Measurements of associate VH production

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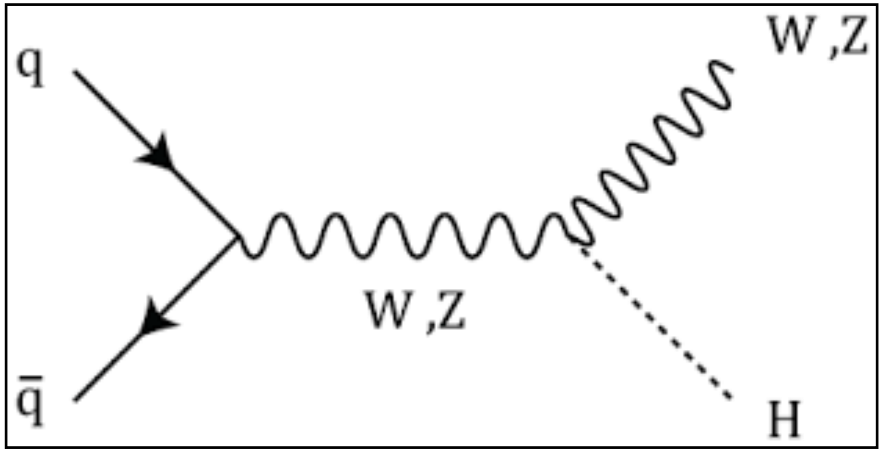
Higgs 2020

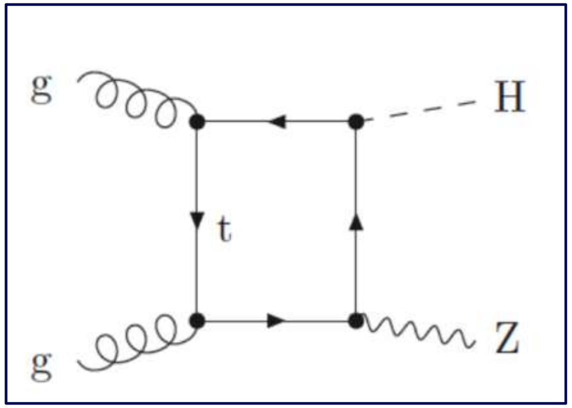
26-30 October 2020

Higgs boson associated production



Higgs-Strahlung (associated production)

- 4% of Higgs production mechanism
- Full EW corrections known: they decrease the cross section by 5-10%



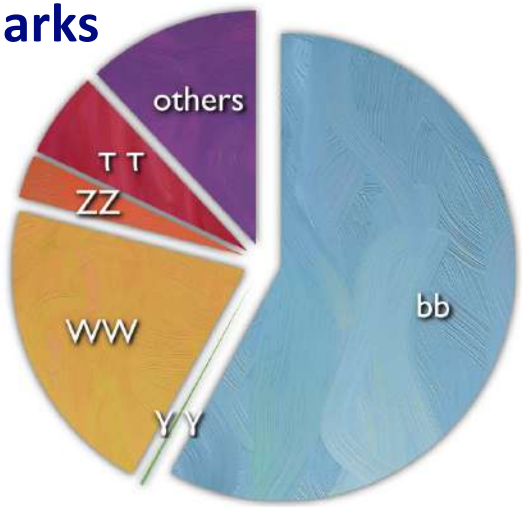
- For ZH at NNLO, further diagrams from gg initial state
- Important at the LHC (+2-6% effect up to +14% at high-p_T)

Experimental advantages:

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

H→bb physics case and VH role

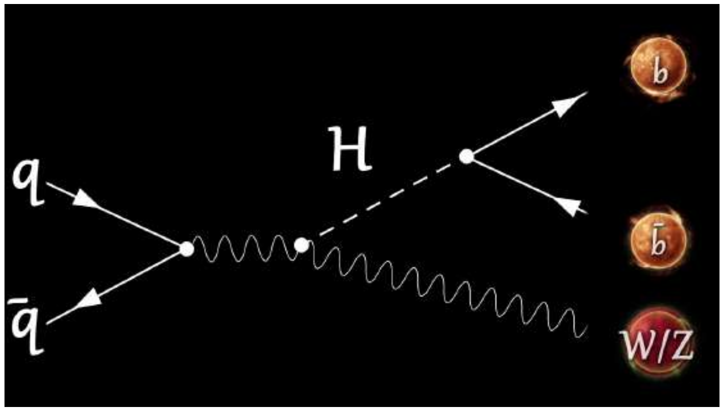
- Unique final state to measure **coupling with down-type quarks**
- **H→bb has the largest BR (58%) for m_H=125 GeV**
- **Drives the uncertainty on the total Higgs boson width**
  - **Constraints potential BSM contributions**
- **Only recently observed by both ATLAS and CMS**



- **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**



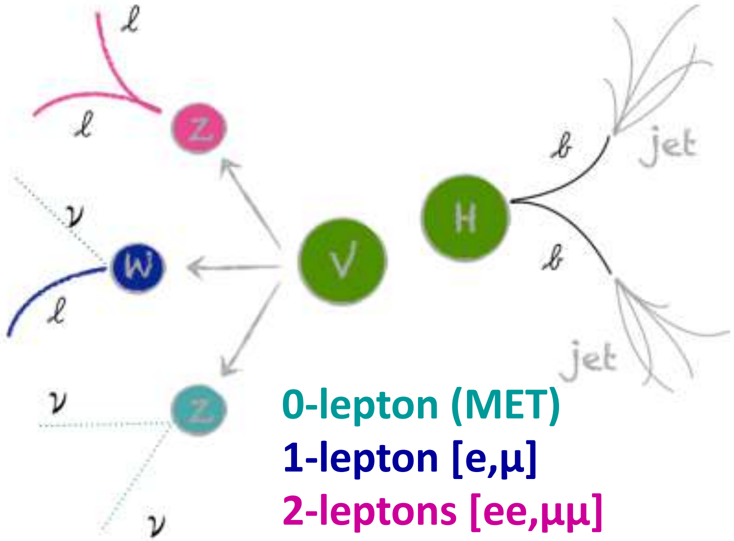
VH production plays a crucial role

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

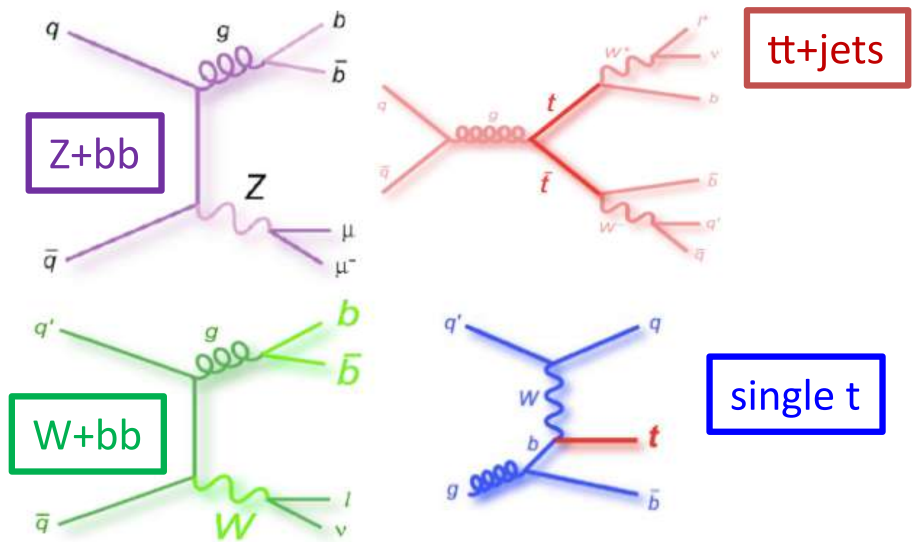
→ **Provides the highest sensitivity to H→bb**

VH(H→bb) Analysis Strategy

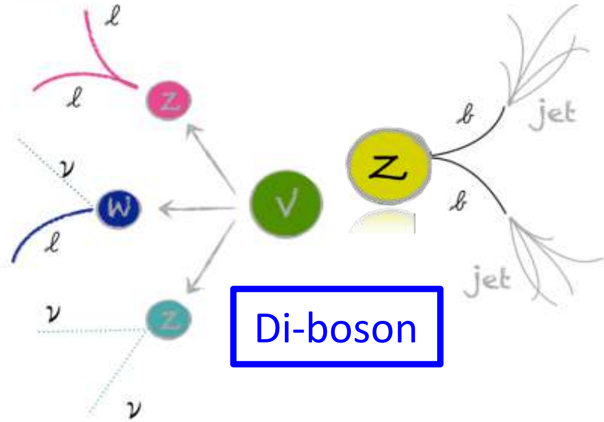
SIGNAL PROCESSES



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)



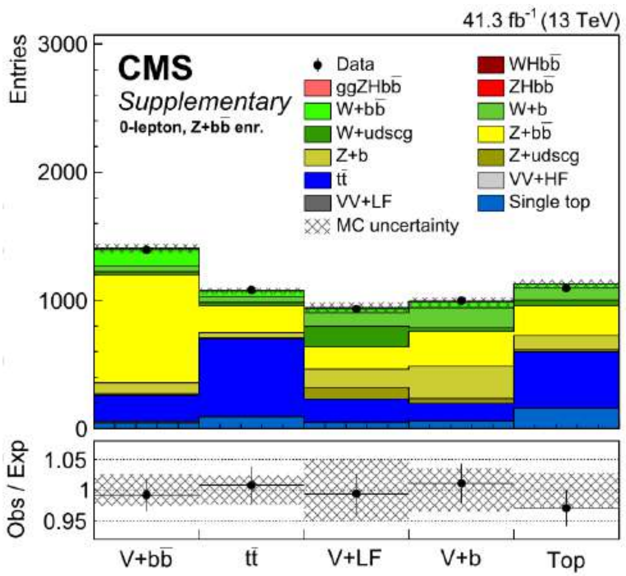
- **Control regions to validate backgrounds and constrain normalizations**
- **Signal extraction:** binned maximum likelihood fit of final MVA/mass distribution

CMS - Event Selection+Categorization

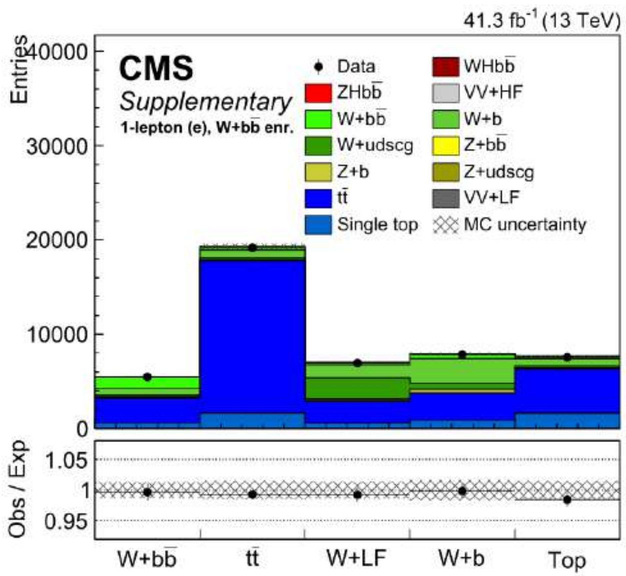
- **Selections (jets, leptons, b-tagging) optimized separately by channel**
  - 4 analysis categories:
    - 0-lepton: **p_T(Z) > 170 GeV**
    - 1-lepton: **p_T(W) > 150 GeV**
    - 2-lepton High-Vp_T: **p_T(Z) > 150 GeV**
    - 2-lepton Low-Vp_T: **50 GeV < p_T(Z) < 150 GeV**

- **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**

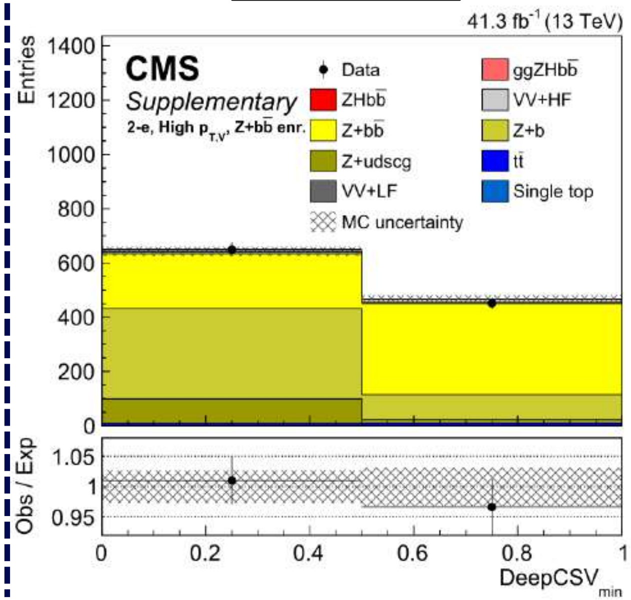
0-Lepton



1-Lepton

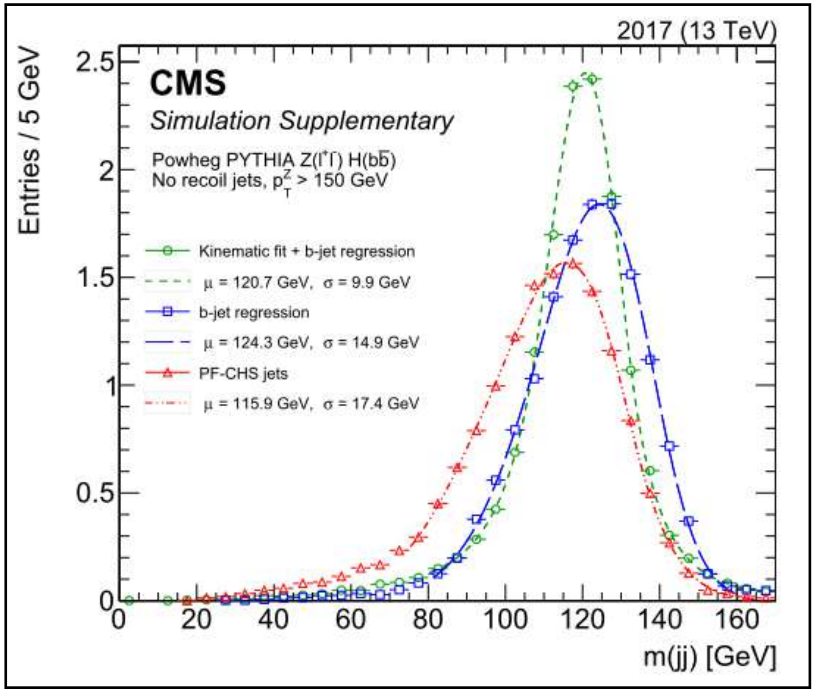


2-Lepton



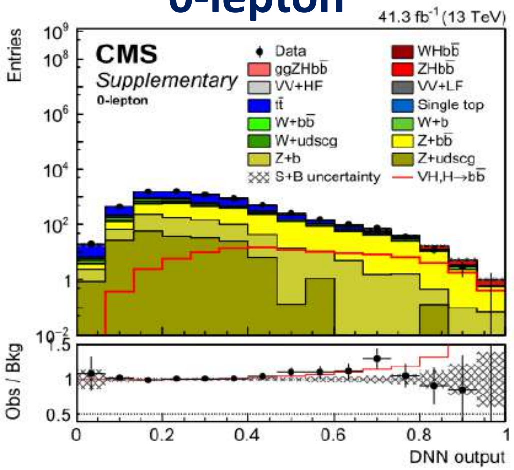
CMS - Improvements in m(jj) resolution

- **Improvements in di-jet mass resolution:**
  - 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

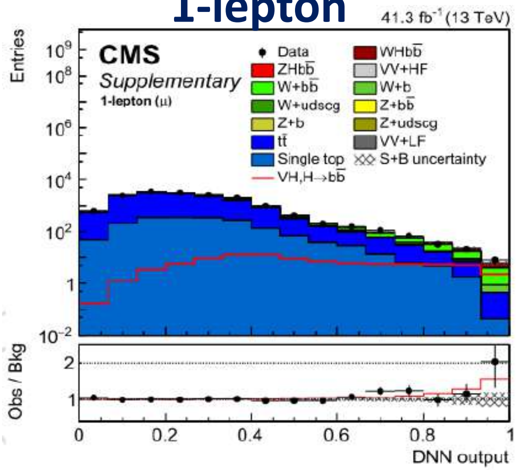


- <u>**Signal extraction:**</u>
  - Use of (DNN) to discriminate sig. from bkg. in SR + various bkg in CRs

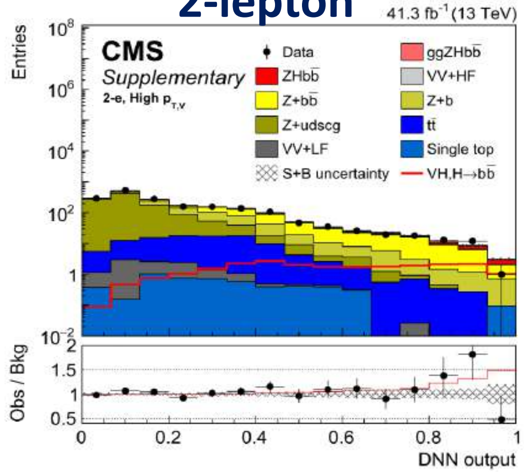
0-lepton



1-lepton

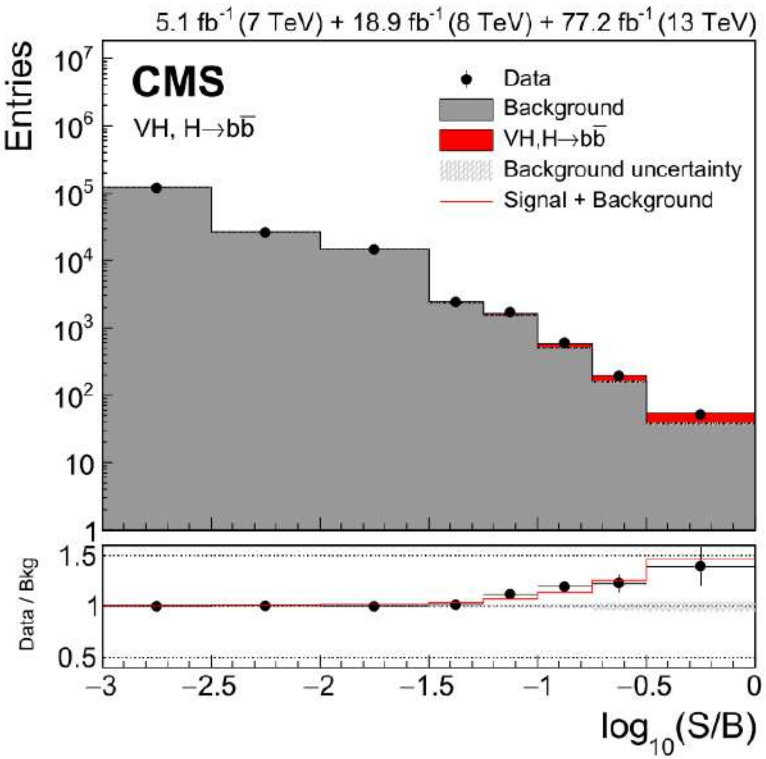


2-lepton

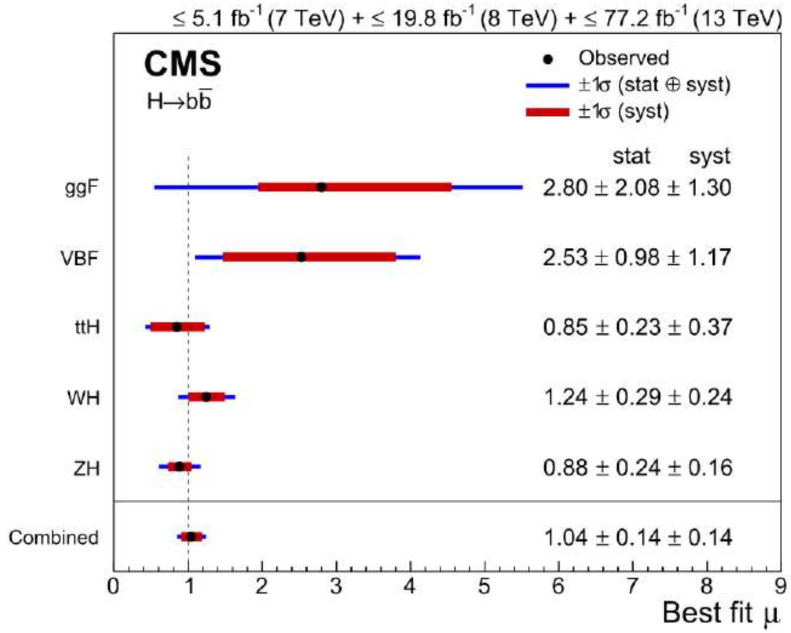


- **Combination of VH(H→bb) measurement**

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



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



Significance:
5.5σ expected
5.6σ observed

Measured signal strength:
μ = 1.04 ± 0.20

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

ATLAS VH→bb - Full Run-2

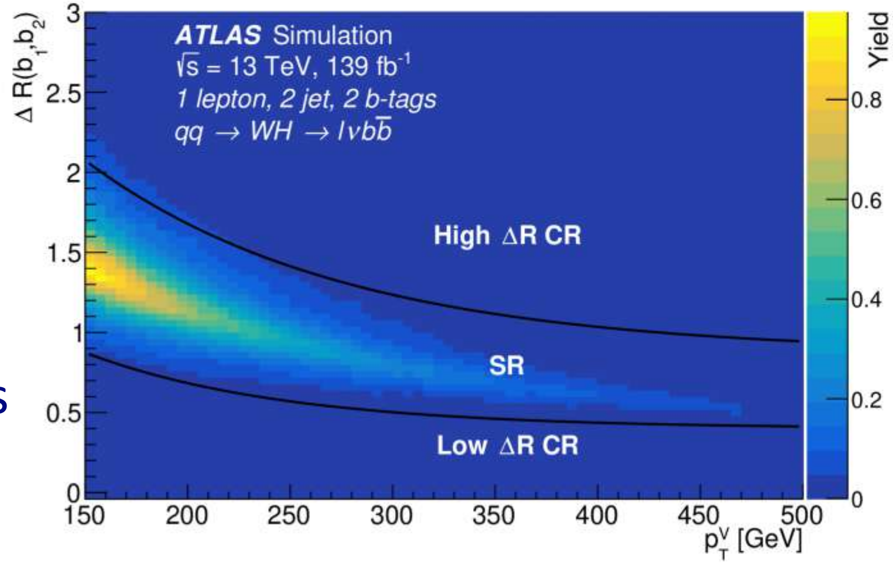
- **Physics case:**
  - VH(bb) analysis with full run-2 dataset, provides best constraint to Higgs boson width
  - Provides best sensitivity to WH(bb) and ZH(bb) decays
  - Interpretation within the STXS framework and EFT

