production channels for the decays H$\rightarrow$bb and H$\rightarrow\tau\tau$ and in the ttH production process.**

- **First simplified cross section measurements (STXS)** available for Hbb and H$\tau\tau$,
- **First limits on anomalous couplings available for H$\rightarrow$bb vertex**

- **Just started towards measuring Higgs-Yukawa couplings with high precision expect rel. precisions well below the 10% for HL-LHC**

- All this only thanks to the **fantastic running of LHC,**
  and the ATLAS and CMS detector performances

In case of discussions and questions …

BACKUP SLIDES

Backup

Top-Yukawa coupling in ttH

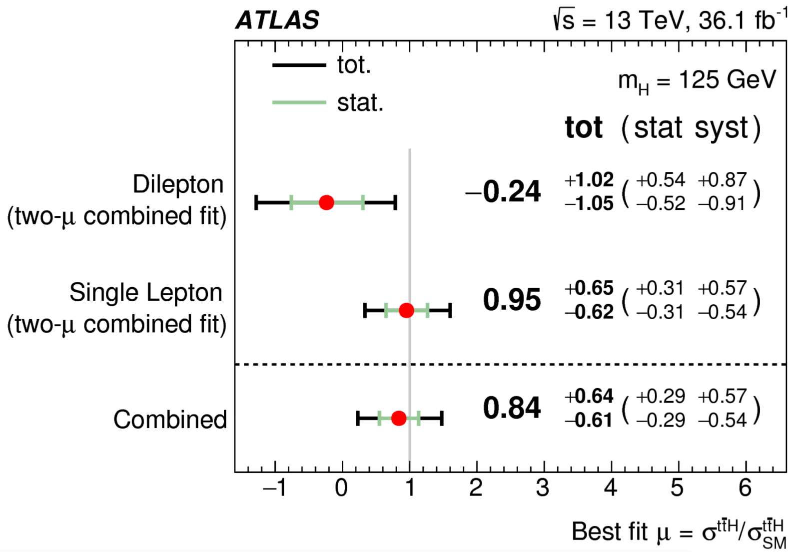
Results of ttH→bb

Backup

ATLAS

Phys.Rev.D 97, 072016 (2018)

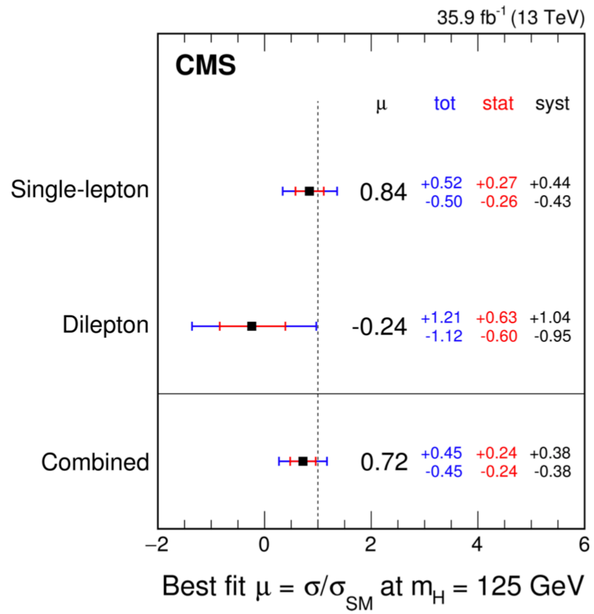
- Analysis in single, dilepton and boosted region
- b-tagging working points and jet multiplicity used to build regions
- Theoretical background uncertainty dominated by tt+heavy flavour process
- Signal: BDT for signal reconstruction; additional BDT for BGND separation (ttH vs ttbb) based on FS-kinematics and b-tagging
- BDT in SR +scalar sum pt(jet) or single bin in CR
- Expected (obs) significance: 1.6σ (1.4σ)



CMS

PLB 776 (2018) 355

- Large uncertainty on tt+bb BGND driven by modelling of tt+jets process in MC simulation
- Normalisation to NNLO gen; split into tt+b, tt+bb, tt+3b, tt+ light-jets - 50% uncertainty associated
- Signal extraction: matrix-element method (MEM) and MVA approaches (BDT and DNN)
- Fully-hadronic final state also included (main background is QCD multi-jet production)
- Exp (obs) significance: 2.2σ (1.6σ), exp (obs) UL for full-had xsec: <3.8σ (3.1σ)



