Higgs production in the VH mode at ATLAS and CMS

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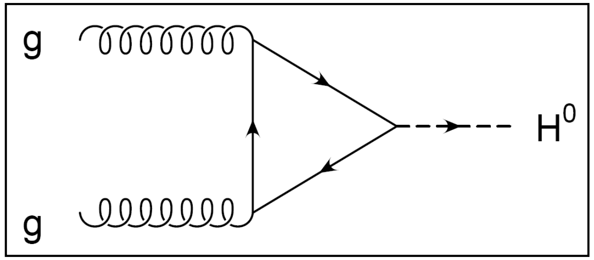
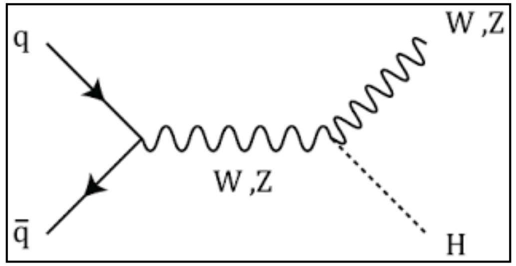
LHCP2019: 7th Edition of the Large Hadron Collider Physics Conference

Benemérita Universidad Autónoma de Puebla, Puebla (Mexico),
20-25 May 2019

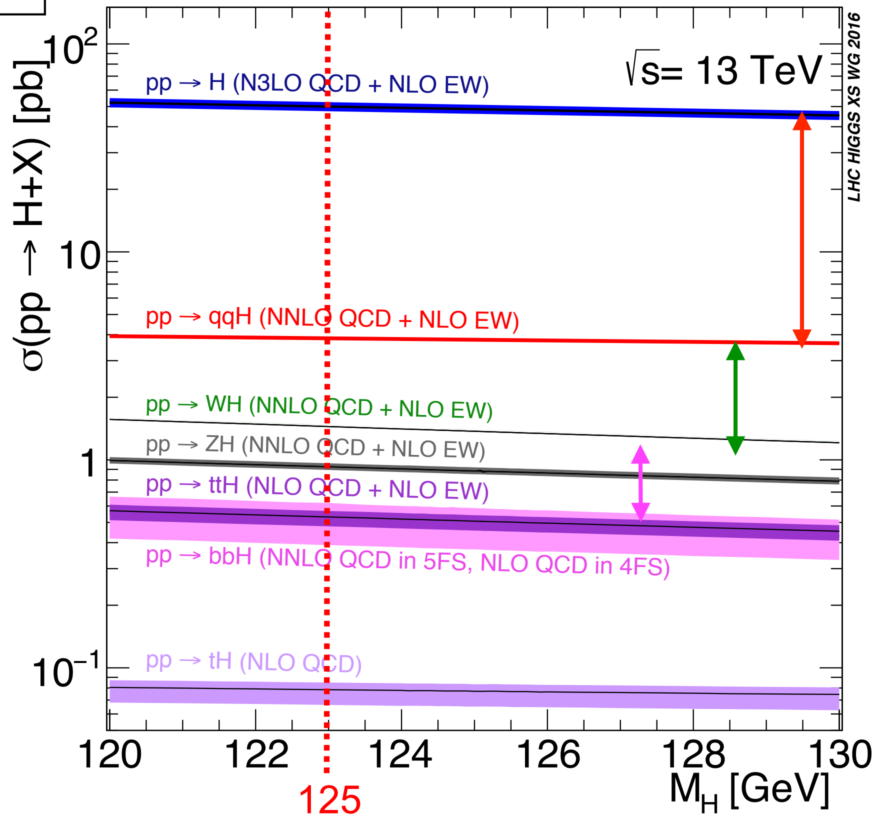
- **Main Higgs boson production mechanism at the LHC:**

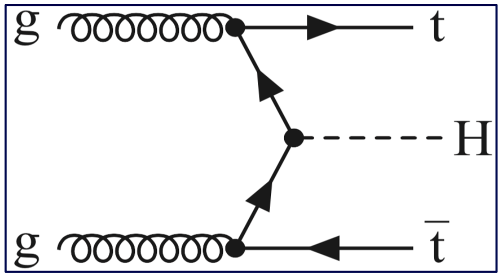


Gluon-fusion: 87%

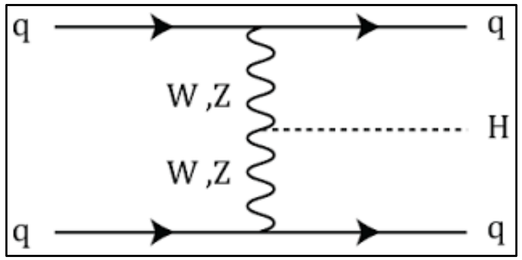


WH: 3%
ZH: 2%

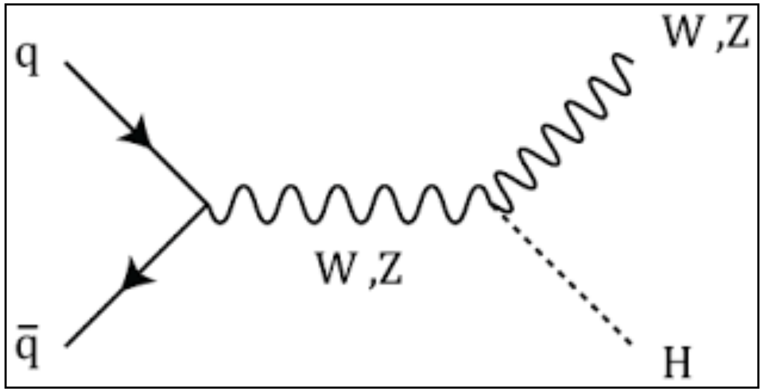




ttH: 1%

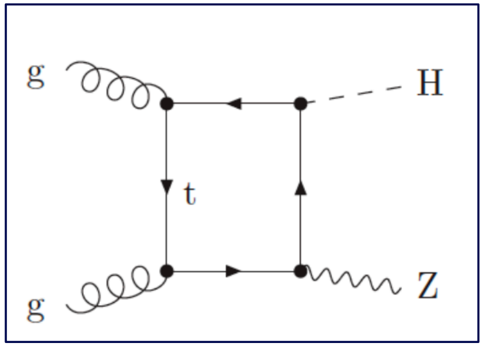


VBF (qqH): 7%



Higgs-Strahlung (associated production)

- 4% of Higgs production mechanism
- NLO QCD corrections can be obtained from those to Drell-Yan: +30% (also NNLO QCD)
- Full EW corrections known: they decrease the cross section by 5-10%



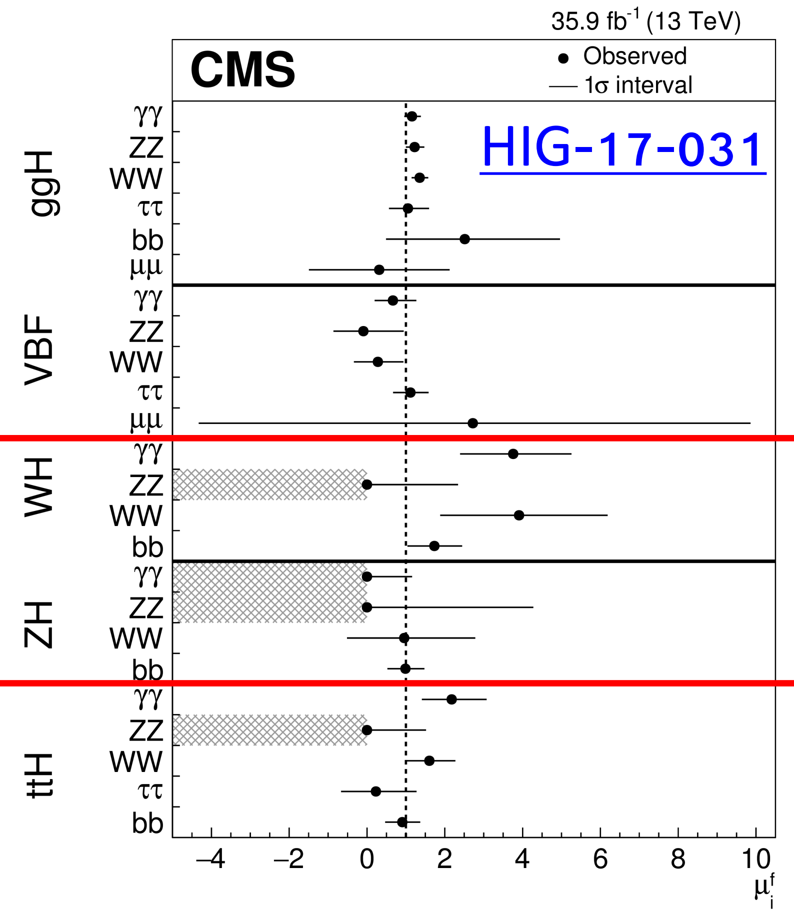
- For ZH at NNLO further diagrams from gg initial state
- Important at the LHC (+2-6% effect up to +14% at high-p_T)

Experimental advantages:

- **Vector boson (V) decay leptonically**: → Benefit from lepton triggers
- **V-Boost**: Further reduce background requiring high vector-p_T

VH production mode: State of the art

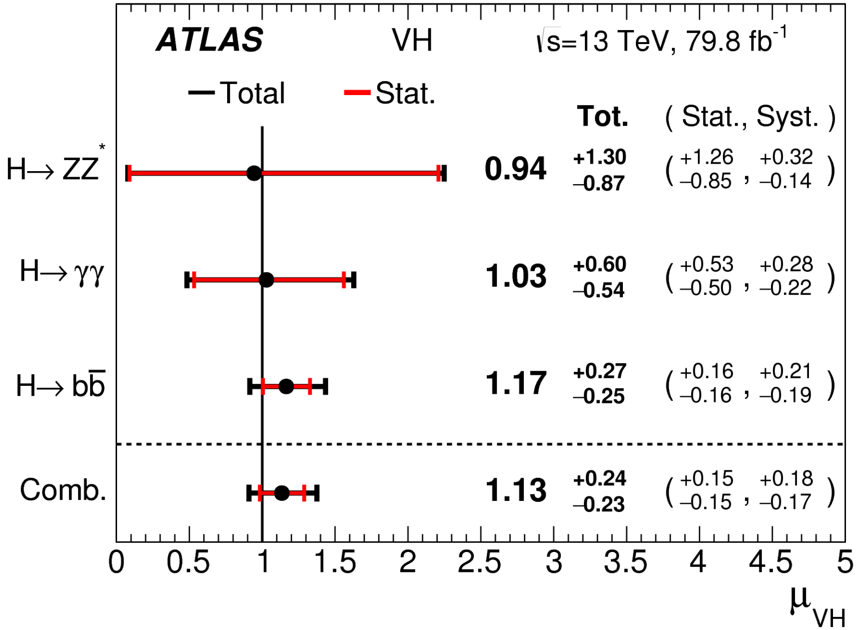
- Combined measurements of Higgs production cross-sections in the ZZ, $\gamma\gamma$, WW, bb, ττ, and μμ decay modes



- Integrated luminosity of 36 fb^{-1}

- ATLAS observation of VH production
- Driven by VH(H→bb) search
- Integrated luminosity of 80 fb^{-1}

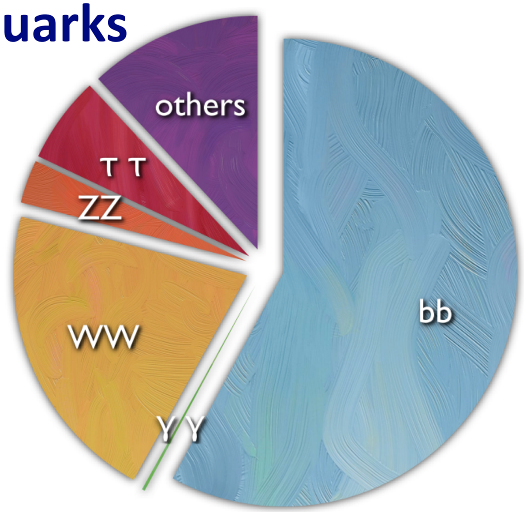
HIGG-2018-04



Generally consistent with SM predictions

H→bb physics case and VH role

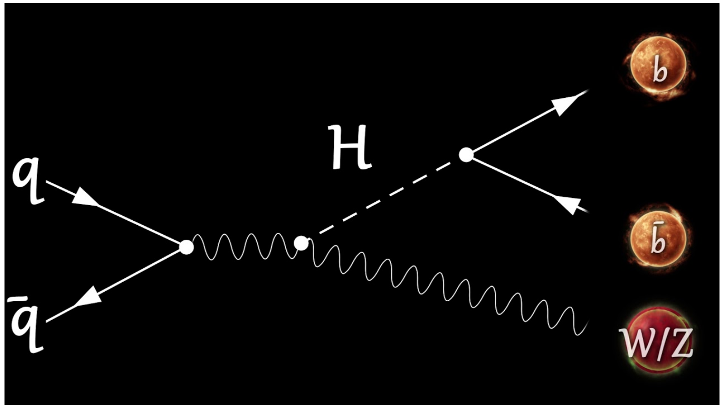
- Unique final state to measure **coupling with down-type quarks**
- **H→bb has the largest BR (58%) for m_H=125 GeV**
- **Drives the uncertainty on the total Higgs boson width**
  - **Limits the sensitivity to BSM contributions**
- **Only recently observed by both ATLAS and CMS**



- **High BR**
- **Low mass resolution**
- **Low S/B**

→

- **Highly efficient b-jets identification**
- **Improved resolution on m(bb)**
- **Full event information to increase S/B**



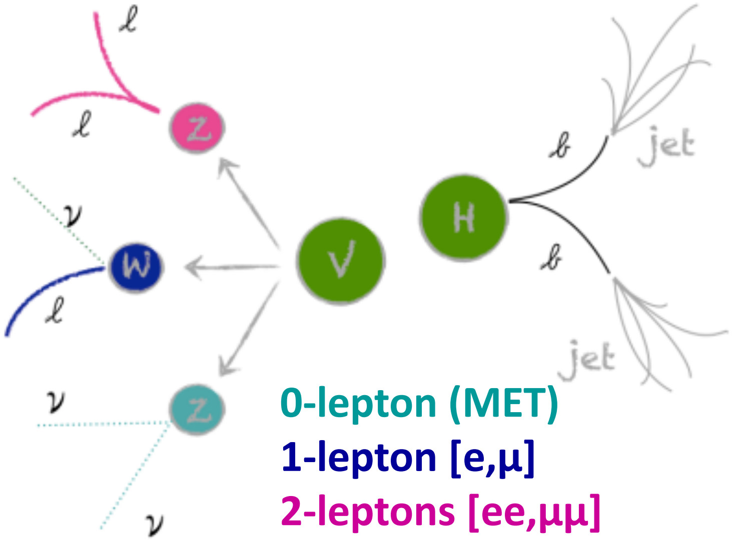
VH production plays a crucial role

- W/Z decays leptonically
- W/Z produced generally back-to-back vs Higgs
- Possible to exploit the W/Z transverse boost

➔ **Provides the most sensitive channel for H→bb**

VH(H→bb) Analysis Strategy - ATLAS and CMS

SIGNAL PROCESSES

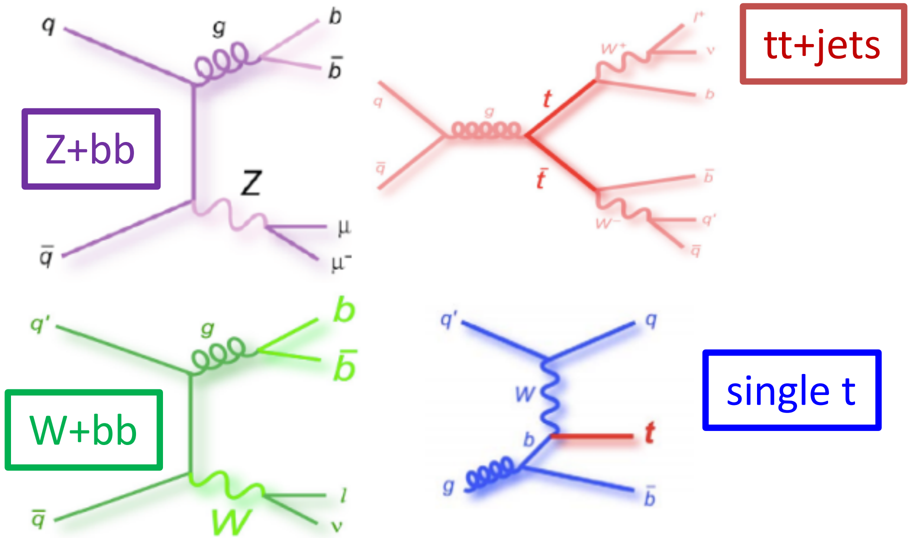


0-lepton (MET)

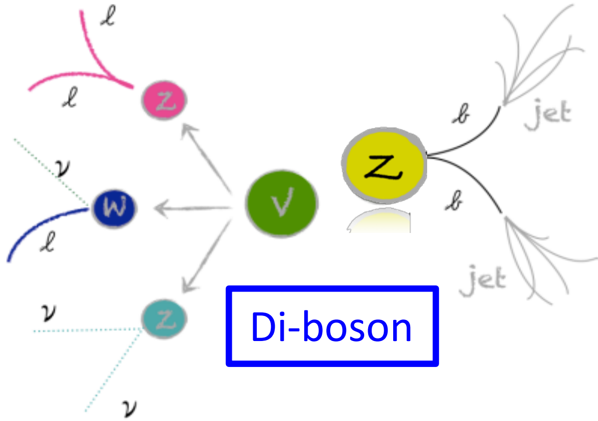
1-lepton [e,μ]

2-leptons [ee,μμ]

IRREDUCIBLE BACKGROUNDS



- **3 channels** with 0, 1, and 2 leptons and 2 b-tagged jets
  - Target **Z(νν)H(bb)**, **W(lν)H(bb)** and **Z(ll)H(bb)**
- **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 constrain normalizations**
- **Signal extraction:** binned maximum likelihood fit of final MVA/mass distribution

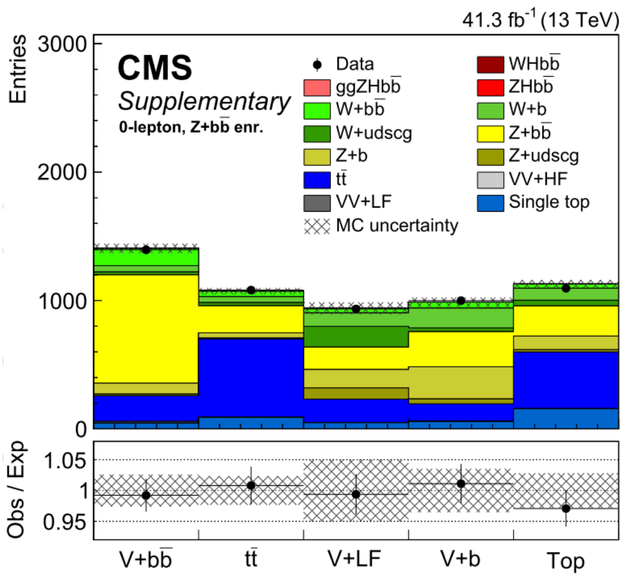
Event Selection+Categorization - CMS

- **Selections** (jets, leptons, b-tagging) **optimized separately by channel**
  - 4 analysis categories:
    - 0-lepton: **$p_T(Z)$ > 170 GeV**
    - 1-lepton: **$p_T(W)$ > 150 GeV**
    - 2-lepton High-Vp_T: **$p_T(Z)$ > 150 GeV**
    - 2-lepton Low-Vp_T: **50 GeV < $p_T(Z)$ < 150 GeV**

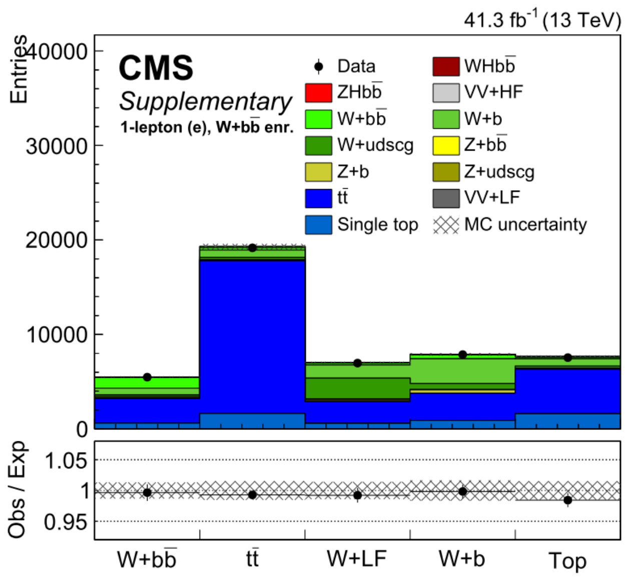
- **Control regions** designed to map closely each signal region
  - Inverted selections to **enhance purity in targeted backgrounds:**

tt, V+light flavor, and V+heavy flavor

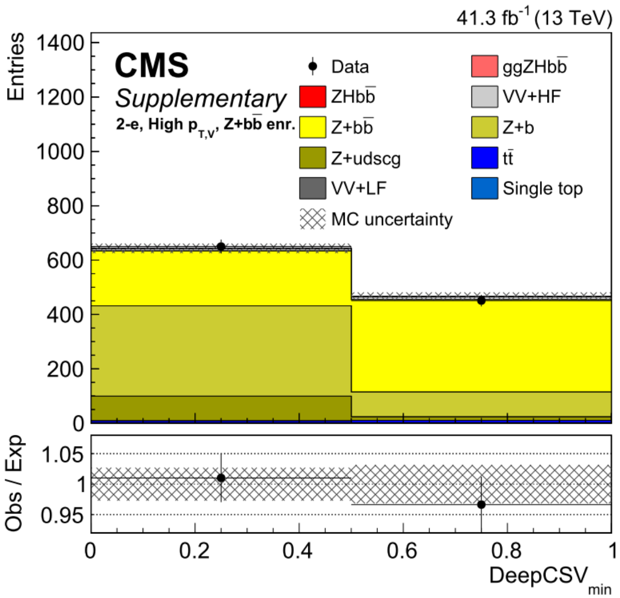
0-Lepton



1-Lepton



2-Lepton

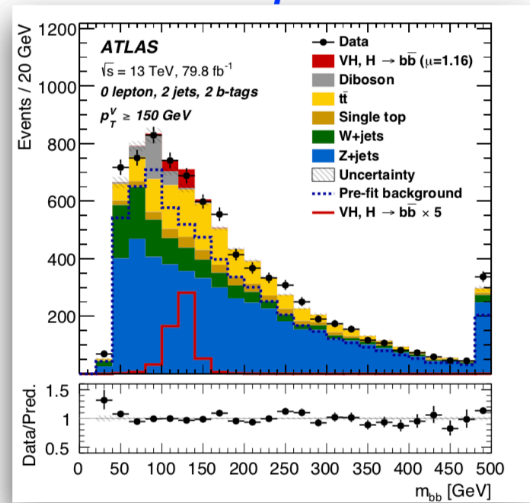


Event Selection+Categorization - ATLAS

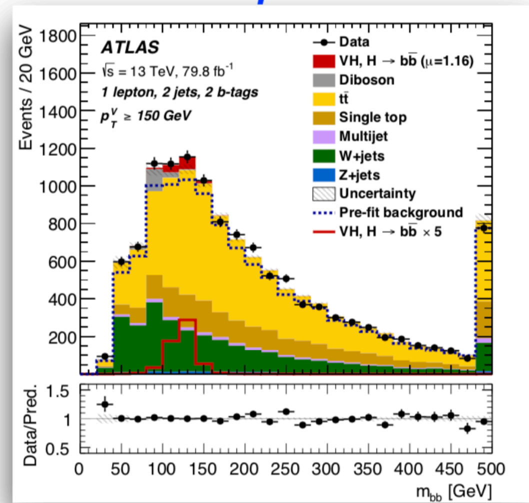
- **Selections** (jets, leptons, b-tagging) **optimized separately by channel**
  - 4 analysis categories + split in 2- and 3-jets:
    - 0-lepton: **$p_T(Z)$ > 150 GeV**
    - 1-lepton: **$p_T(W)$ > 150 GeV**
    - 2-lepton High-Vp_T: **$p_T(Z)$ > 150 GeV**
    - 2-lepton Low-Vp_T: **75 GeV < $p_T(Z)$ < 150 GeV**

- **6 Control regions:**
  - 2 W+HF CRs
  - 4 top CRs

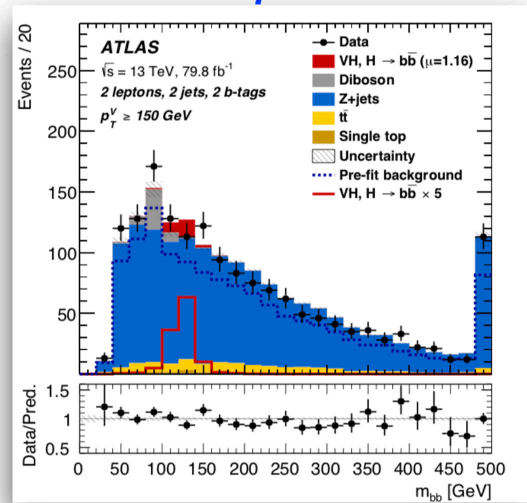
0-lepton



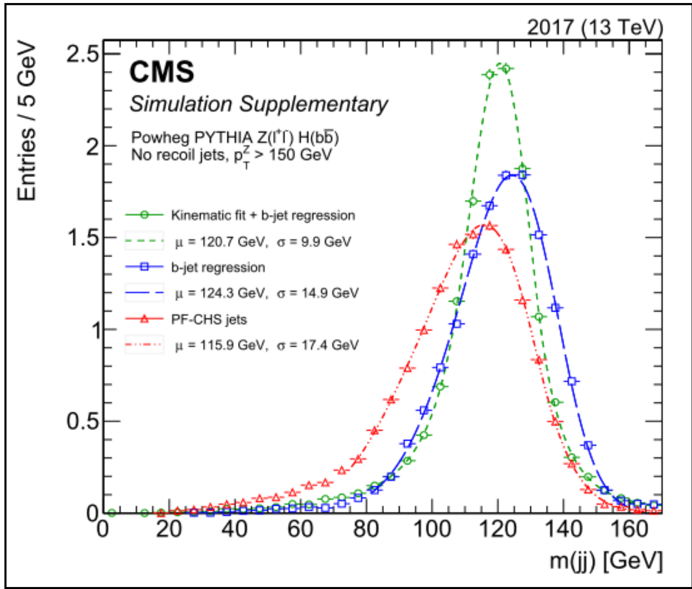
1-lepton



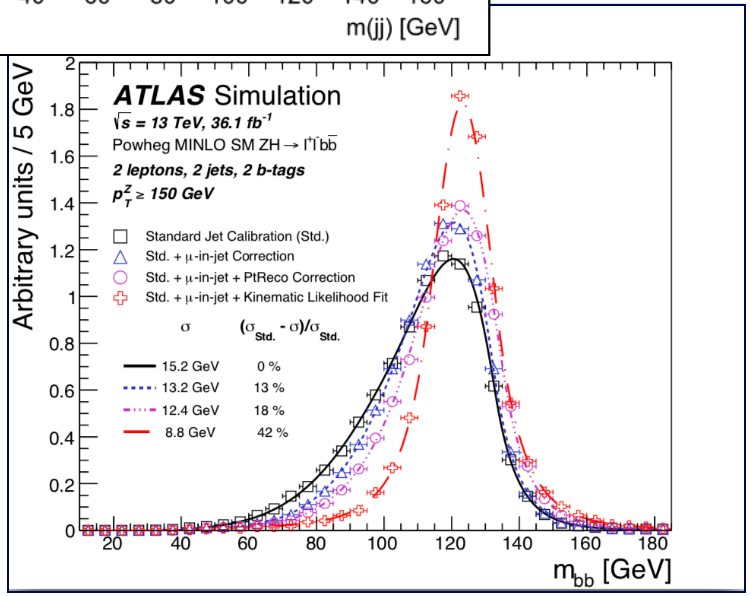
2-lepton



Improvements in invariant mass resolution



- **CMS:**
  - Better b-jet identification vs 2016
    - ➔ Improved b-tagger (2017)
    - ➔ + new pixel detector (2017)
  - b-jet energy regression + FSR
  - Kinematic fit in 2-lepton channel