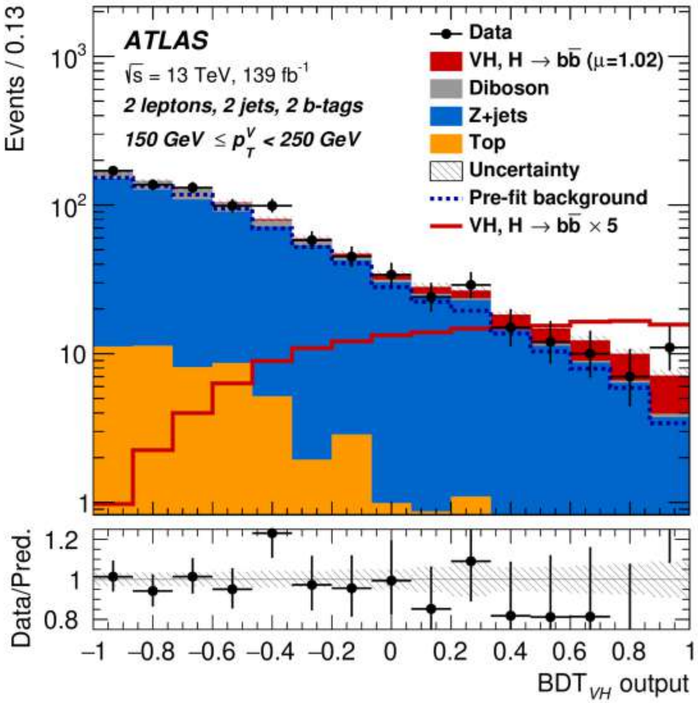
- **H→bb analysis strategy**
  - Full Run-2 dataset (~139 fb^{-1})
    → MET and single-lepton triggers
  - Categorization based on lepton multiplicity (targeting Z(ll), Z(nn), W(ln))
  - MV2c10 tagger, based on BDT, receiving as inputs the tracks d_0, displaced vertex collection, and the topological decay chain reconstruction to identify b-jets
  - Higgs boson reconstructed via 2 AK4 jets

ATLAS VH→bb - Full Run-2

[2007.02873](2007.02873)

- **Improvements**
  - Enhanced object calibrations
  - More coherent categorisation (selection vs STXS binning)
  - Re-optimised multivariate discriminants
  - Redefinition of signal and control regions
  - Significant increase in MC stats





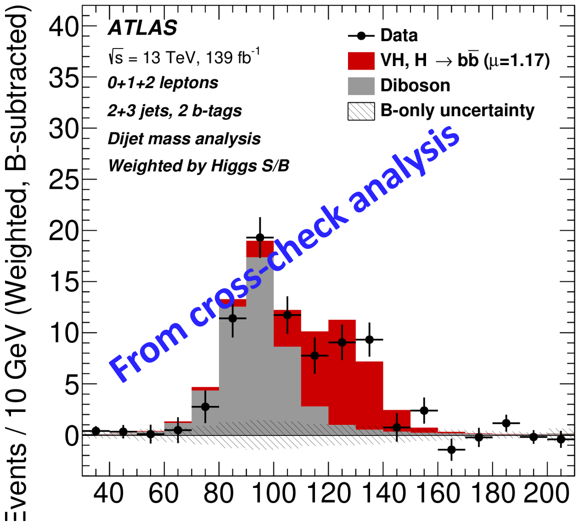
ATLAS Simulation — √s = 13 TeV — Signal fraction [%]

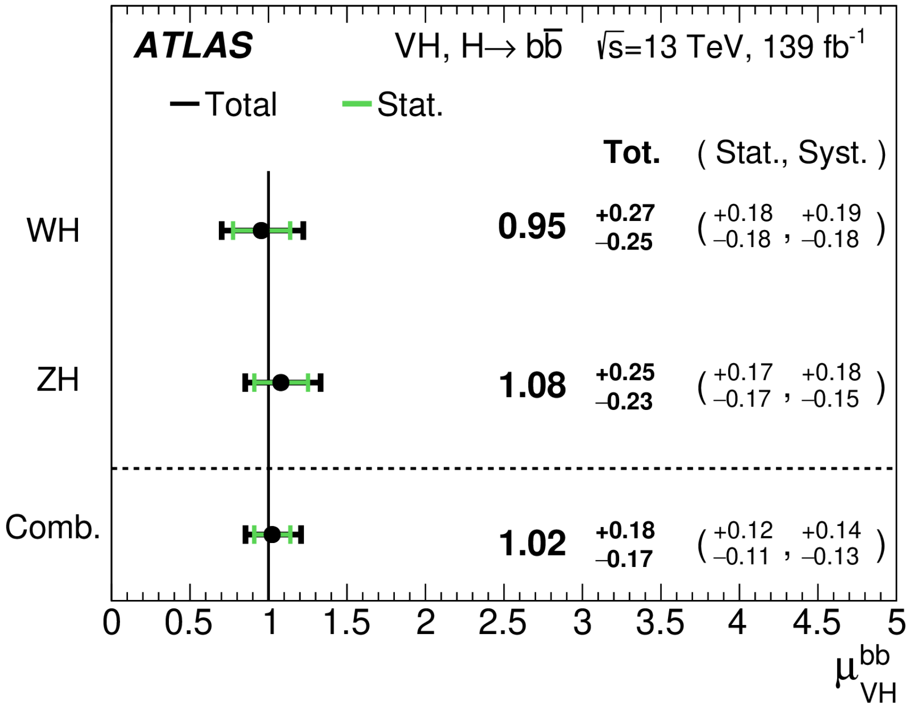
	WH, $p_T^{W,t}$ < 150 GeV	WH, 150 < $p_T^{W,t}$ < 250 GeV	WH, $p_T^{W,t}$ > 250 GeV	ZH, $p_T^{Z,t}$ < 75 GeV	ZH, 75 < $p_T^{Z,t}$ < 150 GeV	ZH, 150 < $p_T^{Z,t}$ < 250 GeV	ZH, $p_T^{Z,t}$ > 250 GeV
2 lep, ≥ 3 jets, p_T^V > 250 GeV						3.3	96.6
2 lep, 2 jets, p_T^V > 250 GeV						3.2	96.7
2 lep, ≥ 3 jets, 150 < p_T^V < 250 GeV					2.0	96.3	1.6
2 lep, 2 jets, 150 < p_T^V < 250 GeV					2.4	96.2	1.4
2 lep, ≥ 3 jets, 75 < p_T^V < 150 GeV				1.0	96.7	2.2	
2 lep, 2 jets, 75 < p_T^V < 150 GeV				1.1	97.2	1.7	
0 lep, 3 jets, p_T^V > 250 GeV		1.1	16.1			9.0	73.8
0 lep, 2 jets, p_T^V > 250 GeV		0.8	17.5			6.5	75.2
0 lep, 3 jets, 150 < p_T^V < 250 GeV	1.9	15.2	5.0		8.5	62.7	6.7
0 lep, 2 jets, 150 < p_T^V < 250 GeV	1.4	15.1	5.3		7.4	63.4	7.4
1 lep, 3 jets, p_T^V > 250 GeV	0.1	9.2	88.8			0.1	1.7
1 lep, 2 jets, p_T^V > 250 GeV		7.1	91.7			0.1	1.1
1 lep, 3 jets, 150 < p_T^V < 250 GeV	11.1	76.0	9.3		0.5	2.4	0.8
1 lep, 2 jets, 150 < p_T^V < 250 GeV	8.4	79.1	10.2		0.3	1.6	0.4

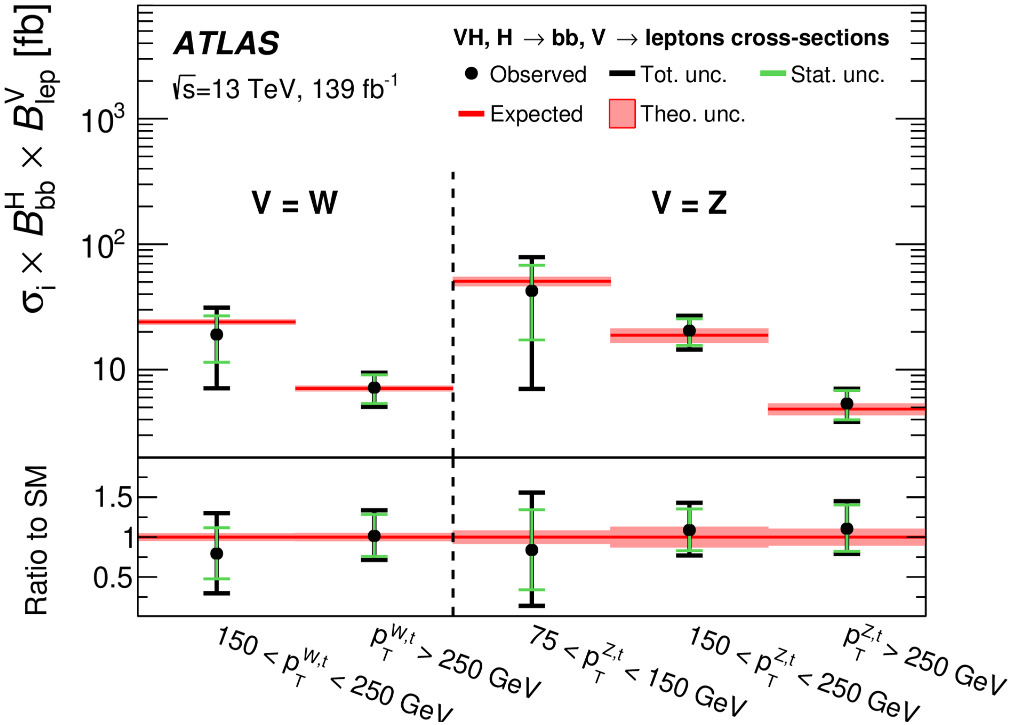
ATLAS VH→bb - Full Run-2

Results:

- Signal extraction: Likelihood fit to MVA discriminant in signal regions + normalization taken from fit in control regions.
- Inclusive analysis dominated by systematics
- Reached >5σ in ZH channel and >4σ in WH







ATLAS - VH→bb in boosted category

2008.02508

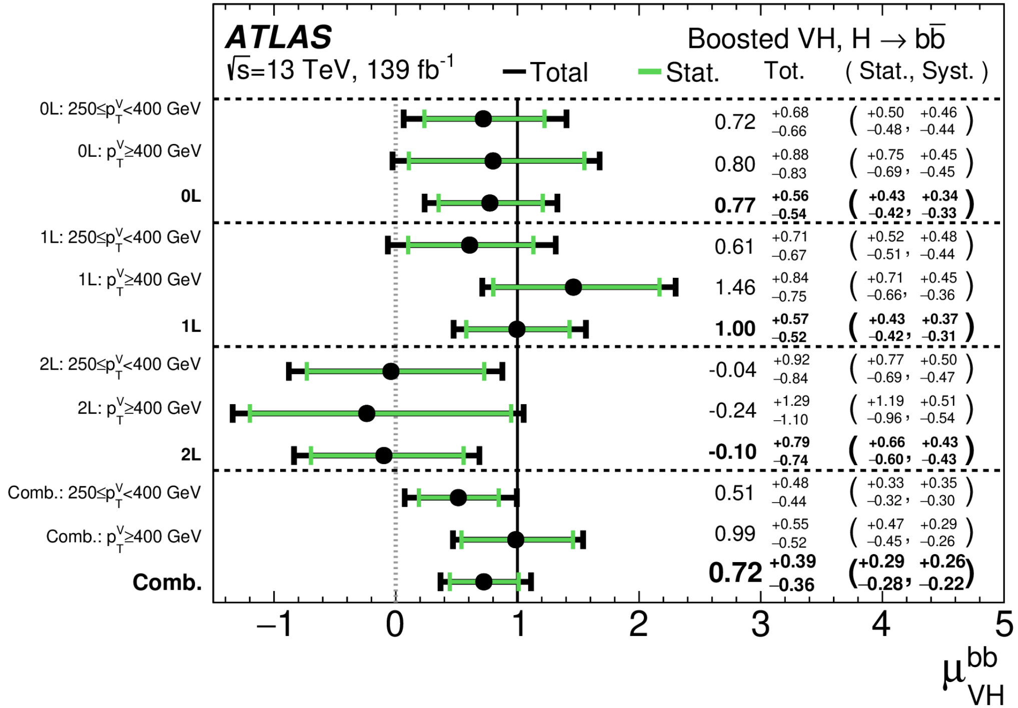
- **Physics case:**
  - The previous ATLAS analyses were mainly sensitive to Higgs boson with a $100<p_T<300$geV
  - For higher Higgs boson p_T, the Higgs decay product can be so close that it results difficult to reconstruct them as two distinct jets

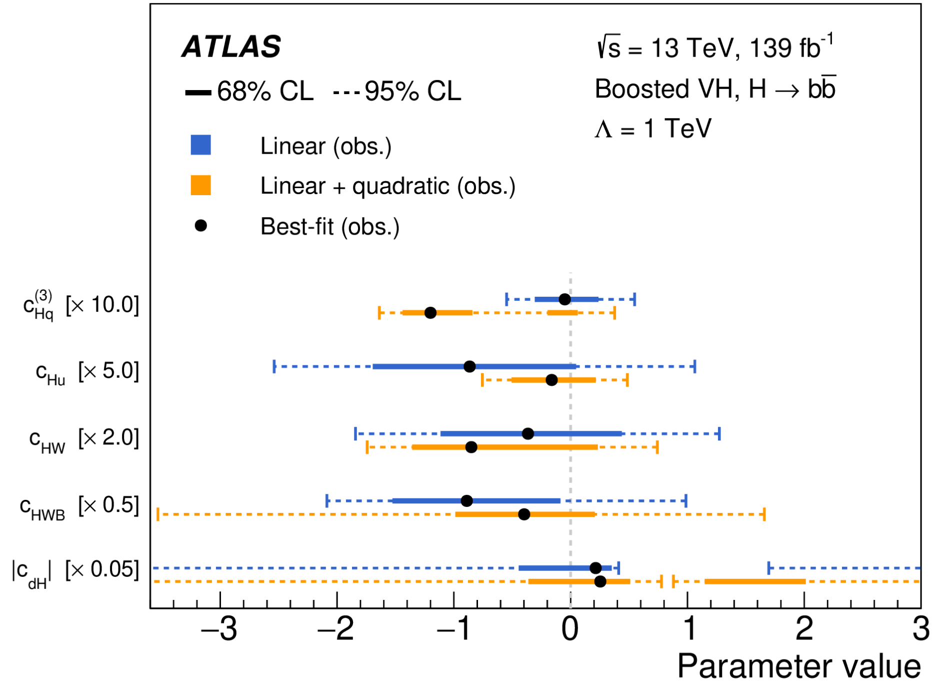
- **H→bb boosted analysis strategy**
  - Full Run-2 dataset (~139 fb^{-1}) → selected by MET and single-lepton triggers
  - Categorization based on lepton multiplicity (targeting Z(ll), Z(nn), W(ln))
  - Higgs boson reconstructed in a single large calorimeter jet (R=1.0) with ≥2 constituents and a p_T>250 GeV (same threshold also for vector p_T)
  - The b-tagging algorithm used to identify b-jet is the same as in the resolved analysis
  - Dominant background: V+jets, tt+jets, single-top, di-bosons

ATLAS - VH→bb in boosted category

Results:

- Signal extraction: Likelihood fit to large-jet mass, combined in signal and control regions
- Measurement of the signal strength $\mu_{VH}^{bb} = 0.72^{+0.39}_{-0.36} = 0.72^{+0.29}_{-0.28}(\text{stat.})^{+0.26}_{-0.22}(\text{syst.})$
- STXS analysis + constraints on anomalous Higgs boson interactions
- Significant overlap with the "resolved" H(bb) analysis, difficult to combine
- The analysis still dominated by statistical uncertainties





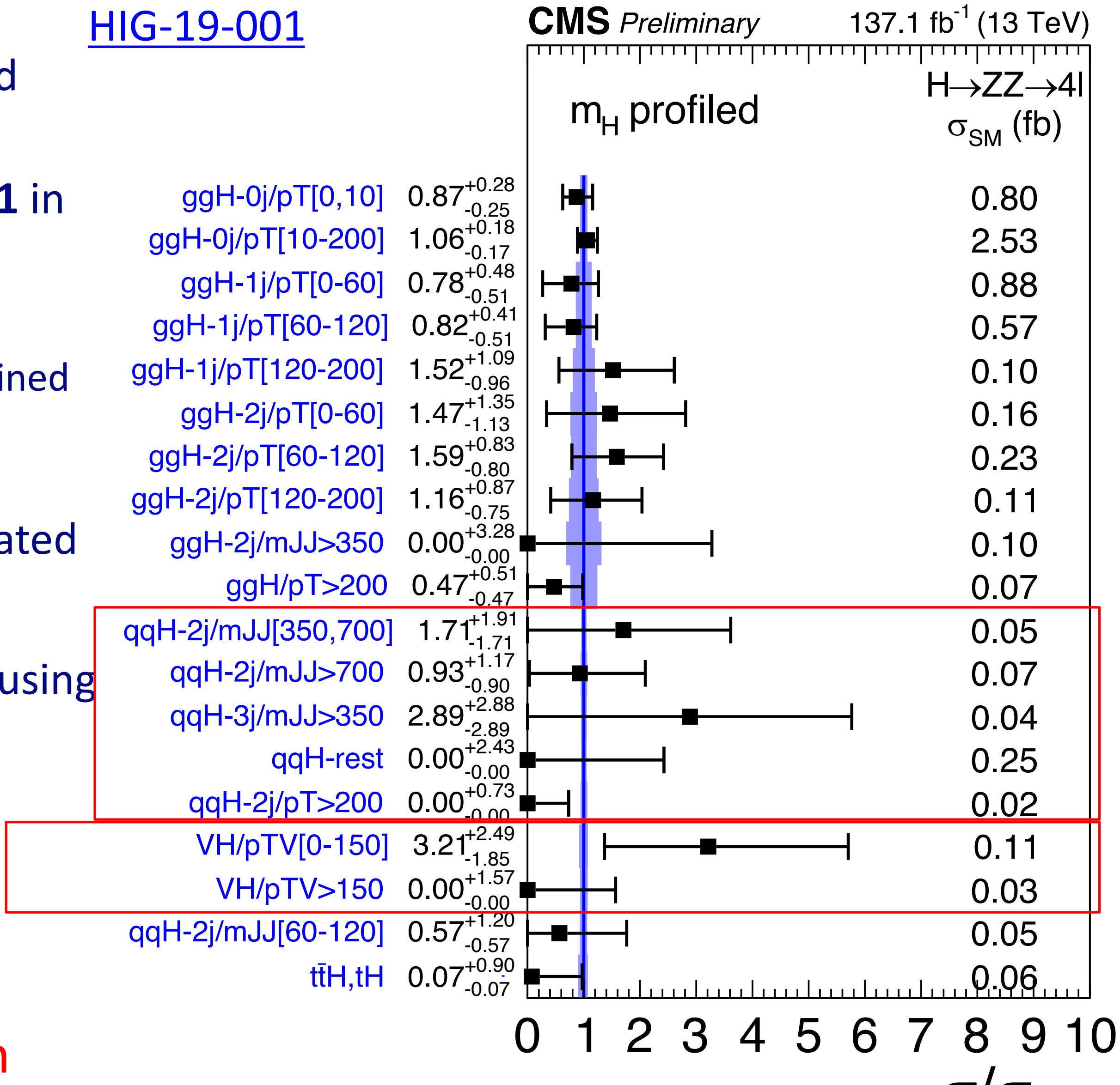
CMS - H→ZZ→4ℓ Full Run-2 (STXS)

1st CMS analysis with full Run-2 data!

HIG-19-001

- **Analysis strategy:**
  - Measurements of inclusive and differential cross-sections
  - Measurements of the **stage 1.1** in **STXS** framework:
    - 22 sub-categories
    - Different production bins defined by LHCXSWG
  - Requiring 4 identified and isolated leptons: 4e, 4μ, 2e2μ
  - **Kinematic discriminants** built using the **matrix element**
  - Exploiting the full kinematic information of H decay and production

All results consistent with the SM expectations!