Evidence for ttH→ZZ*/WW*/ττ

ATLAS

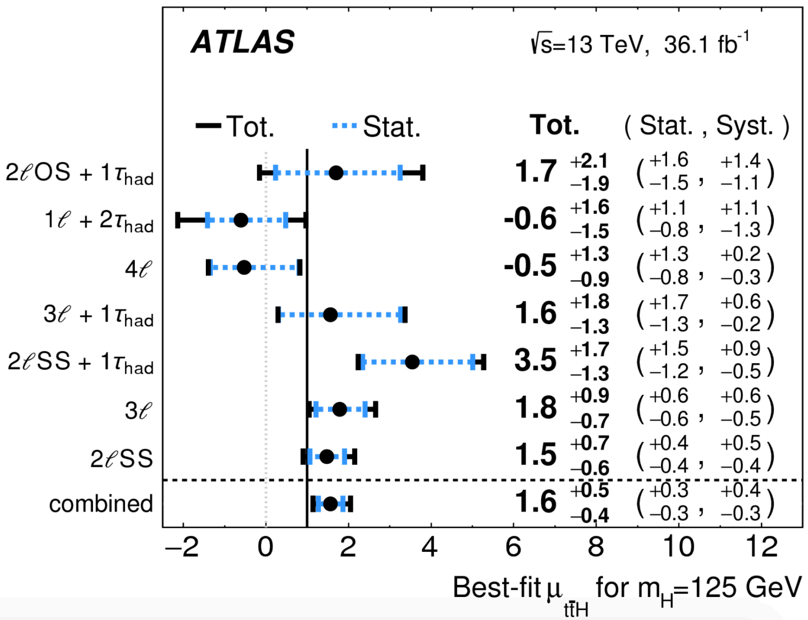
Phys.Rev.D 97, 072003 (2018)

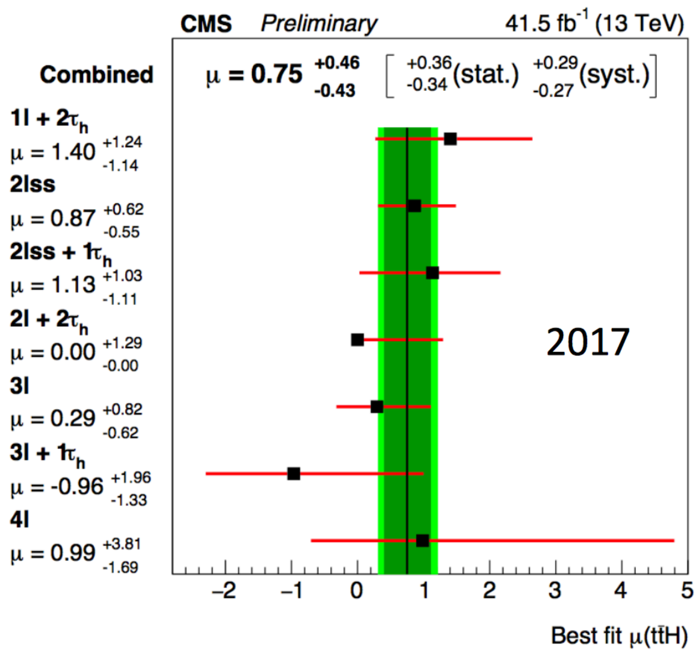
- Based on lepton and hadronic τ multiplicities
- Background: MC (tt+V and diboson) and validated in data or from data control regions (non prompt leptons, charge mis-id)
- BDT discriminant: event kinematics in signal region - control regions used to constrain background components
- Expected (observed) significance: 2.8σ (4.1σ)

CMS

CMS-HIG-08-19

- Analysis strategy based on combination of sim yield, BDT and MEM according to final state
- Categories combined with maximum likelihood fit
- Dominant systematics uncertainties: theoretical modelling of tt+V and diboson backgrounds, lepton reconstruction efficiency
- Expected (observed) significance: 4.0σ (3.2σ)