- **ATLAS:**
  - Recovery of soft muon inside b-jet cone
  - Scaling of jet p_T to compensate for υ's
  - Kinematic fit in 2-lepton channel

- **Signal extraction:**

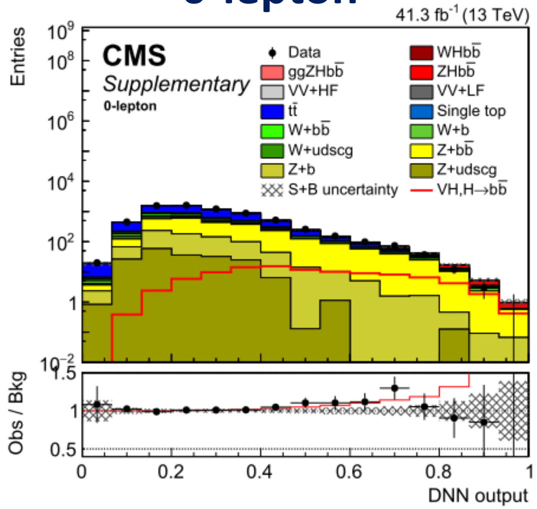
CMS ➔ Use of (**DNN**) to discriminate sig. from bkg. in SR + various bkg in CRs

ATLAS ➔ Use of (**BDT**) in each signal region

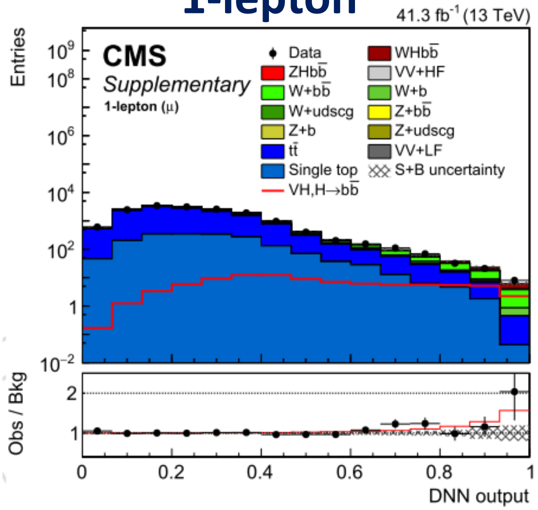
Signal extraction – CMS

- **CMS**

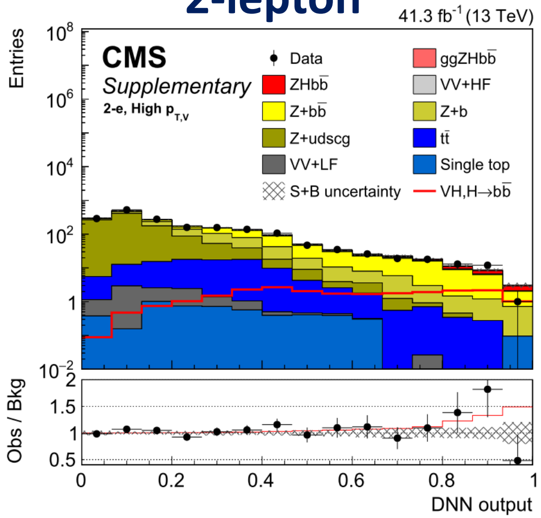
0-lepton



1-lepton

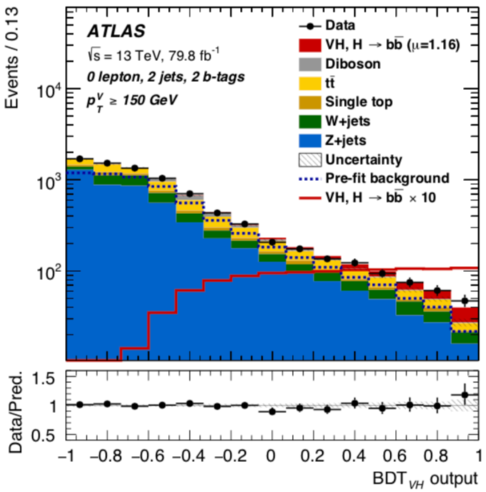


2-lepton

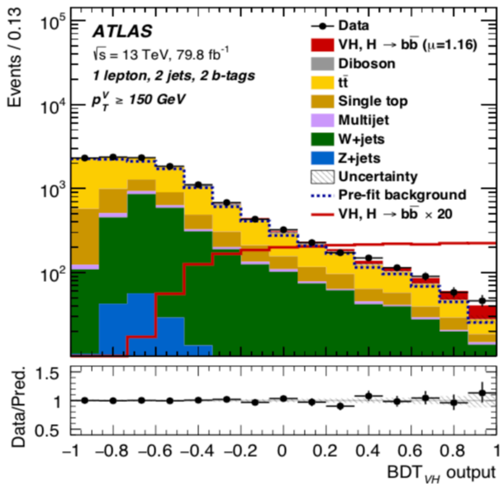


- **ATLAS**

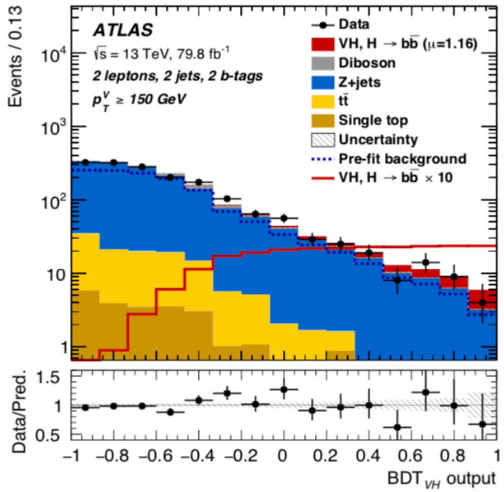
0-lepton



1-lepton



2-lepton



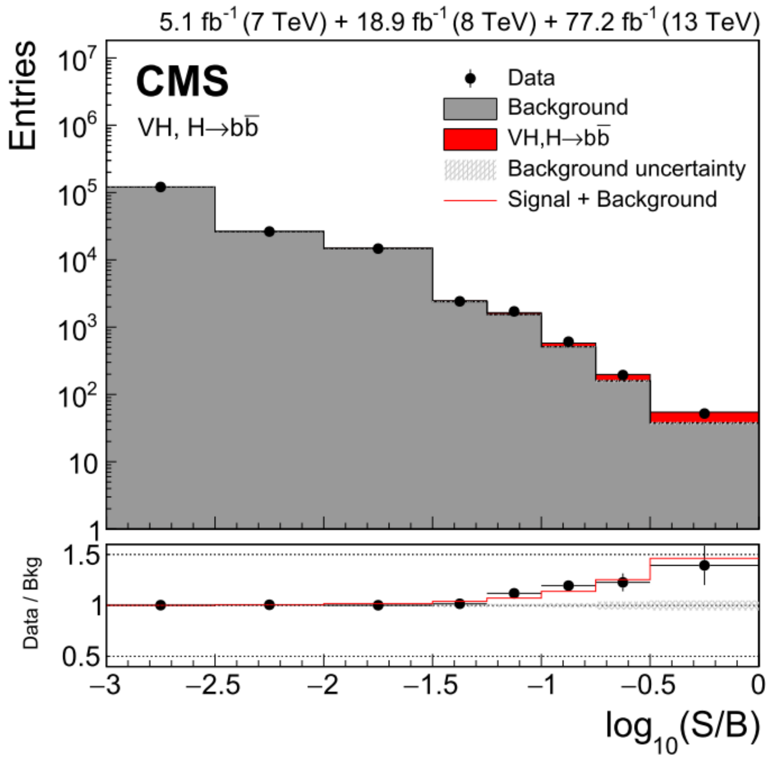
Combination of VH(H→bb) measurements

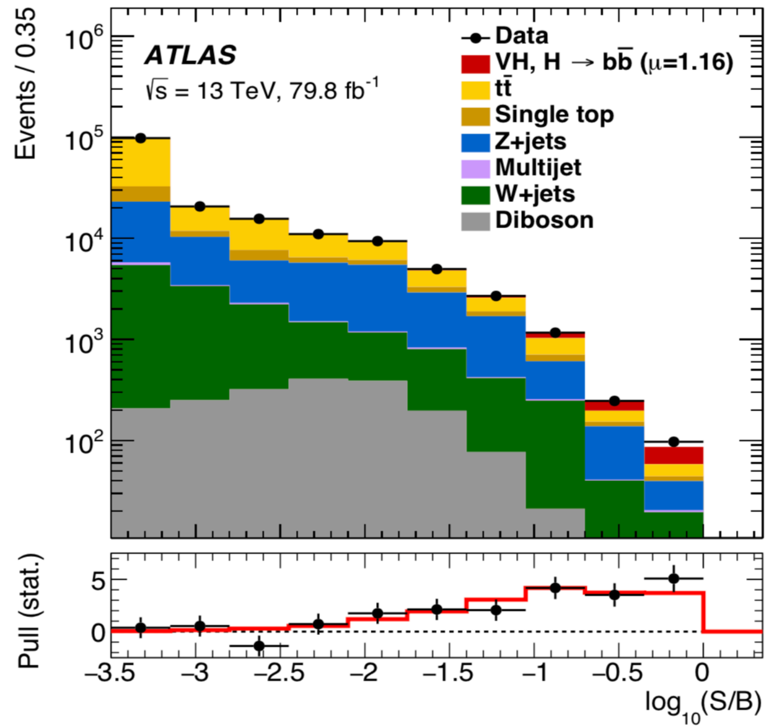
- **Combination of VH(H→bb) measurement**

Data set	Significance (σ) Expected	Observed	Signal strength
2017	3.1	3.3	1.08 ± 0.34
Run 2	4.2	4.4	1.06 ± 0.26
Run 1 + Run 2	4.9	4.8	1.01 ± 0.23

Run-2

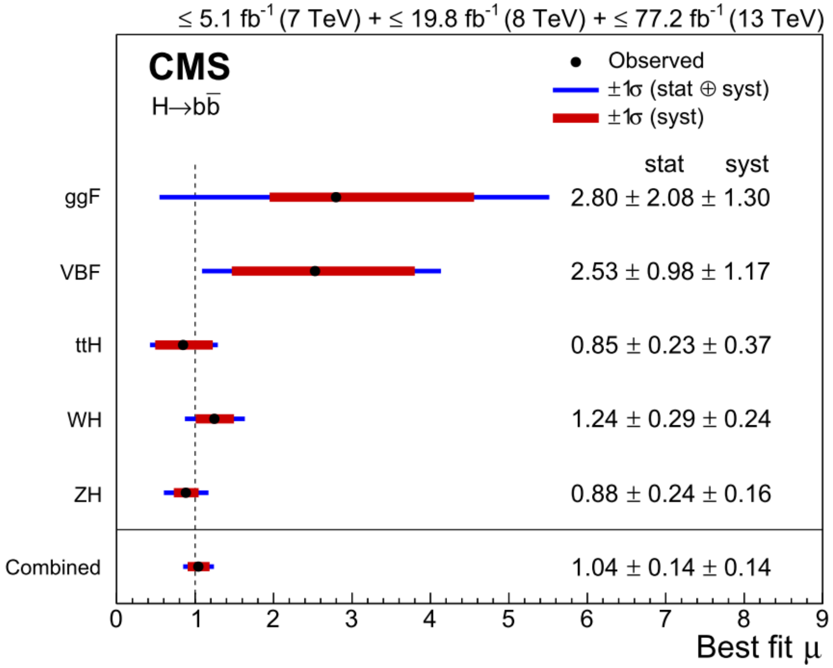
Signal strength	Signal strength	p_0 Exp.	p_0 Obs.	Significance Exp.	Significance Obs.
0-lepton	$1.04^{+0.34}_{-0.32}$	$9.5 \cdot 10^{-4}$	$5.1 \cdot 10^{-4}$	3.1	3.3
1-lepton	$1.09^{+0.46}_{-0.42}$	$8.7 \cdot 10^{-3}$	$4.9 \cdot 10^{-3}$	2.4	2.6
2-lepton	$1.38^{+0.46}_{-0.42}$	$4.0 \cdot 10^{-3}$	$3.3 \cdot 10^{-4}$	2.6	3.4
$VH, H \to b\bar{b}$ combination	$1.16^{+0.27}_{-0.25}$	$7.3 \cdot 10^{-6}$	$5.3 \cdot 10^{-7}$	4.3	4.9

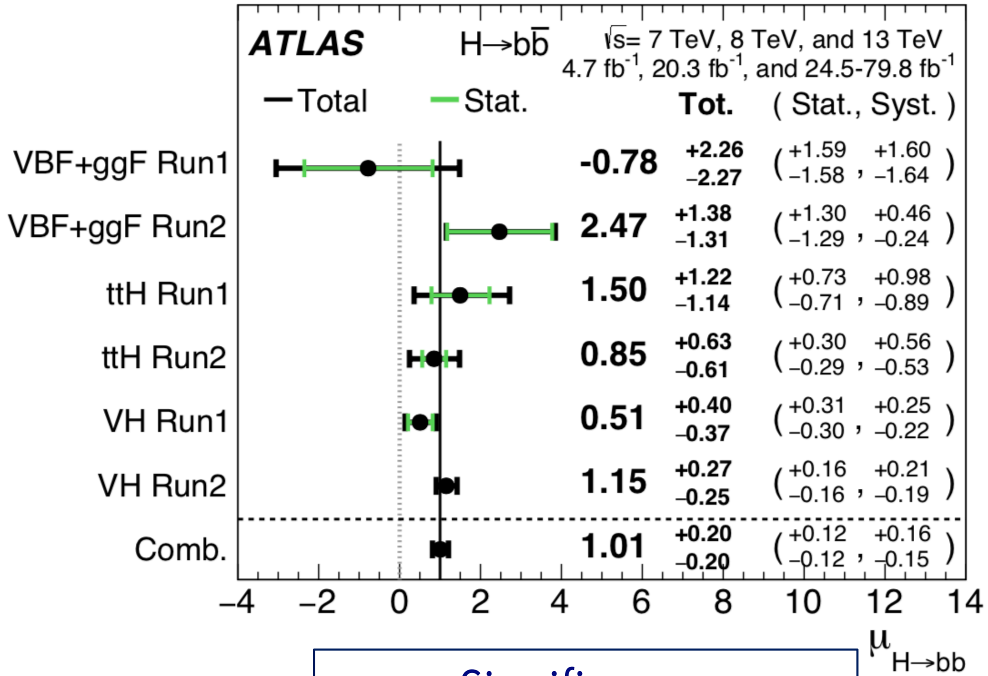




Observation of H→bb decay mode

- **Combination of VH(H→bb) with other H→bb measurement**





Significance:
5.5σ expected
5.6σ observed

Significance:
5.5σ expected
5.4σ observed

Measured signal strength:
μ = 1.04 ± 0.20

Measured signal strength:
μ = 1.01 ± 0.20

Phys.Rev.Lett. 121 (2018) no.12, 121801

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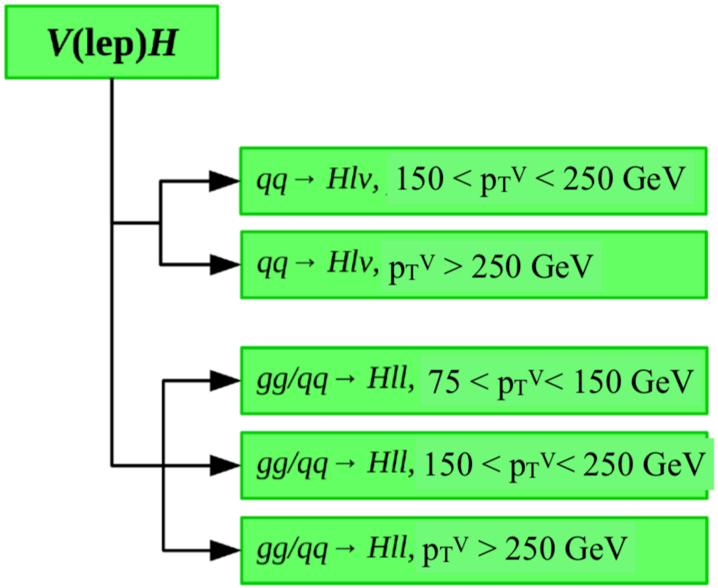
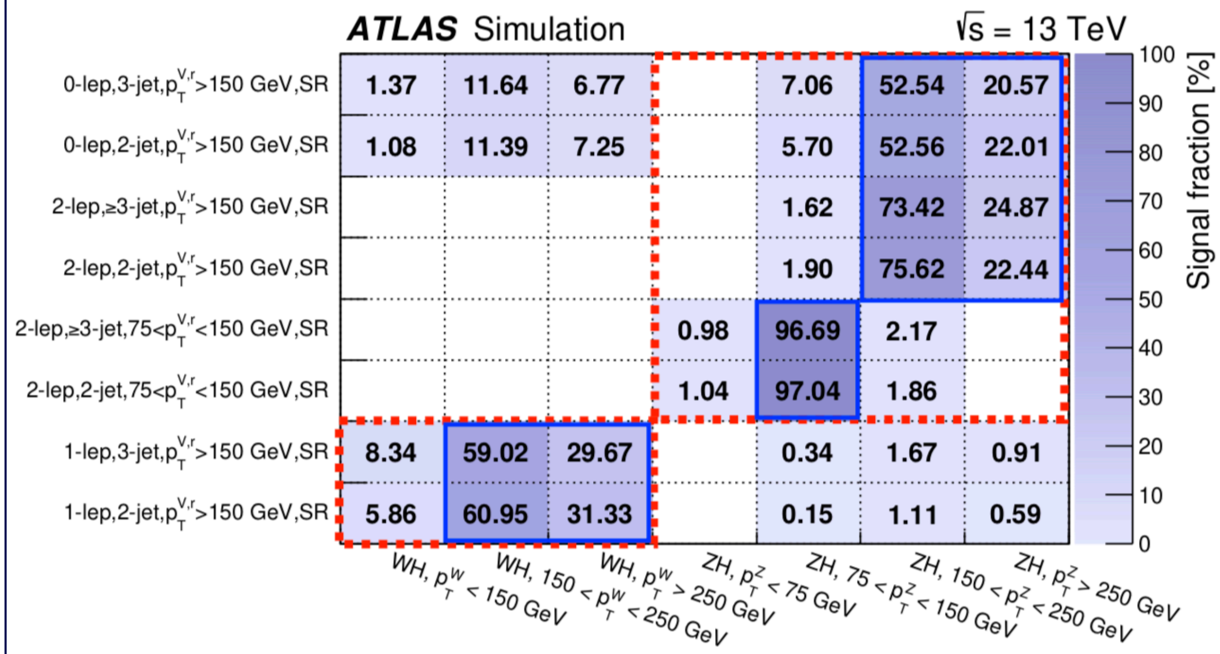
Simplified template cross section (STXS)

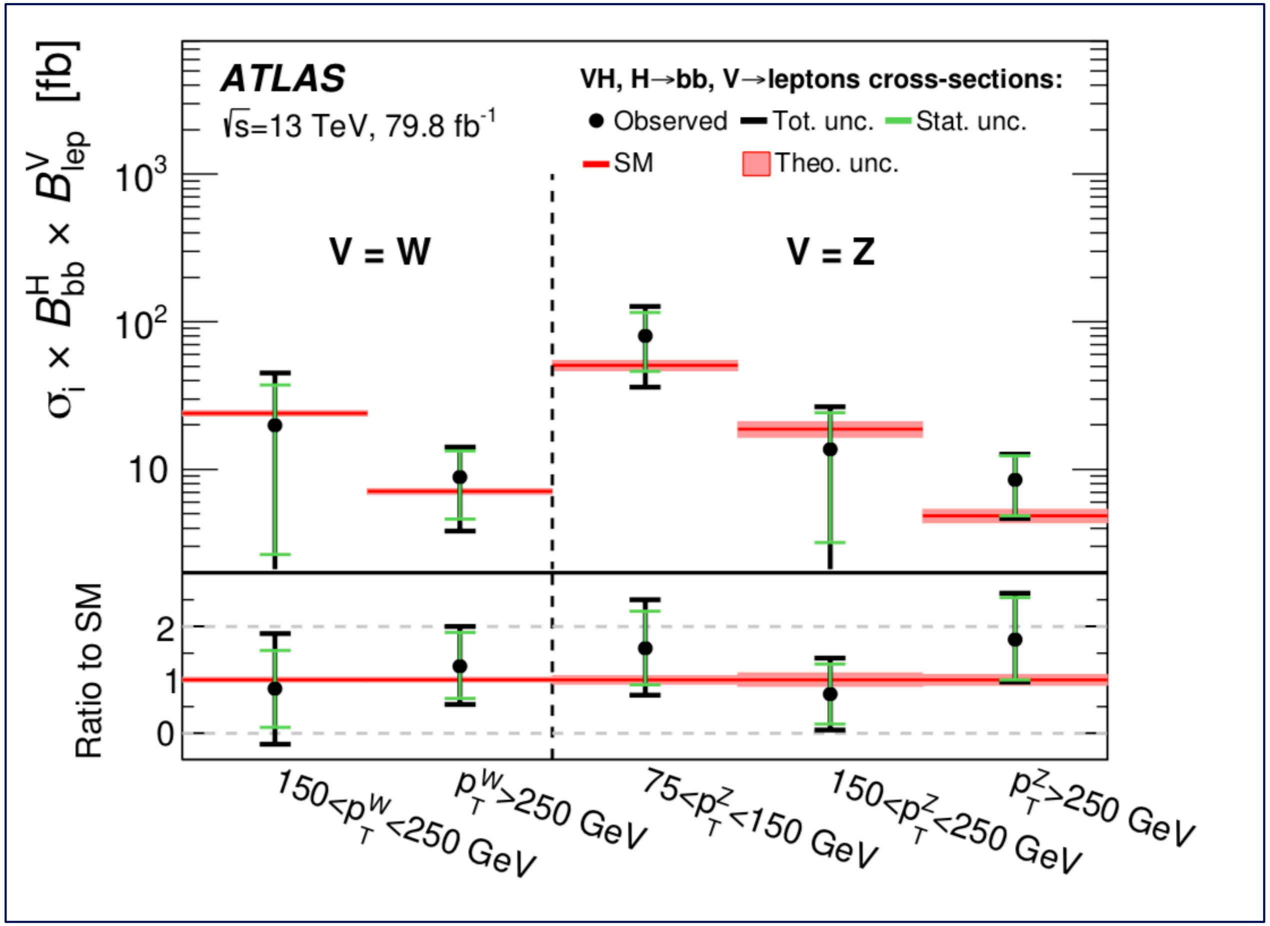
- **Re-interpreting observation result, measuring cross section in bins of $p_T(V)$ separately for WH and ZH production:**
  - Modification of cross section in bins of $p_T(V)$ could point to new physics
  - Reduces amount of extrapolation to inclusive result
  - Following analysis categorization: split at 250 GeV exploits BDT shape

HIGG-2018-50





Simplified template cross section (STXS)

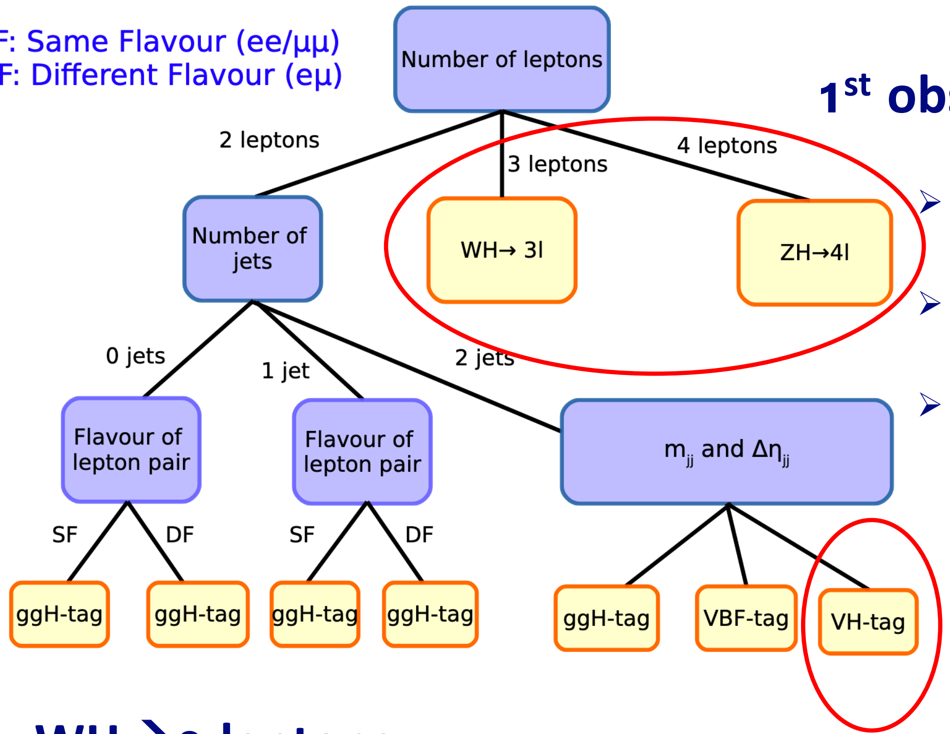


- **First STXS in VH(H->bb):**
  - All bins have obs./exp. significance between 1 and 2 sigma
  - Still dominated by statistical uncertainty
- **High p_T bins particularly suited to study effects from new physics**

Measurement of VH(H→WW) - CMS

[10.1016/j.physletb.2018.12.073](https://doi.org/10.1016/j.physletb.2018.12.073)

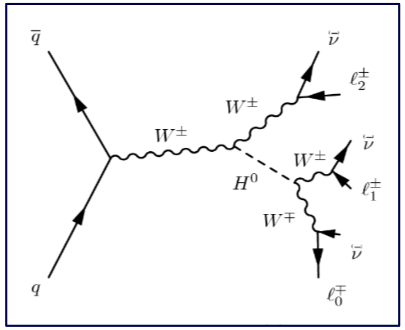
SF: Same Flavour (ee/μμ)
DF: Different Flavour (eμ)



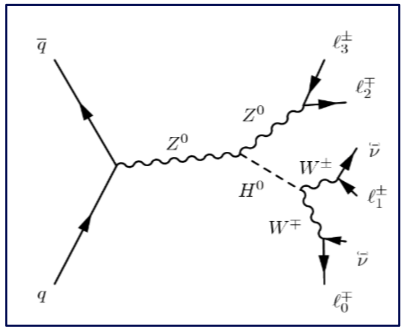
1st observation of the H→WW process in CMS

- Higgs production via ggH, VBF and **VH**
- Analysis based on the 2016 data (35.9 fb^{-1})
- Categorization in Nr.-leptons and Nr.-jets