bbH floated with ggH and tH with ttH

ATLAS - H→ZZ→4ℓ Full Run-2

- **Higgs boson properties**

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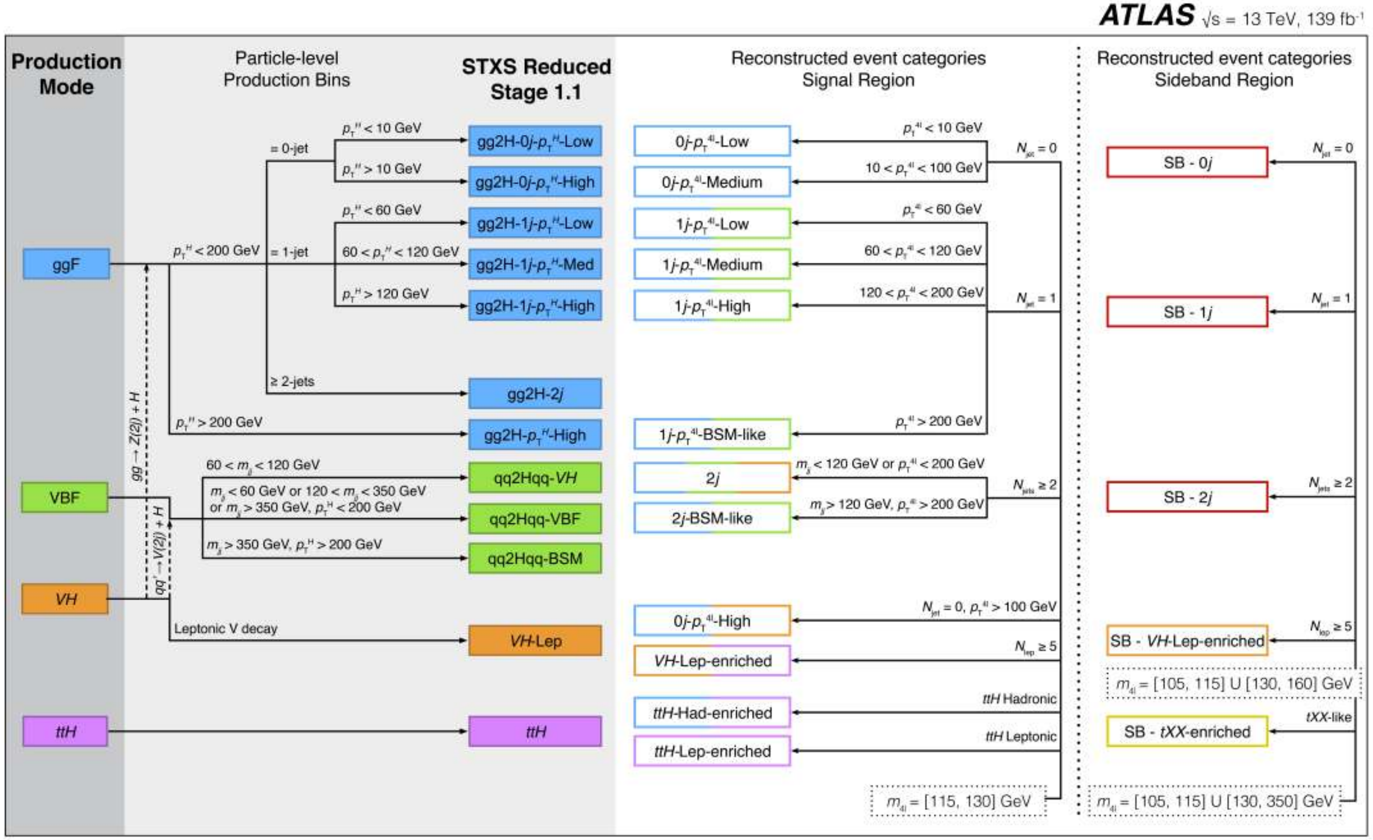
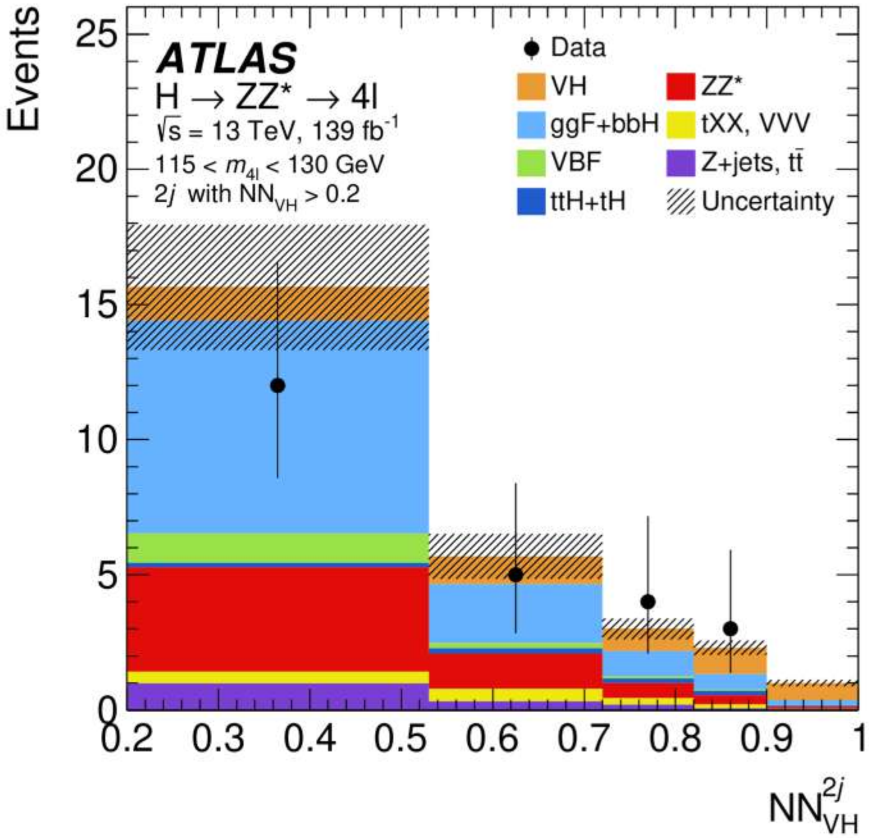
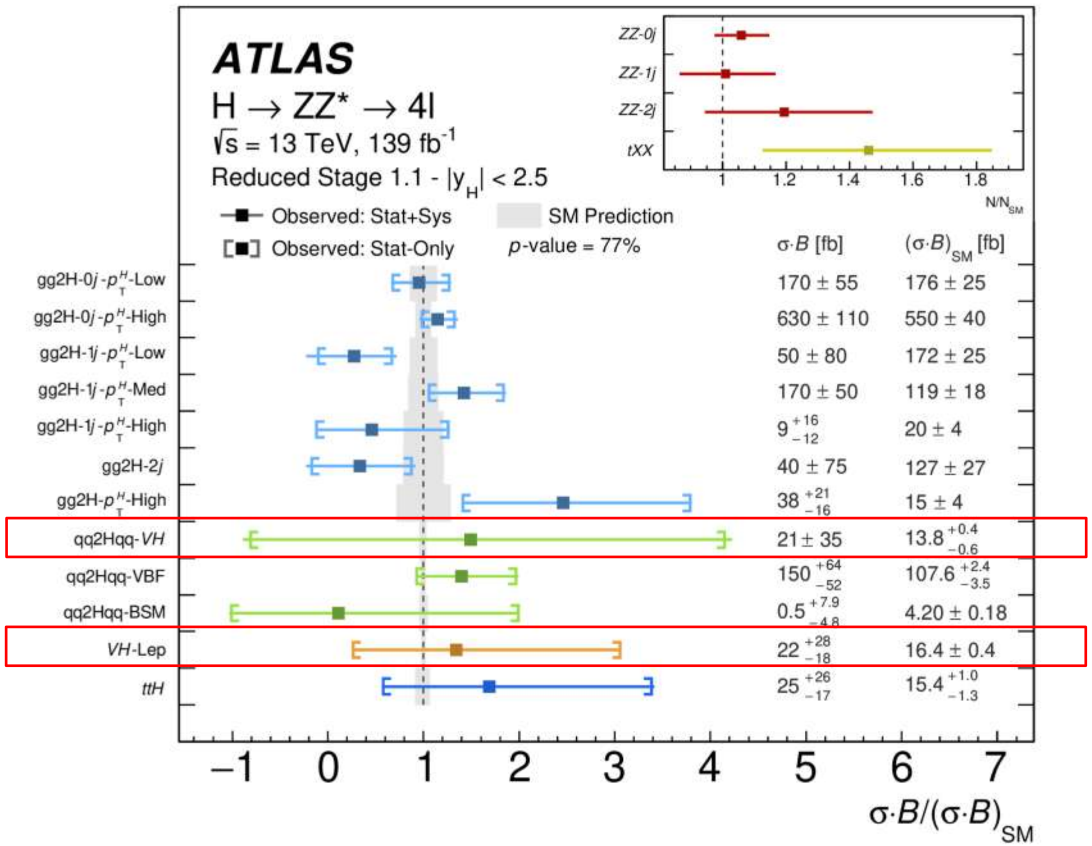
  - Inclusive cross section measurement
  - Cross section measurements for different production mode (STXS)
  - Interpretation of coupling modifier and tensor structure within EFT theory
  - Re-analysis with full run-2 data to increase the sensitivity



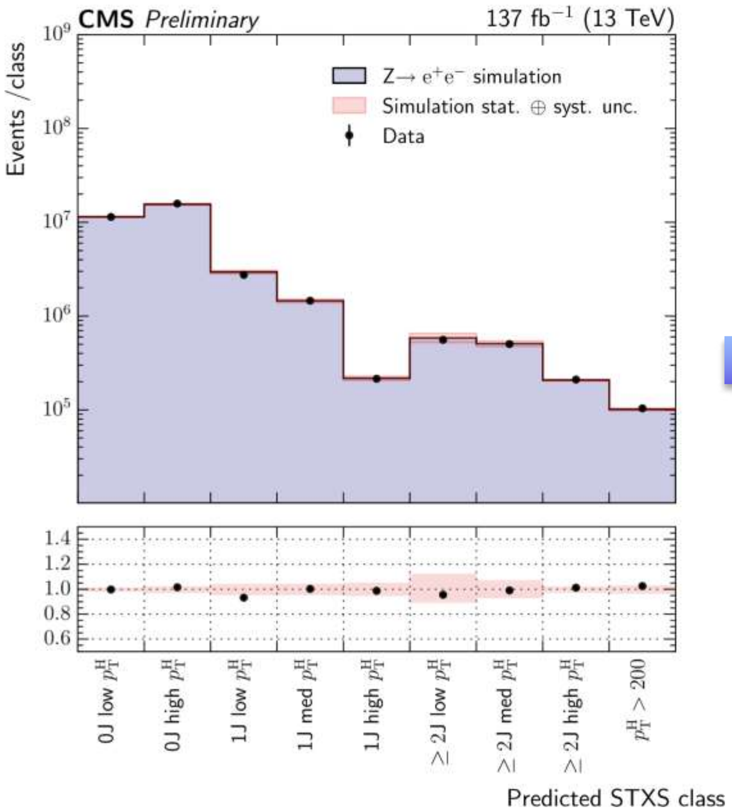
- **Higgs boson properties**
  - Extensive categorization used to target different production mode
  - Categorization based on decay of Ws in ttH mode, lepton multiplicity (VH) and number of jets (ggH, VBF)
  - MLP and RNN used to separate signal from background in final fit



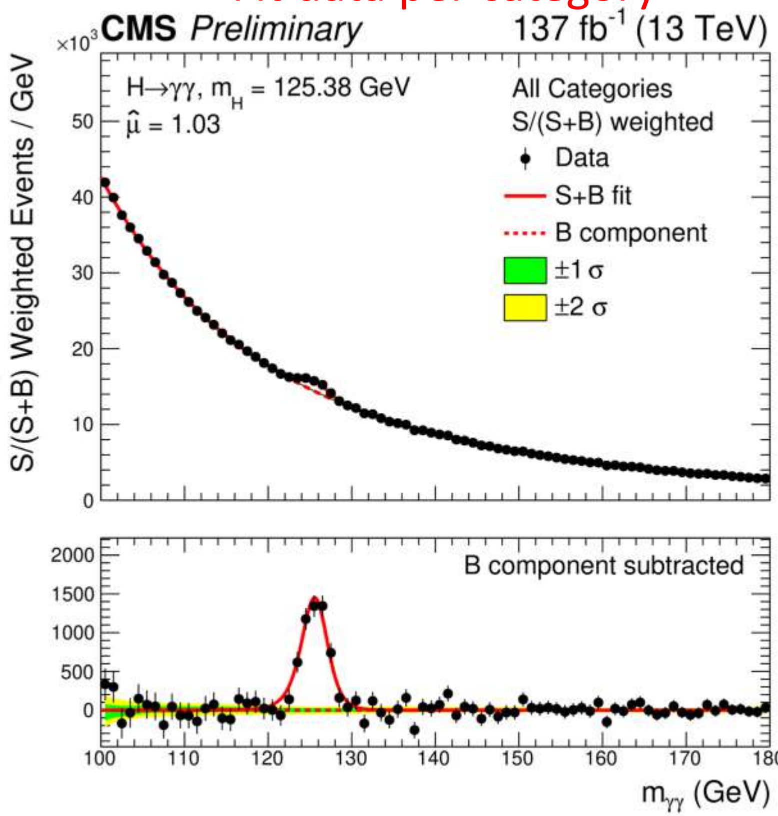


- **Analysis strategy**
  - The di-photon signal is very well reconstructed thanks to the excellent energy resolution of the CMS ECAL
  - Select events with 2 isolated photons from full Run-2 dataset (137 fb^{-1})
  - Categorization to tag ggH, VBF, VH and ttH production mechanisms

Classify



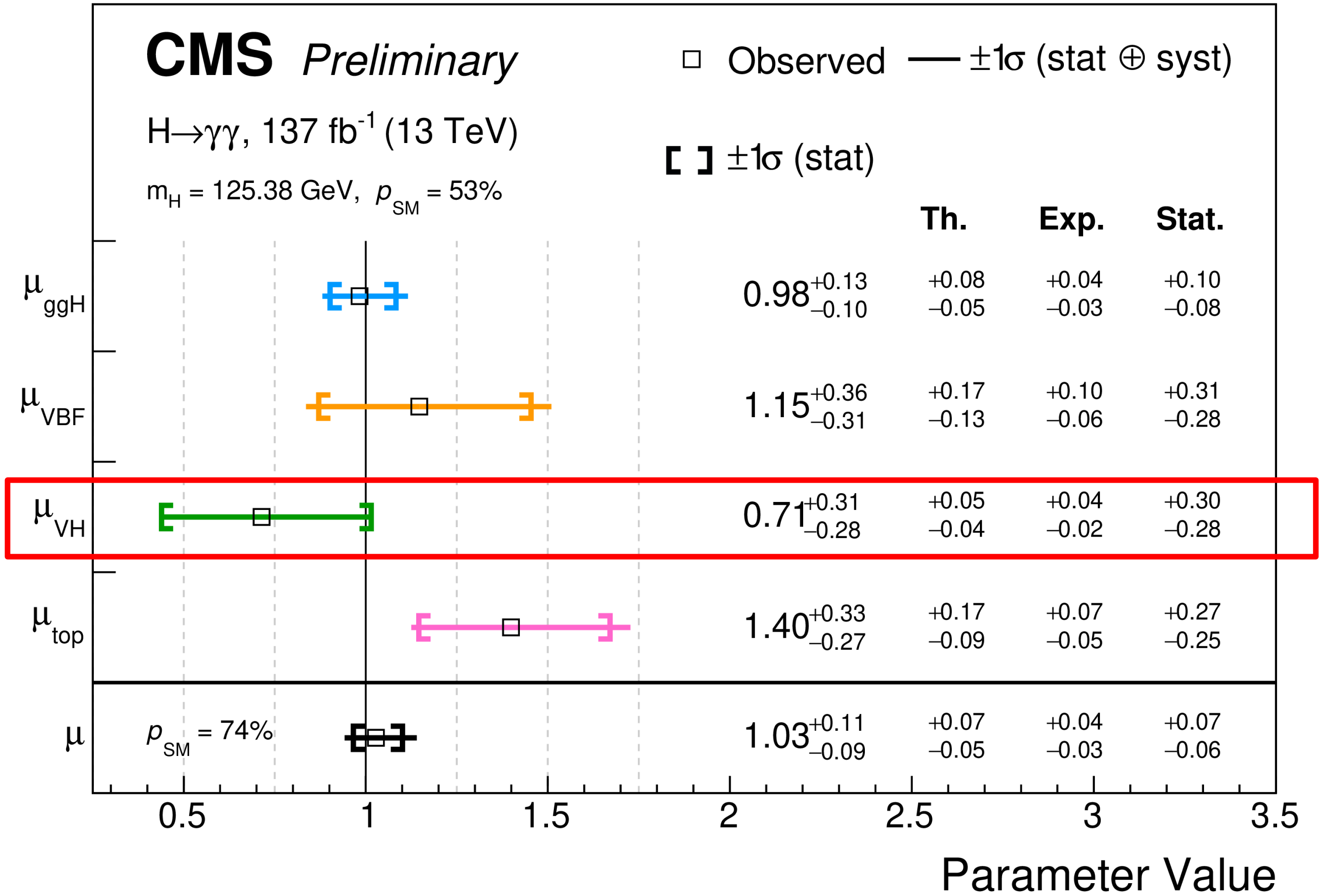
Fit data per category



CMS - H→$\gamma\gamma$ Full Run2

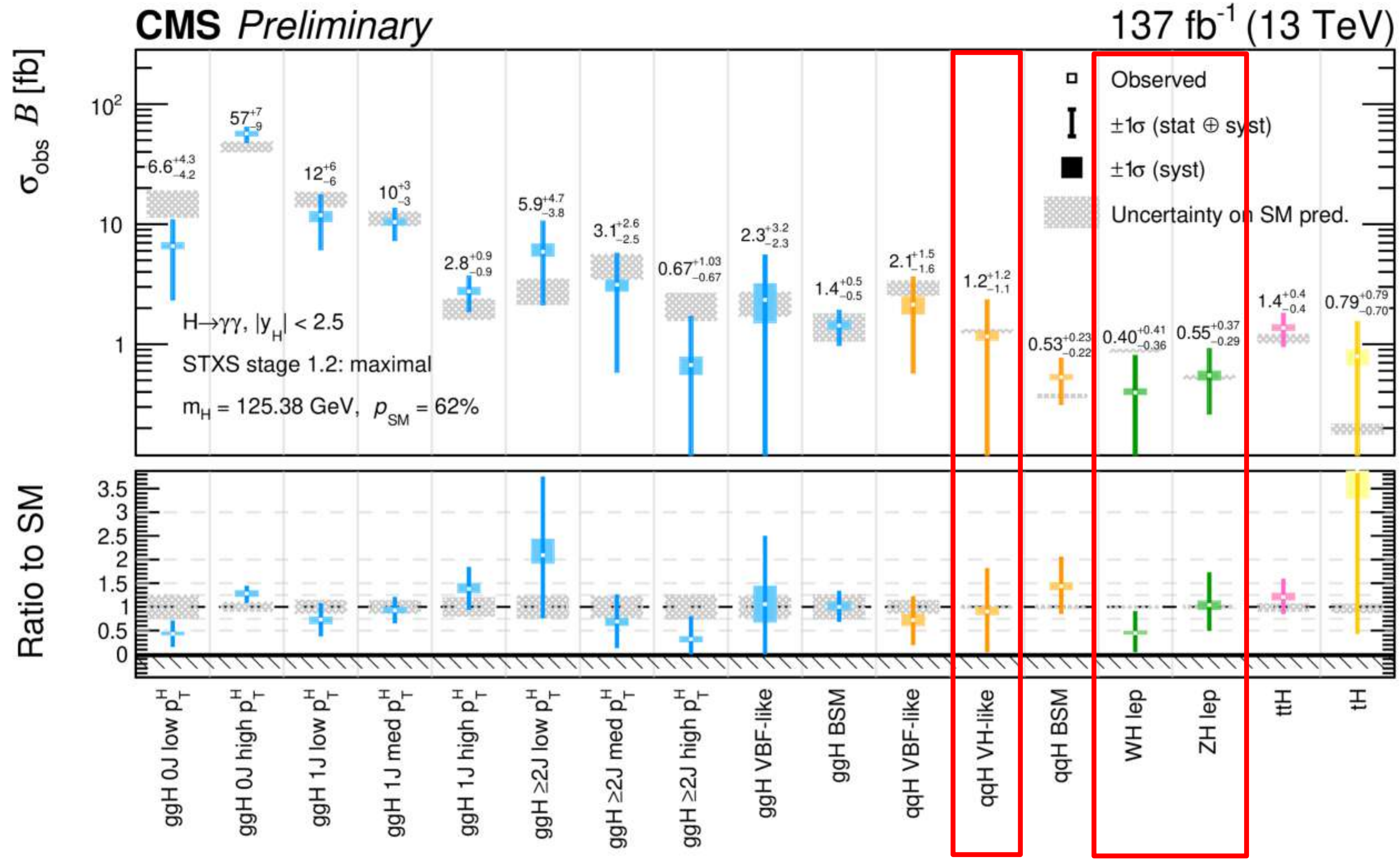
Results

- Assuming SM couplings, an 8% uncertainty on the signal strength is achieved (neglecting theory uncertainties) $\mu = 1.03^{+0.11}_{-0.09} = 1.03^{+0.07}_{-0.05}\,(\text{theo})^{+0.04}_{-0.03}\,(\text{syst})^{+0.07}_{-0.06}\,(\text{stat})$
- All μ's targeting specific production modes are in agreement with the SM
- Analysis start be limited by theory uncertainties



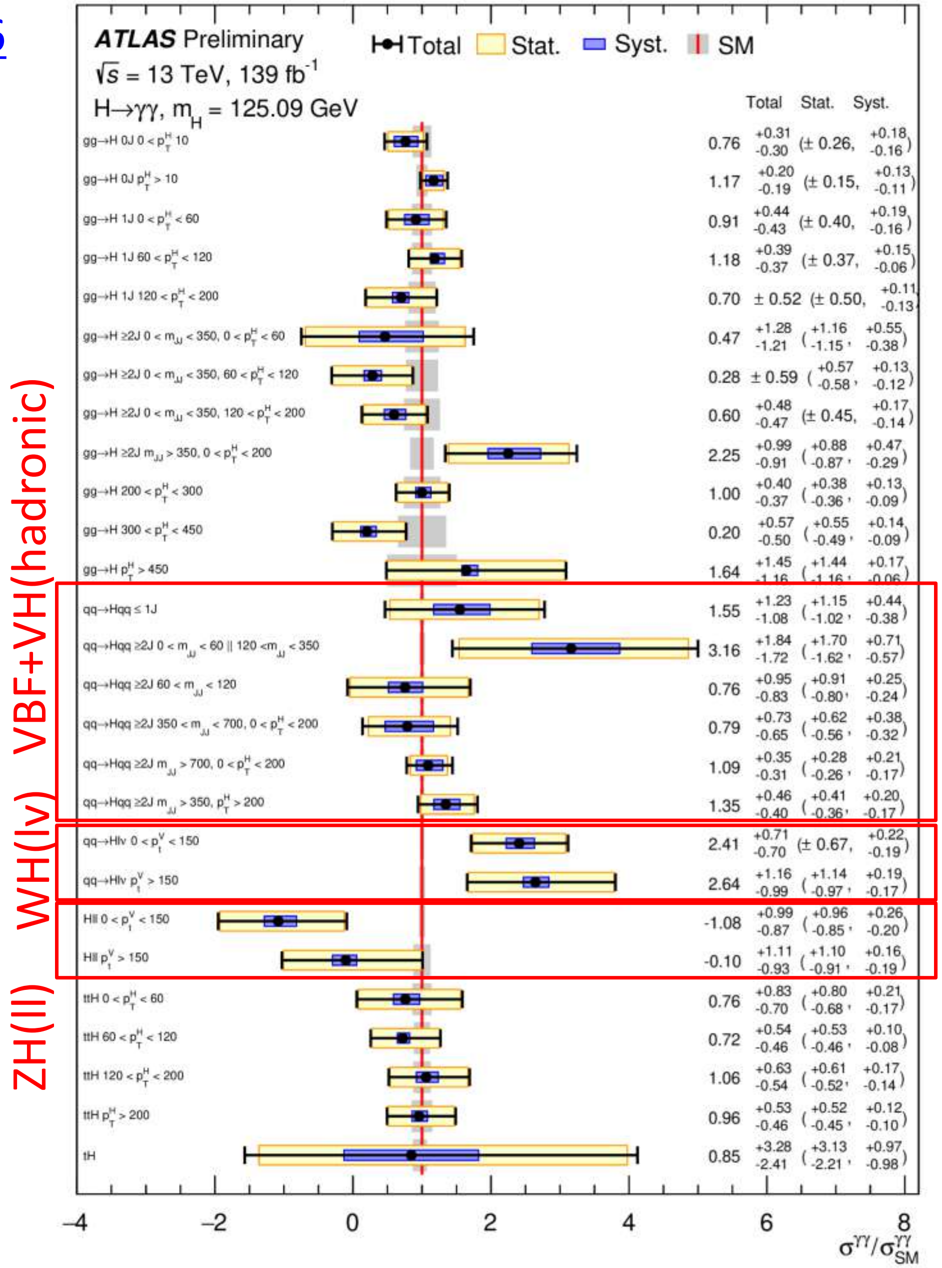
CMS - H→$\gamma\gamma$ Full Run2

- **Results**
  - Analysis designed to enable measurements within STXS framework (stage 1.2)
  - All results are found to be in agreement with the SM expectations