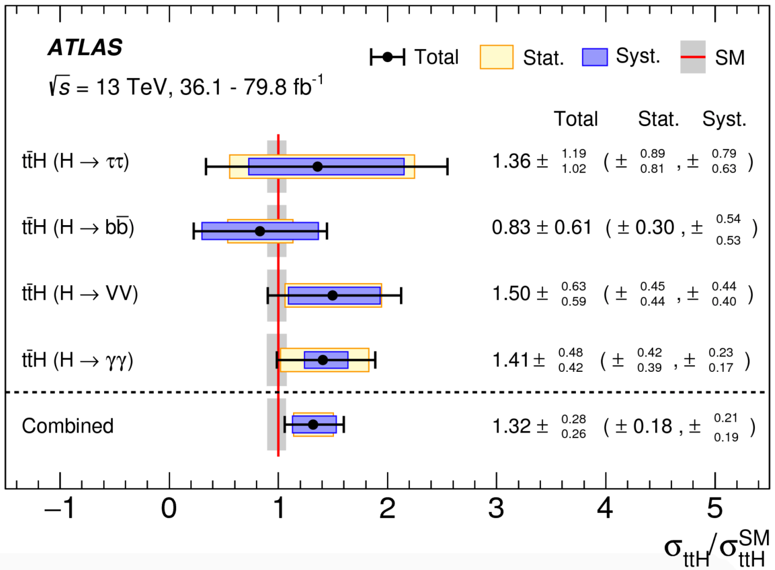
Combination of ttH Results

Backup

ATLAS Phys.Lett. B784 (2018) 173

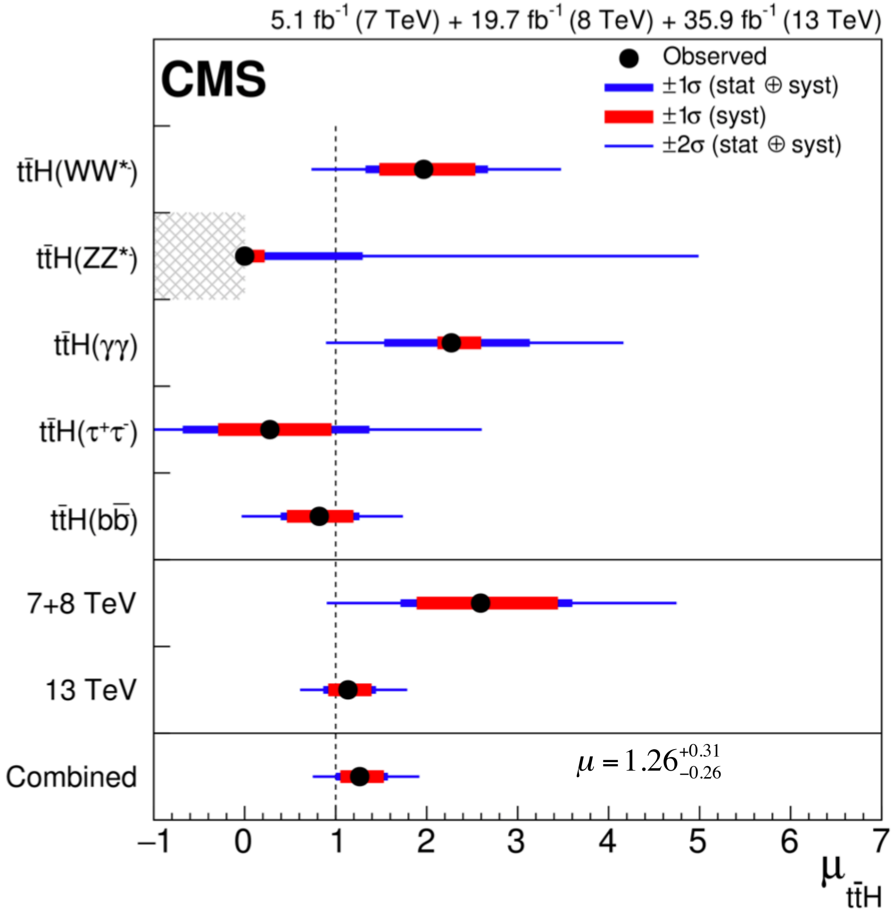
- Channels: bb, multi-lepton (36.1 /fb), γγ and ZZ*→4l (79.8 /fb)
- Dominant systematics → theory and MC model
- Combined significance: **6.3σ obs (5.1σ exp)**

Analysis	Integrated luminosity [fb^{-1}]	Expected significance	Observed significance
$H \to \gamma\gamma$	79.8	3.7 σ	4.1 σ
$H \to$ multilepton	36.1	2.8 σ	4.1 σ
$H \to b\bar{b}$	36.1	1.6 σ	1.4 σ
$H \to ZZ^* \to 4\ell$	79.8	1.2 σ	0 σ
Combined (13 TeV)	36.1−79.8	4.9 σ	5.8 σ
Combined (7, 8, 13 TeV)	4.5, 20.3, 36.1−79.8	5.1 σ	6.3 σ



CMS CMS_HIG-17-031

- bb, multilepton and γγ final states
- Combined significance (7, 8 and 13 TeV datasets) **5.2σ observed (4.2σ expected)**



Backup

More backup

Search for boosted resonances Z′⟶bb +j

Backup

- Search signal = boosted resonance (e.g. Z′) decaying to bb and ONE additional jet - in ggF, VBF and VH ; using Run-2 (80.5 1/fb)