- **WH→3 leptons**
  - WZ and Zγ normalizations estimated from data with CR
  - Shape analsysis



- **ZH→4 leptons**
  - Categorization in the flavor of leptons from the Higgs
  - ZZ bkg normalization taken from data with CR.
  - Cut&Count analysis

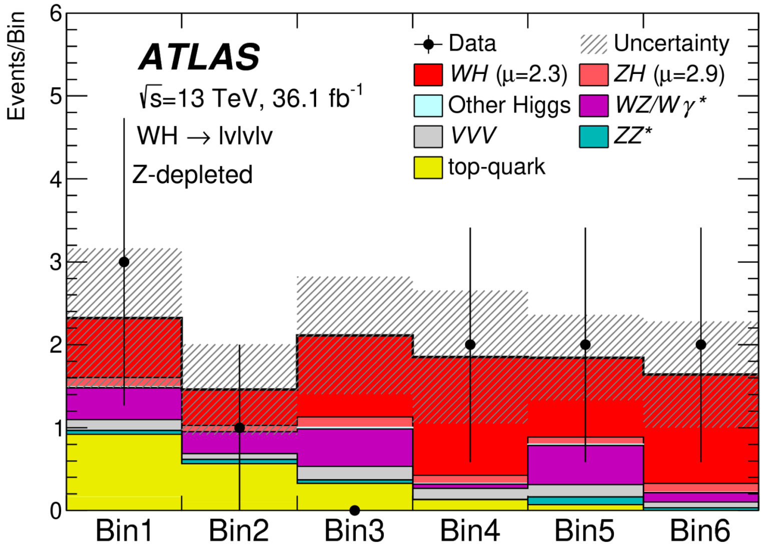


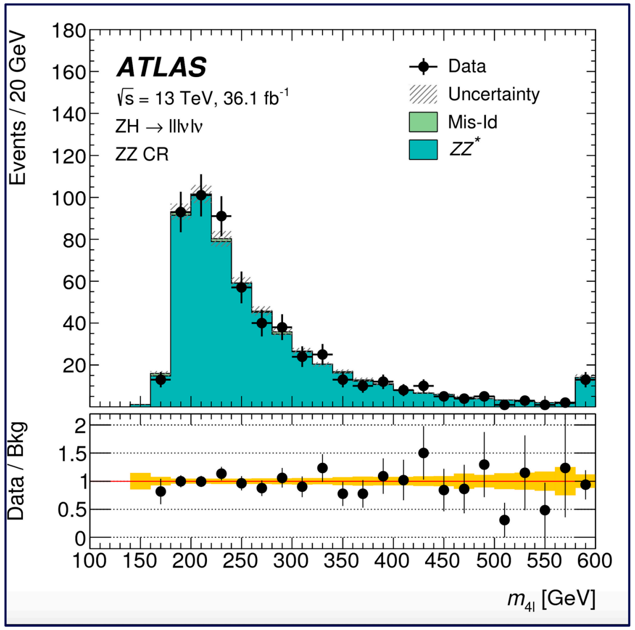
Measurement of VH(H→WW) - ATLAS

Measure of the VH production cross section using H→WW*→2l2υ HIGG-2017-14

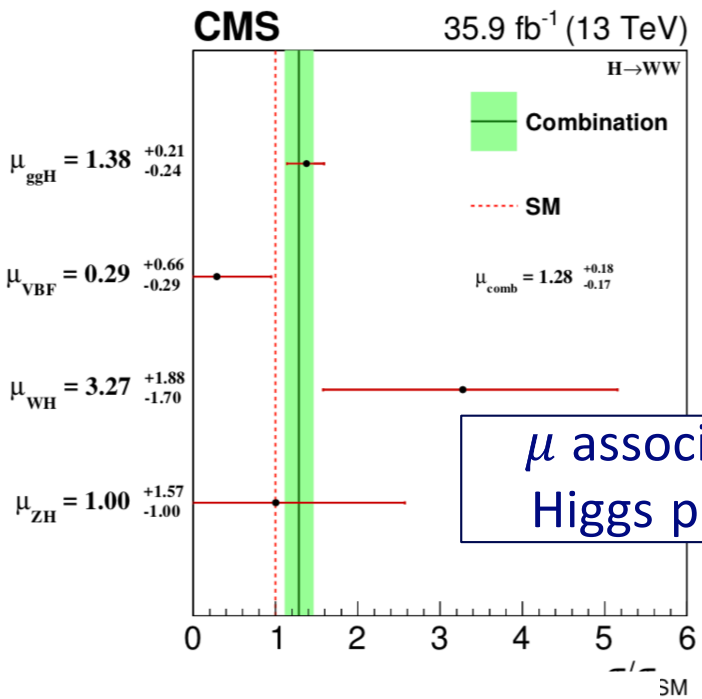
- Higgs production via VH
- Analysis based on the 2015+2016 data (35.1 fb^{-1})

- **WH→3 leptons + ZH→4 leptons**
  - Z+jets and Zγ estimated with data-driven techniques
  - Normalization of the main background from CRs
  - Cut&Count method used in ZH
  - BDT used to maximise the sensitivity in WH





Measurement of VH(H→WW) - Results



μ associated to the main Higgs production modes

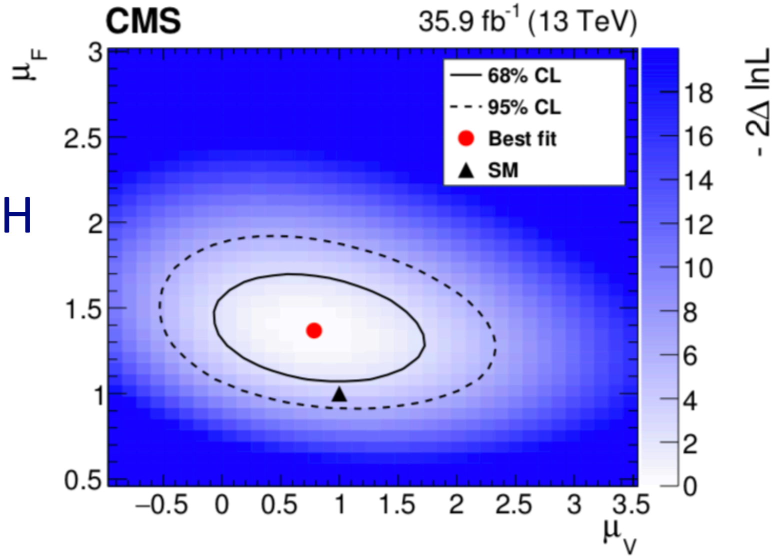
CMS combining all categories:

$$\mu_{WH} = 3.27^{+1.88}_{-1.70}$$
$$\mu_{ZH} = 1.0^{+1.57}_{-1.0}$$

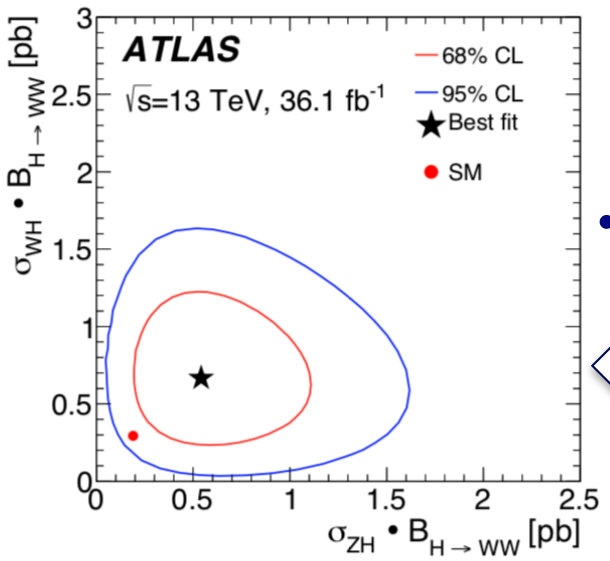
ATLAS signal sytrength for VH processes:

$$\mu_{WH} = 2.3^{+1.2}_{-1.0}$$
$$\mu_{ZH} = 2.9^{+1.9}_{-1.3}$$

- simultaneous fits are performed to probe the Higgs boson couplings to fermions and vector bosons



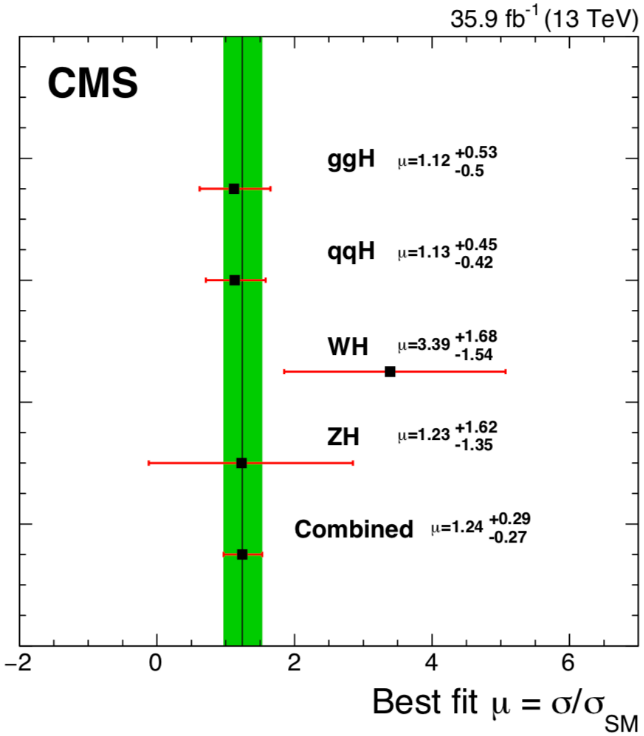
- Comparison of the WH and ZH productions



Measurement of VH(H→$\tau\tau$) - CMS

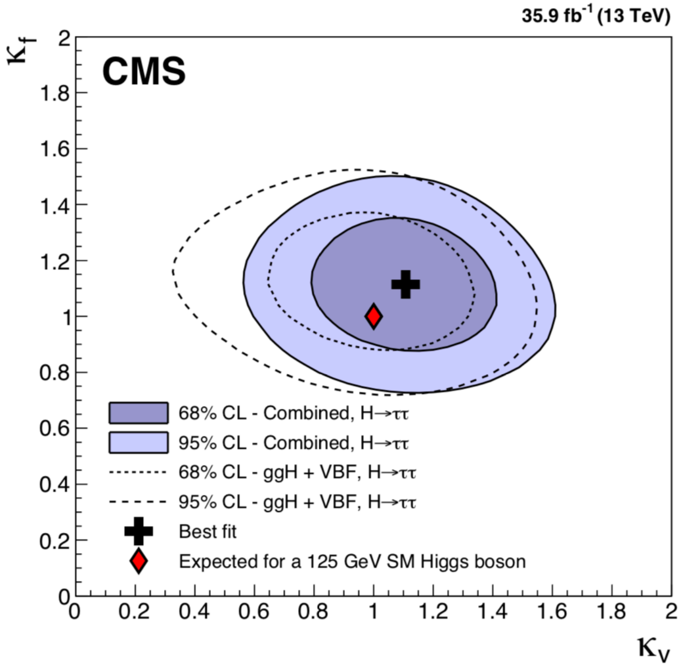
The H→$\tau\tau$ decay is the second most sensitive channel to establish VH production

- WH semi-leptonic: W($e\nu$)H($\mu\tau_h$), W($\mu\nu$)H($\mu\tau_h$)
- WH hadronic: W($e\nu$)H($\tau_h\tau_h$), W($\mu\nu$)H($\tau_h\tau_h$)
- With Z(ee)+H($\tau_e\tau_\mu$), H($\tau_e\tau_h$), H($\tau_\mu\tau_h$), H($\tau_h\tau$)
- With Z($\mu\mu$)+H($\tau_e\tau_\mu$), H($\tau_e\tau_h$), H($\tau_\mu\tau_h$), H($\tau_h\tau_h$)



Main Background:

- Irreducible: WZ, ZZ estimated from MC
- tt+jets, Z+jets, estimated with fake rate method



VH signal strength: [CMS-HIG-18-007]

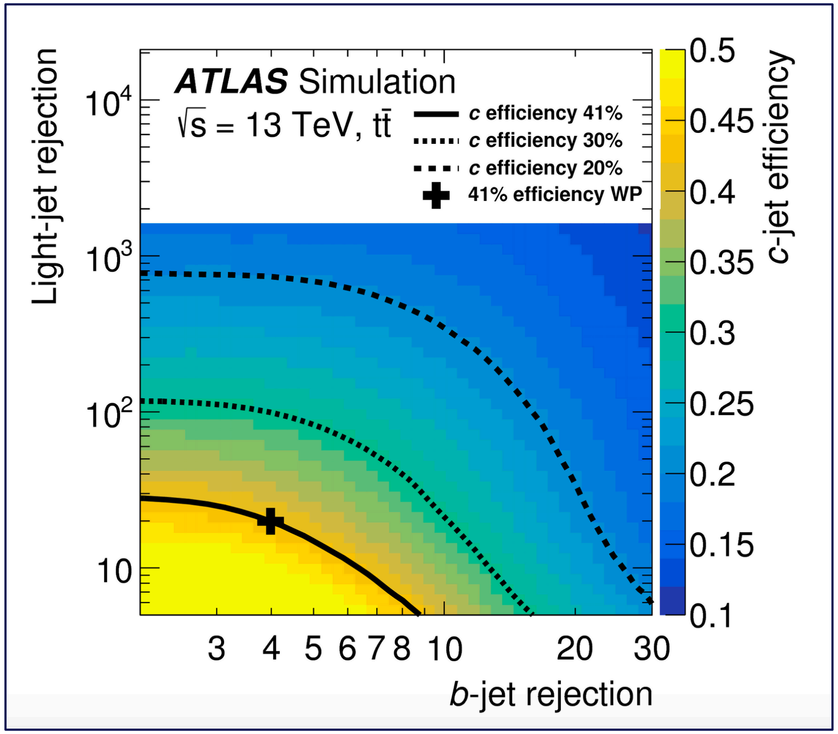
$$\mu = 2.54^{+1.35}_{-1.26}\ (obs.)$$

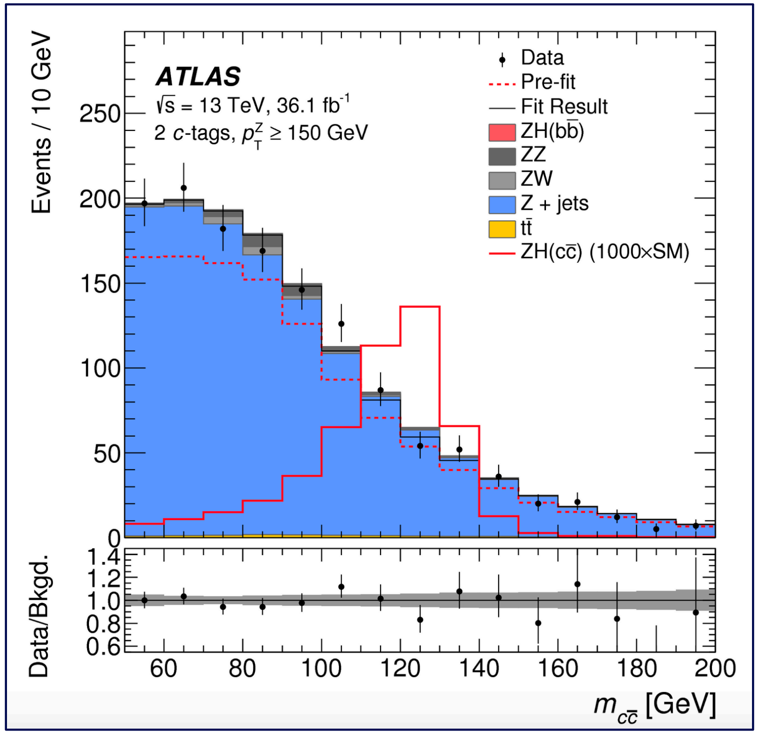
$$\mu = 1.00^{+1.08}_{-0.97}\ (exp.)$$

Measurement of VH(H→cc) - ATLAS

ATLAS-CONF-2017-078

- New search for ZH(cc) production exploiting new c-tagging techniques
- Categorization as function of number of c-tag jets and $p_T(Z)$
- Provides observed (expected) upper limit of:
  (pp→ZH) x BR(HH→cc) < 2.7($3.9^{+2.1}_{-1.1}$) pb @95% C.L.
- Excluded 110xSM prediction with 36.1 fb^{-1} of data collected





Conclusions

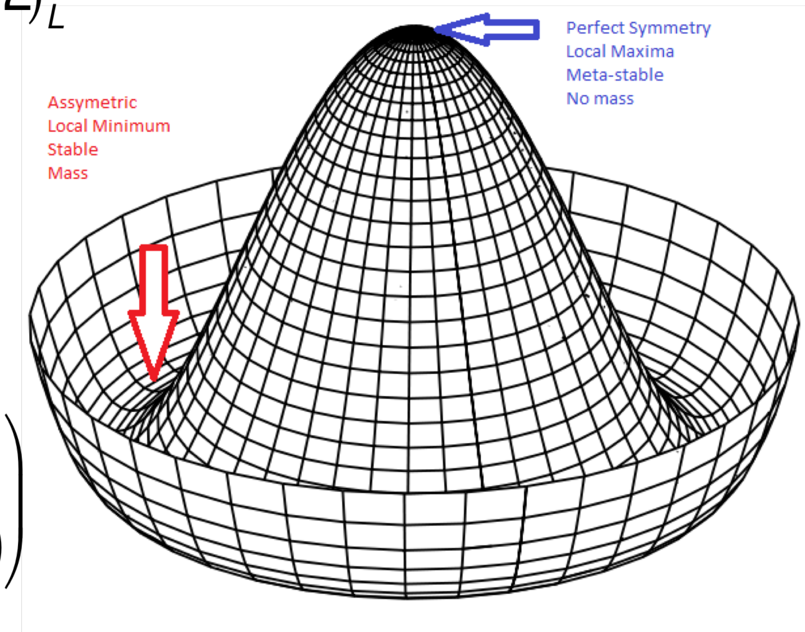
- **ATLAS and CMS have both achieved a >5σ observation of the H→bb decay**
  - Combination of several channels, dominated by VH(bb)
- **SM** assumption on **Yukawa coupling to b's is confirmed** within uncertainty (20%)
  ➔ **All 3rd generation fermion couplings are now observed!**
- ATLAS observation of VH: all major production channels now observed.
- Recently ATLAS has published a re-interpretation of the observation result, measuring cross section in bins of pT(V) separately for WH and ZH (STXS)
- The VH production mode contributed to the first CMS observation of the H→WW* decay mode. ATLAS recently measured the production cross section for WH and ZH with H→WW*
- The VH production mode represents a unique bench test also to probe the coupling of the Higgs boson to lepton (CMS, VH($\tau\tau$)) and to the second-generation quarks (ATLAS ZH(cc))

Back-Up

Higgs Mechanism

- **No explicit mass term in the SM lagrangian**
  - Adding by "hand" such terms ($m\Psi\overline{\Psi}$) would spoil the renormalizability of the theory
  - Particle can gain mass through the electroweak symmetry breaking mechanism

- **Introducing the "*Higgs potential*":** $V(\Phi) = -\mu^2\Phi\,\Phi + \lambda(\Phi\,\Phi)^2$
  - Invariant under local transformation $U(1)_Y \otimes SU(2)_L$
  - It must preserve Lorentz invariance
  - It breaks $U(1)_Y \otimes SU(2)_L \rightarrow U(1)_{em}$



$$\Phi = \begin{pmatrix} \Phi^+ \\ \Phi^0 \end{pmatrix}_L \xrightarrow[\text{Choice of a ground state}]{\text{small oscillations around the ground state}} \Phi = \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$

$$\Phi_0 = \begin{pmatrix} 0 \\ v \end{pmatrix}$$ vacuum expectation value

Higgs Mechanism

- **When the symmetry is spontaneously broken:**
  - The mass terms for the vector bosons naturally appear → $m_W = \frac{vg}{2}$ and $m_Z = \frac{v\sqrt{g^2 + g'^2}}{2}$
  - A new massive particle emerges: the Higgs boson → $m_H = \sqrt{2\lambda}v$
  - Fermion mass generation → **Yukawa couplings**

$$L_Y = f_l \overline{\chi}_L \phi l_R + f_u \overline{q}_L \tilde{\phi} u_R + f_d \overline{q}_L \phi d_R + \text{h.c.}$$

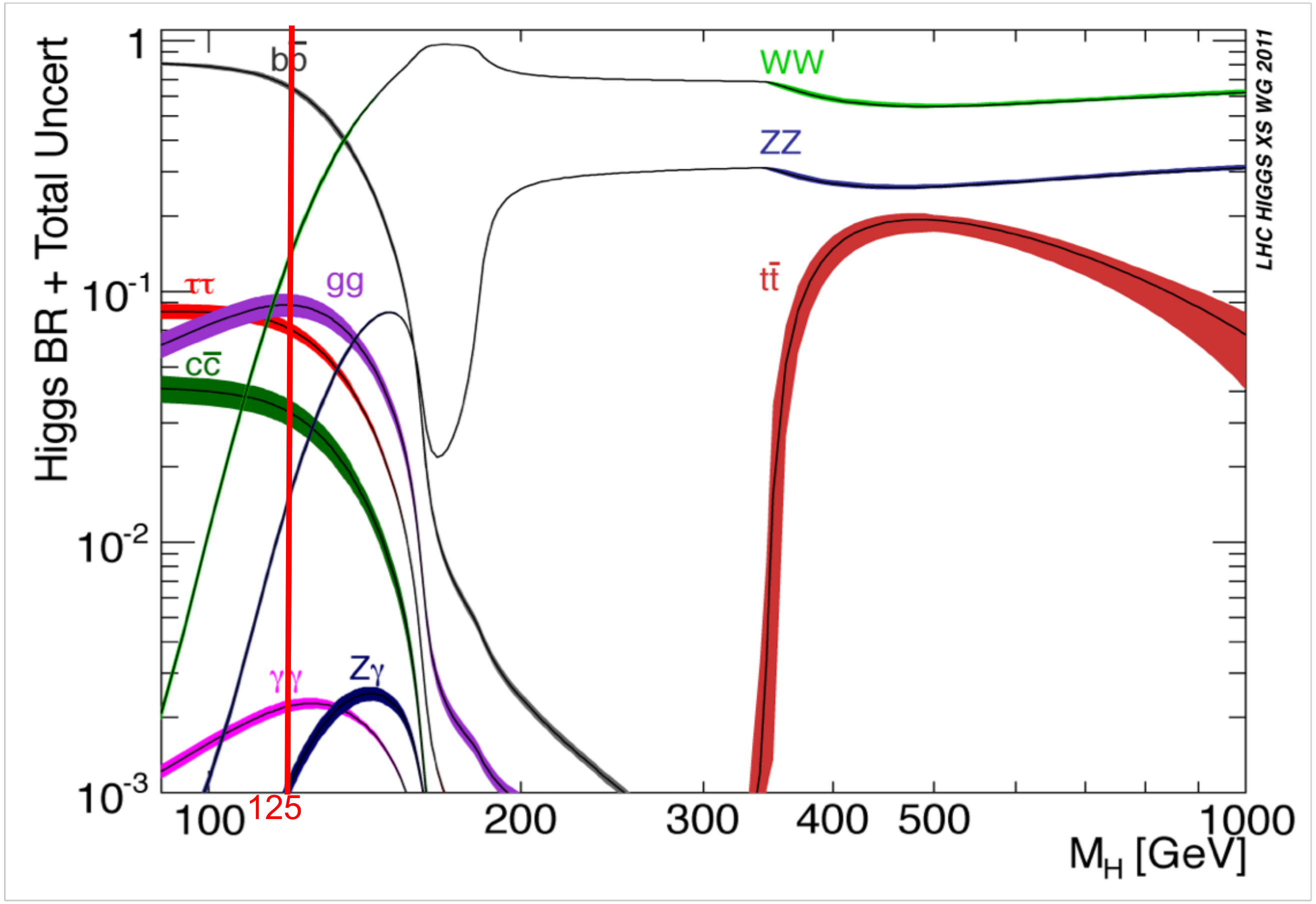
$$\phi = \begin{pmatrix} 0 \\ v + h \end{pmatrix} \rightarrow \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h \end{pmatrix}$$

$$L_Y = \frac{v f_l}{\sqrt{2}} \left(\bar{l}_L l_R + \bar{l}_R l_L \right) + \frac{v f_u}{\sqrt{2}} \left(\overline{u}_L u_R + \overline{u}_R u_L \right) + \frac{v f_l}{\sqrt{2}} \left(\overline{d}_L d_R + \overline{d}_R d_L \right)$$

$$f_i = \frac{m_i}{v} \sqrt{2}$$

The Yukawa couplings bring new non-gauge interactions!
Represents something never proved before

The SM Higgs boson decay channels



- At 125 GeV, the highest branching ratio is into H→bb (about 60%), followed by the WW channel (about 20%). Then, the other sensitive channels also studied at the LHC are **ττ** (about 6%), ZZ and **γγ**
- The most sensitive channels are ZZ→4l, **γγ**, WW→lνlν

Analysis in the main H decay channels

- $H \to ZZ \to 4l$
- $H \to \gamma\gamma$
- $H \to VV$
- $H \to b\bar{b}$ — No evidence in 2012
- $H \to \tau\tau$ — No evidence in 2012

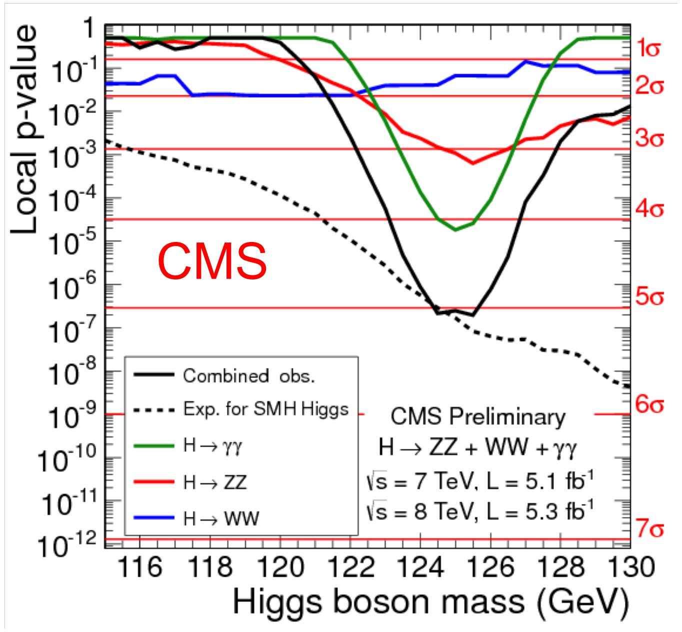
Discovery in the bosonic decays (first three): 5.1σ