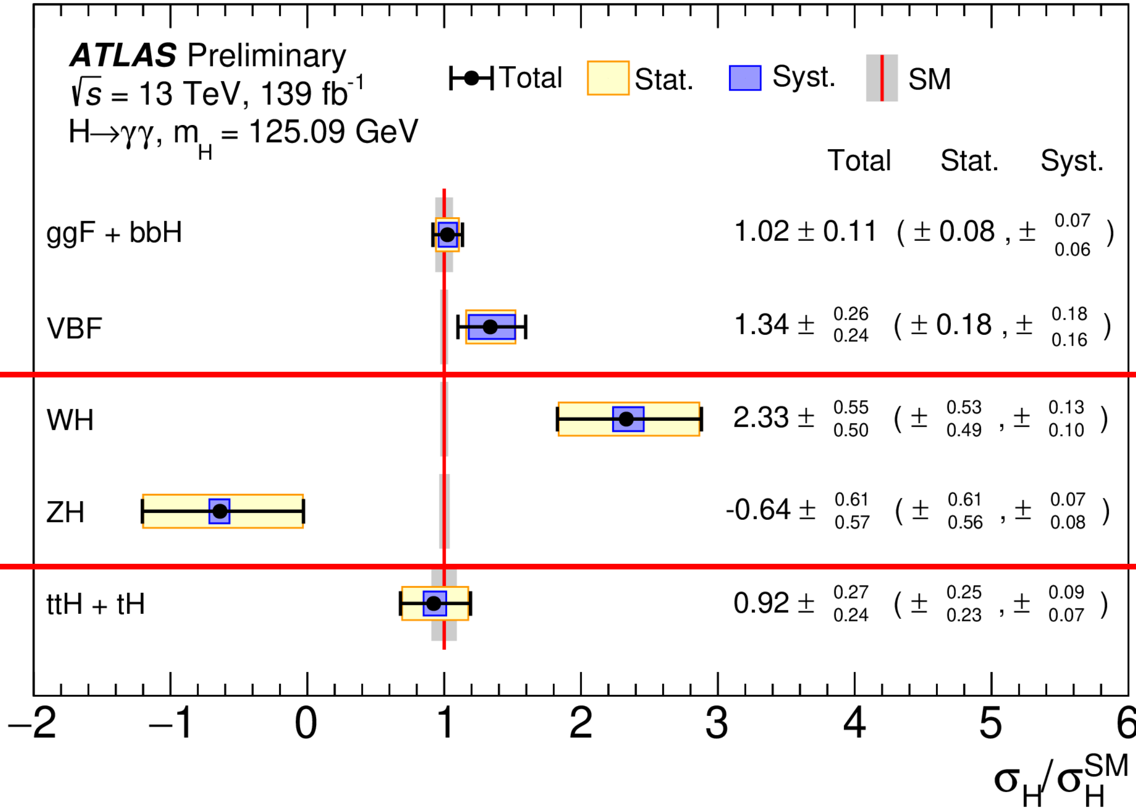
ATLAS - H→$\gamma\gamma$ Full Run-2

- **Analysis strategy** ATLAS-CONF-2020-026
  - Analysis optimized to measure x-sec in STXS-1.2 framework (in $|y_H|<2.5$)
  - Each class is divided into multiple categories via binary BDT classifier
  - The analysis is sensitive to the x-sec of the different production modes
  - Signal modelled with DSCB and the continuous background with function that fit template build out of MC and data in control regions



ATLAS - H→$\gamma\gamma$ Full Run-2

- **Results**
  - Inclusive cross section measurement: $(\sigma \times B_{\gamma\gamma})_{obs} = 127 \pm 10\,\text{fb} = 127 \pm 7\,(\text{stat.}) \pm 7\,(\text{syst.})\,\text{fb}$
    → SM expected: $(\sigma \times B_{\gamma\gamma})_{exp} = 116 \pm 5\,\text{fb}.$
  - ZH and WH:
    - Higher uncertainties
    - Small tension if compared to SM, but still compatible within 2 sigma



- If VH is considered, the compatibility with SM 50% (p-value)
- High correlation between ZH and WH = 41%

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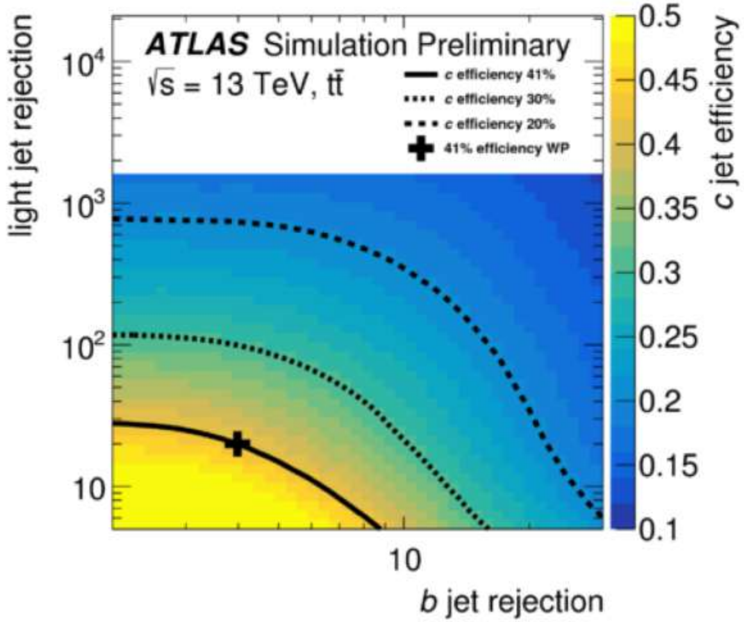
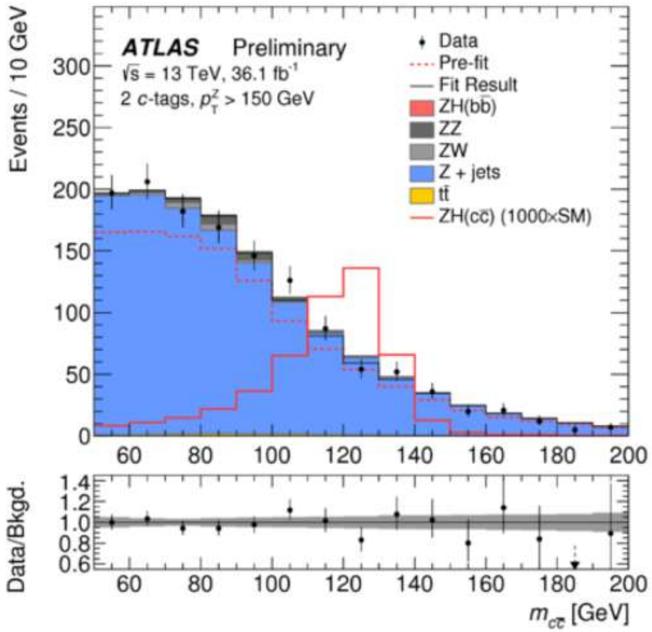
- **VH(cc) search:**
  - Targeting VH(cc) process in the di-lepton Z final state
  - Exploit lepton trigger + boost of Z boson to reduce background
  - Categorization in number of c-tagged jets





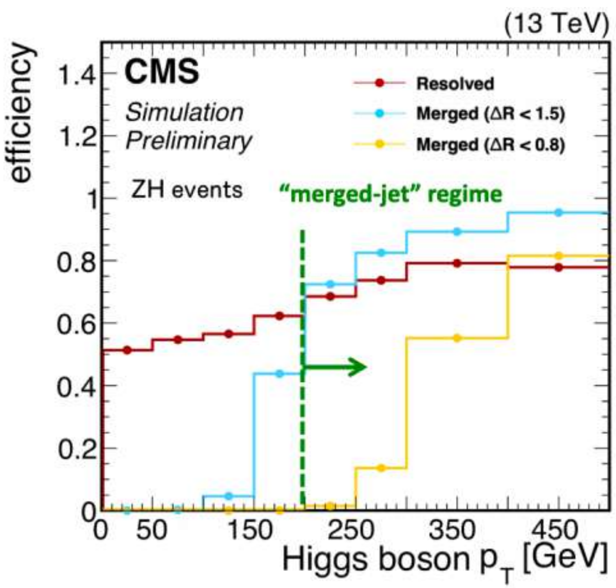
  - New search for ZH(cc) production exploiting new c-tagging techniques provides 95% C.L exclusion limit of (pp→ZH)xBR(H→cc)<2.7 pb
  - Excluded 110xSM prediction with 36.1fb^{-1} of data collected

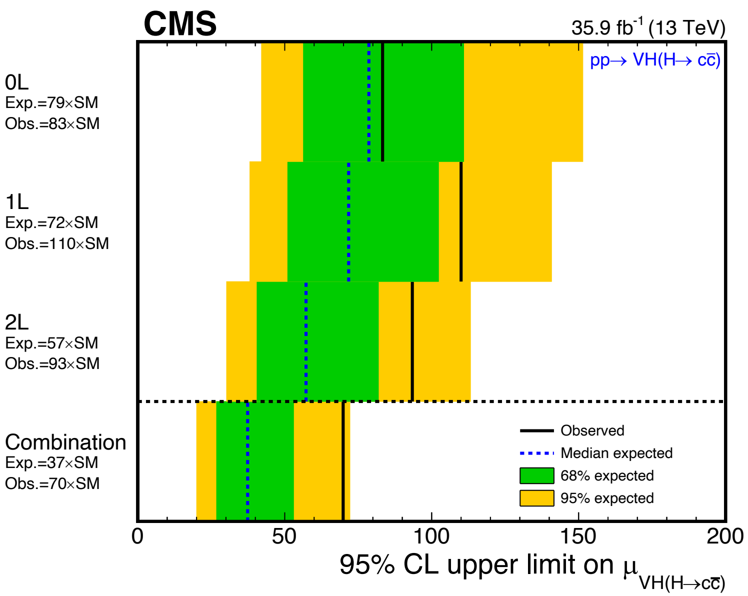
CMS - Searches: VH(cc) (2016)

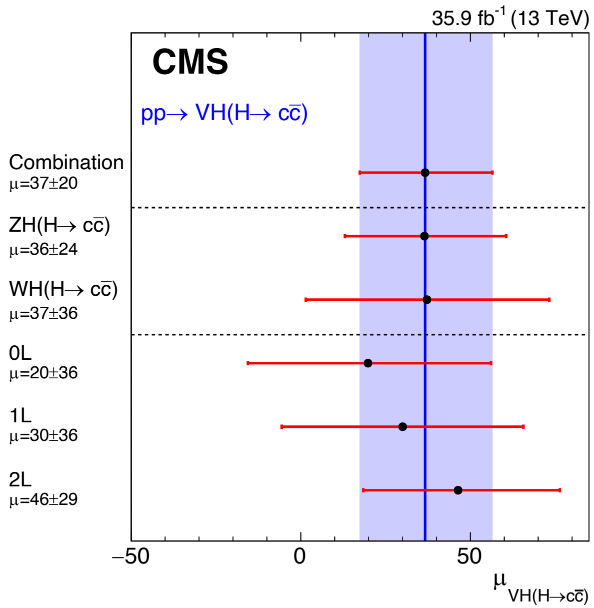
JHEP03(2020)131

- Combination: resolved-jet: $p_T(V) < 300$ GeV / merged-jet: $p_T(V) > 300$ GeV
  - Systematics: correlated, but: c/cc-tagging efficiency & PDF, μR, μF for V+jets
- Validation with VZ(Z→cc) : $\mu_{VZ(Z\to cc)} = 0.55^{+0.86}_{-0.84}$ with 0.7σ obs. (1.3σ exp.)

	95% C.L. Exclusion Limits					
	Resolved-jet	Boosted-jet	Combination			
	$p_T(V)$<300 GeV	$p_T(V)$>300 GeV	0L	1L	2L	**All. Ch.**
Exp.	45^{+18}_{-13}	73^{+34}_{-22}	79^{+32}_{-22}	72^{+31}_{-21}	57^{+25}_{-17}	$\mathbf{37^{+16\,(+35)}_{-11\,(-17)}}$
Obs.	86	75	83	**110**	93	**70**







Conclusions

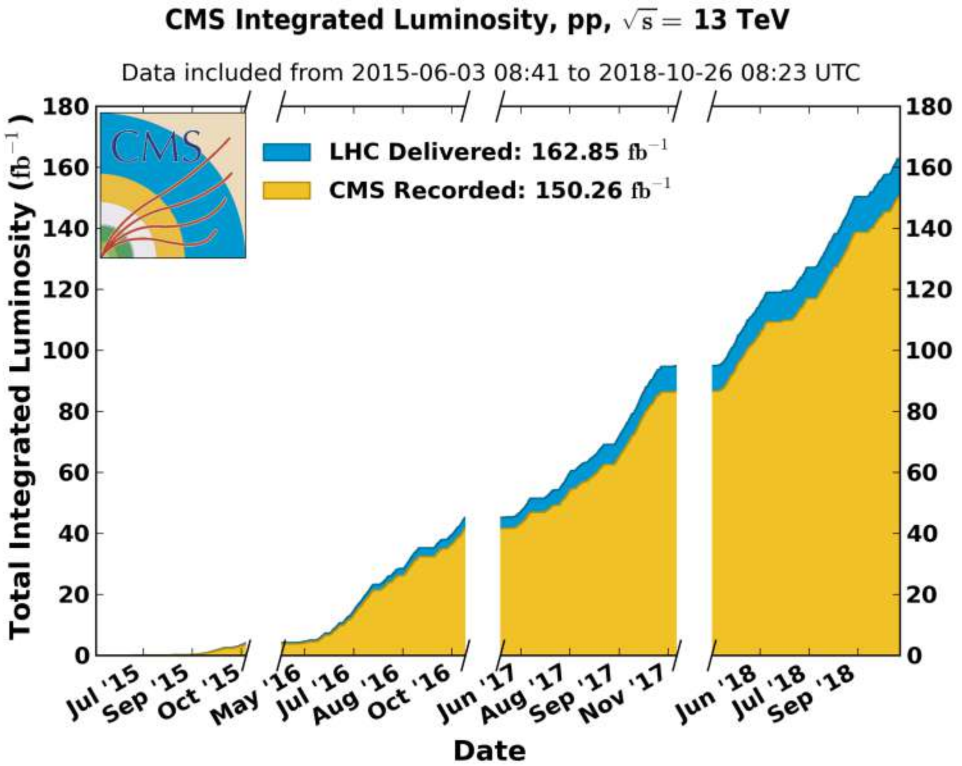
- The excellent LHC performance has delivered an enormous dataset:
  - With full Run-2 dataset, we are measuring precise features of the Higgs boson, with particular focus on its couplings and CP properties

- During Run-2, ATLAS and CMS have both achieved a >5σ observation of the $H \to bb$ decay
  - Combination of several channels: sensitivity dominated by VH(bb)

- Exploring more detailed kinematic regions sensitive to BSM effects through STXS and differential distributions
  - VH production mode has been investigated by ATLAS and CMS in $H \to \gamma\gamma$ and $H \to ZZ \to 4\ell$
  - ATLAS carried out the measurements of the VH(bb) process with full Run-2 data, targeting the resolved and boosted regimes of the Higgs boson
  - ATLAS observed ZH production mode and reached a strong evidence of WH with the full Run-2 analysis
  - CMS VH(bb) full Run-2 will be out soon as well

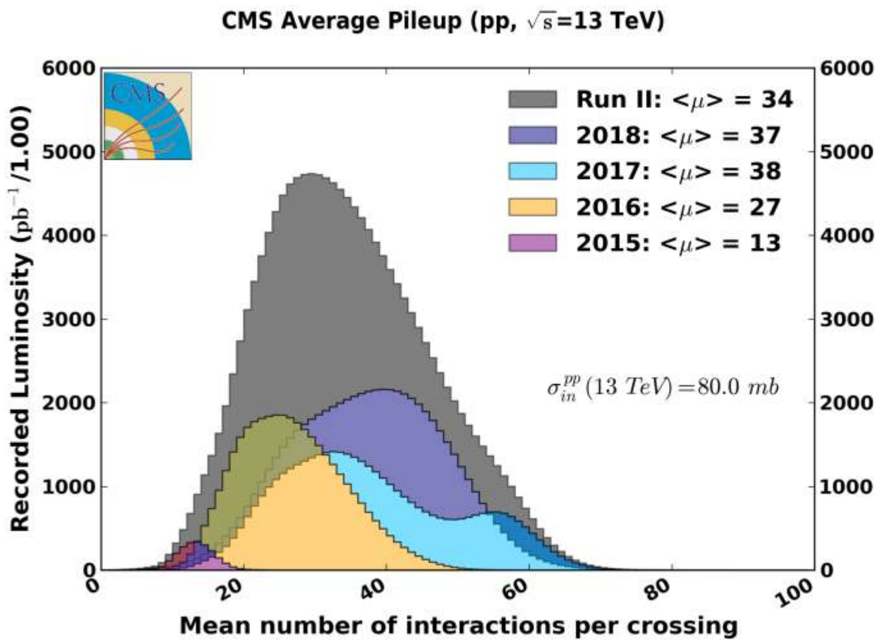
Back Up

Introduction



- **Data-taking in Run-2**
  - LHC outperformed expectation, delivering 163 fb^{-1} (>8x10^6 Higgs boson produced!)
  - CMS recorded more than 92% of the delivered luminosity
  - Thanks LHC!

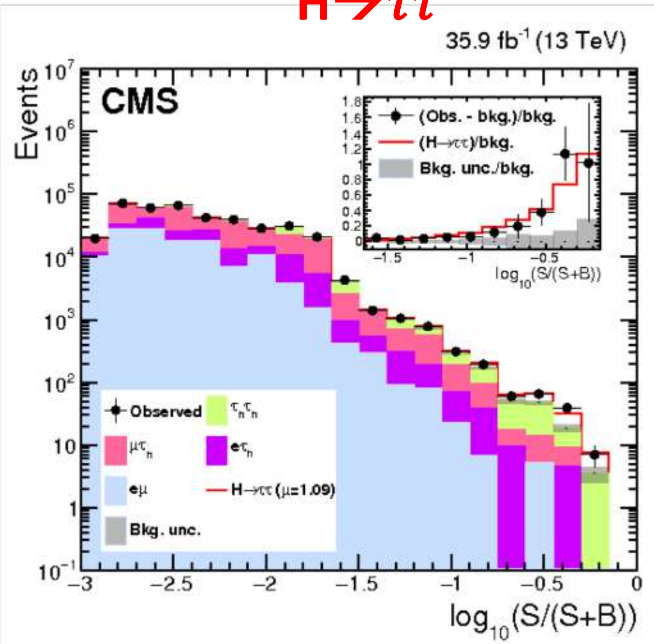
- Average of 34 pile-up interaction per bunch crossing
- During 2017, max pile-up in data-taking, reaching >60
- Great challenge for CMS event reconstruction



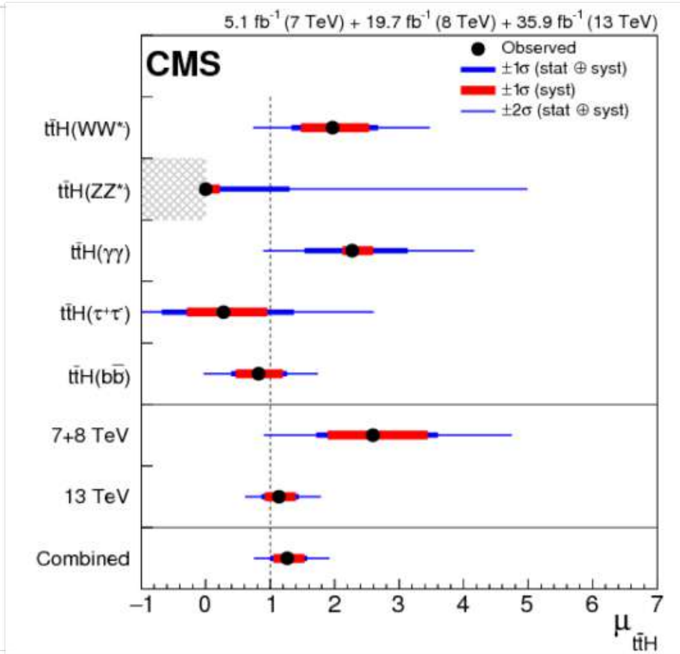
Biggest achievement during Run-2

- **Couplings to 3rd generation fermions**
  - In 2016, CMS observed $H\rightarrow\tau\tau$. It was the first evidence of such decay by a single experiment (previously observed in 2015 by ATLAS+CMS)
  - In 2018, observation of ttH
  - In 2018, observation of H→bb

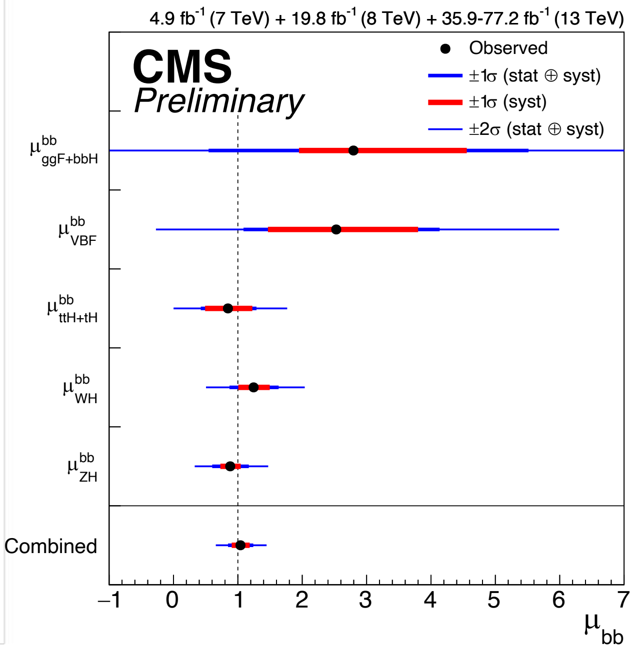
$H\rightarrow\tau\tau$



ttH

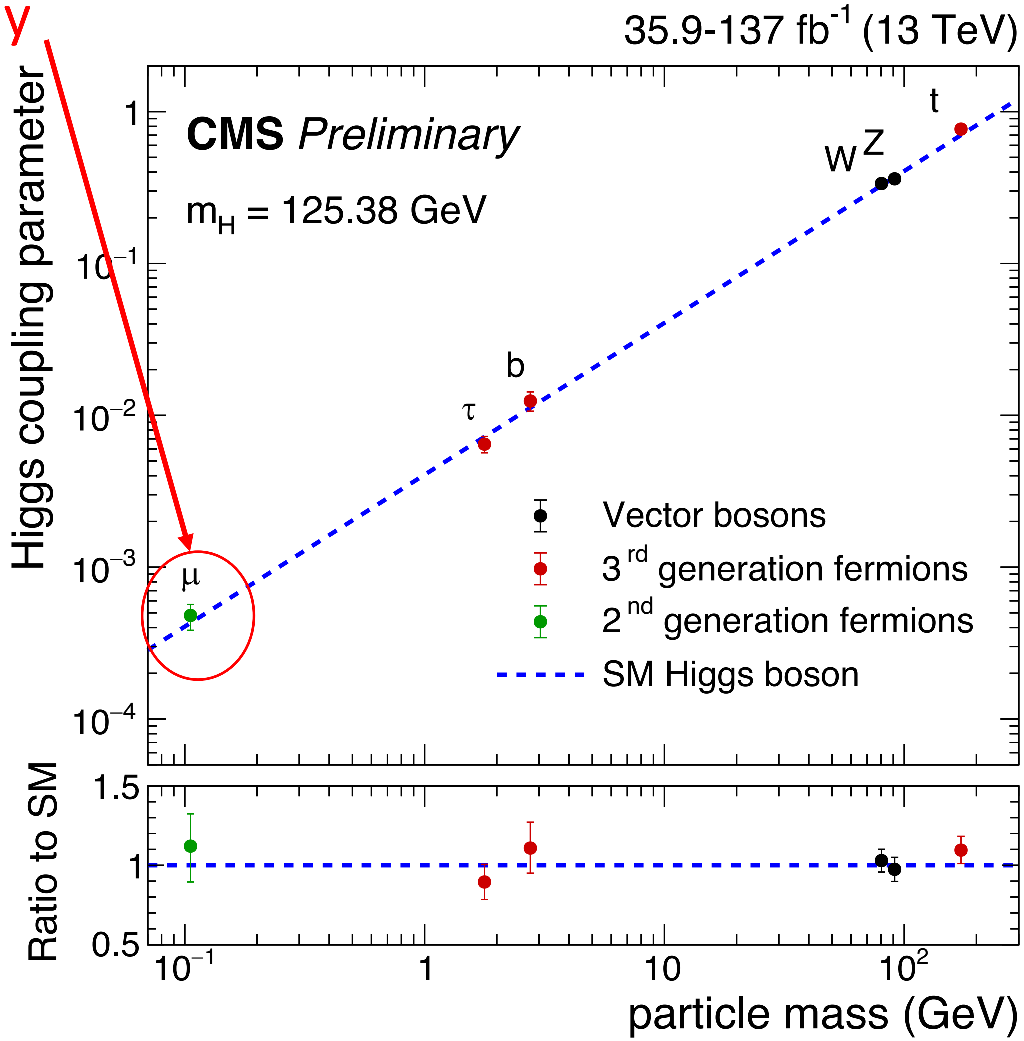


H→bb



Biggest achievement during Run-2

- **Couplings to 2rd generation fermions**
  - CMS evidence for H→$\mu\mu$ decay
  - Searches for H→cc decay
- **Non-universal coupling**
  - Function of the particle mass
  - Run-1 assessed for vectors
  - Run-2: assessed for fermions
- **Last frontier:**
  - Higgs self-coupling
  - Production mechanism
  - Differential distributions