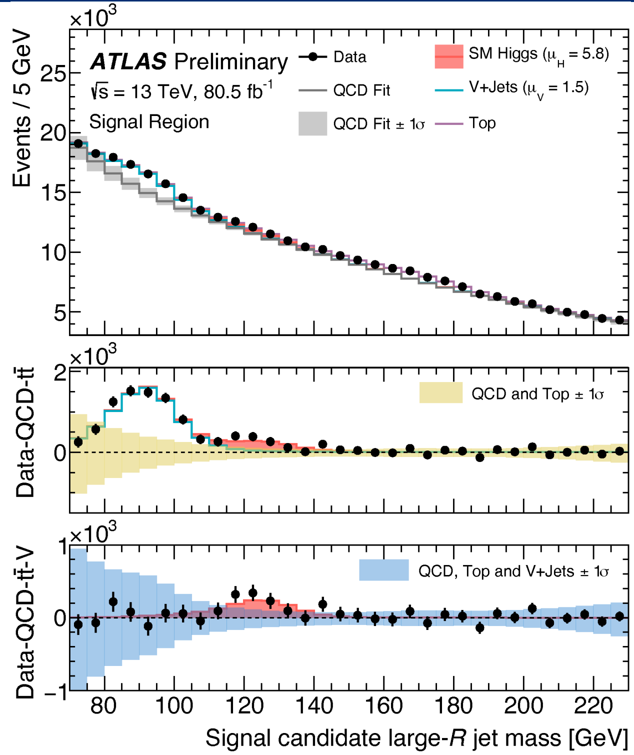
- Mass range searched 70-230 GeV for boosted decays ($2m_J/p_T<1$)

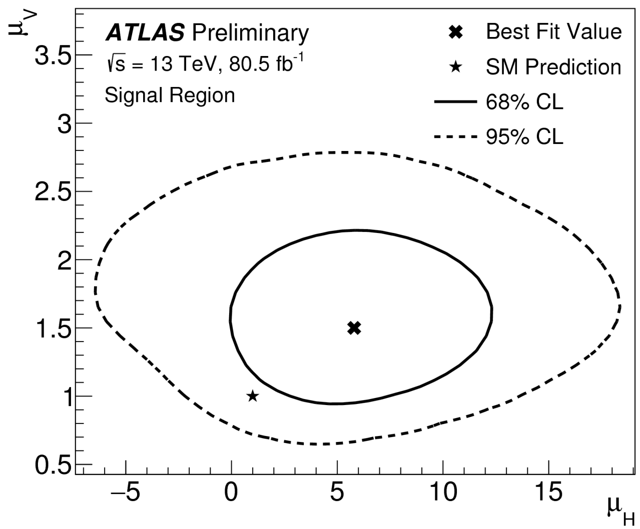
- **Deduced limits on leptophobic Z′ bosons** with democratic axial couplings to all quark families are set using Bayesian method

- Combined simultanous LL-fit (V+jets and H+jets) yields signal strengths for standard V + jets and H+jets processes of :

  μ_{V+jets}= 1.5 ±0.22(stat.) +0.29/-0.25(syst.) ±0.18 (th.) (>5 s.d.)

  μ_{H+jets} = 5.8 ±3.1 (stat.) ±1.9(syst.) ±1.7 (th.)





ATLAS-CONF-2018-052/

CMS-PAS-FTR-18-011

Backup

VH, H→b$\bar{b}$ at HL-LHC

- Consider various scenarios for uncertainties:
  - **With Run-2 systematic uncertainties**: uncertainties as in Run 2 (S1)
  - **With YR18 systematic uncertainties**: most experimental uncertainties scale down with sqrt(L), until a lower limit is reached. Theoretical uncertainties are assumed halved. (S2)
  - **Stat. Only.**: No systematic uncertainties considered
- At 3 ab^{-1}, measurement will be driven by theoretical uncertainties, ggZH QCD scale uncertainty becomes important.
- All channels contribute ~equally: challenge experimentally to maintain trigger thresholds.
- Effect of changing b-tagging efficiency is non-negligible.

	S1	S2
Total uncertainty	7.3%	5.1%
Signal theory uncertainty	5.4%	2.6%
Inclusive	4.6%	2.2%
Acceptance	2.7%	1.3%
Background theory uncertainty	2.8%	2.3%
Experimental uncertainty	2.6%	2.2%
b-tagging	2.2%	2.0%
JES and JER	0.7%	0.6%
Statistical uncertainty	3.2%	3.2%