The CMS full combination in the five main decay modes: 4.9σ

m_H=125.3±0.6 GeV

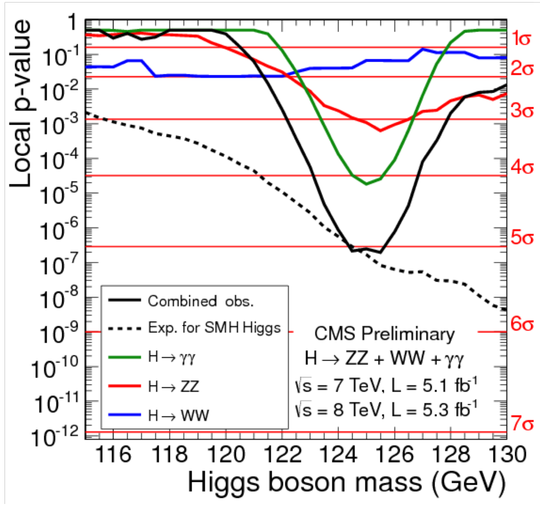
One year later…

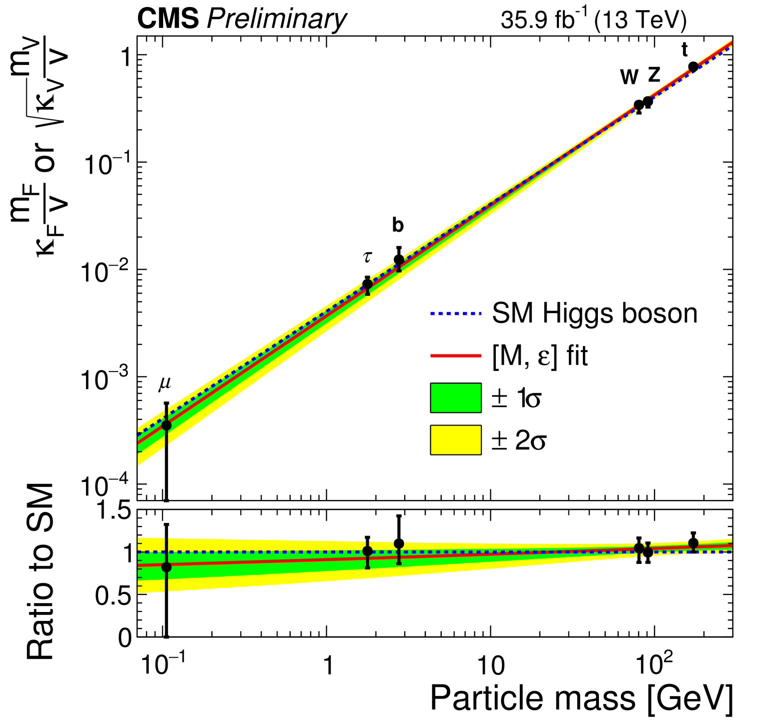
P.Higgs and F. Englert were awarded the Nobel Prize in Physics



Higgs boson discovery and established properties

- **Higgs discovery in 2012 ➔ characterization**
  - **Mass:** $125.09 \pm 0.21\,(\text{stat.}) \pm 0.11\,(\text{syst.})$ GeV
    - ATLAS+CMS: PRL 114 (2015) 191803
  - **Spin/Parity:** 0^+
    - ATLAS: EPJC 75 (2015) 476
    - CMS: PRD 92 (2015) 012004
  - **Width:** on-shell + off-shell searches comb .<3.2MeV
    - CMS: JHEP 11 (2017) 047
    - HIG-18-002 — Today result! brand new!!
    - ATLAS: arXiv:1808.01191 submitted to PLB
- **Observed direct coupling** to:
  - **Vector bosons**
    - ATLAS: PLB 716 (2012) 1-29
    - CMS: PLB 716 (2012) 30
  - **τ leptons**
    - ATLAS: ATLAS-CONF-2018-021
    - CMS: PLB 779 (2018) 283
  - **top quarks**
    - ATLAS: PLB 784 (2018) 173
    - CMS: PRL 120 (2018) 231801

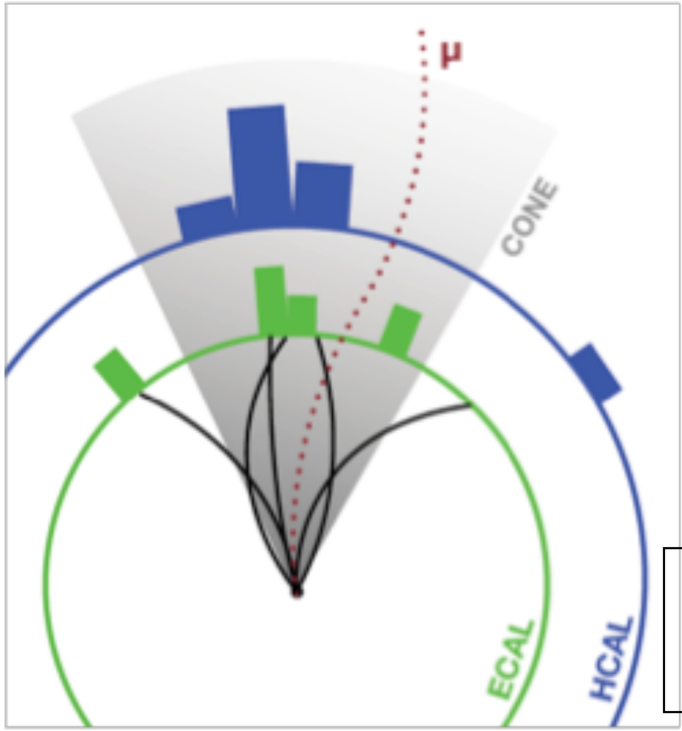




So far, all measurements compatible with SM predictions!

CMS design and 2017/18 Evolution

• Combines the information from the different CMS sub-detectors to identify all the stable particles in the event: $e^{\pm}$, $\mu^{\pm}$, γ, $h^{\pm}$, h^{0}



Inputs to build

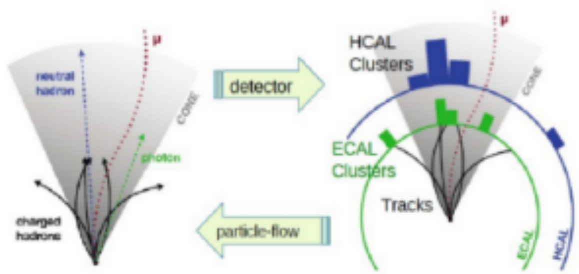
Jets, E_T^{miss}, τ_h,
Lepton/photon Isolation

Exploiting:

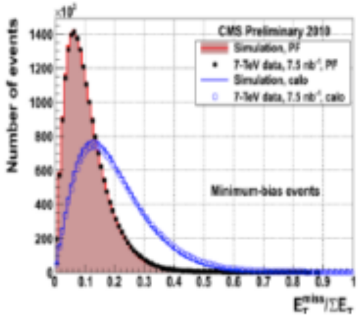
- The **excellent tracking** capability of CMS
- The **very good ECAL granularity** and **resolution**

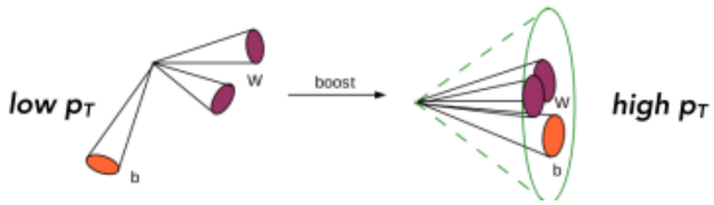
Evolution of Analysis Techniques

J. Butler - 25th Rencontres du Vietnam '18



Particle Flow





Boosted Jets, Jet Substructure

- Particle Flow uses all available information to reconstruct physics objects, e.g. charged track momenta in jets
  - produces a big improvement in jet energy resolution, tau-lepton identification, and helps with high pileup
- PUPPI (PileUp Per Particle Identification) is a special tool to deal with high pileup
- Use of multivariate analysis techniques to maximize power of available statistics
- Boosted jet topologies and jet substructure analysis
- Use of Deep Neural Nets/Machine Learning

Rapid growth in 2017/18

Observation of H→tautau

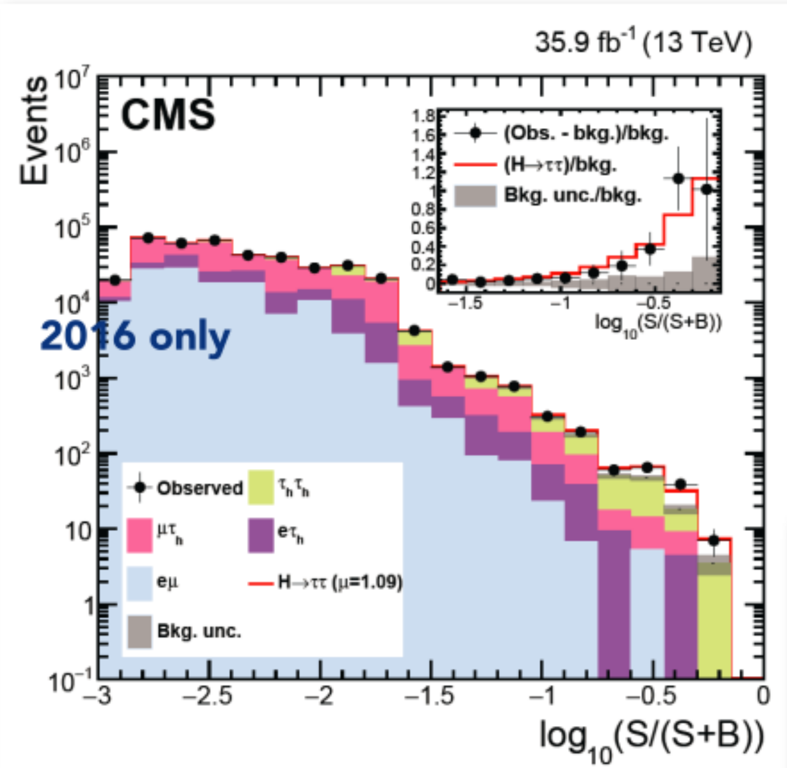
J. Butler - 25th Rencontres du Vietnam ‘18

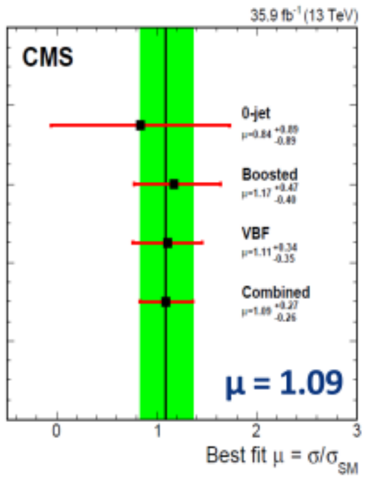
Observation of H → $\tau^+\tau^-$ using 7, 8, and 13 (2016 only) TeV data

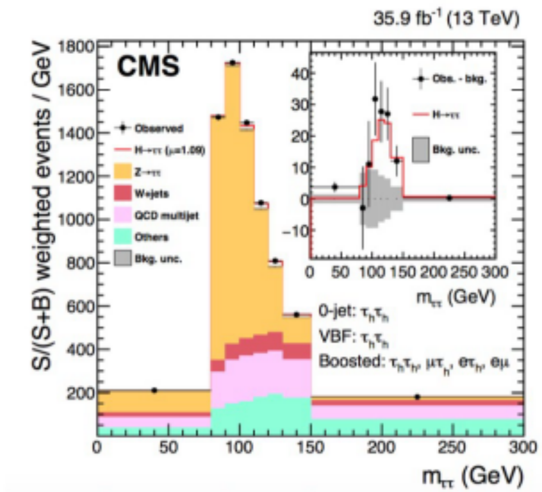
PLB 779 (2018) 283

arXiv:1708.00373

- Branching ratio ~ 6.3%, best channel to establish coupling of Higgs boson to fermions
- Final states: $\tau_h\tau_h$; $e\tau_h$; $\mu\tau_h$; $e\mu$ → Significance of 4.9σ observed (4.7σ expected) with13 TeV data
- **Combination with 7, 8 TeV data: 5.9σ obs. (5.9σ exp.) and μ = 0.98 ± 0.18**







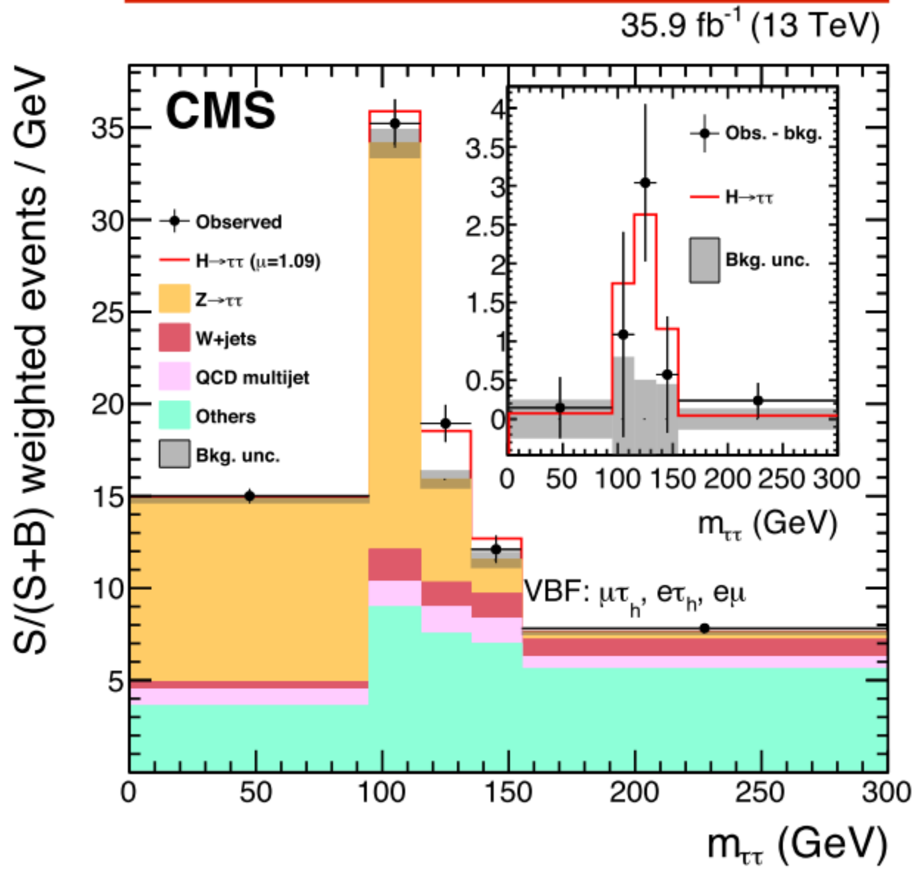
First direct observation by a single experiment of Higgs coupling to fermions!
– **Observed before in CMS+ATLAS combination**

First direct observation of H coupling to leptons and to fermions of the 3rd generation!

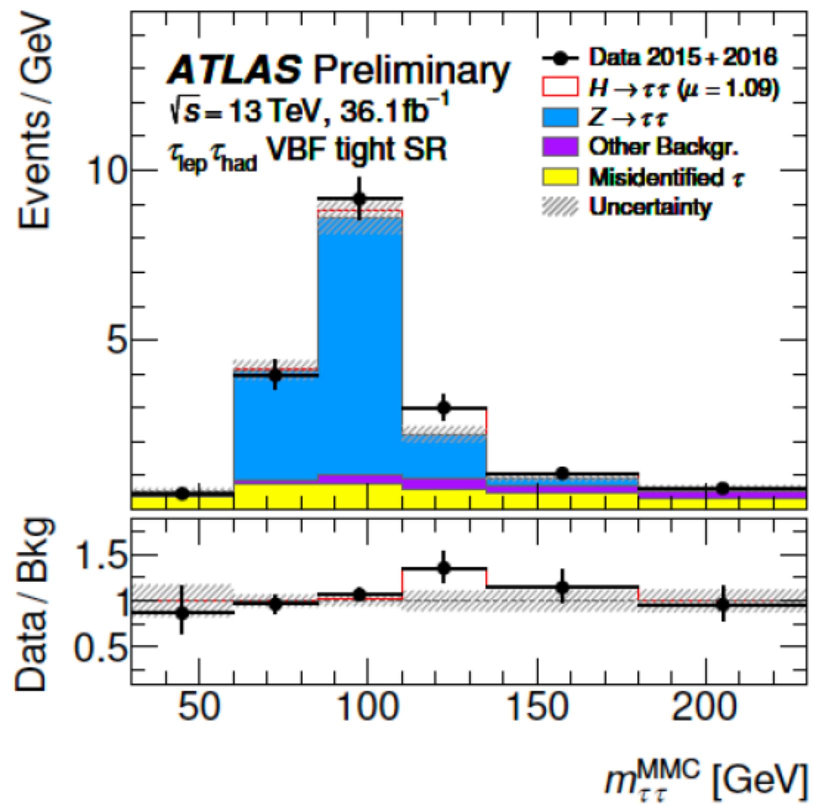
Observation of H→tautau

the news of the past 12 months

A year ago:
CMS >5-sigma H → τ τ



This week:
ATLAS >5-sigma H → τ τ



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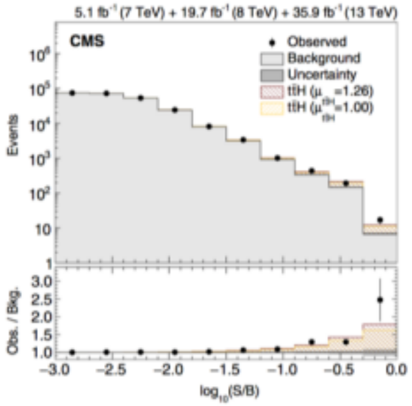
G. Salam, LHCP '18

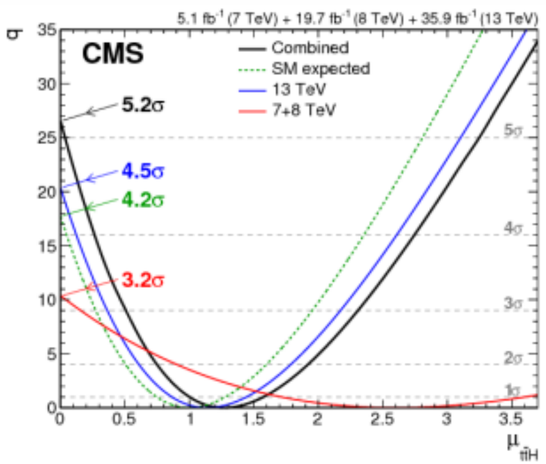
Observation of ttH

J. Butler - 25th Rencontres du Vietnam ‘18

ttH: 7,8, and13 TeV Combined

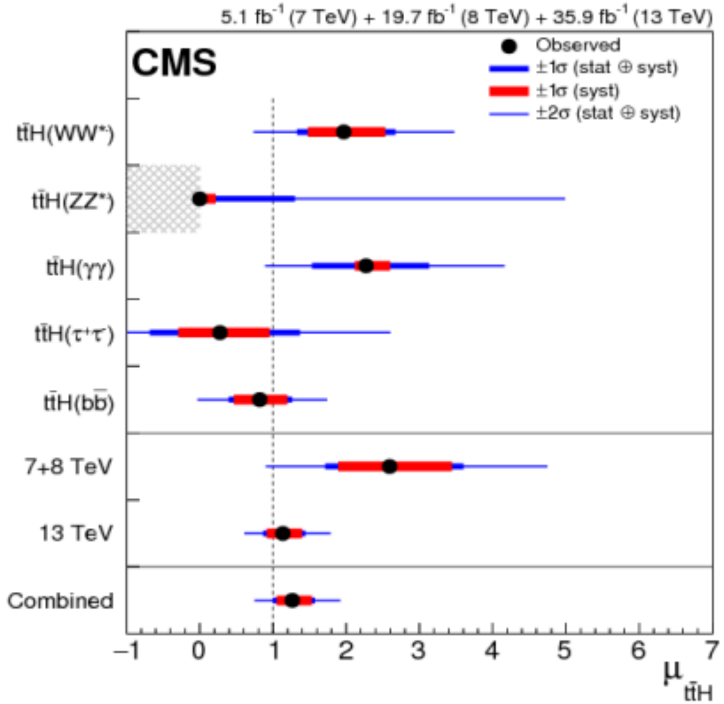
5.1 fb^{-1} (7 TeV)+19.7 fb^{-1} (8 TeV) + 35.9 fb^{-1} (13 TeV)





Test statistic vs coupling strength modifier The horizontal dashed lines indicate the *p*-values for the background-only hypothesis obtained from the asymptotic distribution of *q*,

$$\mu = 1.26^{+0.31}_{-0.26}$$

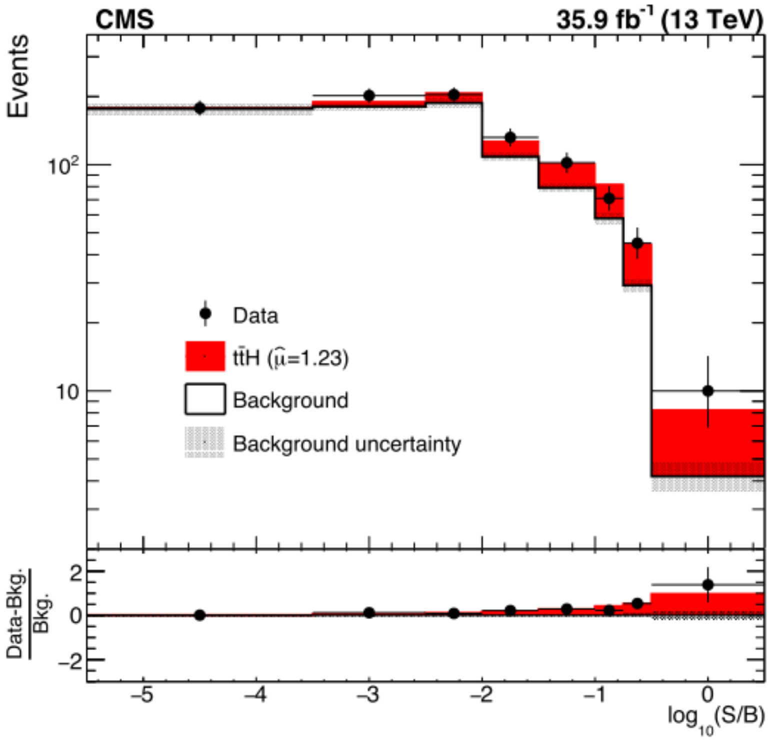


Best fit value of the signal strength modifier for (upper section) the five individual decay channels considered, (middle section) the combined result for 7+8 TeV alone and for 13TeV alone, and (lower section) the overall combined result.

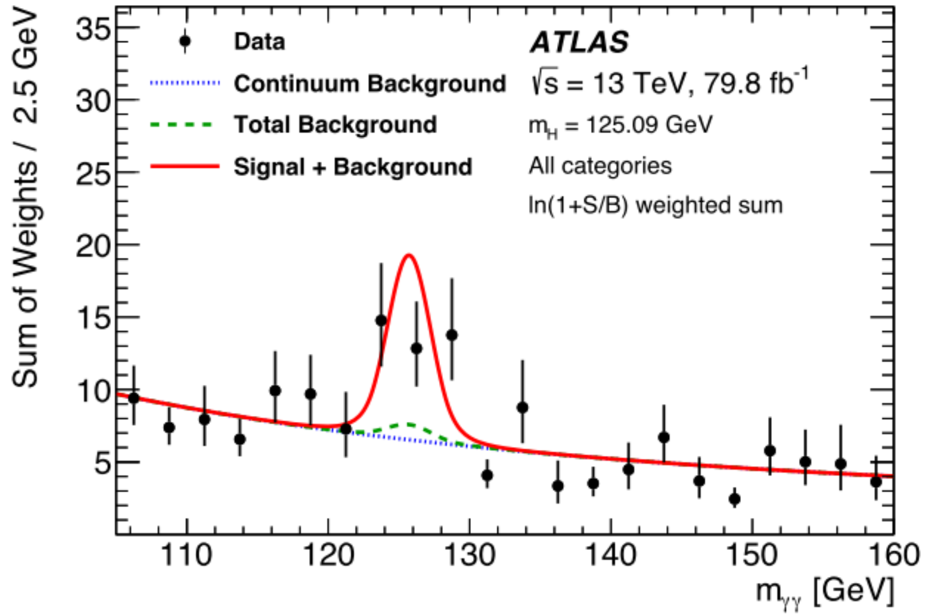
Observation of ttH

the news of the past 12 months

A few weeks ago:
CMS >5-sigma ttH



This week:
ATLAS >5-sigma ttH



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G. Salam, LHCP '18

First H→bb̄ searches started at LEP…

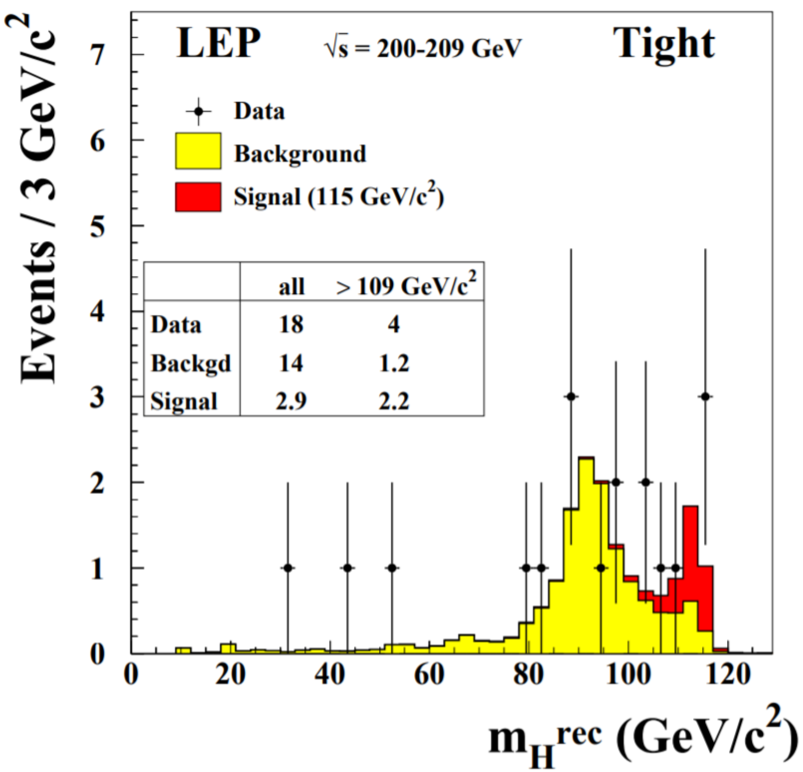
Physics Letters B 565 (2003) 61–75

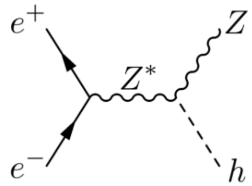
Search for the Standard Model Higgs boson at LEP

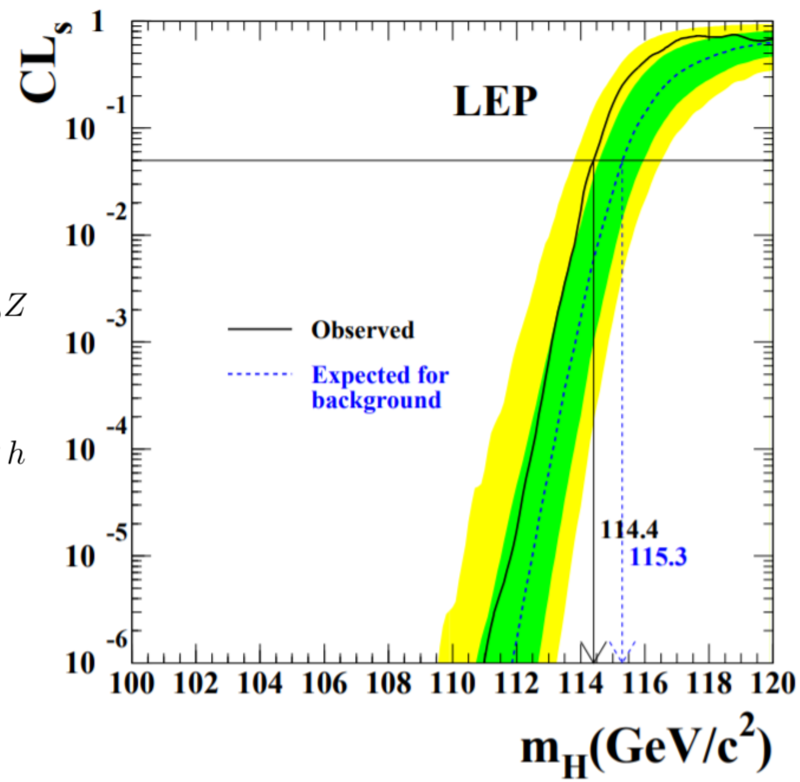
ALEPH Collaboration [1] DELPHI Collaboration [2] L3 Collaboration [3] OPAL Collaboration [4]
The LEP Working Group for Higgs Boson Searches [5]