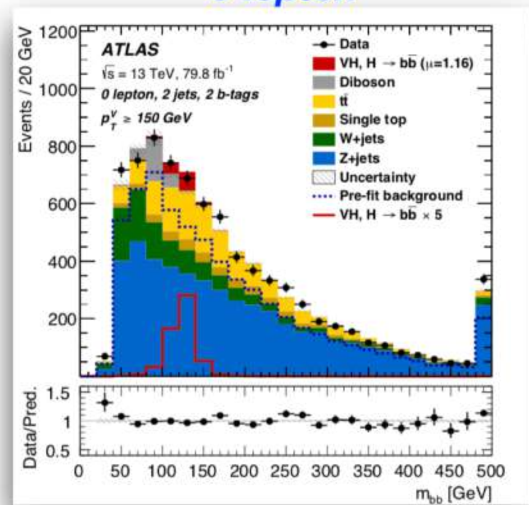


Event Selection+Categorization - ATLAS

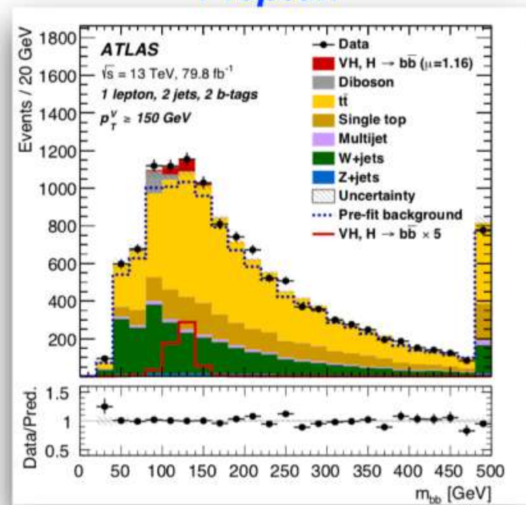
- **Selections (jets, leptons, b-tagging) optimized separately by channel**
  - 4 analysis categories + split in 2- and 3-jets:
    - 0-lepton: **$p_T(Z)$ > 150 GeV**
    - 1-lepton: **$p_T(W)$ > 150 GeV**
    - 2-lepton High-Vp_T: **$p_T(Z)$ > 150 GeV**
    - 2-lepton Low-Vp_T: **75 GeV < $p_T(Z)$ 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

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

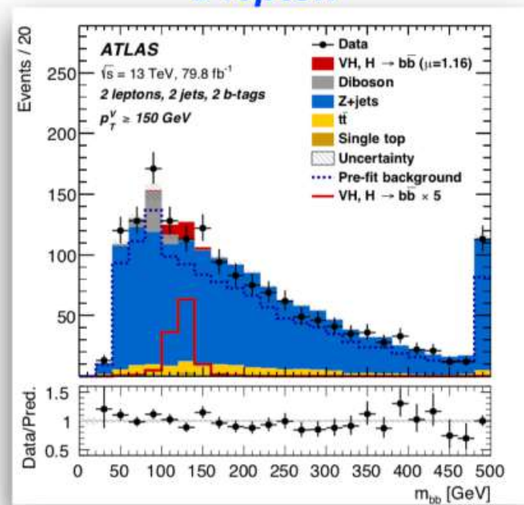
0-lepton



1-lepton



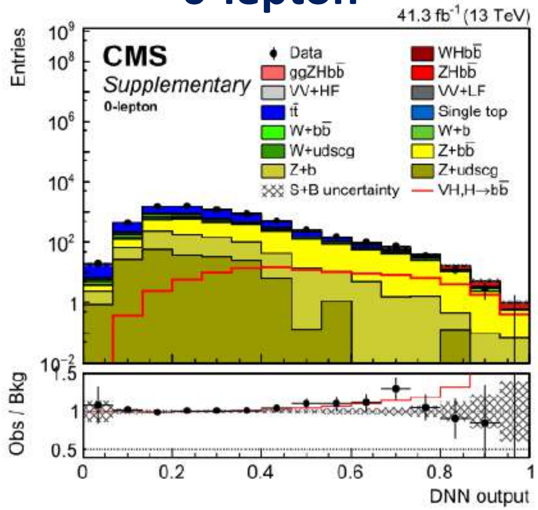
2-lepton



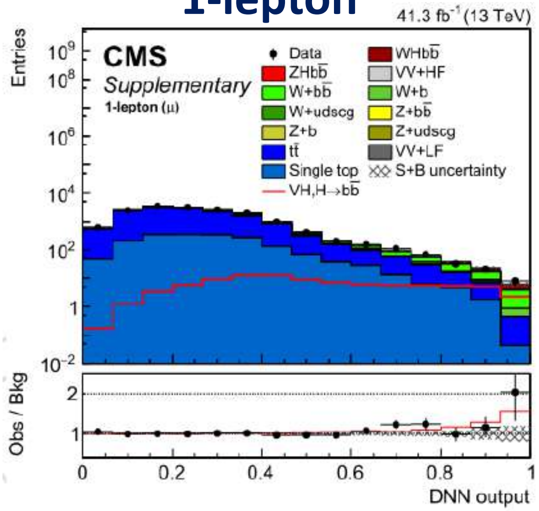
Signal extraction – CMS

- **CMS**

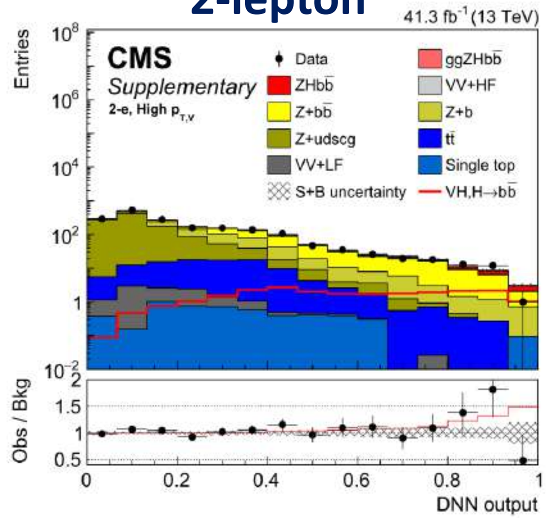
0-lepton



1-lepton

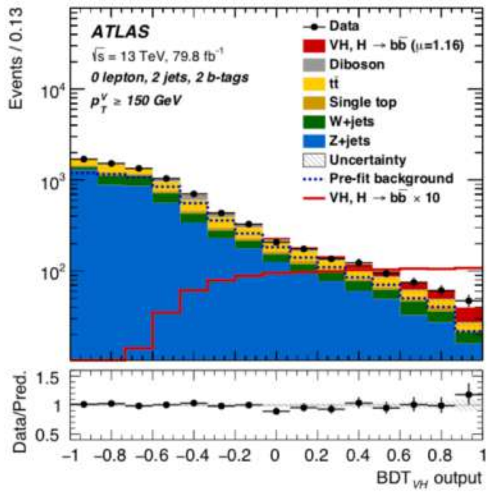


2-lepton

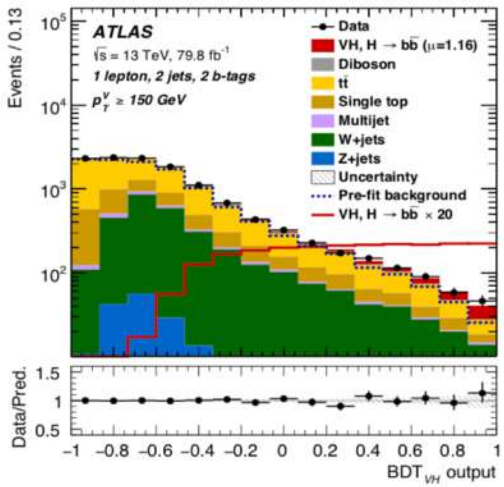


- **ATLAS**

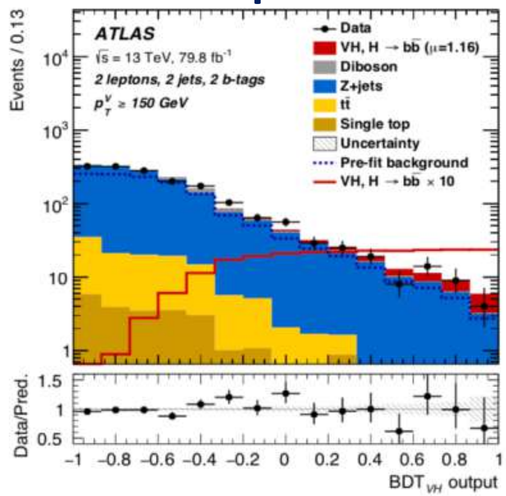
0-lepton



1-lepton

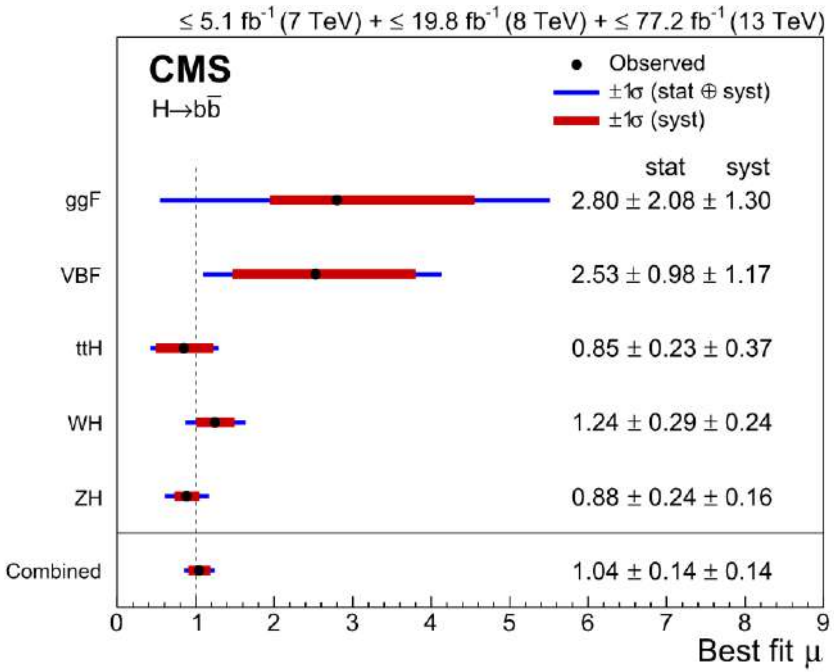


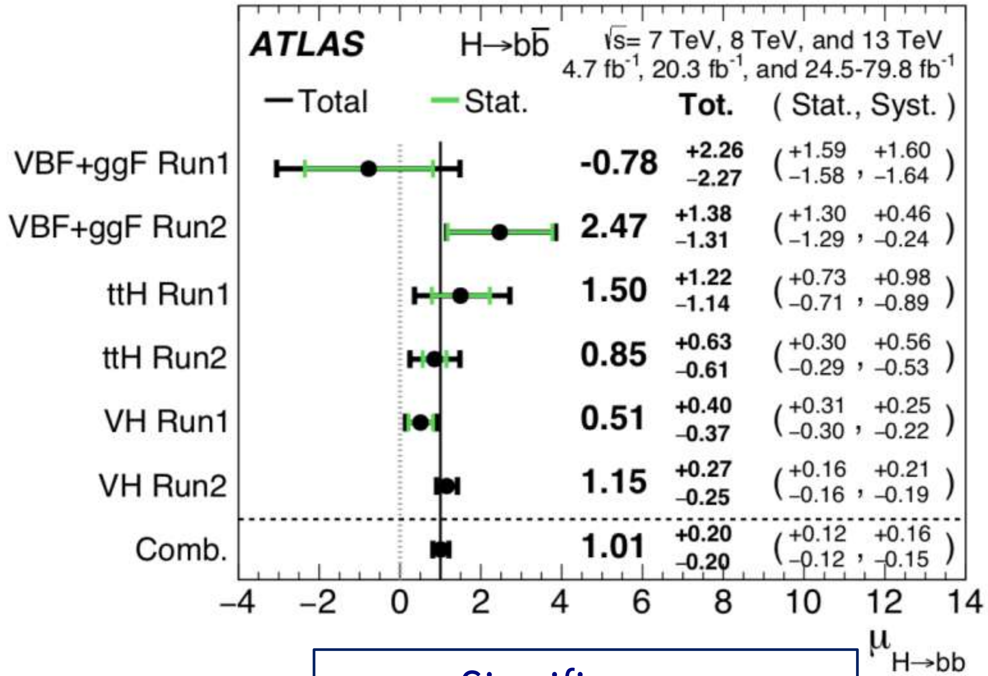
2-lepton



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

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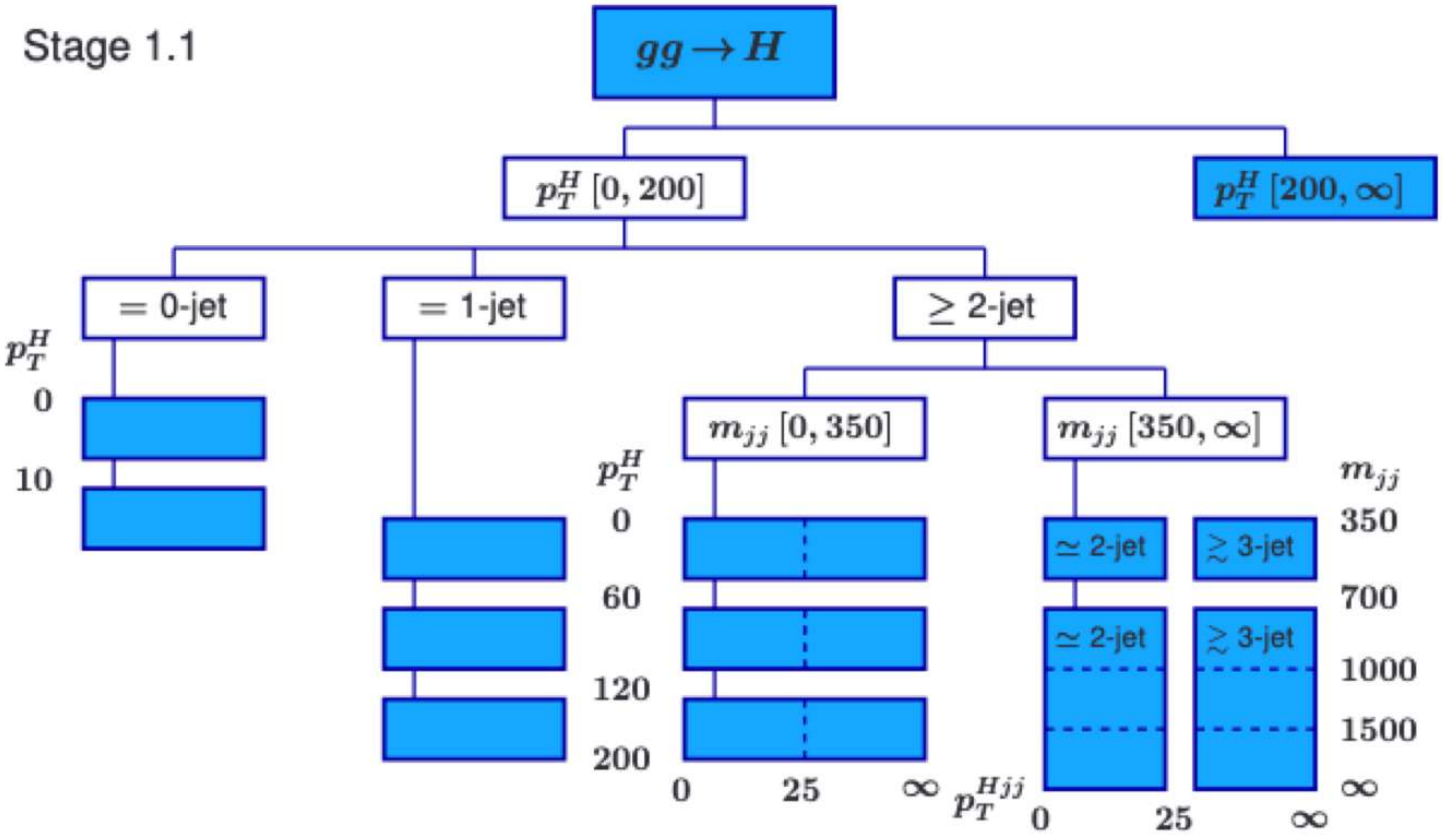
Simplified Template Cross Section

- Adopted by the LHC experiments as a common framework for Higgs measurements
- Purpose: reduce the theoretical uncertainties that are directly folded into the measurements as much as possible
- Allowing for the combination of the measurements between different decay channels as well as between experiments
- When combining measurements in different decay channels, one can either assume the SM branching ratios or consider the ratios of the branching ratios as additionalfree parameters.

Simplified Template Cross Section



Simplified Template Cross Section

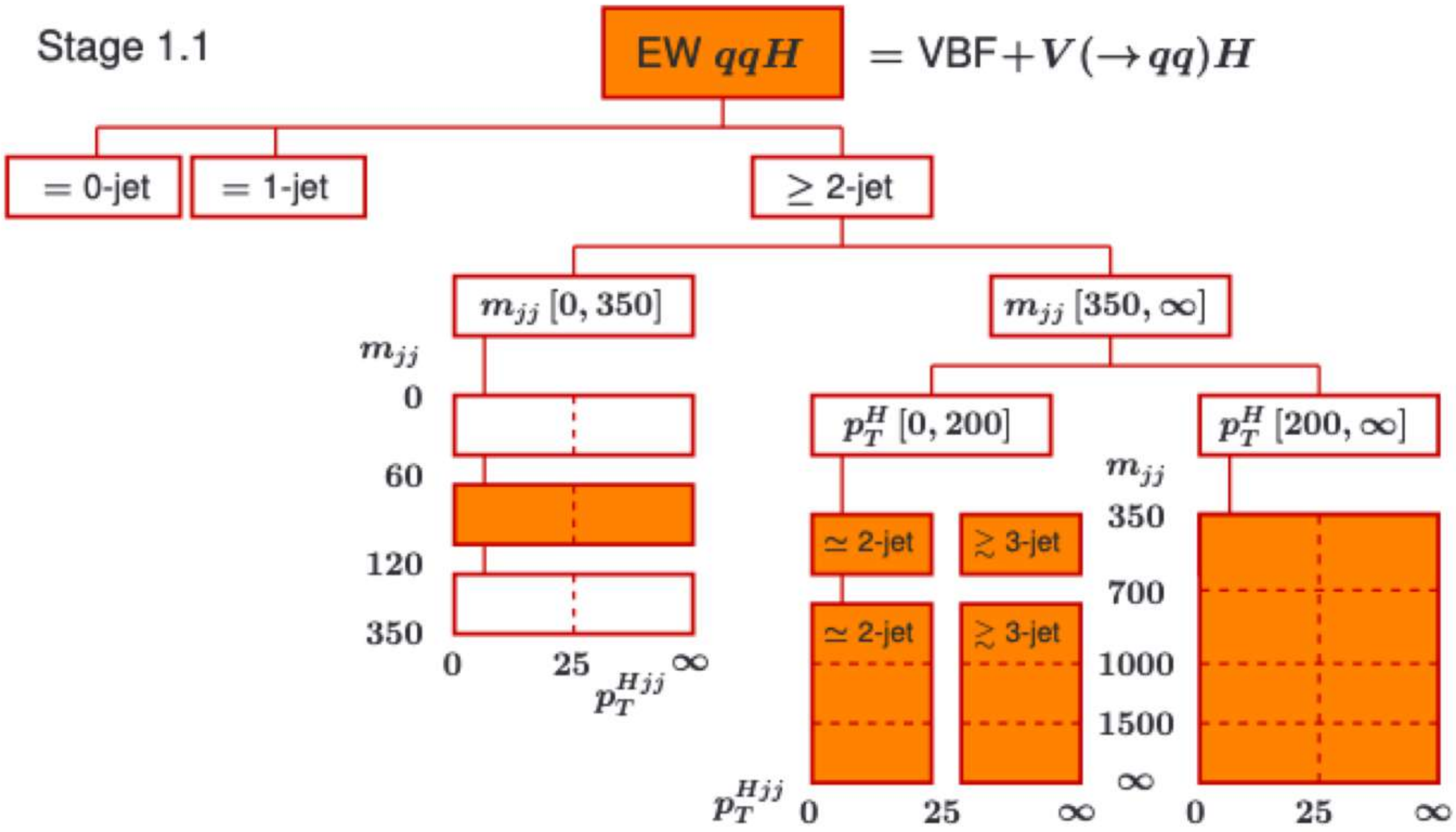


Figure 2. Stage 1.1 bins for electroweak qqH production, VBF$+V(\rightarrow qq)H$.