ELSEVIER
PHYSICS LETTERS B

m_H > 114.4 GeV @ 95%CL





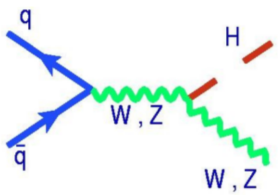


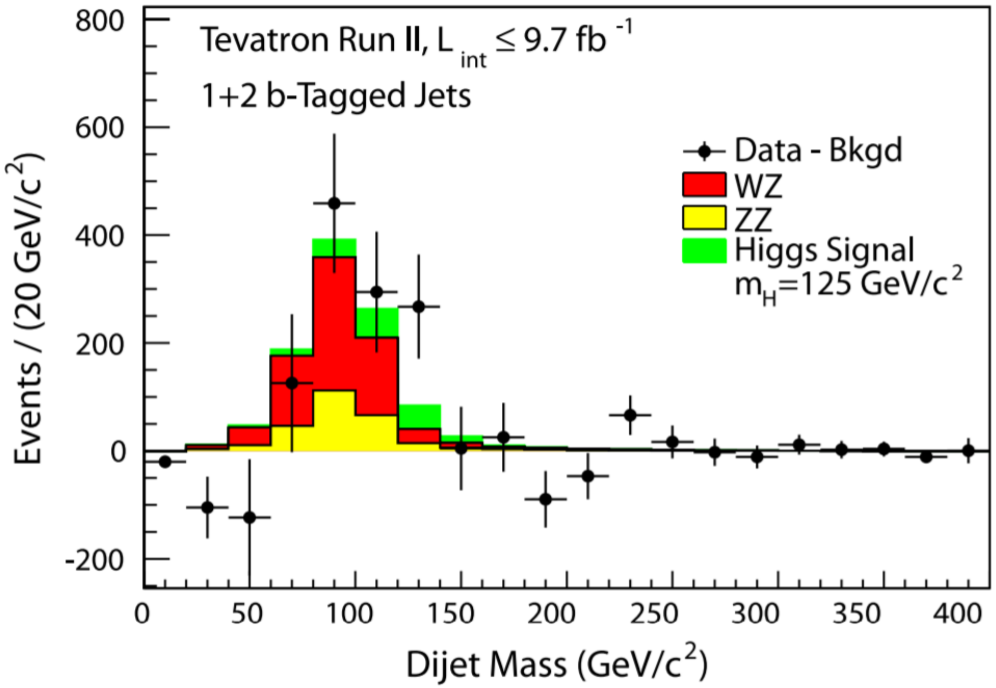
…and continued at Tevatron…

PRL **109**, 071804 (2012) PHYSICAL REVIEW LETTERS week ending 17 AUGUST 2012

Evidence for a Particle Produced in Association with Weak Bosons and Decaying to a Bottom-Antibottom Quark Pair in Higgs Boson Searches at the Tevatron

(*CDF Collaboration)
(†D0 Collaboration)



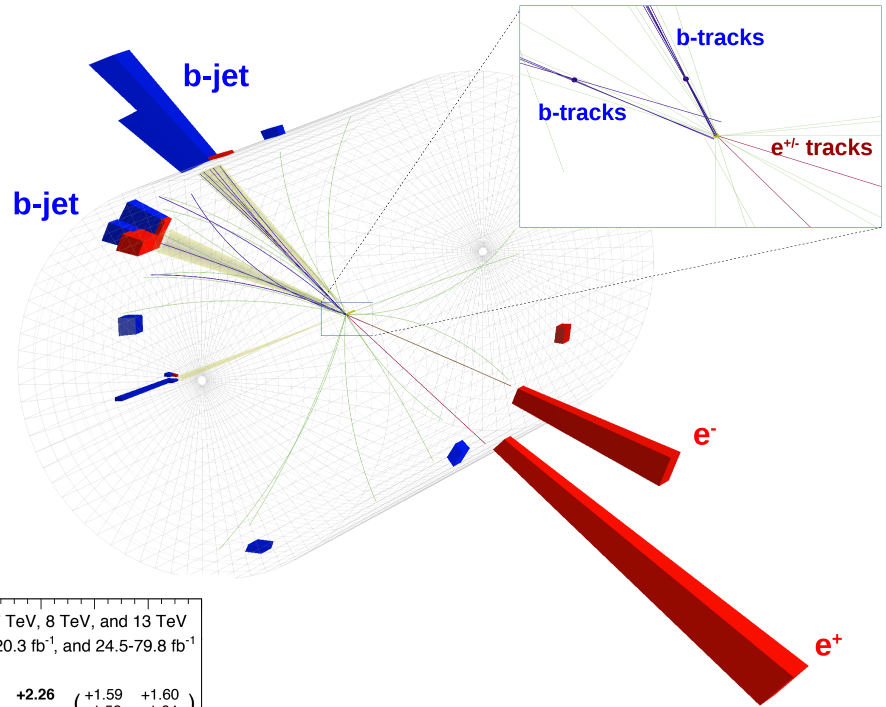


<u>Significance</u>

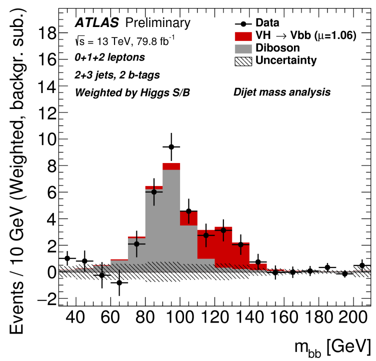
2.8σ observed @ 125 GeV

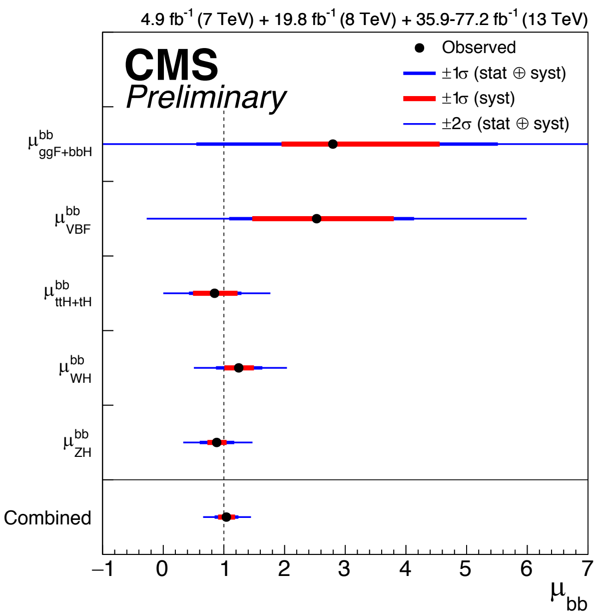
...ending at the LHC!

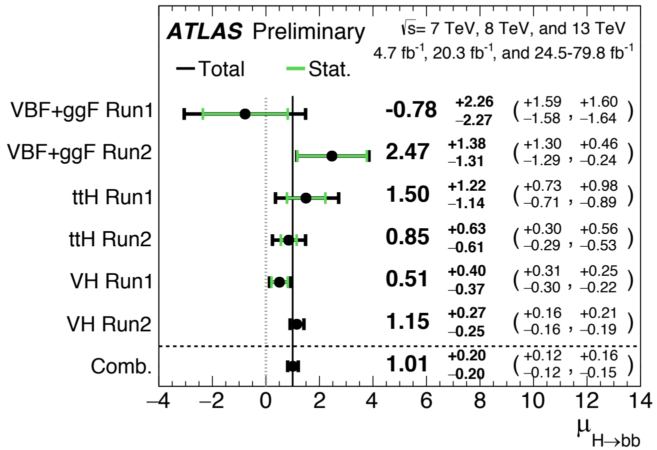
- **Why b-tagging?**
  - B-tagging is an essential tool to be exploited to study physics processes with b-jets in their final state:
    - **SM Higgs sectors (H->bb, HH->bbbb,...)**
    - **Top physics (t->Wb)**
    - **BSM searches (X -> bY)**
    - **Also used as veto for many backgrounds (H->WW)**



➔Lead to discovery of H➔bb!





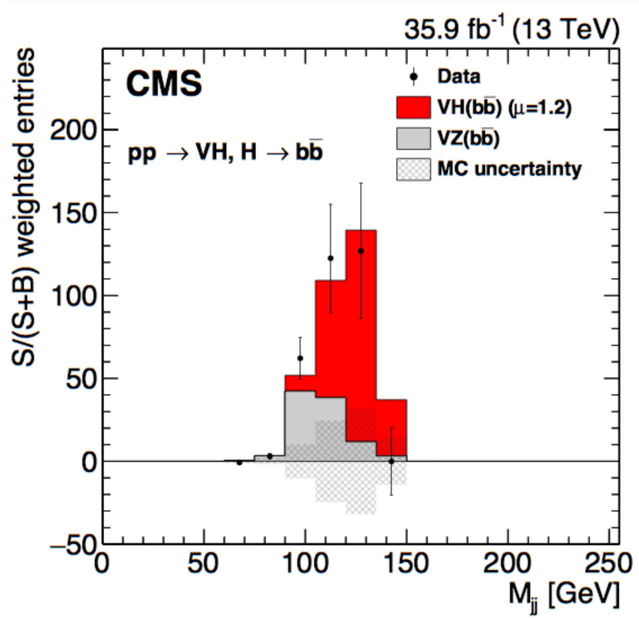


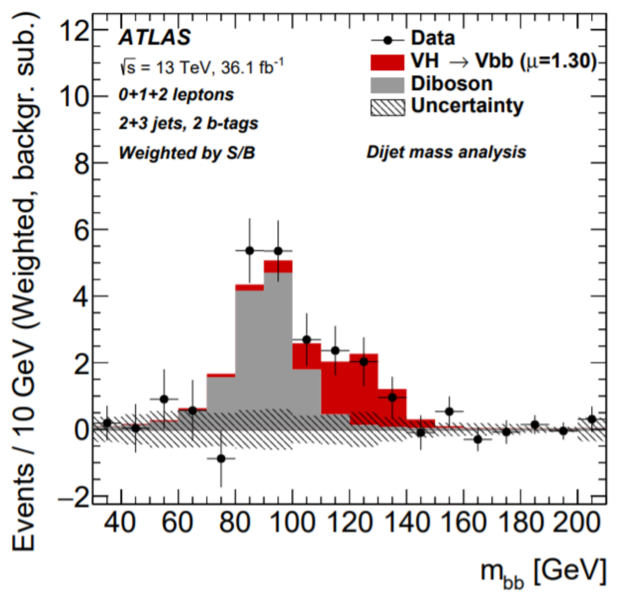
H->bb (cmb)	Exp.	Obs.	μ
ATLAS	5.5	5.4	1.01 ± 0.20
CMS	5.6	5.5	1.04 ± 0.20

VH(H→$b\bar{b}$) results at LHC

- **VH(bb) evidence at LHC established with 2016 data by both ATLAS and CMS**
  - Detectors demonstrated ability to deal with very high PU
  - For 2016 analyses used ~40fb^{-1}
- **Signal strength uncertainty ~40%**

	μ	Significance (exp.)	Significance (obs.)
ATLAS Run 1 [1]	$0.52^{+0.40}_{-0.37}$	2.6σ	1.4σ
CMS Run 1 [2]	$0.89^{+0.47}_{-0.44}$	2.5σ	2.1σ
ATLAS+CMS Run 1 [3]	$0.79^{+0.29}_{-0.27}$	3.7σ	2.6σ
ATLAS 2015+2016 [4]	$1.20^{+0.42}_{-0.36}$	3.0σ	**3.5σ**
CMS 2016 [5]	$1.19^{+0.40}_{-0.38}$	2.8σ	**3.3σ**



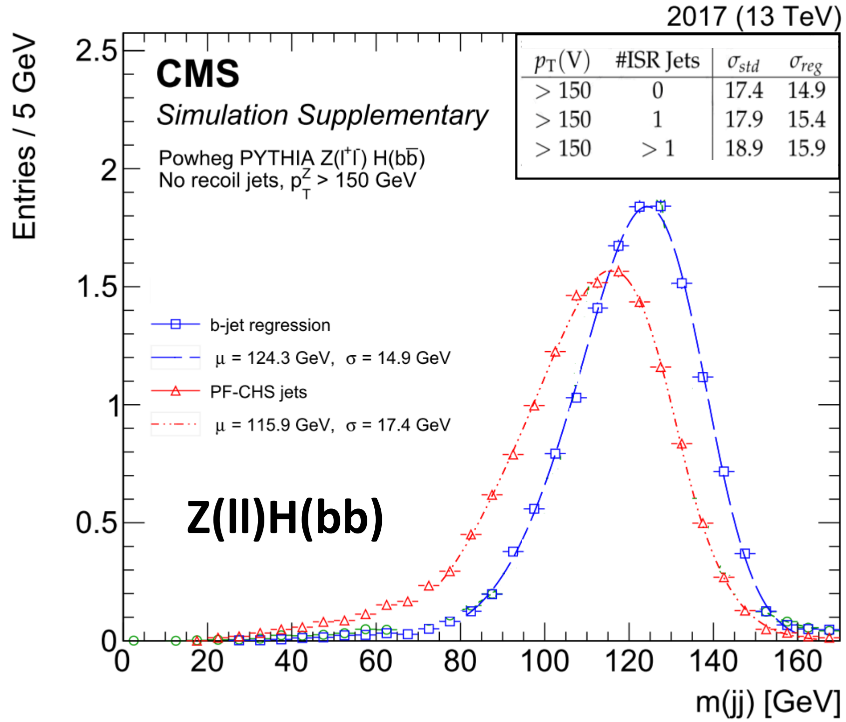


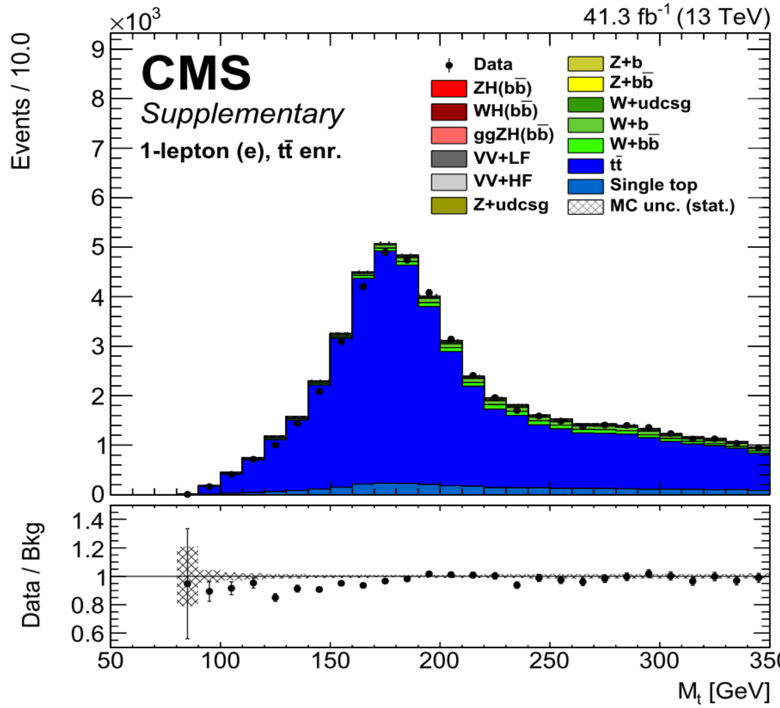
[1] JHEP 01 (2015) 069
[2] JHEP 08 (2016) 045
[3] JHEP 08 (2016) 045
[4] JHEP 12 (2017) 024
[5] PLB 780 (2018) 501

b-jet energy regression

- **Regression mainly recovers missing energy in the jet due to neutrino**
  - Switch from Boosted Decision Trees to DNN algorithm
- **Extended set of input variables** now including lepton flavor (μ/e), jet mass and energy fractions in ΔR rings
- **Significant m_{bb} resolution improvement without mass sculpting**
  - σ/peak down to 11.9% in 2017 wrt 13.2% in 2016 ➔ + O(10%)
  - dedicated calibration of b-jets with Z+b events + measure JER

Higgs mass in 2-lep SR

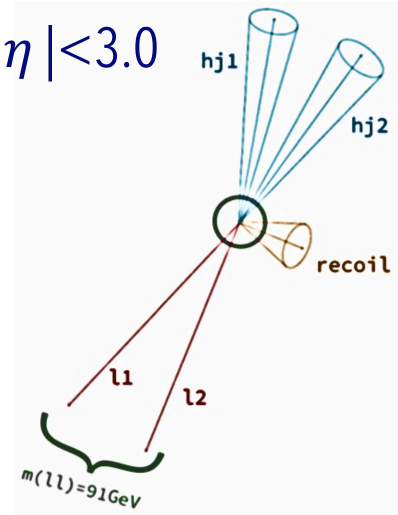


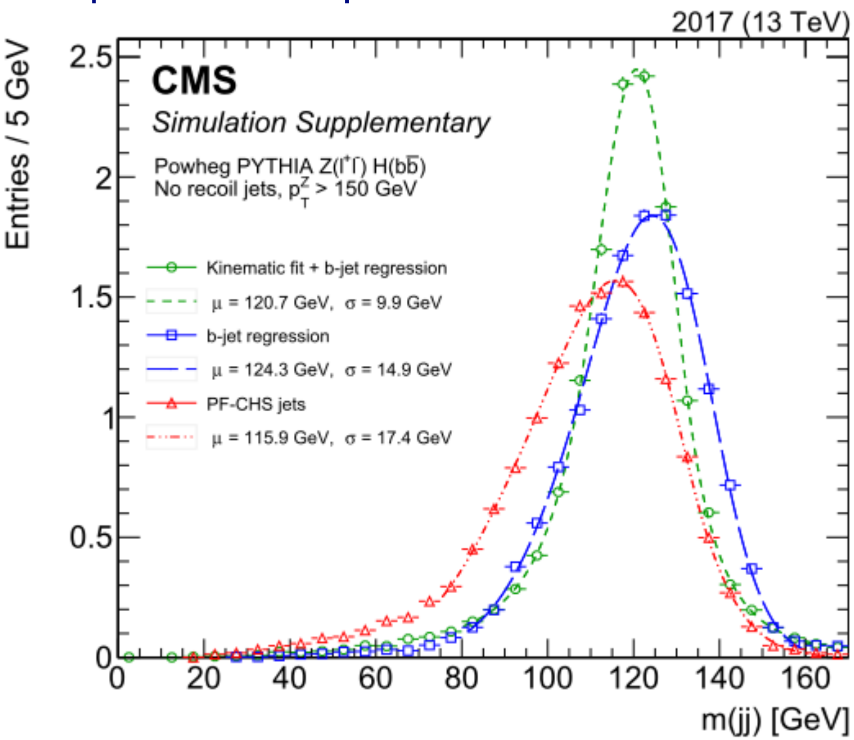


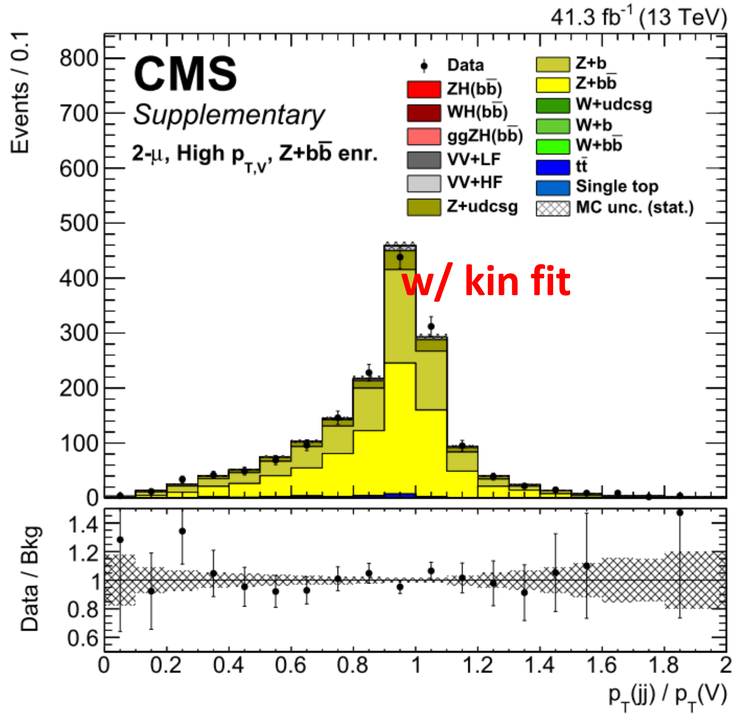
Top mass in 1-lep tt CR

FSR+Kinematic fit in 2-lepton channel

- **FSR-recovery:** additional jets in dR<0.8 cone with pt>20GeV and $|\eta|<3.0$
- **No intrinsic missing energy in the Z(ll)H(bb) process**
- Improve jet p_T measurement through kinematic fit procedure
  - Constrain di-lepton system to Z mass
  - **Balance the ll+bb+(jet) system in the (p_x, p_y) plane**
  - MET allowed to adjust within experimental resolution
- Improvement up to 36% on m(bb) resolution







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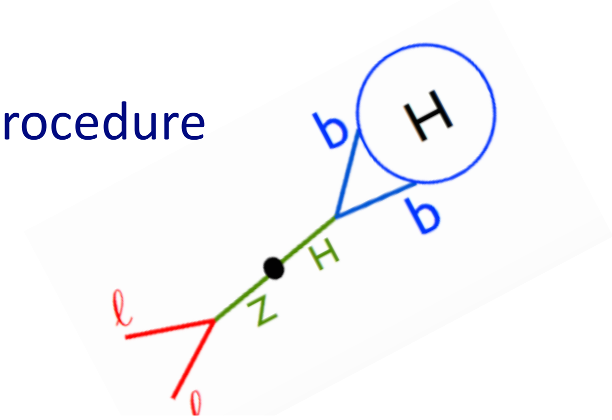
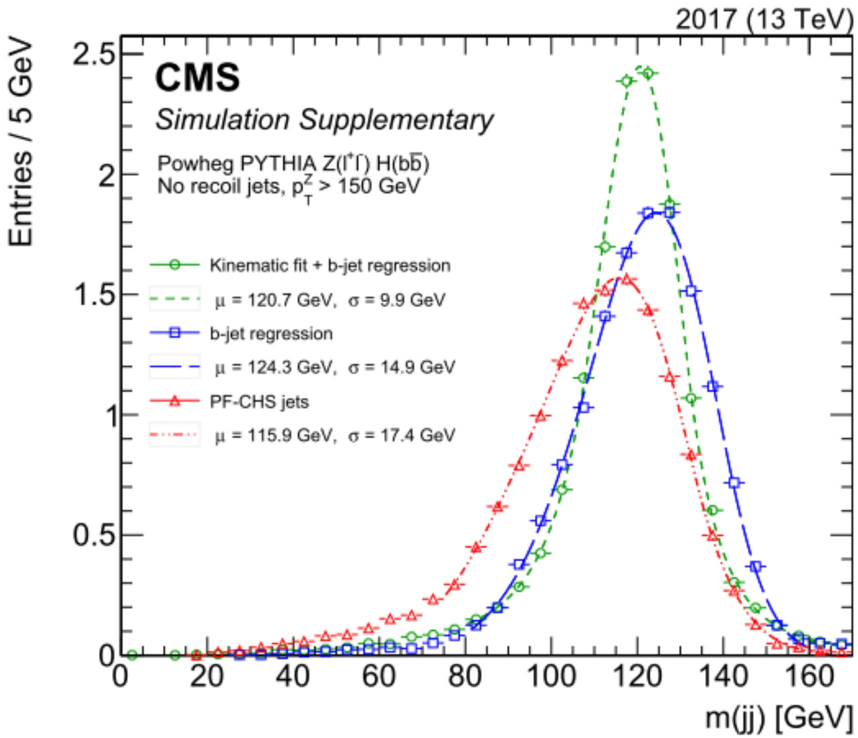
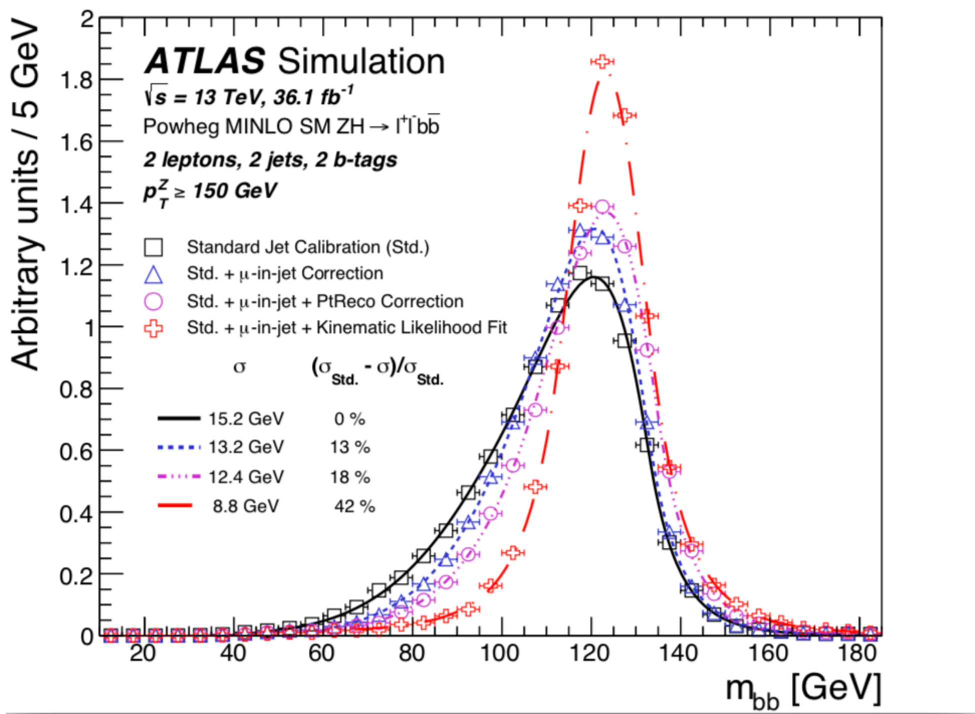