Simplified Template Cross Section

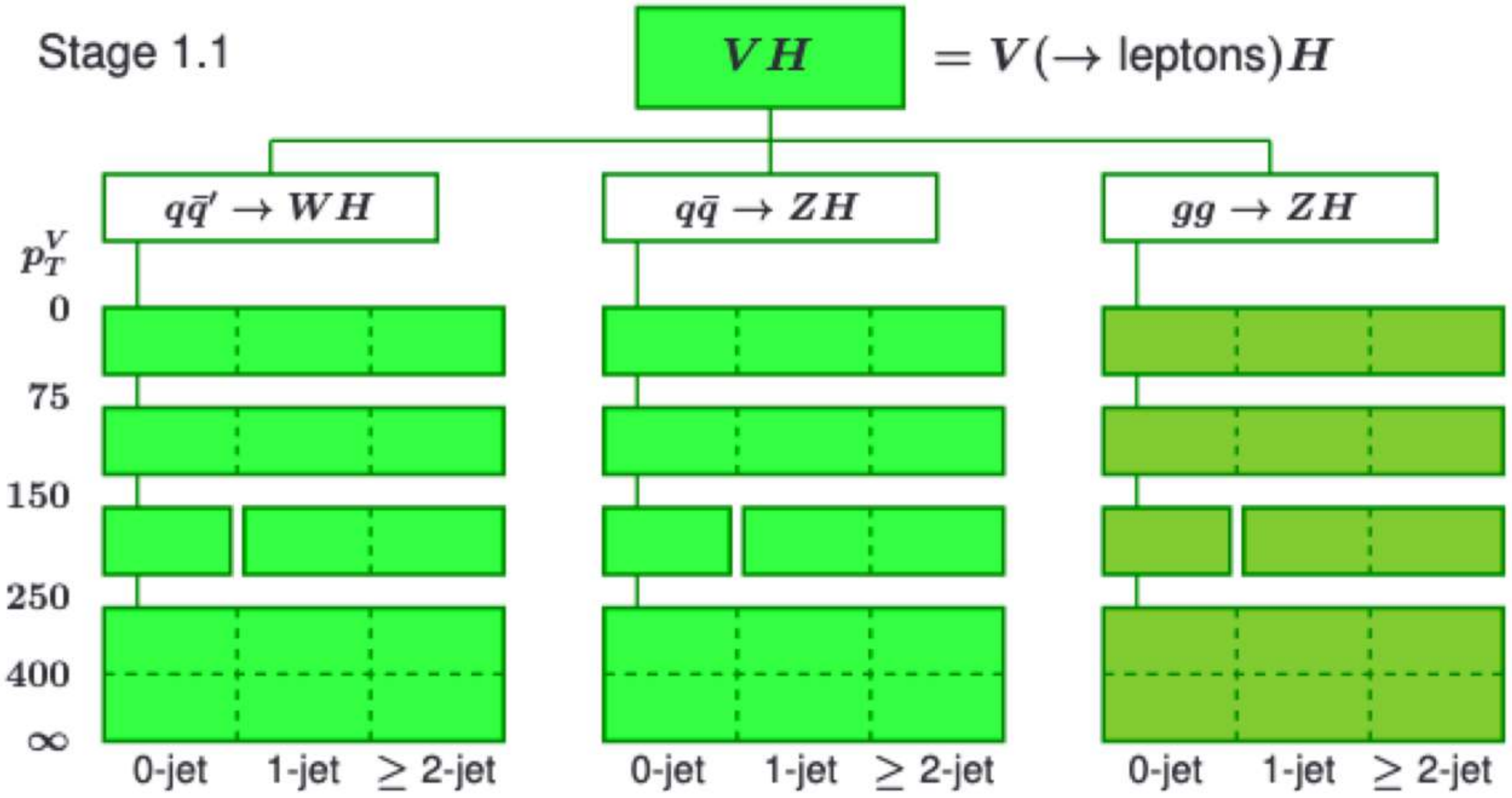
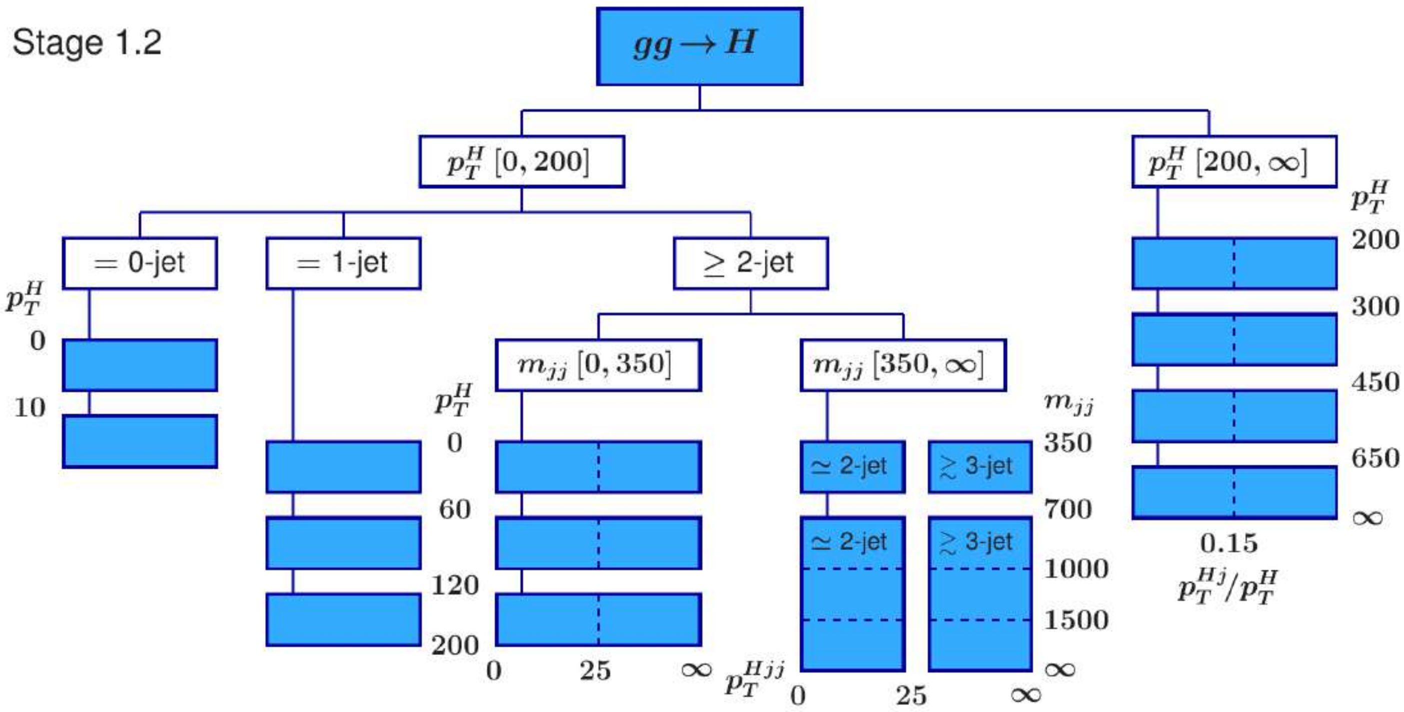
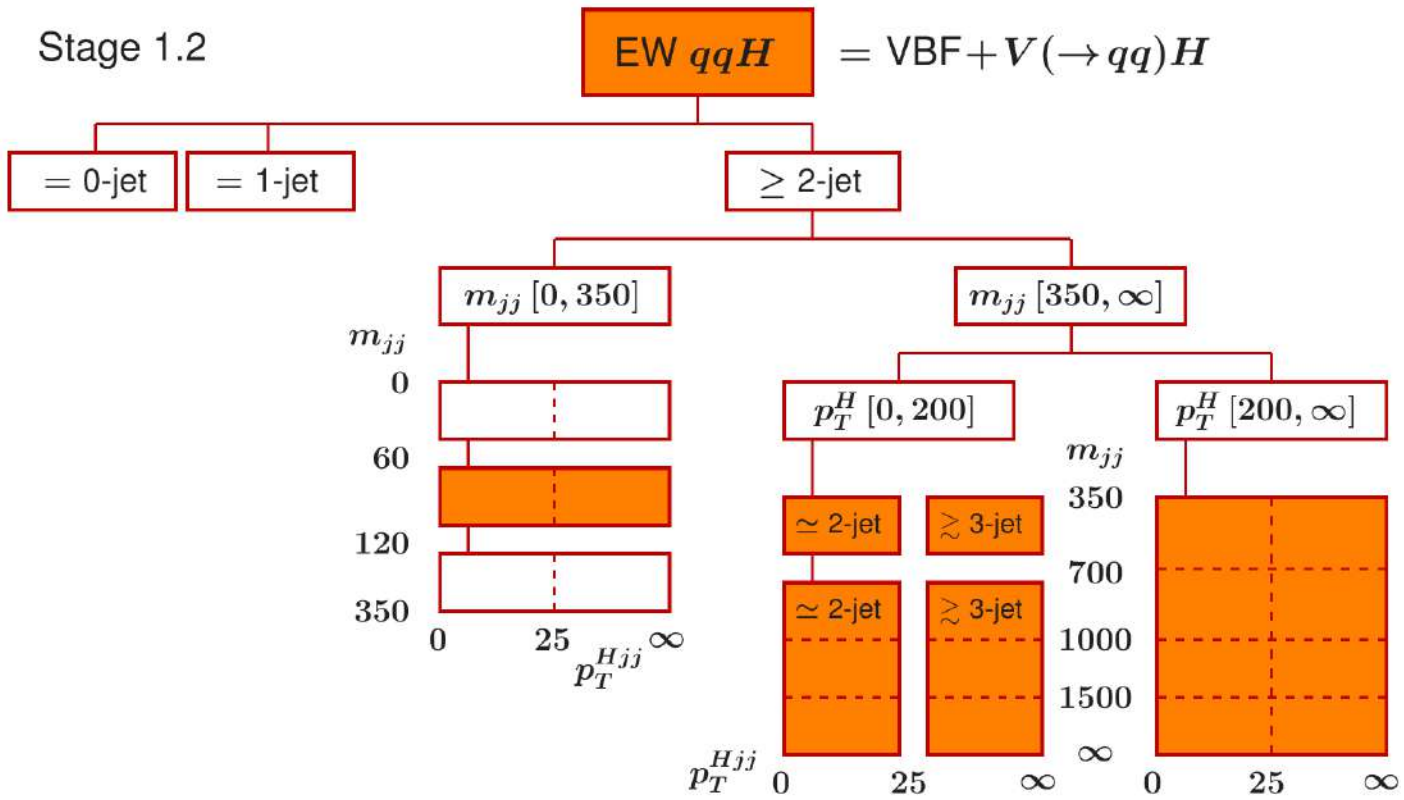


Figure 3. Stage 1.1 bins for VH production, $V(\rightarrow \text{leptons})H$.

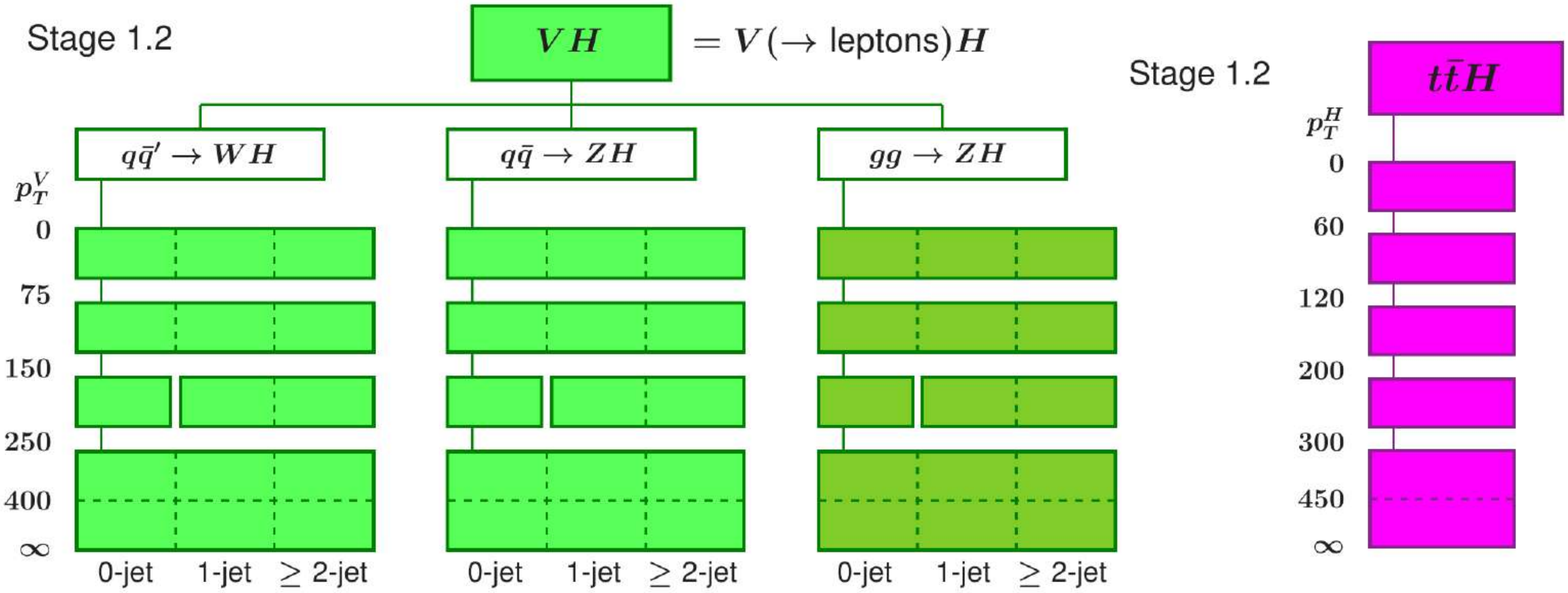
Simplified Template Cross Section



Simplified Template Cross Section

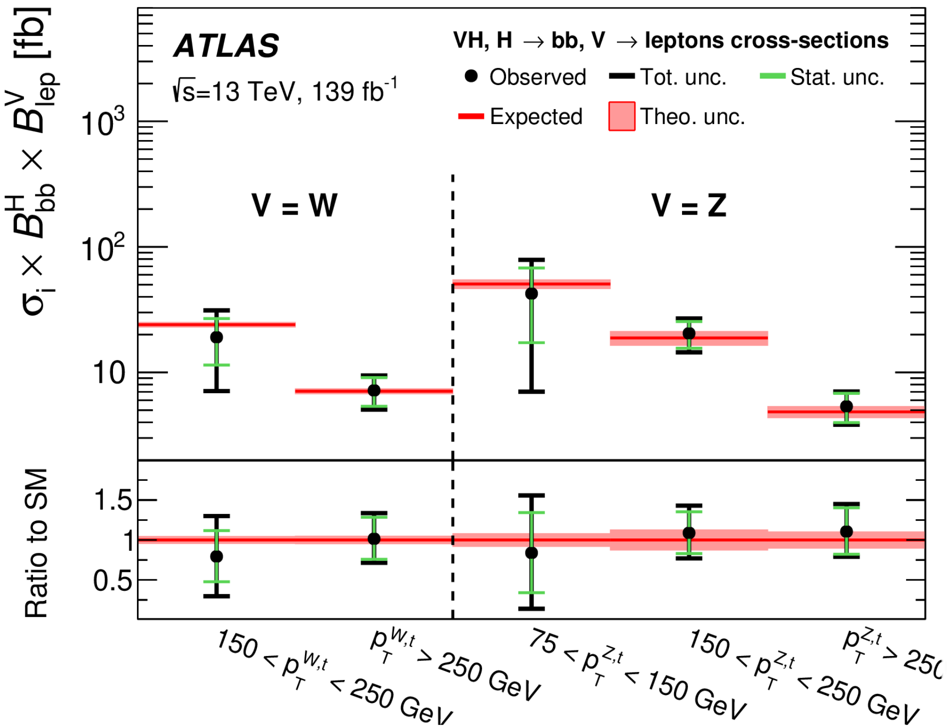


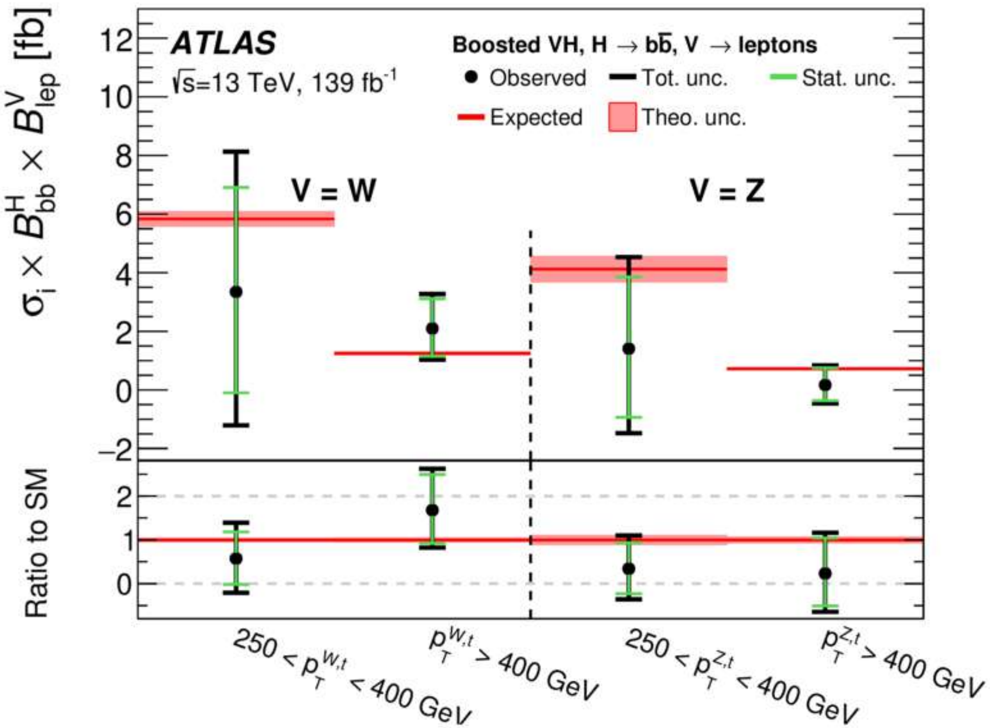
Simplified Template Cross Section



ATLAS - VH→bb

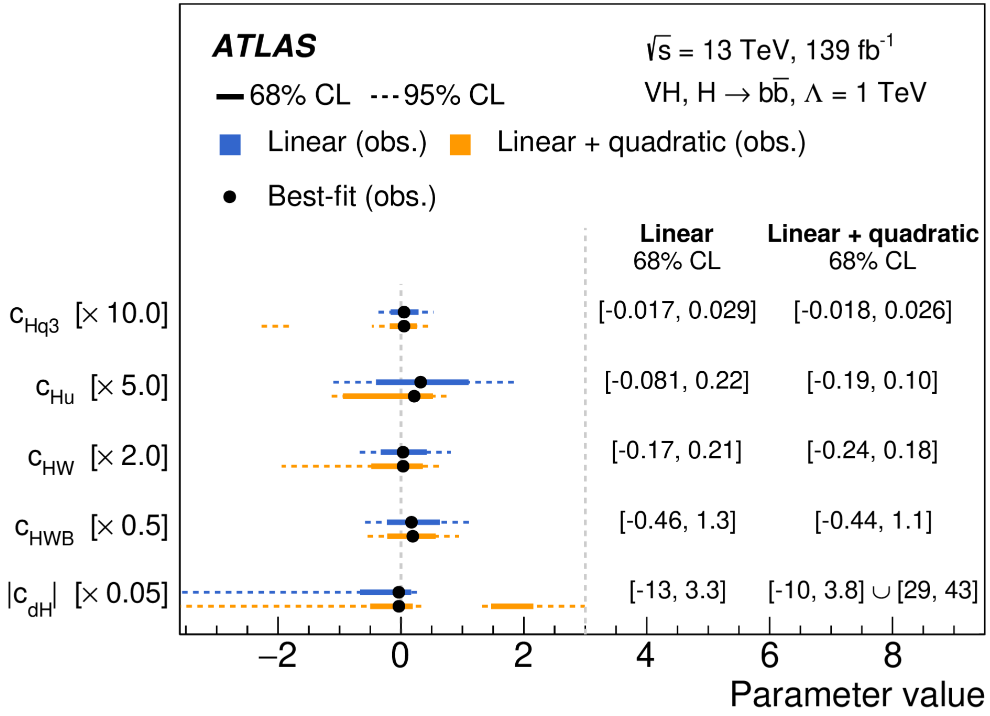
- **STXS results**

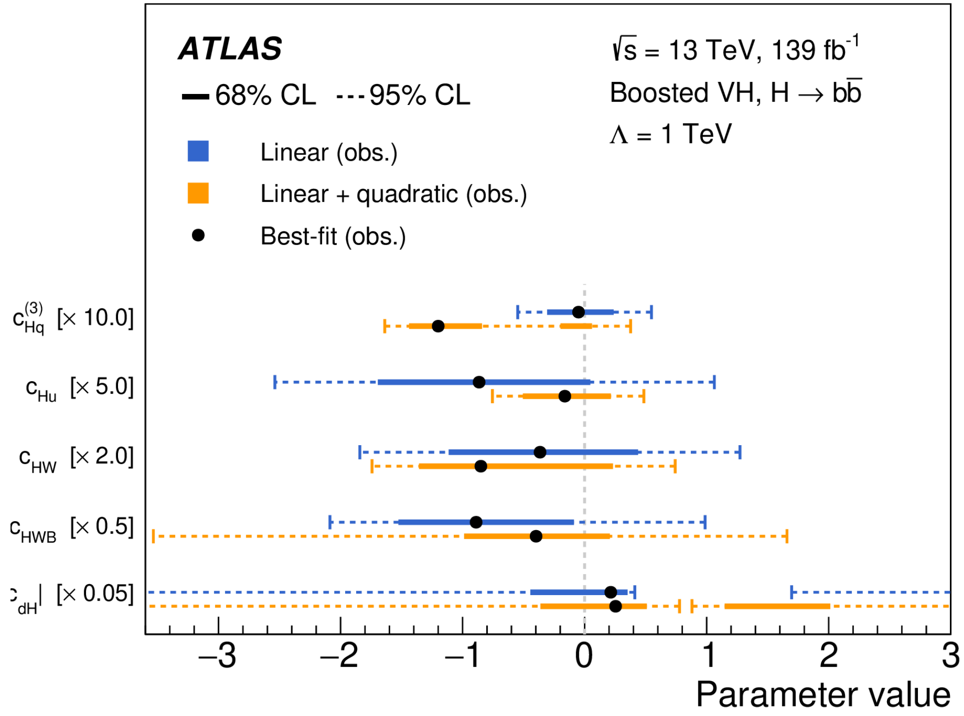




ATLAS - VH→bb

▪ EFT interpretation





H→ZZ→4ℓ Full Run-2 (STXS)

HIG-19-001

- News:

  STXS stage 1.2;

  rare signal included: bbH, tHW, tqH (then bbH merged con ggH e tH con ttH);

  electroweak bkg included (VVV e tt+V(V) e VBS);
  signal strength mu_WH and mu_ZH splitted (always VH merged).