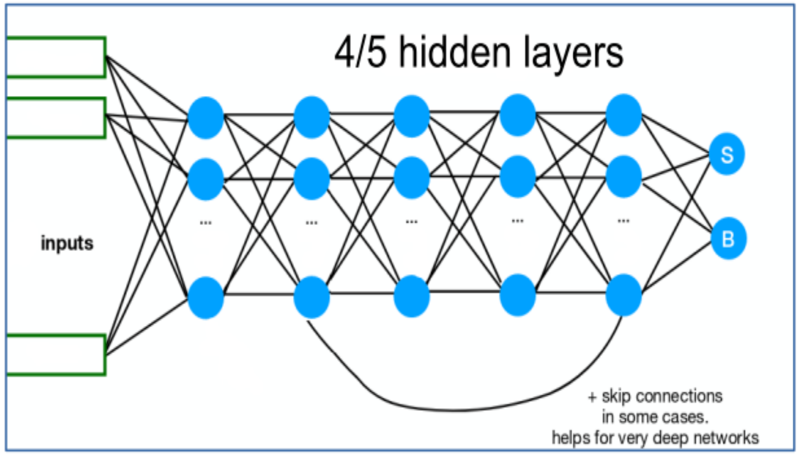




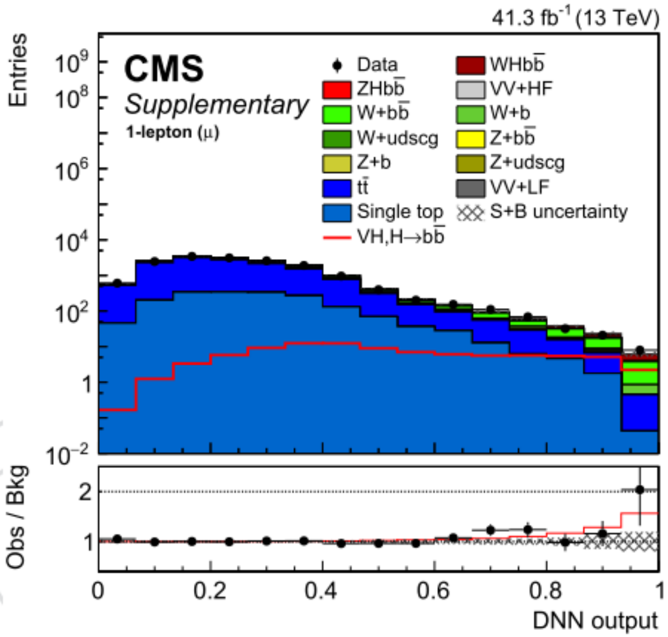
Signal vs Background discriminator

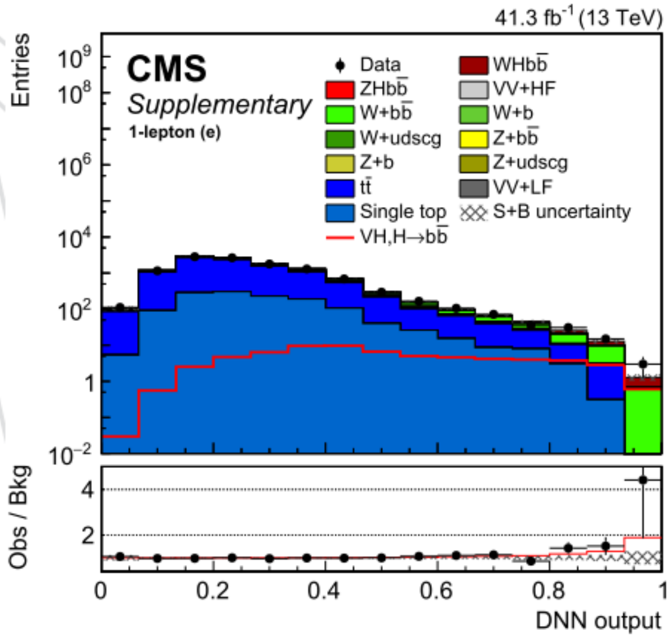
- To increase sensitivity, use **DNN discriminator to extract signal**
  - DNN outperforms BDT due to network depth
    - Same input variables as 2016 (b-jet properties, di-jet kinematics, event topology)
    - Validated through data/MC comparison
  - Trained separately in each channel to discriminate VH(b$\bar{b}$) from the weighted sum of all backgrounds
  - Parameters optimized to maximize sensitivity

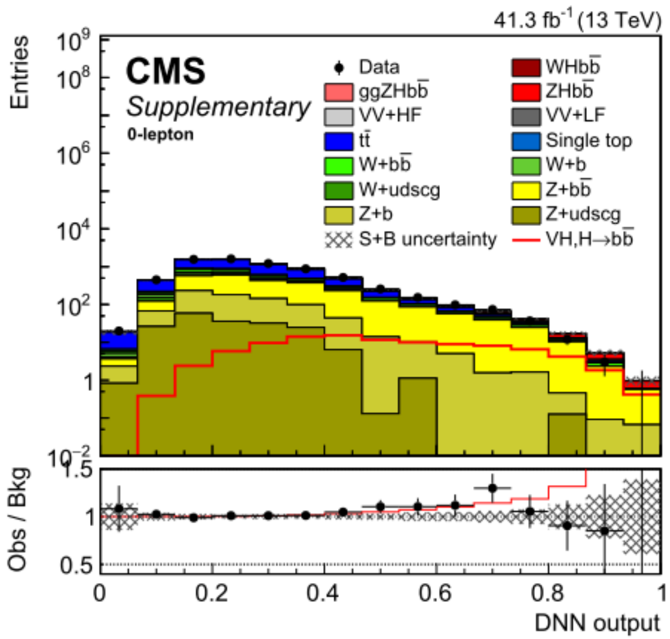
Variable	Description	0-lepton	1-lepton	2-lepton
$M(jj)$	dijet invariant mass	✓	✓	✓
$p_T(jj)$	dijet transverse momentum	✓	✓	✓
$p_T(j_1)$, $p_T(j_2)$	transverse momentum of each jet	✓		✓
$\Delta R(jj)$	distance in η–ϕ between jets			✓
$\Delta\eta(jj)$	difference in η between jets	✓		✓
$\Delta\varphi(jj)$	azimuthal angle between jets	✓		
$p_T(V)$	vector boson transverse momentum		✓	✓
$\Delta\phi(V,H)$	azimuthal angle between vector boson and dijet directions	✓	✓	✓
$p_T(jj)/p_T(V)$	p_T ratio between dijet and vector boson			✓
M_Z	reconstructed Z boson mass			✓
$btag_{max}$	value of the b-tagging discriminant (DeepCSV) for the jet with highest score	✓		✓
$btag_{min}$	value of the b-tagging discriminant (DeepCSV) for the jet with second highest score	✓	✓	✓
$btag_{add}$	value of b-tagging discriminant for the additional jet with highest value	✓		
E_T^{miss}	missing transverse momentum	✓	✓	✓
$\Delta\phi(E_T^{miss},j)$	azimuthal angle between E_T^{miss} and closest jet with $p_T > 30$ GeV	✓		
$\Delta\phi(E_T^{miss},\ell)$	azimuthal angle between E_T^{miss} and lepton		✓	
m_T	mass of lepton $\vec{p}_T + E_T^{miss}$		✓	
M_t	reconstructed top quark mass		✓	
N_{aj}	number of additional jets		✓	✓
$p_T(add)$	transverse momentum of leading additional jet	✓		
SA5	number of soft-track jets with $p_T > 5$ GeV	✓	✓	✓



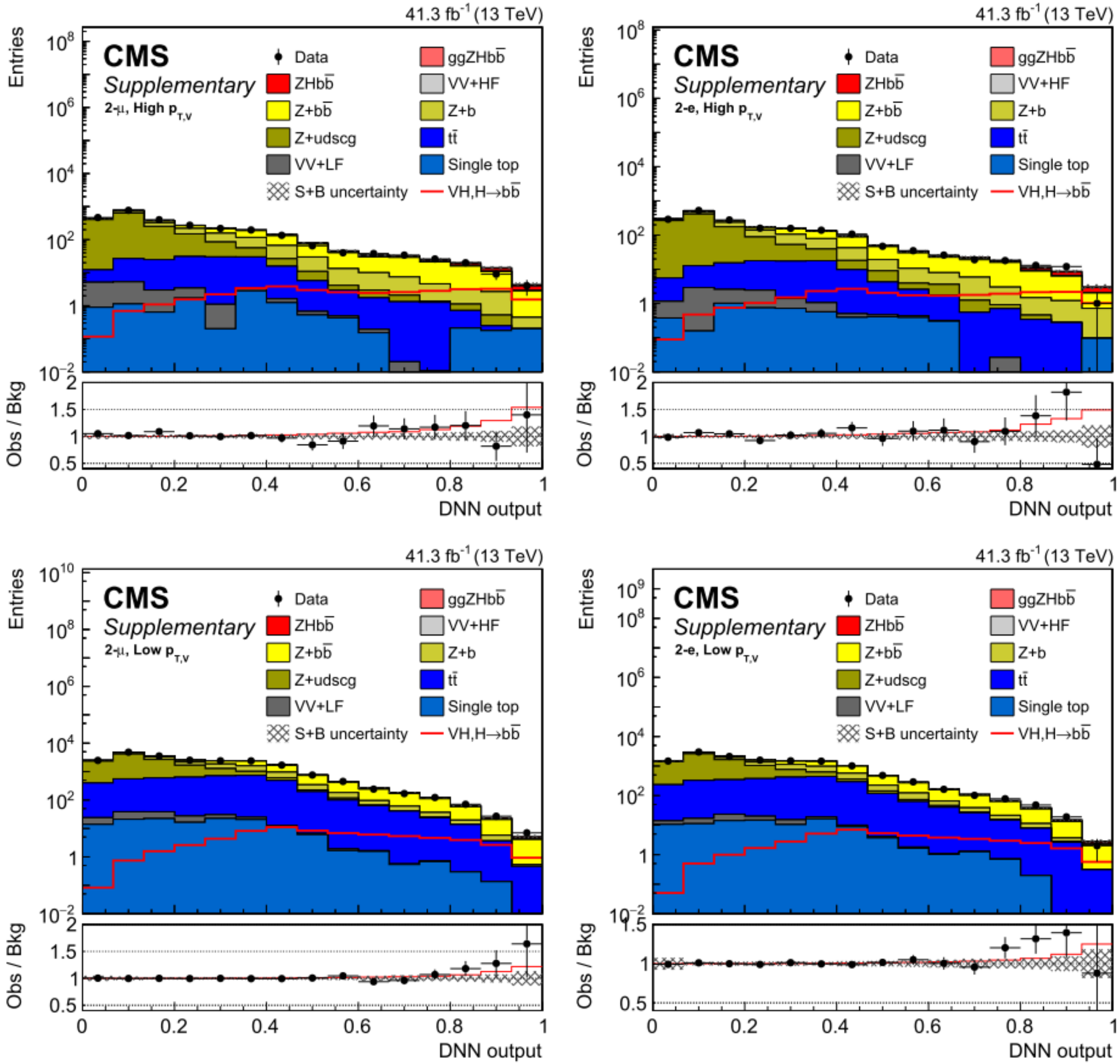
0- and 1-lepton signal regions' DNN





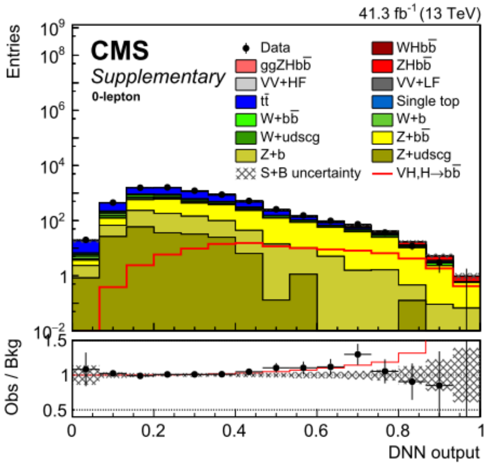


2-lepton signal regions' DNN

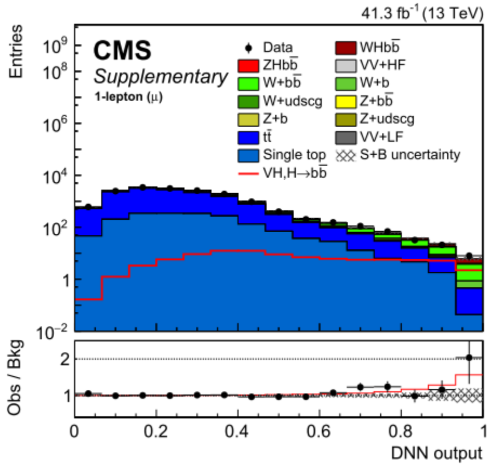


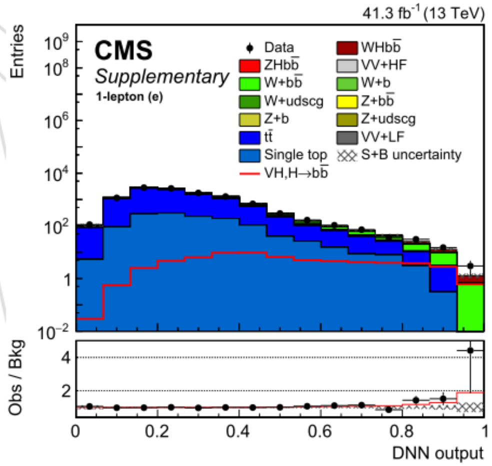
VH(bb) DNN distributions

0-lepton

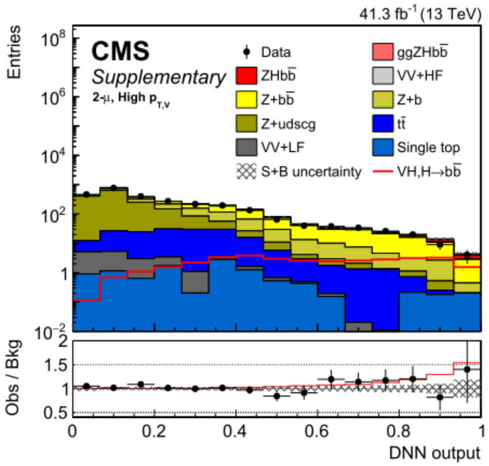


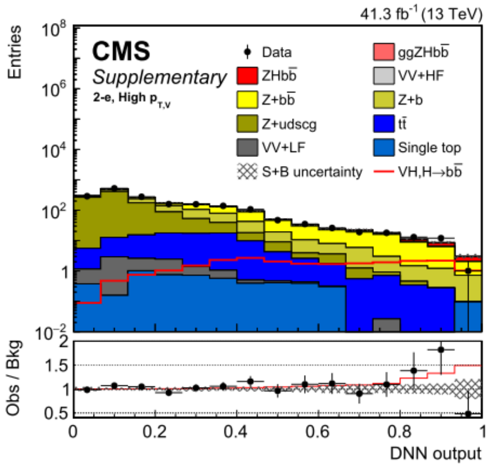
1-lepton

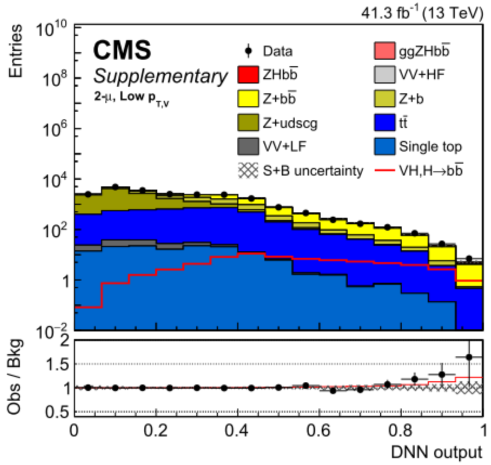


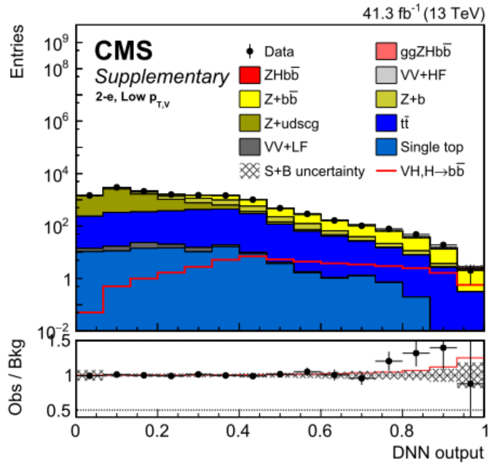


2-lepton





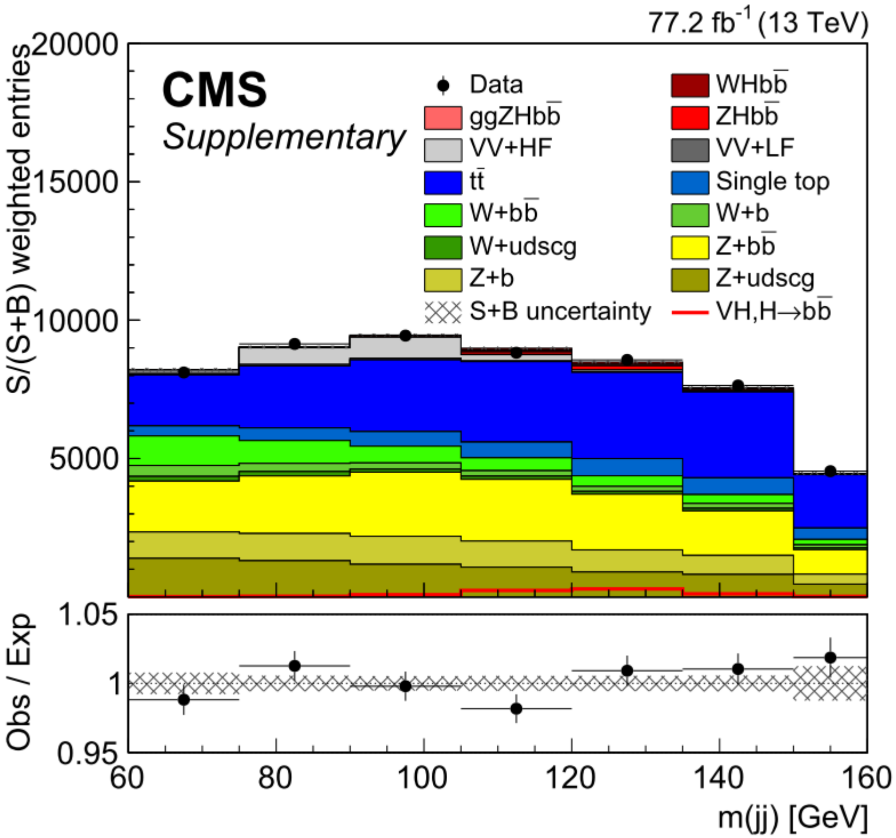


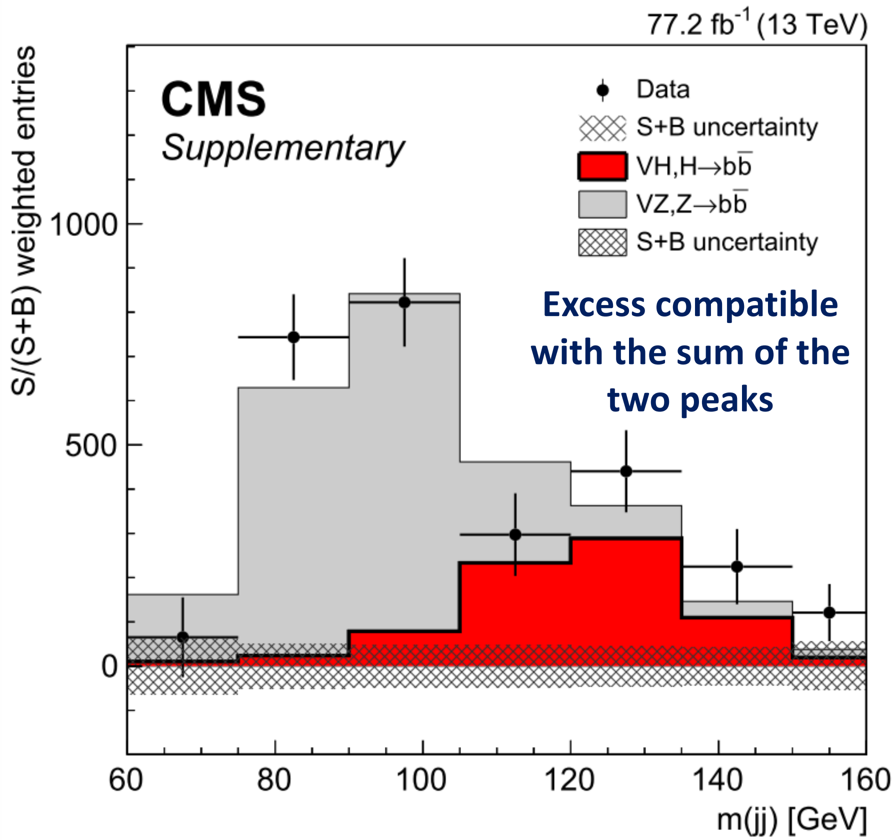


DNN distributions can also be sorted into bins of similar signal-to-background ratio, and combined

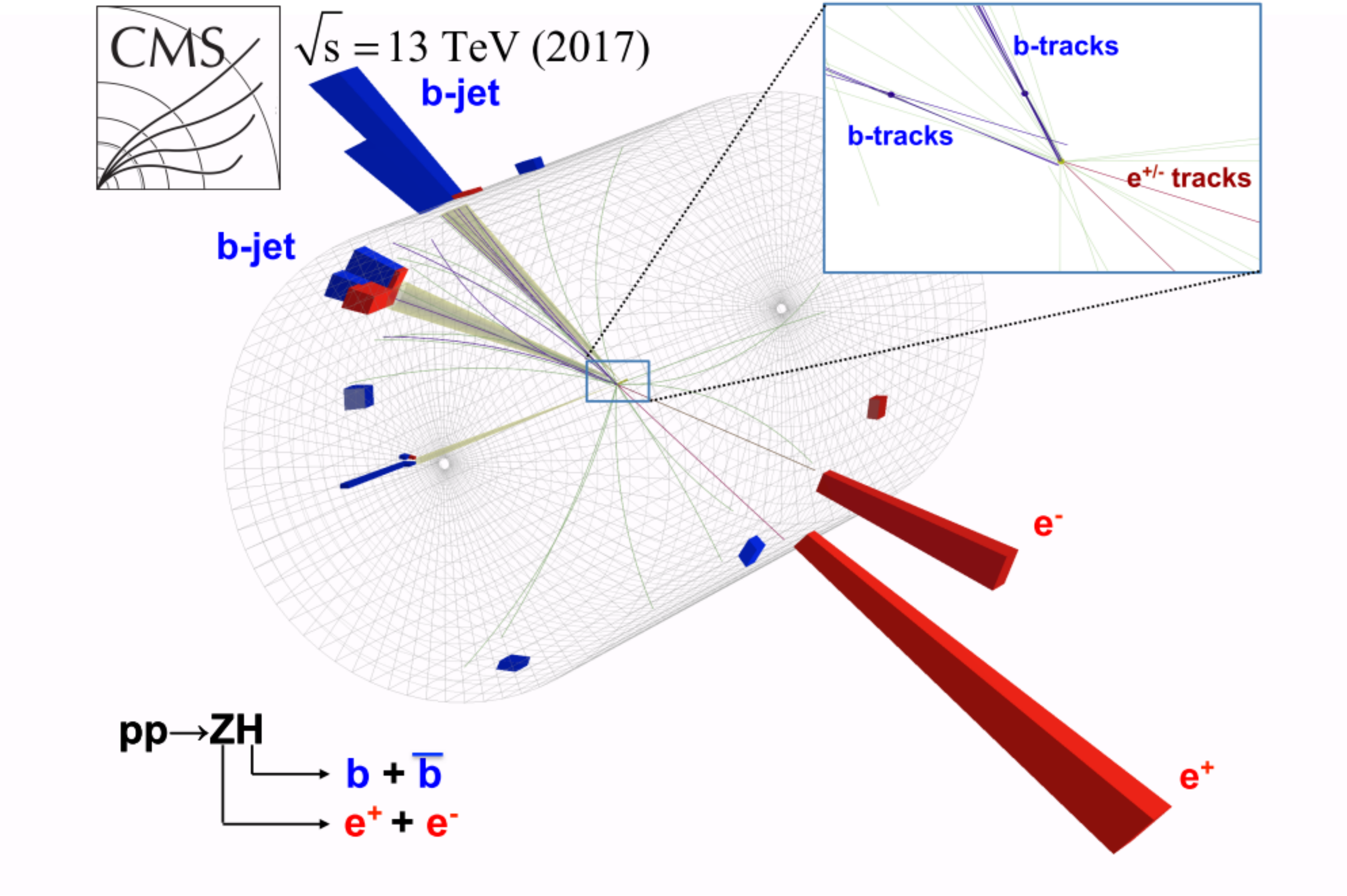
Visualizing the excess: m(jj) analysis

- **Fit to the m(jj)**: lower sensitivity but direct visualization of the Higgs boson signal
- **Events 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





Candidate event for Z(ee)H(bb)



Post-fit normalization + systematics

- MC shapes floated within constraints from systematic uncertainties through nuisance param.
- MC normalization truly float ➔ fitted SFs in agreement with those measured in 2016 analysis

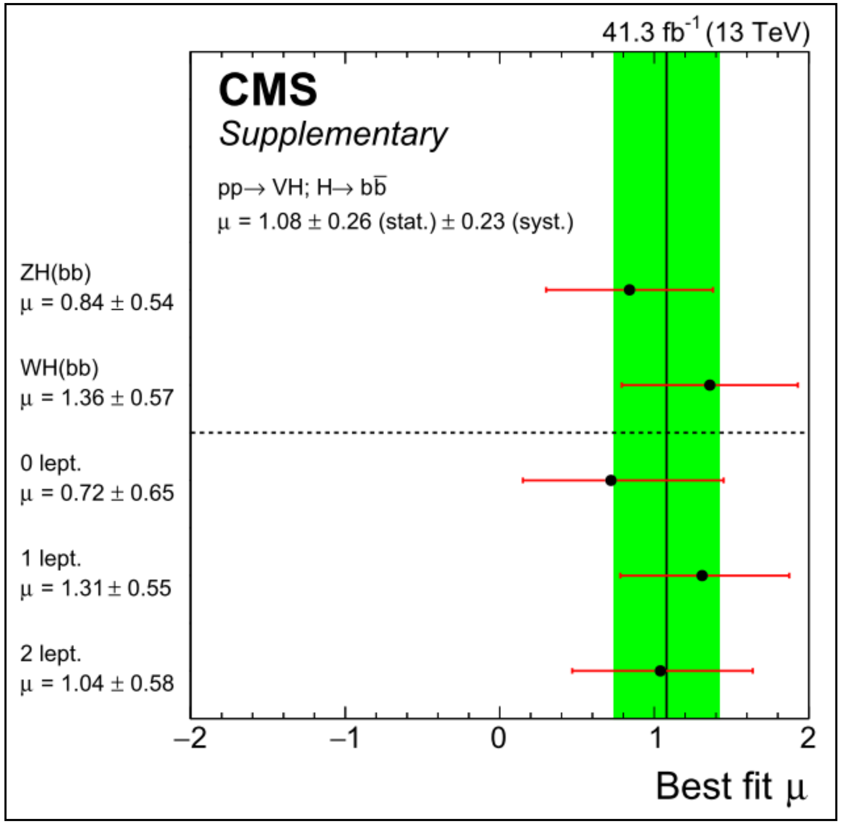
Process	Z($\nu\nu$)H	W($\ell\nu$)H	Z($\ell\ell$)H low-p_T	Z($\ell\ell$)H high-p_T
W + udscg	1.04 ± 0.07	1.04 ± 0.07	–	–
W + b	2.09 ± 0.16	2.09 ± 0.16	–	–
W + $b\bar{b}$	1.74 ± 0.21	1.74 ± 0.21	–	–
Z + udscg	0.95 ± 0.09	–	0.89 ± 0.06	0.81 ± 0.05
Z + b	1.02 ± 0.17	–	0.94 ± 0.12	1.17 ± 0.10
Z + $b\bar{b}$	1.20 ± 0.11	–	0.81 ± 0.07	0.88 ± 0.08
$t\bar{t}$	0.99 ± 0.07	0.93 ± 0.07	0.89 ± 0.07	0.91 ± 0.07

- **Total uncertainty on μ ~34%**
- Major sources of systematic uncertainties:
  - background normalization
  - background modeling
  - b-tagging
  - MC sample size

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

VH(H→bb̄) Results with 2017 data

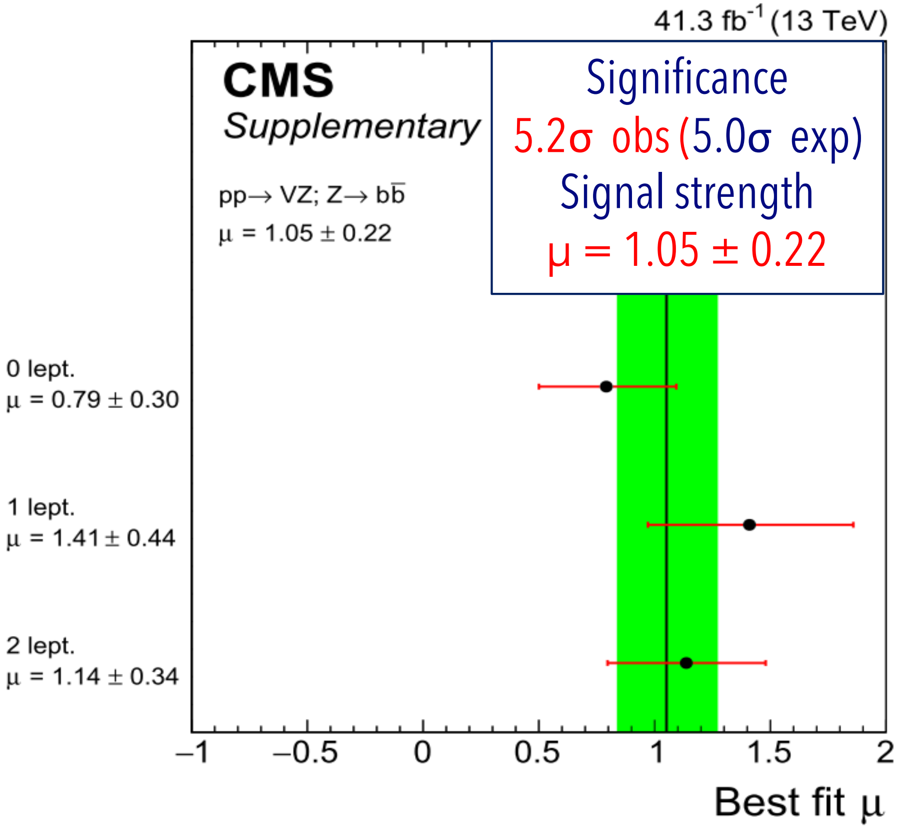
Data set	Significance (σ) Expected	Observed	Signal strength
2017			
0-lepton	1.9	1.3	0.73 ± 0.65
1-lepton	1.8	2.6	1.32 ± 0.55
2-lepton	1.9	1.9	1.05 ± 0.59
Combined	3.1	3.3	1.08 ± 0.34
2016	2.8	3.3	1.2 ± 0.4



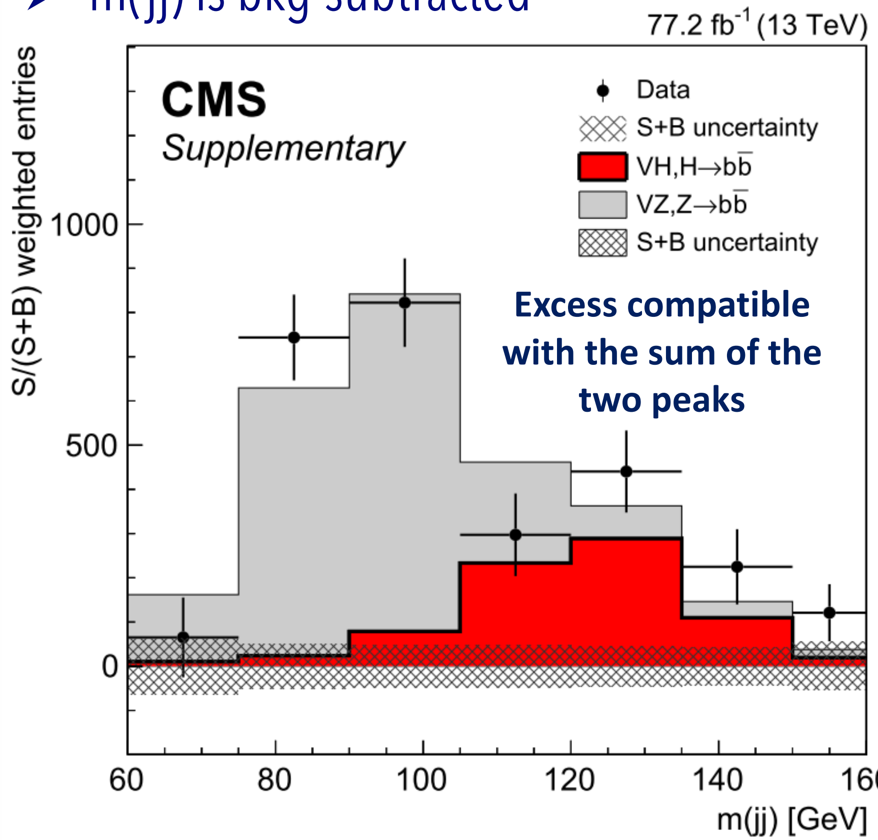
- **Standalone evidence for H->bb̄ with 2017 data**
  - **Observed significance 3.3σ, signal strength 1.08 ± 0.34**
  - O(5-10%) increase in analysis sensitivity wrt 2016, depending on channel
  - Signal strengths extracted from each channels are compatible

Validation (VZ$b\bar{b}$) and Visualization (m_{jj})

- **VZ analysis** using Z($b\bar{b}$) standard candle
- **Same "technology" as used for VH(bb)**
  - Same DNN inputs and CRs
  - VH(bb) normalized to SM
  - Larger m(bb) window in SR



- **Fit to the m(jj)**:
  - Lower sensitivity
  - direct visualization of the signal
  - m(jj) distributions combined and weighted by S/(S + B)
  - m(jj) is bkg-subtracted



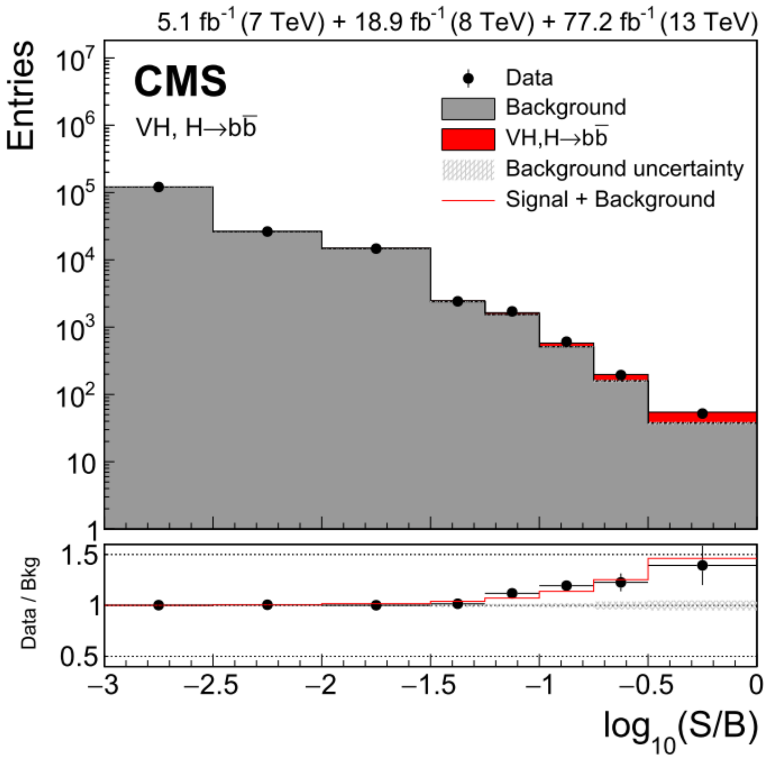
H→bb combination: syst. unc. correlation scheme

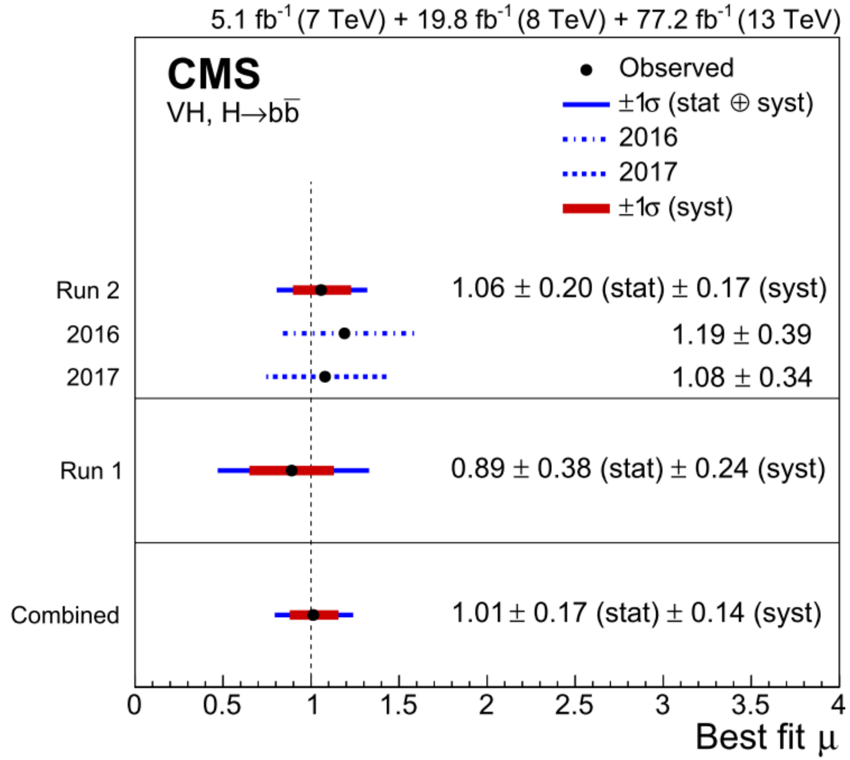
- Inherits from previous combinations:
  - Correlations between run 1 analyses already settled for run 1 coupling combination
  - Correlations between 2016 analyses were already settled for 2016 coupling combination
  - Correlations between run 1 & run 2 ttH and were already settled for ttH combination
- Features of correlations between run 1 VH and run 2, and VH 2016 - 2017 in table below
- Note: we update run 1 cross sections and uncertainties with the values from YR4

Jet energy scale	Between 2016 and 2017 we correlate some of the sources following JME recommendations
b-tagging	Not correlated between 2016-2017 and not correlated between VH and other channels due to different treatment
Signal theory	Inclusive QCD scale and pdf uncertainties correlated between run 1 and run 2. QCD scale acceptance uncertainties correlated between VH 2016 and 2017, pdf acceptance uncertainties not correlated
Background theory	Inclusive cross section uncertainties correlated between VH 2016 and 2017. QCD scale acceptance uncertainties correlated between VH 2016 & 2017, pdf acceptance uncertainties not correlated
Lumi	Uncorrelated between 2016 & 2017
JER	Correlated between 2016 & 2017 (note JER in 2017 split in ‘regular’ JER and regressed jet JER. The latter is not correlated with anything)
PU uncertainty	Correlated between 2016 and 2017

- **Combination of VH(H→b$\bar{b}$) measurement**

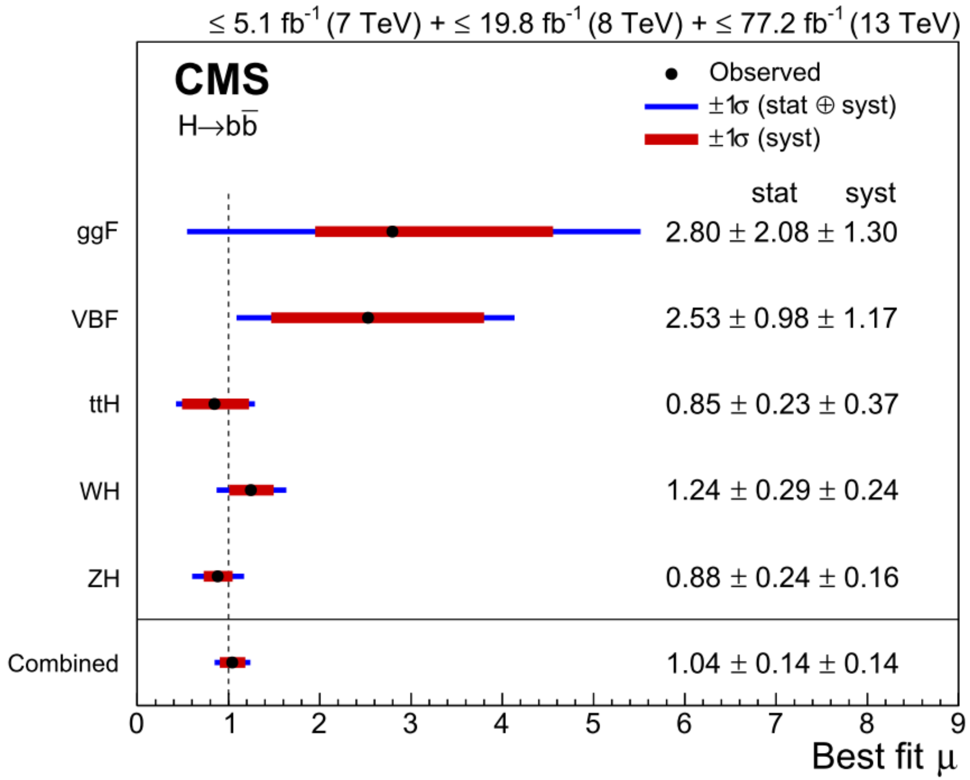
Data set	Significance (σ) Expected	Significance (σ) Observed	Signal strength
2017	3.1	3.3	1.08 ± 0.34
Run 2	4.2	4.4	1.06 ± 0.26
Run 1 + Run 2	4.9	4.8	1.01 ± 0.23





Combination of H→b$\bar{b}$ measurements

- **Combination of all CMS H→b$\bar{b}$ measurements**
  - VH, boosted ggH, VBF, ttH
  - Most sources of systematic uncertainty are treated as uncorrelated
  - Theory uncertainties are correlated between all processes and data sets



Significance:
5.5σ expected
5.6σ observed

Observation of the H→bb decay by the CMS Collaboration

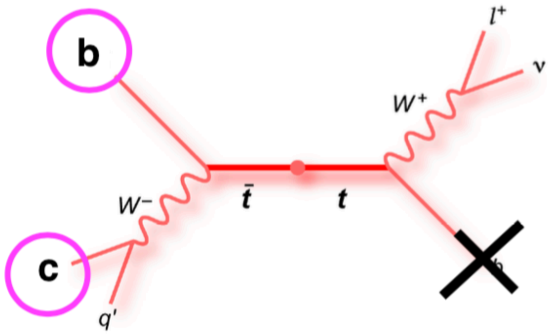
Measured signal strength:
μ = 1.04 ± 0.20

H→bb ATLAS – systematics

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

- ***Analysis systematically dominated*** : syst. component represent ~80% of total error [does not mean that it will not shrink with luminosity]

- ***Detector systematics effects*** dominated by flavour tagging [sensitivity to c-jet mis-tag from ttbar events]



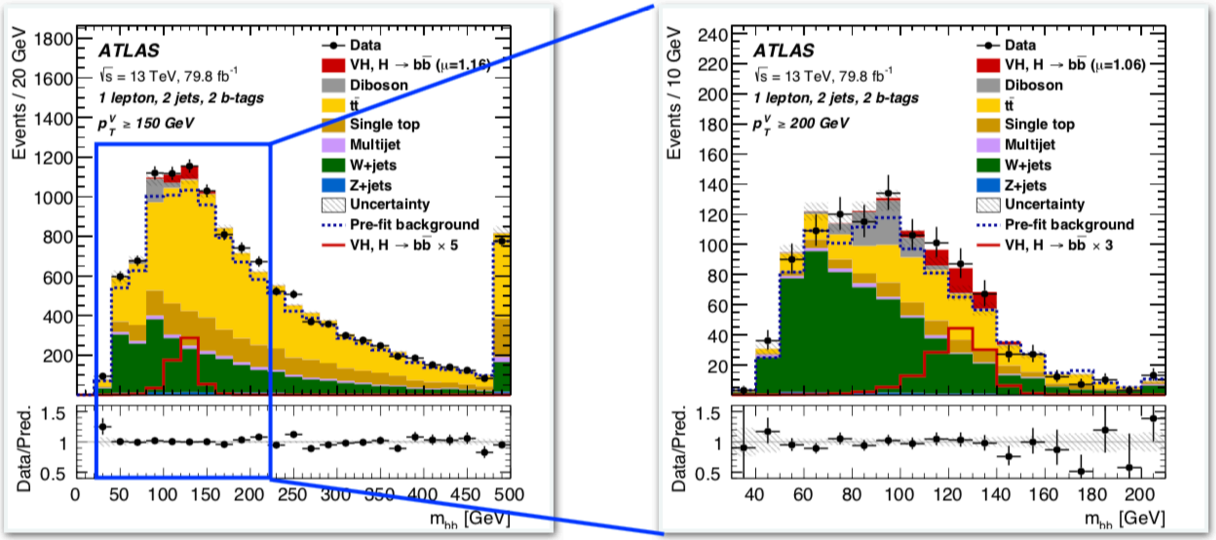
- ***Signal modelling systematics***: dominated by Parton Shower acceptance effects
  - do not impact the significance of the measured signal

- Similar contribution from ***modelling uncertainty*** of various processes:
  - ***W+jets***: W p_T shape uncertainty
  - ***Z+jets***: m_{bb} shape uncertainty
  - ***diboson***: m_{bb} lineshape

- ***MC statistics:*** heavily relying on generator filters at different level to provide enough statistics (huge CPU investment)

H→bb ATLAS – Mass analysis

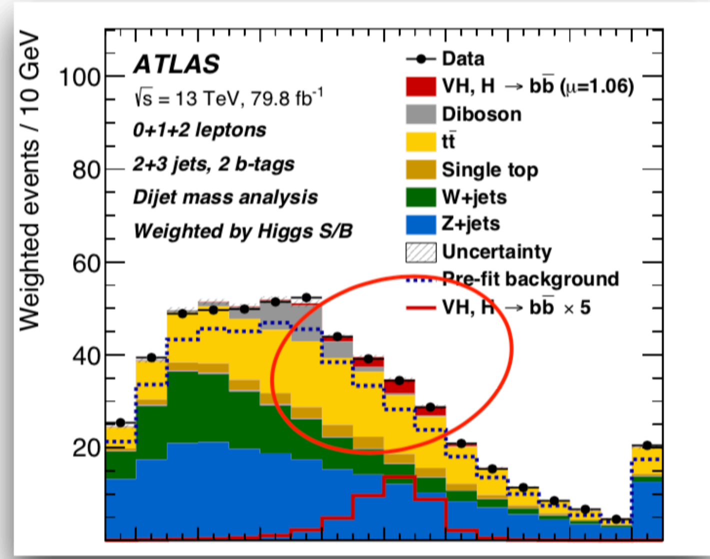
- fitting m_{bb} instead of MVA discriminant:
  - *additional splitting in Vpt: 200 GeV*
  - *additional upper cut on dRbb: 1.2 - 3.0*
  - *additional selection on 1L/2L to reduce ttbar background*

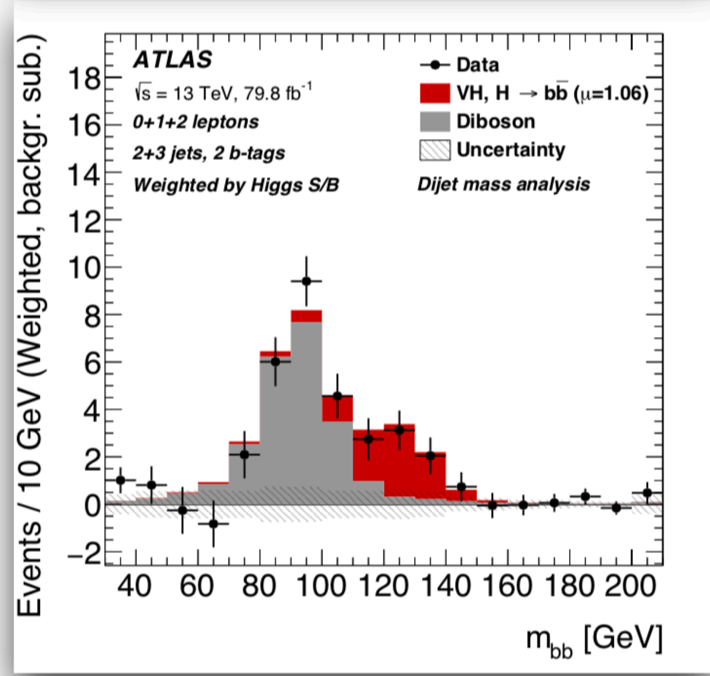


$$\mu_{\mathrm{VH}}^{bb} = 1.06^{+0.36}_{-0.33}$$

Run2 signal significance:

3.6 s.d. obs. *, 3.5 s.d. exp.*





Combination of H→b$\bar{b}$ measurements

- **Combination of all CMS H→b$\bar{b}$ measurements**
  - VH, boosted ggH, VBF, ttH
  - Most sources of systematic uncertainty are treated as uncorrelated
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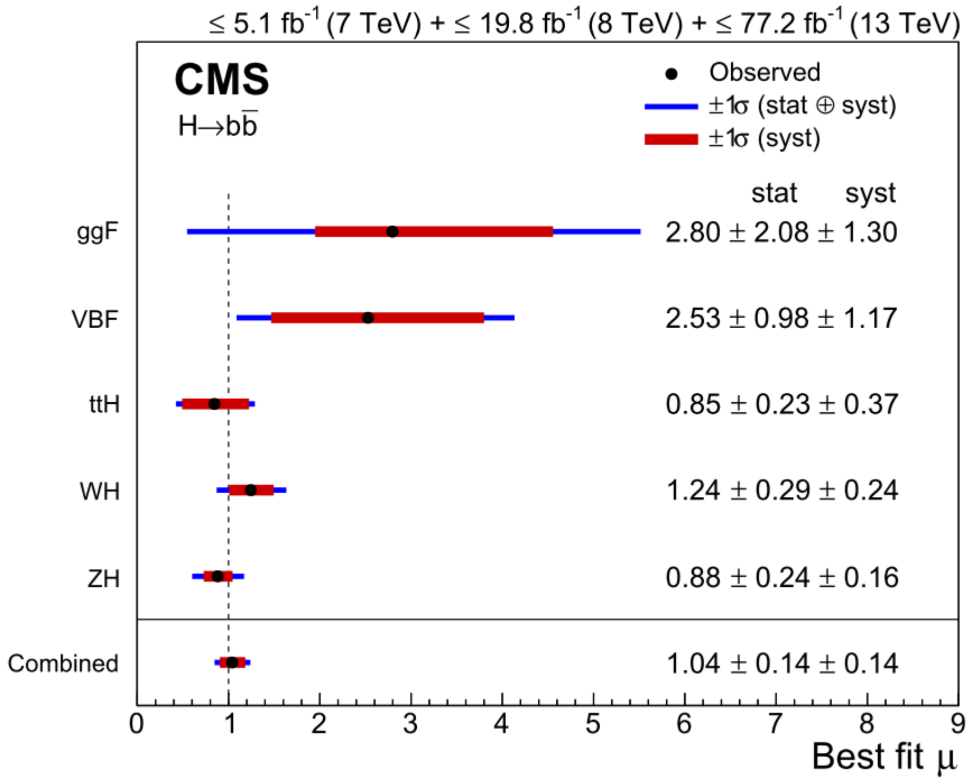


Significance:
5.5σ expected
5.6σ observed

Observation of the H→bb decay by the CMS Collaboration

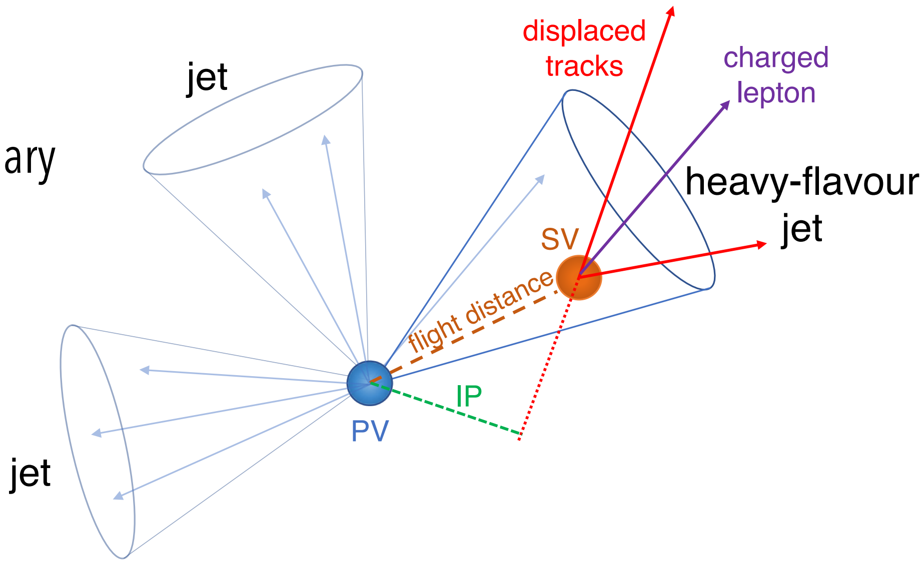
Measured signal strength:
μ = 1.04 ± 0.20

Basics on B-Tagging

▪ Overview on b-tagging

➢ b-jet tagging rely on b-hadron properties

- Displaced vertex (secondary vertex) from primary vertex due to its long life (~1.5ps)
- Large B-hadron mass
- Large impact parameters (d0)
- Semi-leptonic e/μ decay of B-hadron (~40% total B hadron decays)