- Kinematic discriminants: combining information of production and decay;

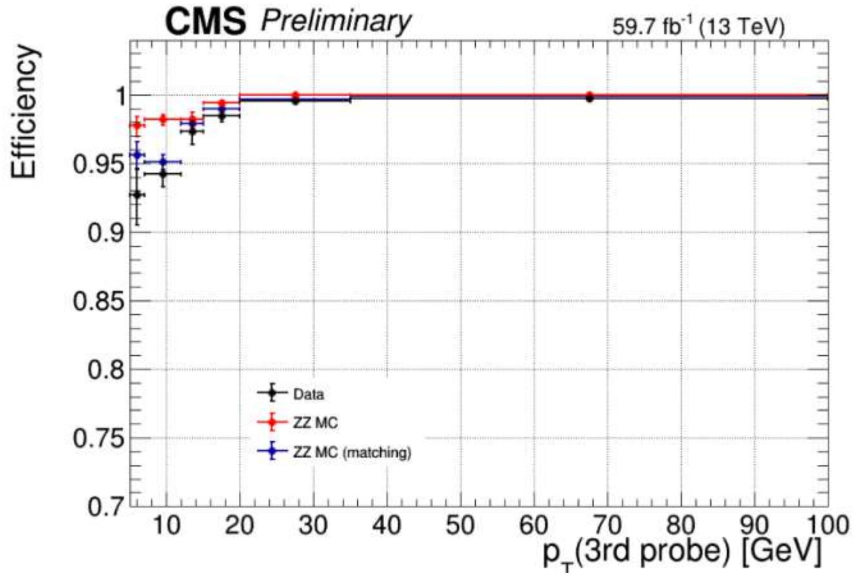
- Objects and event selections common between HIG-19-001 and HIG-19-009;
- Background estimation: qqZZ/ggZZ/EWK =>MC, reducible ZX => Data-driven.

H→ZZ→4ℓ Full Run-2 (STXS)

HLT path	prescale	primary dataset
HLT_Ele23_Ele12_CaloIdL_TrackIdL_IsoVL_v*	1	DoubleEG
HLT_DoubleEle25_CaloIdL_MW_v*	1	DoubleEG
HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_DZ_Mass3p8_v*	1	DoubleMuon
HLT_Mu23_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL_v*	1	MuonEG
HLT_Mu8_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_DZ_v*	1	MuonEG
HLT_Mu12_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_DZ_v*	1	MuonEG
HLT_DiMu9_Ele9_CaloIdL_TrackIdL_DZ_v*	1	MuonEG
HLT_Ele32_WPTight_Gsf_v*	1	SingleElectron
HLT_IsoMu24_v*	1	SingleMuon

Event is required to trigger on at least one of listed HLT paths

- Trigger eff. measured using TnP approach on events triggering single lepton HLT paths.
- Propagated to systematic uncertainty.



H→ZZ→4ℓ Full Run-2 (STXS)

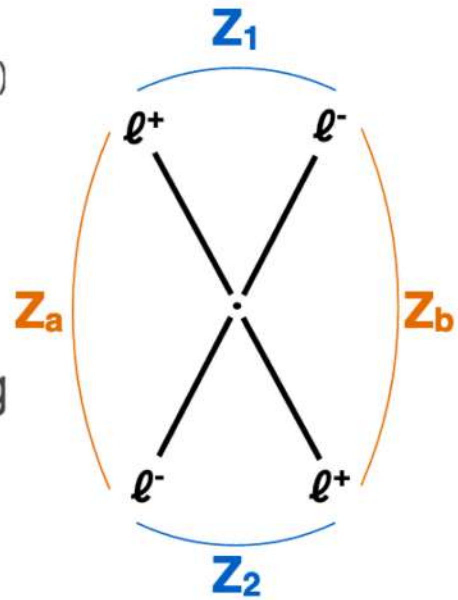
ZZ CANDIDATE SELECTION

17

Z candidate = any OS-SF pair that satisfy 12 < $m_{ll(\gamma)}$ < 120 GeV

Build all possible ZZ candidates, define Z_1 candidate with $m_{ll(\gamma)}$ closest to the PDG m(Z) mass

- m_{Z1} > 40 GeV, $p_T(l1)$ > 20 GeV, $p_T(l2)$ > 10 GeV
- ΔR>0.02 between each of the four leptons
- m_{ll} > 4 GeV for OS pairs (regardless of flavour)
- reject 4μ and 4e candidates where the alternate pairing Z_aZ_b satisfies $|m(Z_a)-m(Z)|<|m(Z_1)-m(Z)|$ and $m(Z_b)<12$ GeV
- m_{4l} > 70 GeV



If more than one ZZ candidate is left, choose the one of highest $\mathcal{D}^{\text{kin}}_{\text{bkg}}$
If $\mathcal{D}^{\text{kin}}_{\text{bkg}}$ is the same, take the one with Z_1 mass closest to m(Z)*

*For fiducial measurements take the one with Z_1 mass closest to m(Z)

H→ZZ→4ℓ Full Run-2 (STXS)

PRODUCTION DISCRIMINANTS

19

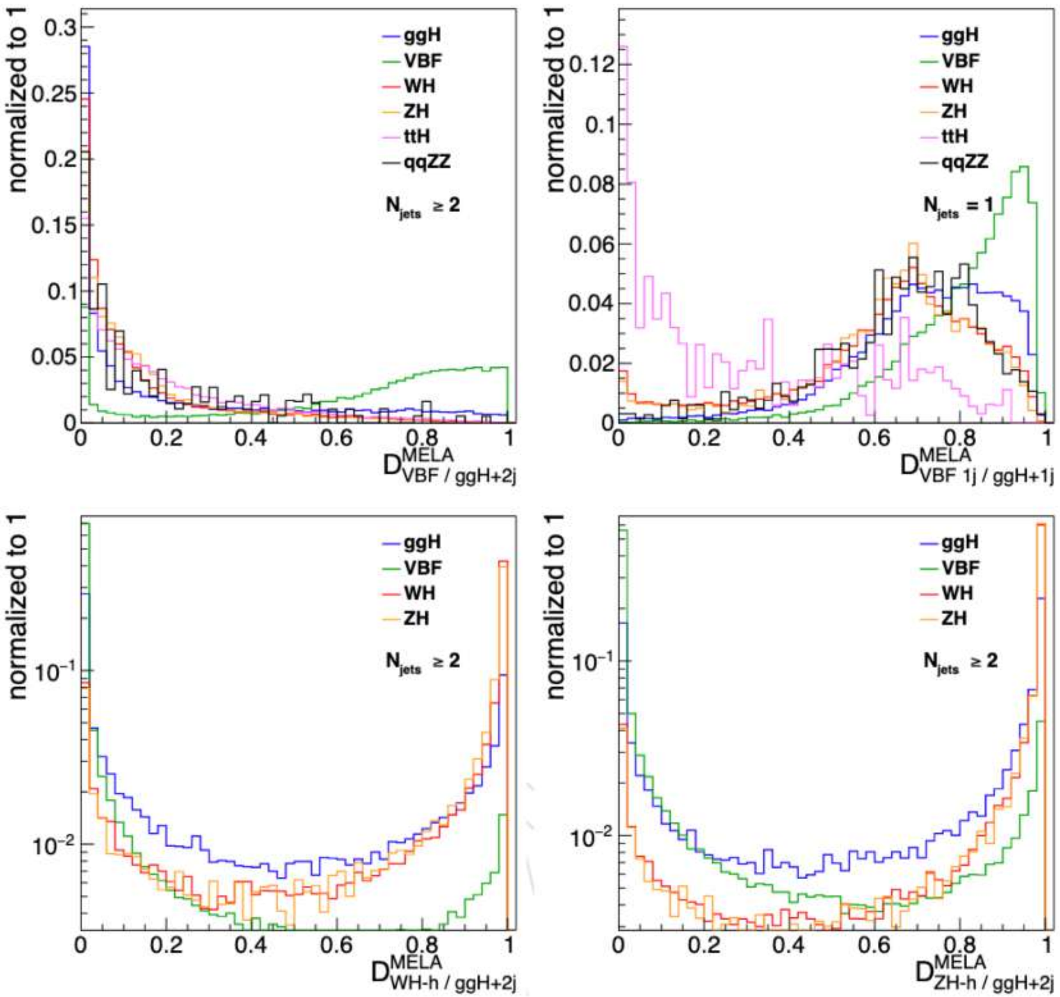
Used in categorisation of events to provide discrimination between different production mode

$$\mathcal{D}_{\mathrm{2jet}} = \left[1 + \frac{\mathcal{P}_{\mathrm{HJJ}}(\vec{\Omega}^{\mathrm{H+JJ}}|m_{4\ell})}{\mathcal{P}_{\mathrm{VBF}}(\vec{\Omega}^{\mathrm{H+JJ}}|m_{4\ell})}\right]^{-1}$$

$$\mathcal{D}_{\mathrm{1jet}} = \left[1 + \frac{\mathcal{P}_{\mathrm{HJ}}(\vec{\Omega}^{\mathrm{H+J}}|m_{4\ell})}{\int d\eta_{\mathrm{J}} \mathcal{P}_{\mathrm{VBF}}(\vec{\Omega}^{\mathrm{H+JJ}}|m_{4\ell})}\right]^{-1}$$

$$\mathcal{D}_{\mathrm{WH}} = \left[1 + \frac{\mathcal{P}_{\mathrm{HJJ}}(\vec{\Omega}^{\mathrm{H+JJ}}|m_{4\ell})}{\mathcal{P}_{\mathrm{WH}}(\vec{\Omega}^{\mathrm{H+JJ}}|m_{4\ell})}\right]^{-1}$$

$$\mathcal{D}_{\mathrm{ZH}} = \left[1 + \frac{\mathcal{P}_{\mathrm{HJJ}}(\vec{\Omega}^{\mathrm{H+JJ}}|m_{4\ell})}{\mathcal{P}_{\mathrm{ZH}}(\vec{\Omega}^{\mathrm{H+JJ}}|m_{4\ell})}\right]^{-1}$$



H→ZZ→4ℓ Full Run-2 (STXS)

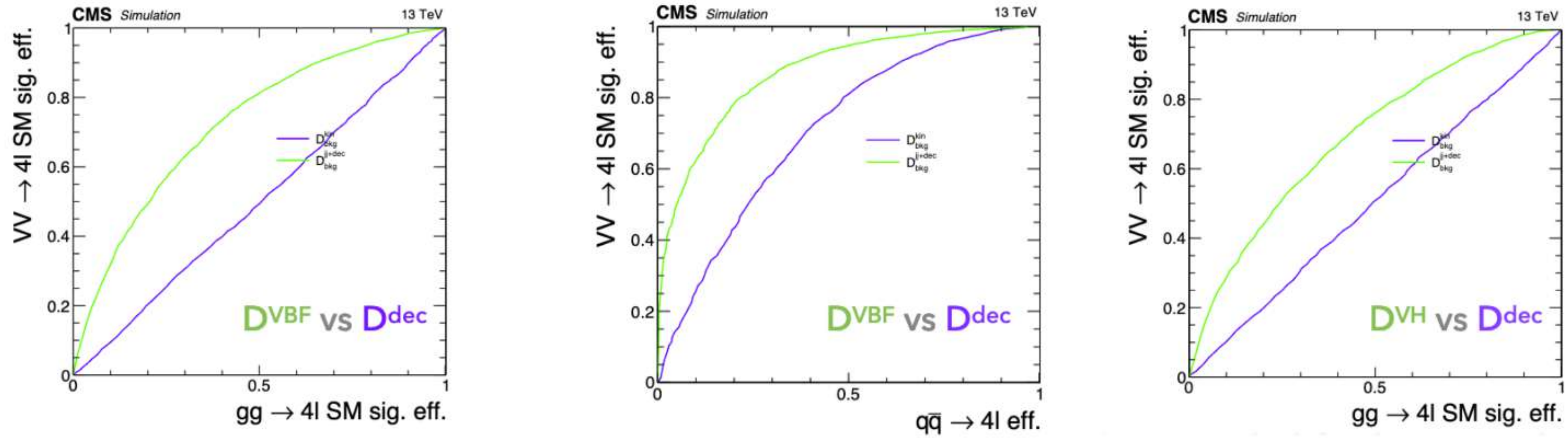
OBSERVABLES

27

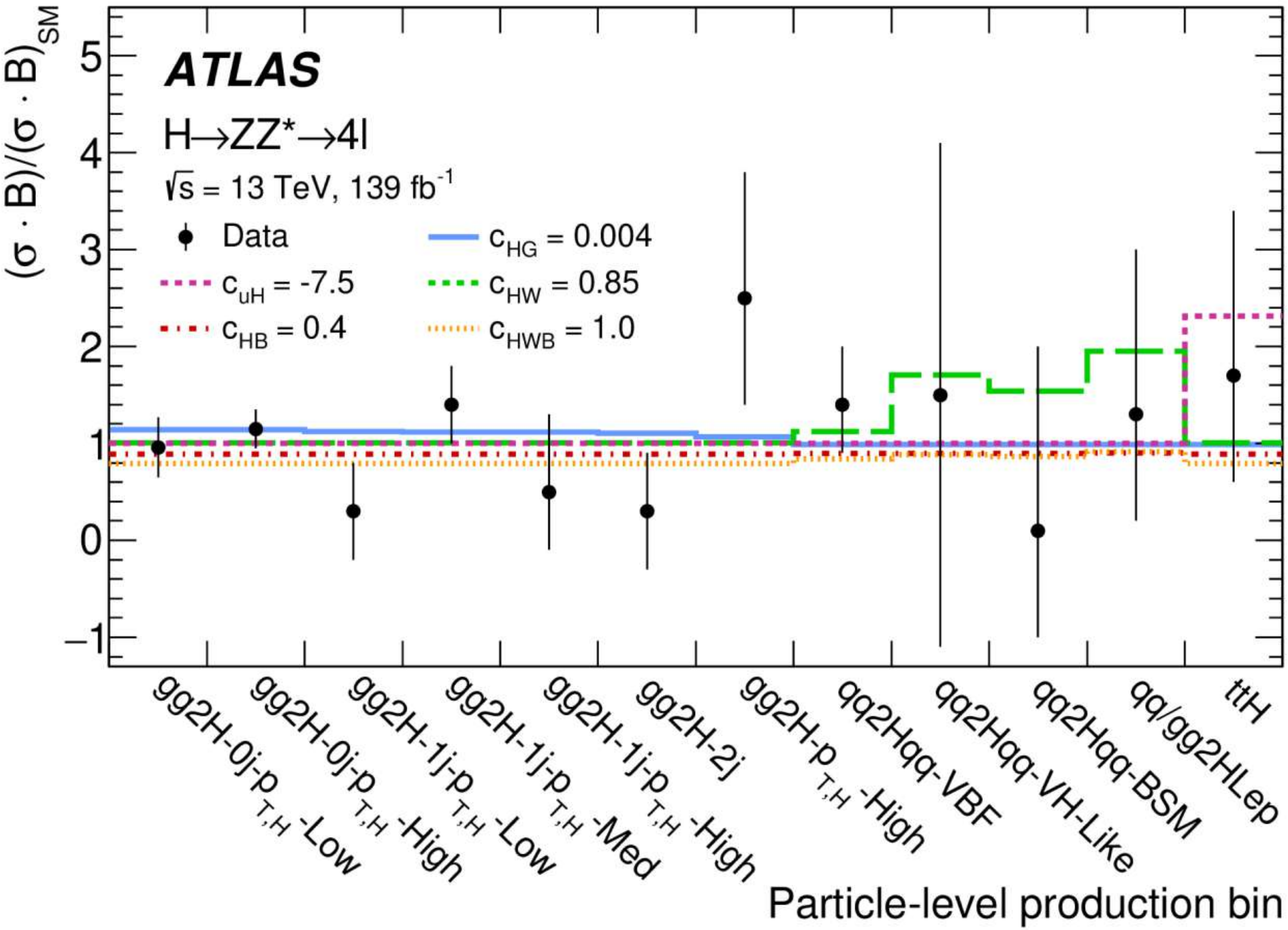
- **Production + decay discriminants** used in VBF-2jet and VH-hadronic categories and their sub-categories exploit jet information to provide separation between different signal production modes

2) $$\mathcal{D}_{\rm bkg}^{\rm VBF+dec} = \frac{\mathcal{P}_{\rm sig}^{{\rm VBF}+VH+{\rm dec}}(\vec{\Omega})}{\mathcal{P}_{\rm sig}^{{\rm VBF}+VH+{\rm dec}}(\vec{\Omega}) + c^{\rm VBF2jet}(m_{4\ell}) \times (\mathcal{P}_{\rm bkg}^{\rm VBS+VVV}(\vec{\Omega}) + \mathcal{P}_{\rm bkg}^{\rm QCD+dec}(\vec{\Omega}))}$$

3) $$\mathcal{D}_{\rm bkg}^{\rm VH+dec} = \frac{\mathcal{P}_{\rm sig}^{{\rm VBF}+VH+{\rm dec}}(\vec{\Omega})}{\mathcal{P}_{\rm sig}^{{\rm VBF}+VH+{\rm dec}}(\vec{\Omega}) + c^{\rm had.VH}(m_{4\ell}) \times (\mathcal{P}_{\rm bkg}^{\rm VBS+VVV}(\vec{\Omega}) + \mathcal{P}_{\rm bkg}^{\rm QCD+dec}(\vec{\Omega}))},$$

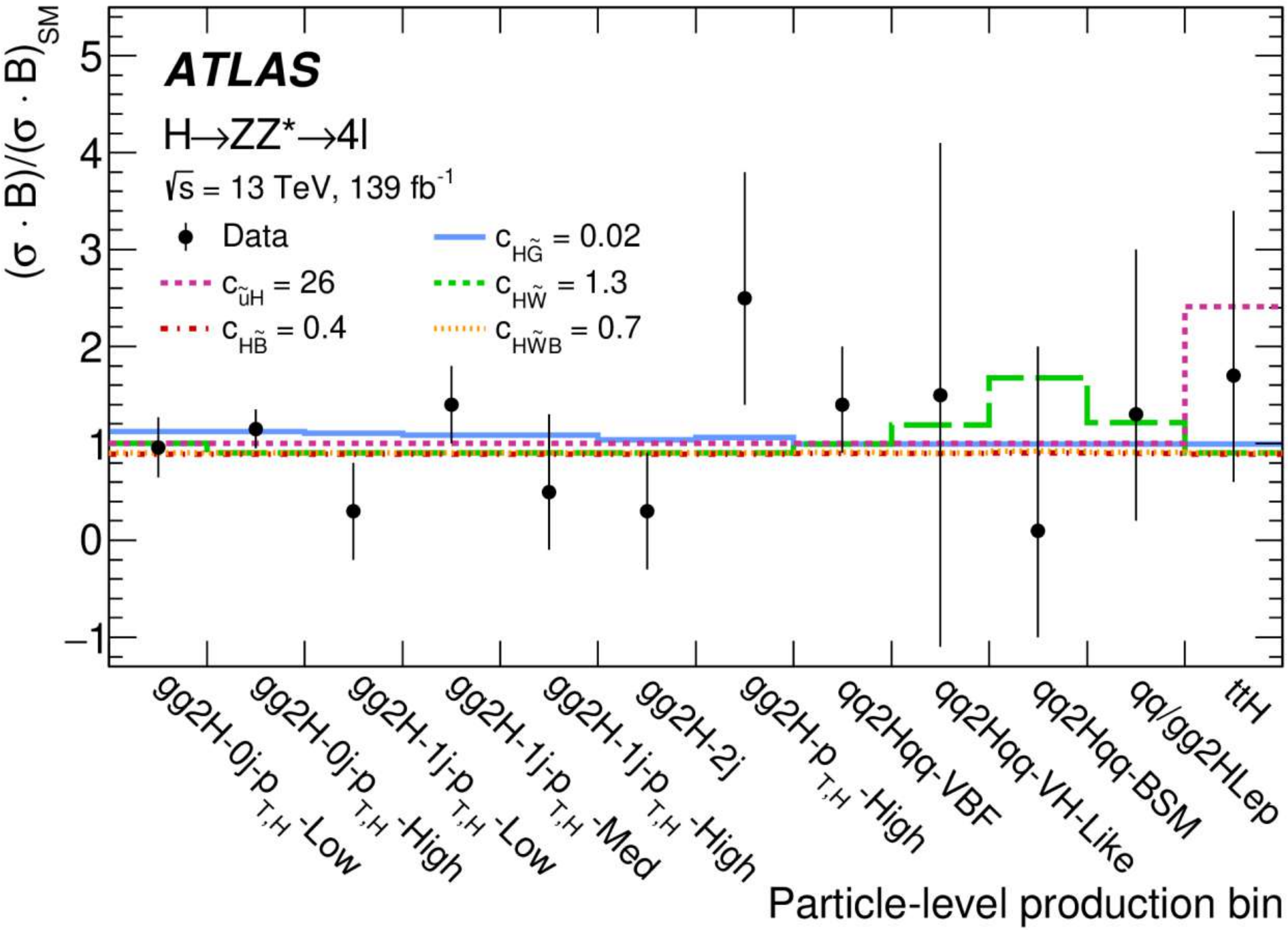


ATLAS - H→ZZ→4ℓ Full Run-2 (STXS)



CP-even

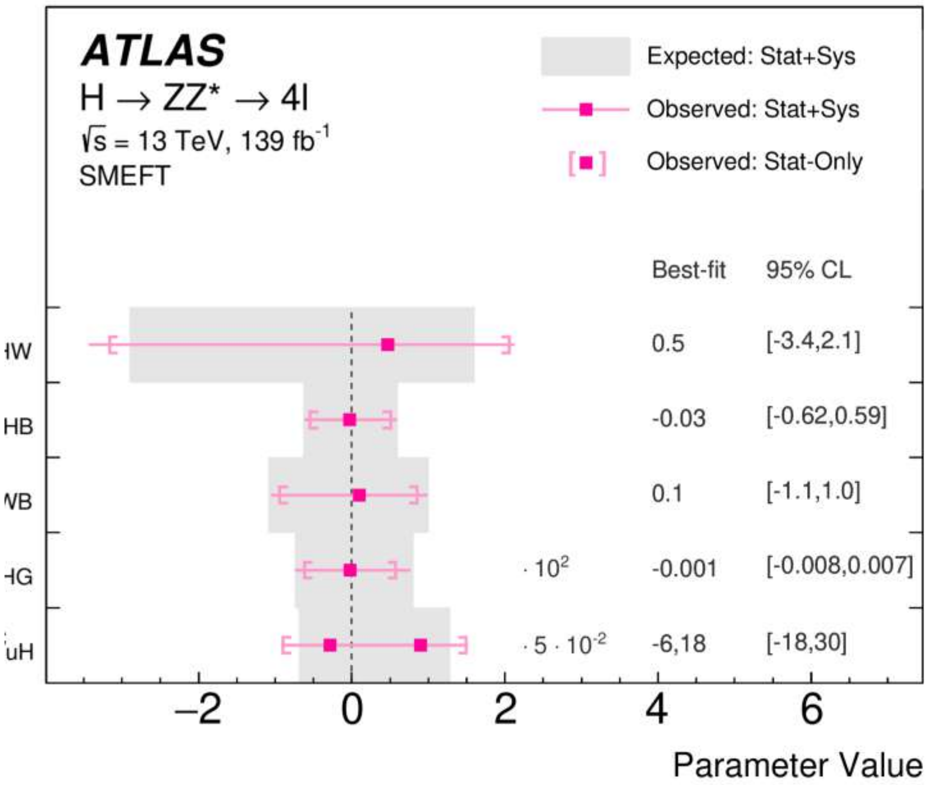
ATLAS - H→ZZ→4ℓ Full Run-2 (STXS)