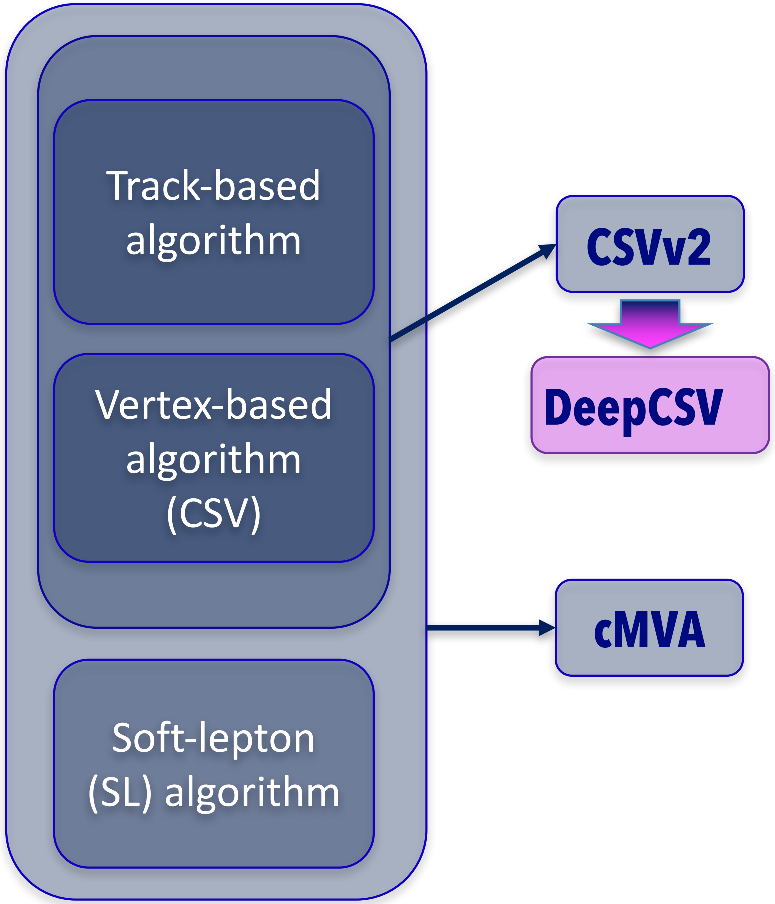
➢ Different optimized WPs in term of b-efficiency vs mistag rate

➢ b-jet efficiency and purity is an important metric to assess tagger performance

A variety of b tagging algorithms has been developed by ATLAS and CMS. After a short overview ➔ focus on latest state-of-the-art techniques.

b-tagging strategy in CMS

- **Overview on b-tagging algorithm in CMS**
  - JP and JBP
    - Likelihood based on the track properties (displacement). Returns p(b-jet)
  - CSV and CSVv2
    - Combine displaced tracks with secondary vertices in BDTs (CSV) and in multilayer perceptrons (CSVv2)
  - DeepCSV (more details in the next slides)
    - DNN Multiclassifier: same inputs as CSVv2 with a simple extension to use more charged particle tracks
  - DeepFlavour (more details in the next slides)
    - DNN Multiclassifier



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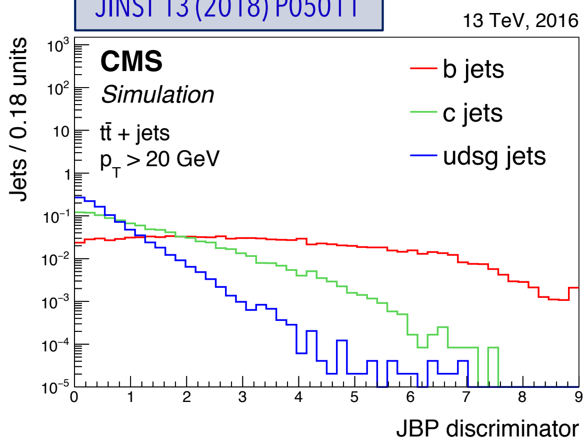

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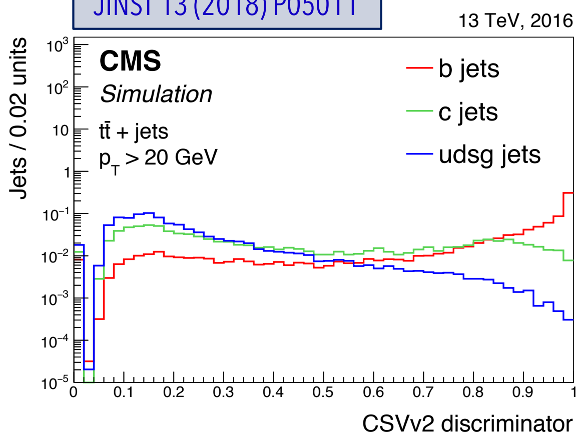
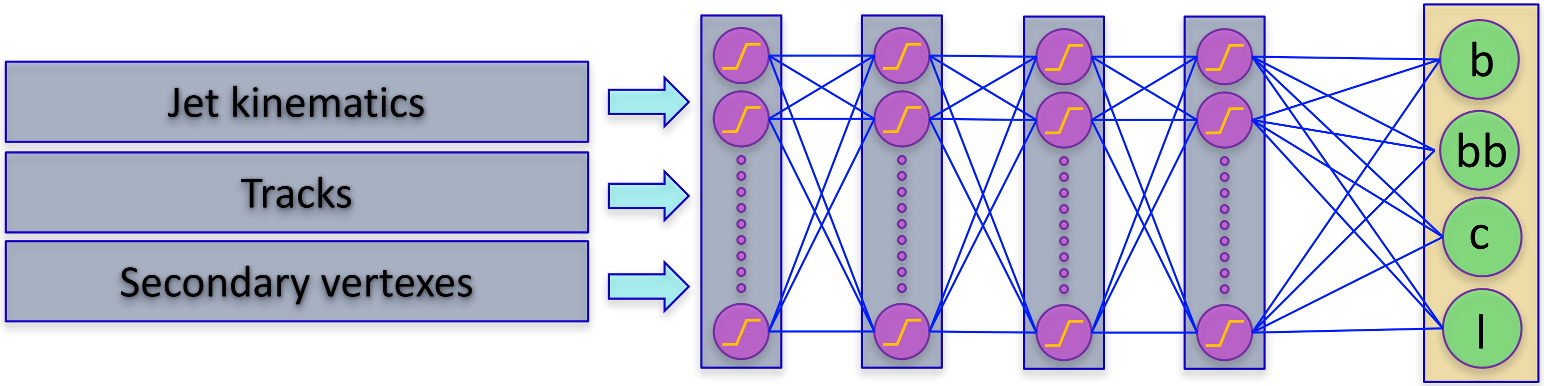


- cMVA: combined multivariate analysis (cMVA) tagger, combines the discriminator values of low-level tagger

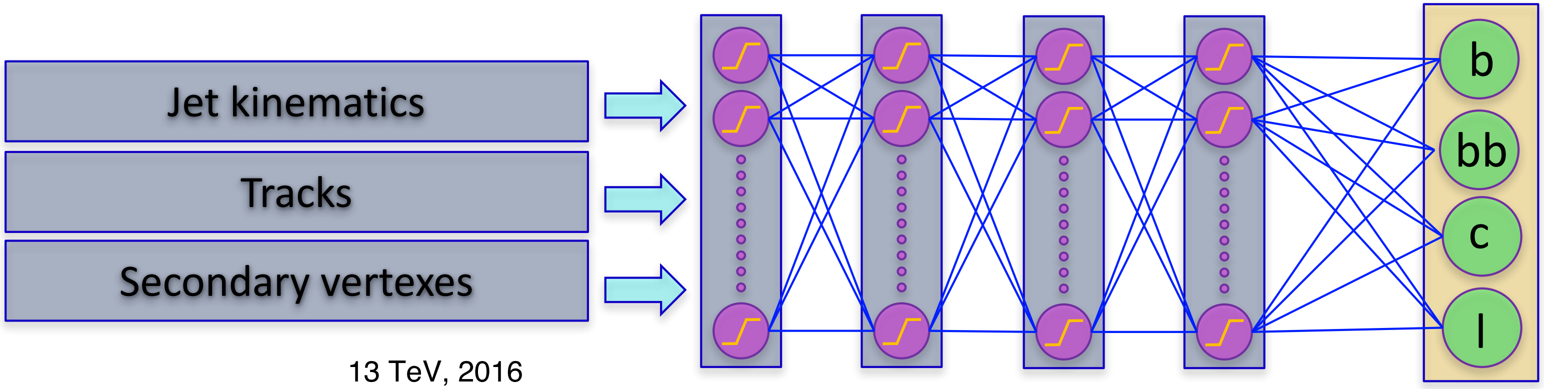
Cutting edge technology - CMS

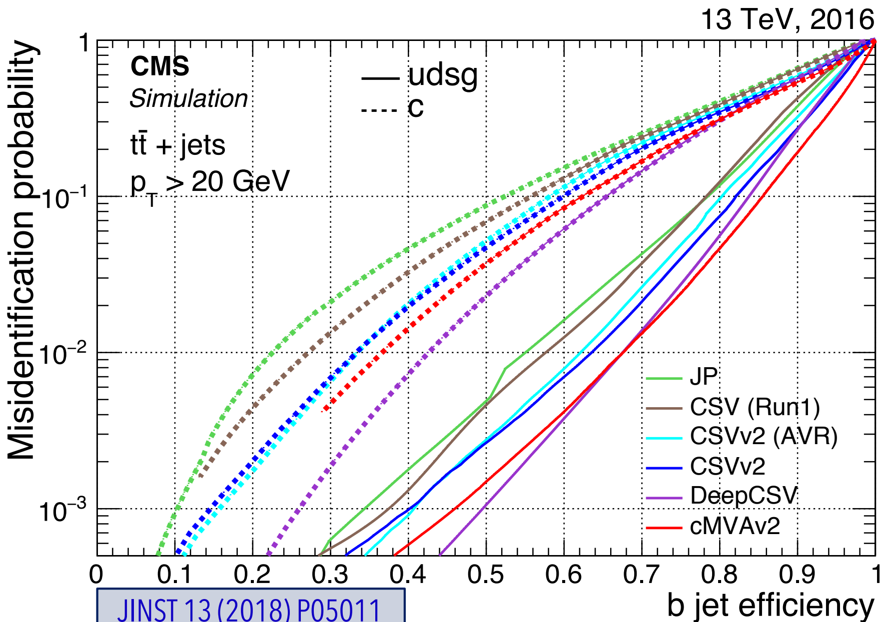
- **DeepCSV: DNN architecture**
  - Input variables go through 4 fully connected layers, each layer has 100 nodes
  - ReLu activation function used in each of the hidden nodes
  - Output layer → softmax activation function → multiclassification



- **DeepCSV: Training**
  - Training performed with Keras DL-library interfaced with Tensorflow
  - Jets with pT in [20,1000] GeV and flavour ratio fixed to **2 : 1 : 4** for **b : c : light**
  - Mixture of tt and multijets events →reduce dependence on heavy-flavour quarks production process

- **DeepCSV: Deep Neural Network architecture**
  - Input variables go through 4 fully connected layers, each layer has 100 nodes
  - ReLu activation function used in each of the hidden nodes
  - Output layer → softmax activation function → multiclassification





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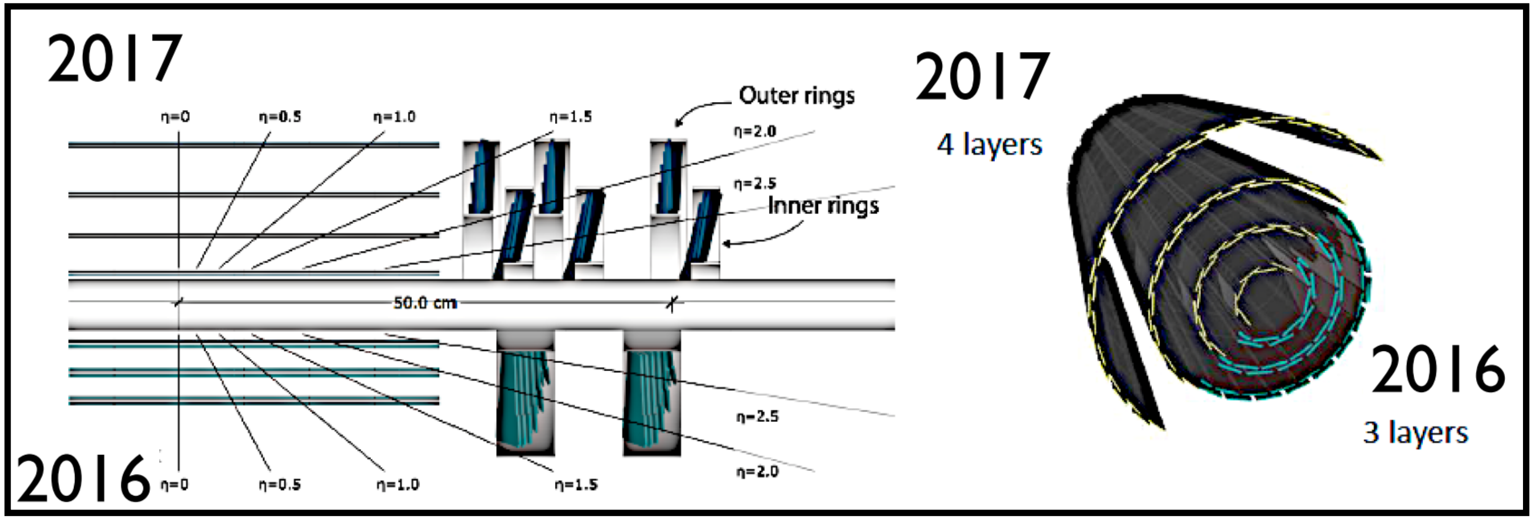
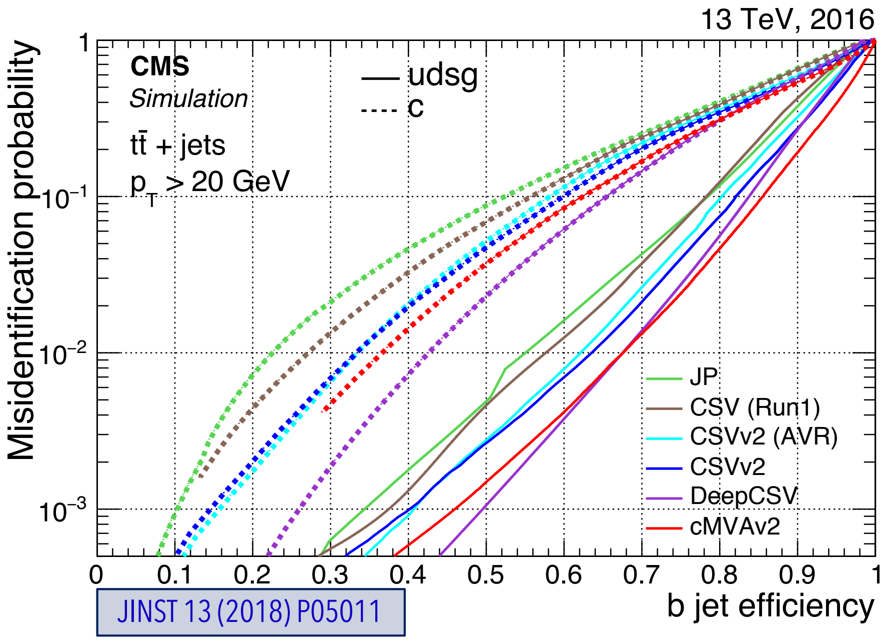
- Three working points commissioned with data
- Available set of data/MC SF for full 2017 run

Tagger	Working point	ε_b (%)	ε_c (%)	ε_{udsg} (%)
	DeepCSV L	84	41	11
Deep combined secondary vertex	DeepCSV M	68	12	1.1
(DeepCSV) $P(b) + P(bb)$	DeepCSV T	50	2.4	0.1

State of the art b-jet identification

- **Upgraded pixel detector**





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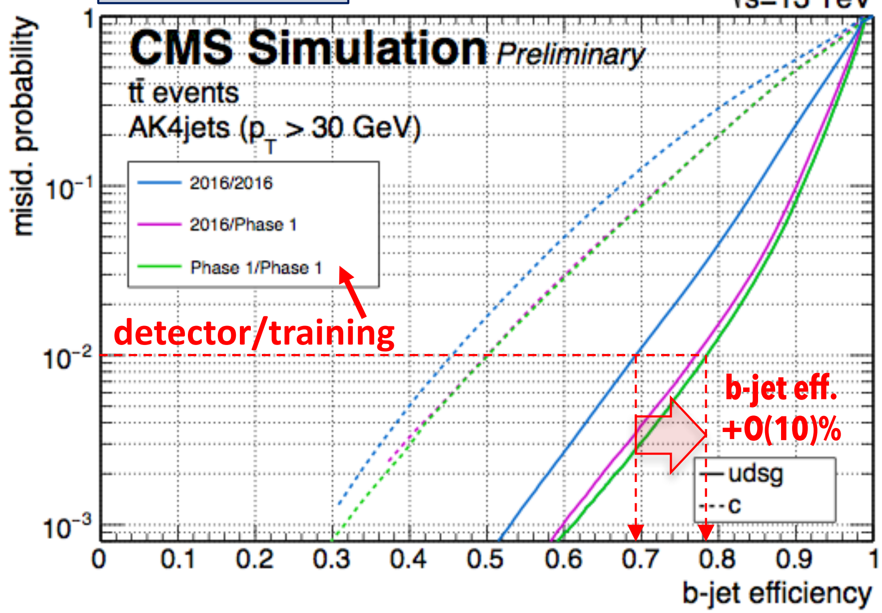
CMS-DP-2017-013

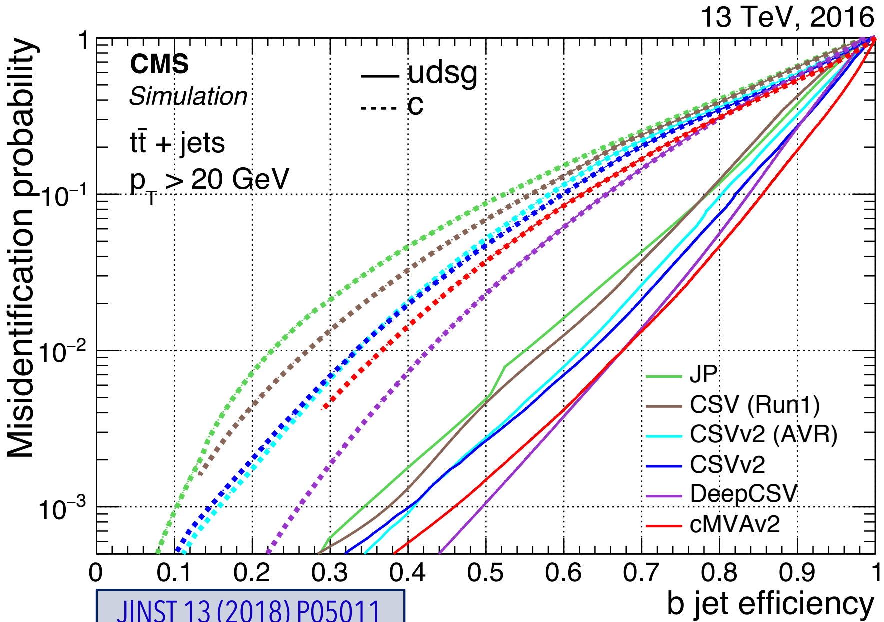


Performance in Simulation - CMS

- **DeepCSV**
  - Performance evaluated in simulated tt events, considering AK4 Jets with pT>20GeV
  - DeepCSV performance are compared against those of other commissioned taggers in CMS
  - DeepCSV WPs are defined as values of the discriminator cut for which the light mistag-rate is 10%, 1%, and 0.1%,

Tagger	Working point	ε_b (%)	ε_c (%)	ε_{udsg} (%)
Deep combined secondary vertex (DeepCSV) $P(b) + P(bb)$	DeepCSV L	84	41	11
	DeepCSV M	68	12	1.1
	DeepCSV T	50	2.4	0.1

- **DeepFlavour**
  - Performance evaluated in simulated tt events (plot), considering AK4 Jets with pT>30GeV
  - Simply adding more information can even degrade performance
  - Adding convolutional layers (exploiting structures) increases the performance significantly



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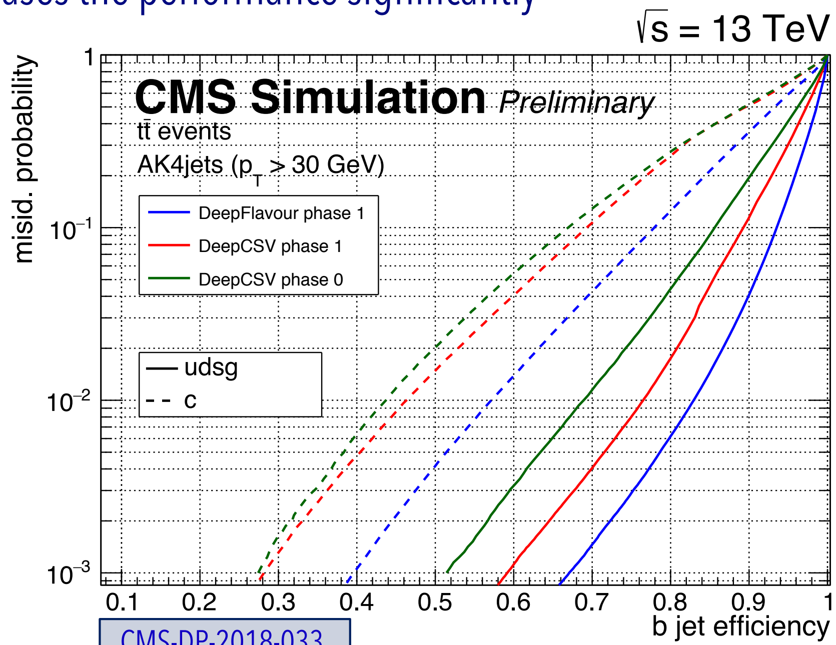

CMS-DP-2018-033

Performance in Simulation - CMS

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Tagger	Working point	ε_b (%)	ε_c (%)	ε_{udsg} (%)
	DeepCSV L	84	41	11
Deep combined secondary vertex	DeepCSV M	68	12	1.1
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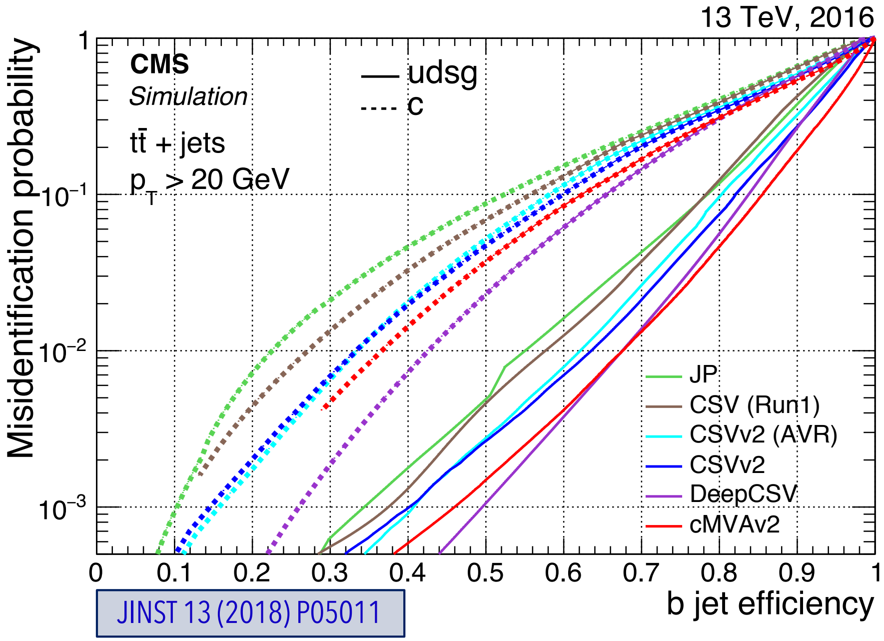

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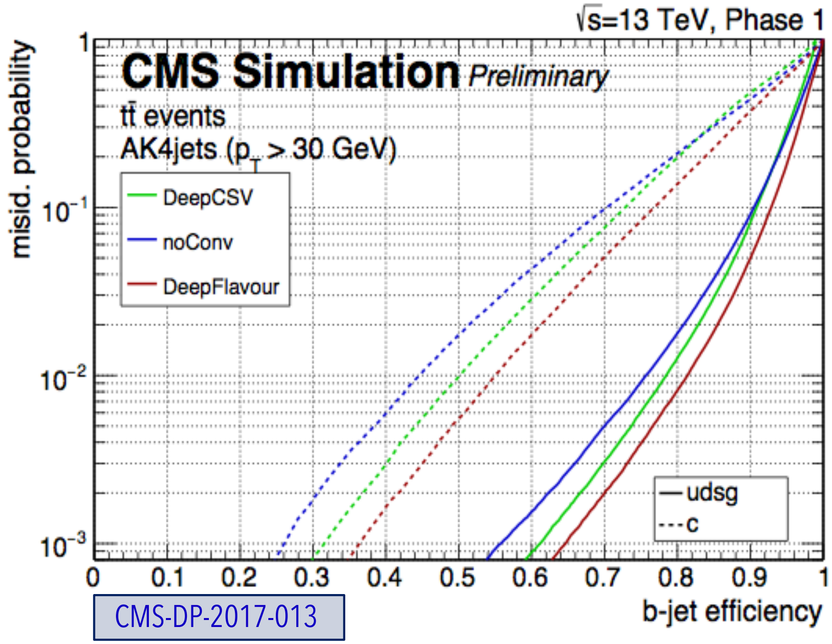

CMS-DP-2017-013

SF comparison: 2016 vs 2017

2016

Process	0-lepton	1-lepton	2-lepton low-p_T(V)	2-lepton high-p_T(V)
W0b	1.14 ± 0.07	1.14 ± 0.07	—	—
W1b	1.66 ± 0.12	1.66 ± 0.12	—	—
W2b	1.49 ± 0.12	1.49 ± 0.12	—	—
Z0b	1.03 ± 0.07	—	1.01 ± 0.06	1.02 ± 0.06
Z1b	1.28 ± 0.17	—	0.98 ± 0.06	1.02 ± 0.11
Z2b	1.61 ± 0.10	—	1.09 ± 0.07	1.28 ± 0.09
$t\bar{t}$	0.78 ± 0.05	0.91 ± 0.03	1.00 ± 0.03	1.04 ± 0.05

2017

Process	$Z(\nu\nu)H$	$W(\ell\nu)H$	$Z(\ell\ell)H$ low-p_T	$Z(\ell\ell)H$ high-p_T
$W + udscg$	1.04 ± 0.07	1.04 ± 0.07	–	–
$W + b$	2.09 ± 0.16	2.09 ± 0.16	–	–
$W + b\bar{b}$	1.74 ± 0.21	1.74 ± 0.21	–	–
$Z + udscg$	0.95 ± 0.09	–	0.89 ± 0.06	0.81 ± 0.05
$Z + b$	1.02 ± 0.17	–	0.94 ± 0.12	1.17 ± 0.10
$Z + b\bar{b}$	1.20 ± 0.11	–	0.81 ± 0.07	0.88 ± 0.08
$t\bar{t}$	0.99 ± 0.07	0.93 ± 0.07	0.89 ± 0.07	0.91 ± 0.07

Systematic uncertainties

- **Jet energy scale:**
  - Split into 27 independent uncertainty sources
- **Jet energy resolution:**
  - 10% uncertainty on regressed b-jets from dedicated study
    - Decorrelated for signal to avoid any possible constraining, covers any uncertainties from PS.
  - Standard JER uncertainty for additional jets.
- **B-tagging:**
  - Split into independent uncertainty sources
  - Further de-correlated based on jet pT/η, as in 2016 analysis
- **Background normalizations:**
  - Derived from fit to data for backgrounds with floating normalisation (V+udcsg, V+b, V+bb, tt)
  - 15% uncertainty on VV and single top cross section.
- **Monte Carlo statistics**
- **QCD scales and PDF variations**
  - Acceptance as well as overall cross section
- **Lepton efficiency, pile-up re-weighting, luminosity**
- **Residual data/MC discrepancies**
  - Δη(jj) LO to NLO re-weighting in V+jets
    - Full correction taken as uncertainty.
  - p_T(W) linear re-weighting for tt (all channels) and W+jets, single top (1-lepton channel only)
    - Statistical uncertainty band from fit to derive corrections

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