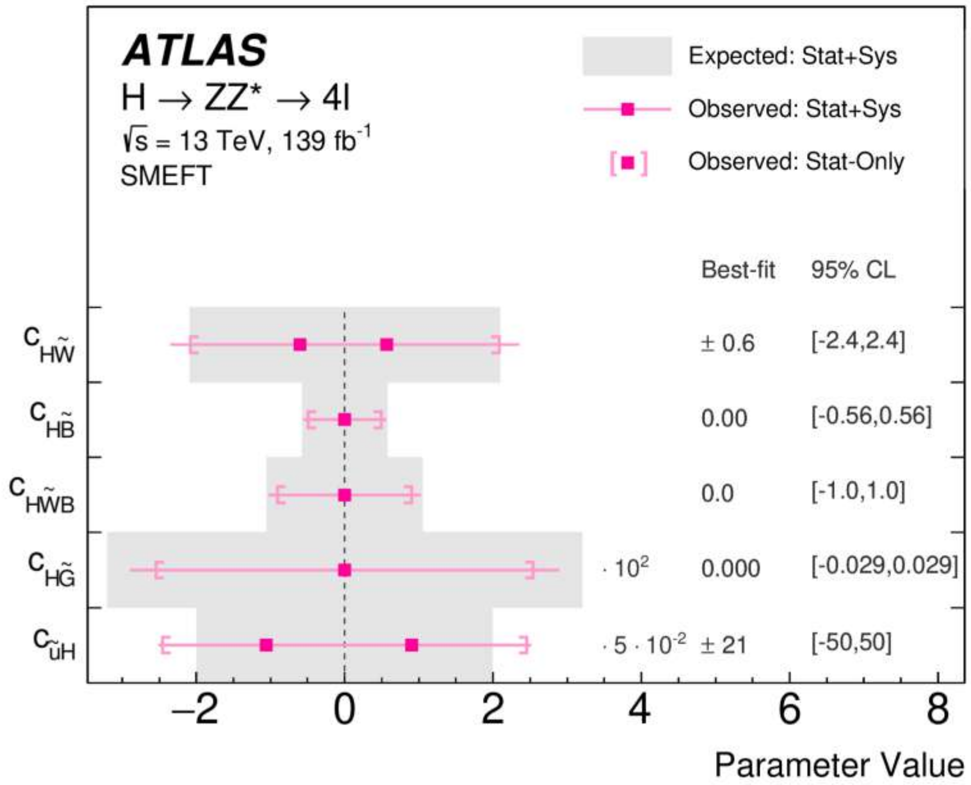
CP-odd

ATLAS - H→ZZ→4ℓ Full Run-2 (STXS)

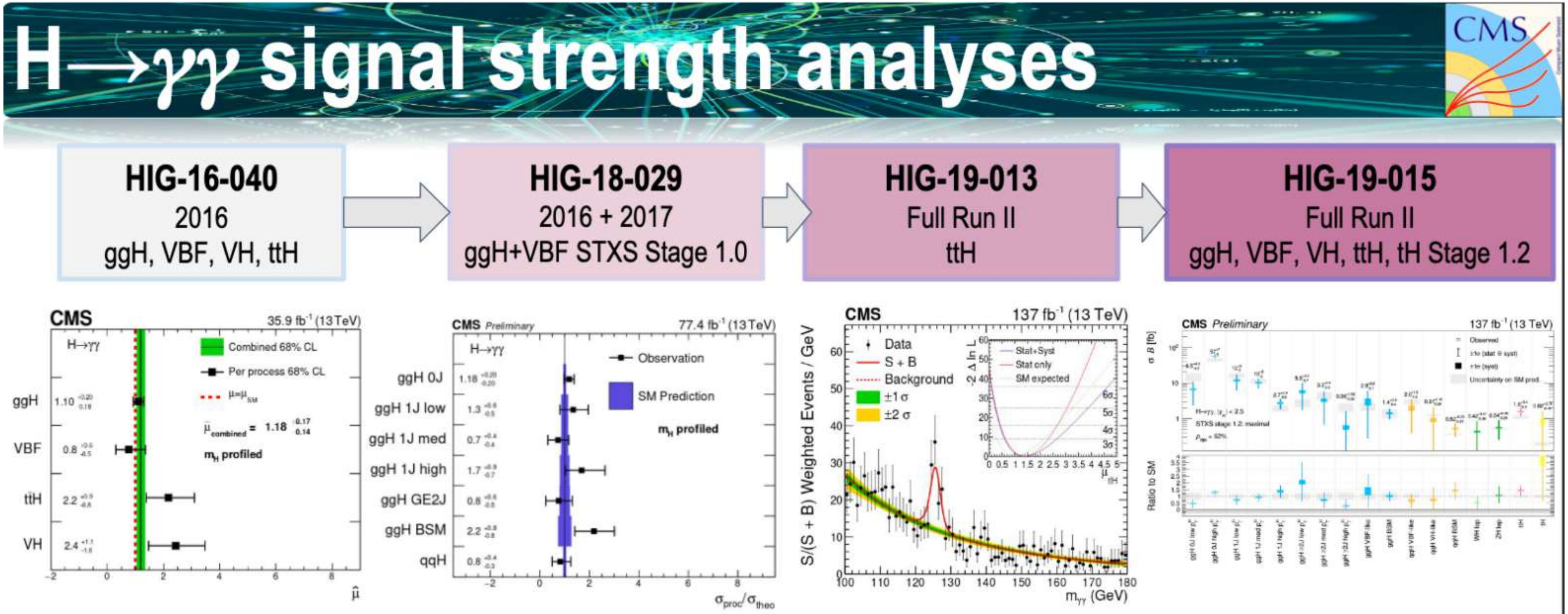
CP-even



CP-odd



H→$\gamma\gamma$ Full Run2 – Higgs boson properties

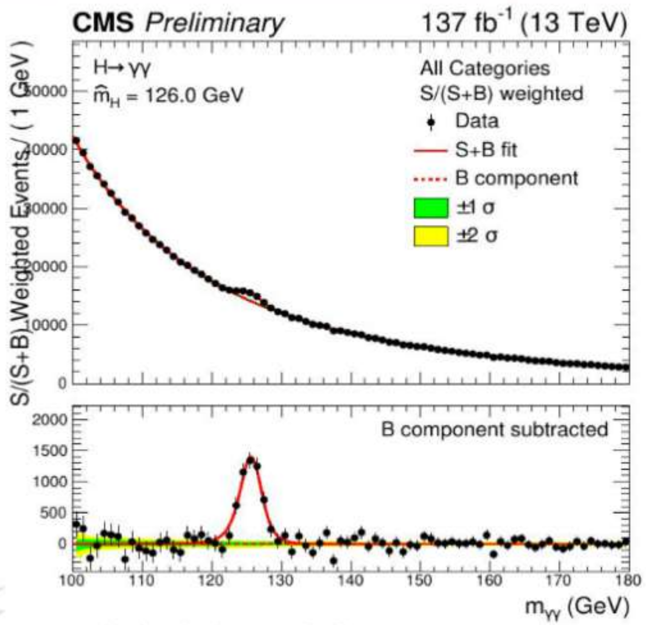


- **evolving from measuring 4 signal strengths (μ) in HIG-16-040 to over 20 parameters in HIG-19-015**
- Not covered in this analysis:
- Higgs boson mass measurement (m_H)
- differential cross-section measurements

H→$\gamma\gamma$ Full Run2 – Higgs boson properties

Analysis strategy

- Aim: to have a pure sample of diphoton events, fit the invariant mass distribution, exploiting the narrow H peak
- Analysis targets ggH, qqH (VBF and VH hadronic), ttH and tH, VH leptonic Stage 1.2 STXS bins
- Categories defined to **target as many STXS bins as possible in each production mode**, category splits made depending on available statistics
- Background reduction, and contamination from other H production modes reduced through the **use of MVAs**
- **Data from all years is merged together**
- Simultaneous fit to the diphoton invariant mass distributions in all categories, with the background determined from data

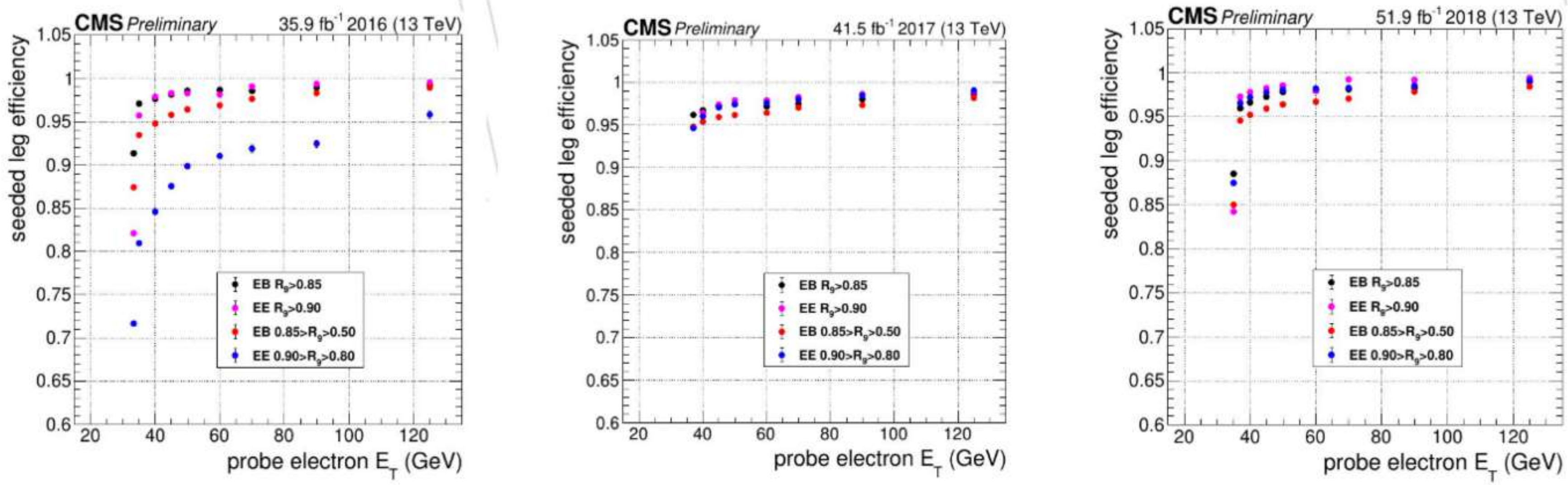


tHq leptonic tag → ttH leptonic tags → VH leptonic tags → VH MET tag → ttH hadronic tags → qqH tags (including VH hadronic) → ggH tags

H→$\gamma\gamma$ Full Run2 – Higgs boson properties

Trigger details

- **Triggers**
  - 2016: HLT_Diphoton30_18_R9Id_OR_IsoCaloId_ANDHE_R9Id_Mass90 ($p^{\gamma 1}_T$ > 30 GeV, $p^{\gamma 2}_T$ > 18 GeV)
  - 2017+2018: HLT_Diphoton30_22R9Id_OR_IsoCaloId_ANDHE_R9Id_Mass90 ($p^{\gamma 1}_T$ > 30 GeV, $p^{\gamma 2}_T$ > 22 GeV)
- **Trigger efficiency**
  - measured using the tag-and-probe method on DY events (less than 1% uncertainty)
  - weights from the trigger efficiency are applied to simulated events in bins of η and R_9



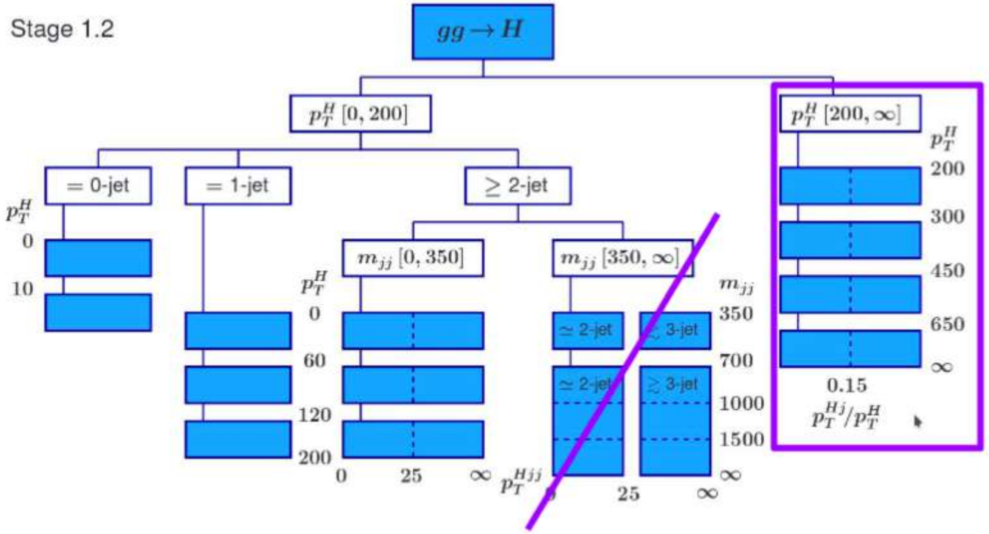
H→$\gamma\gamma$ Full Run2 – Higgs boson properties

ggH categorisation

Ingredients: diphoton BDT score + ggH multiclassifier

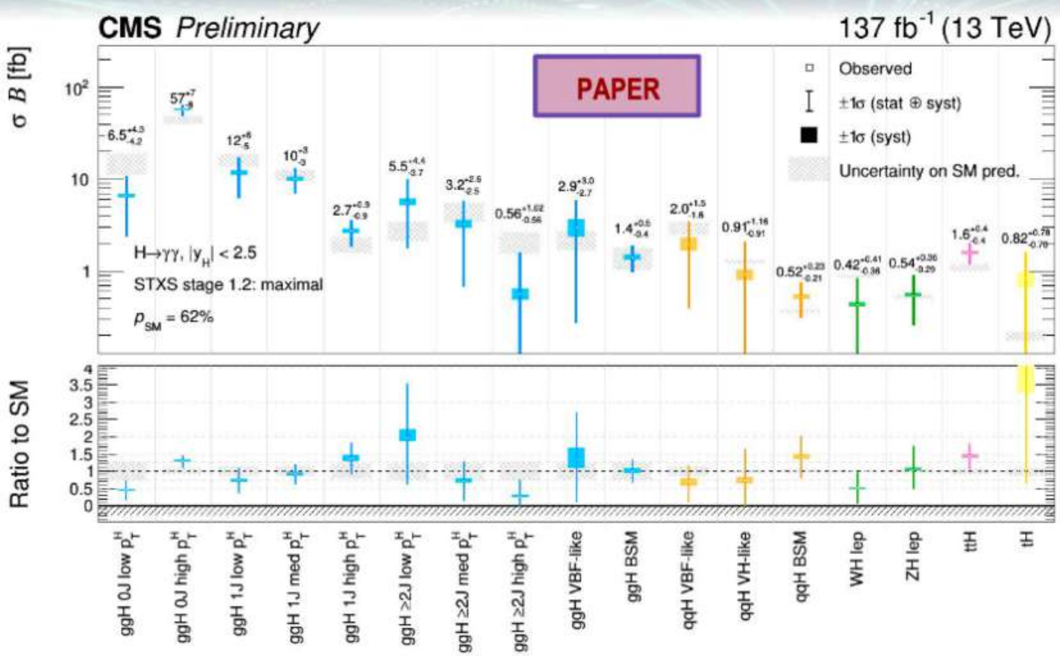
generator-level bins defined with p_T^H, N_{jets}, m_{jj}
- dedicated BSM region with $p_T^H > 200$ GeV
- VBF-like ggH region with $N_{jets} \geq 2$, $m_{jj} > 350$ GeV

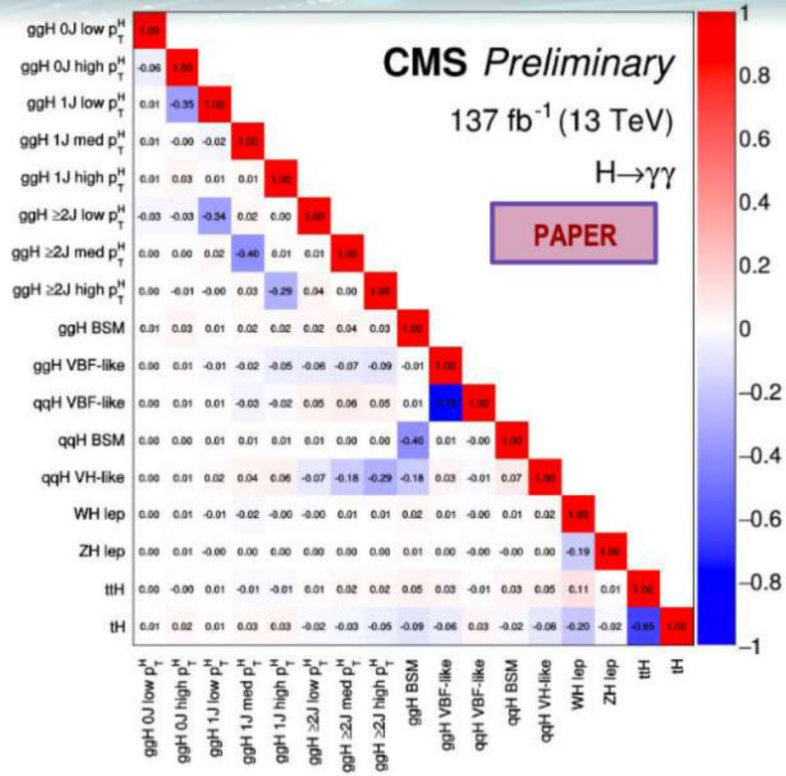
reconstructed STXS 1.2 categories
- events assigned using a multiclass BDT: predicts probability that an event belongs to a given STXS bin
- inputs: jet, photon and diphoton kinematics
- training: ggH simulated events with standard pre-selection and $m_{jj} < 350$ GeV cut (VBF-like region considered in VBF categorisation instead)
- $p_T^H > 200$ GeV events treated as a single class in multiclassifier (further splits made using reco $p_T^{\gamma\gamma}$ value)



H→γγ Full Run2 – Higgs boson properties

Maximal merging scenario





- simultaneous measurement of ttH and tH
- best tH measurement to date
- observed (expected) 95% CL limit is 12 (9) x SM value

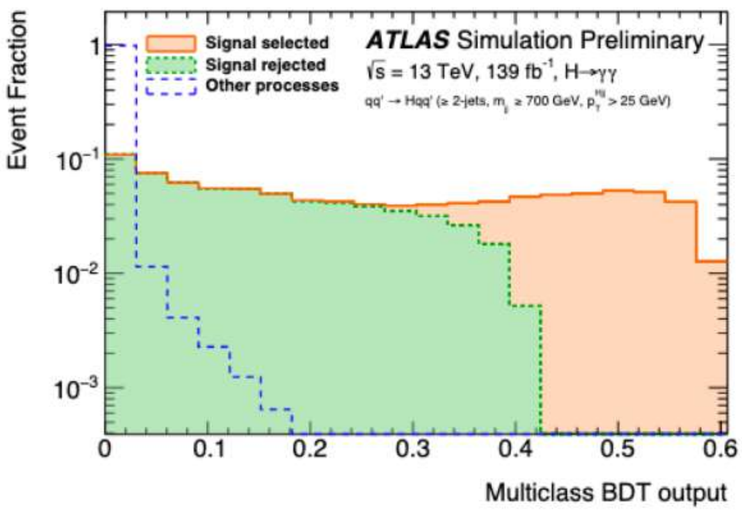
- two pairs of parameters highly correlated (2D fits in backup-S56)
- BSM bins (in qqH and ggH) : in agreement with SM

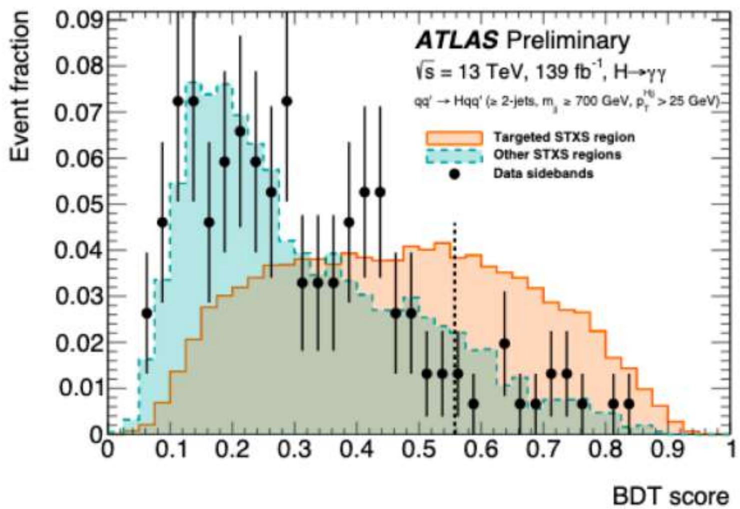
ATLAS - H→$\gamma\gamma$ Full Run2

$H \rightarrow \gamma\gamma$: Categorization

All processes considered simultaneously, maximising global STXS sensitivity. Replaces sequential categorization.

- Step1: **signal: Multi-class BDT** with output discriminant for each STXS bin splits signal into classes, aiming to **minimise determinant of the covariance matrix**.
- Step2: **signal vs continuum background**: binary BDT in each class.

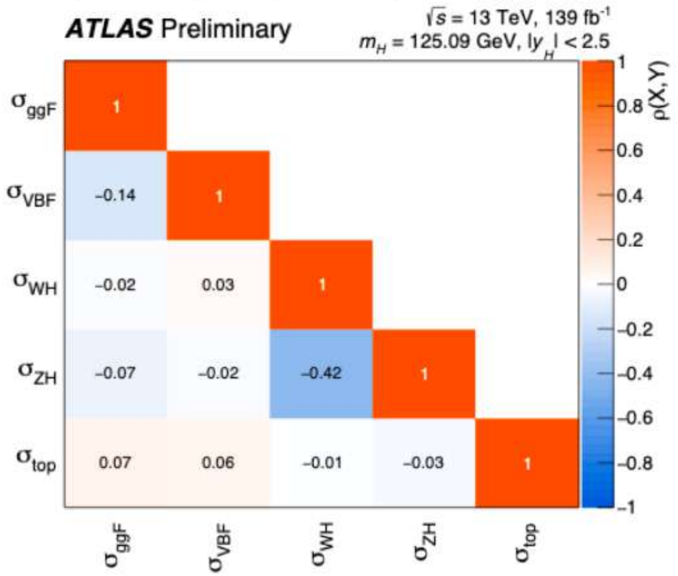




ATLAS - H→$\gamma\gamma$ Full Run2

$H \to \gamma\gamma$: VH

WH and *ZH* anti-correlated main source: *WH* events populating 0 charged lepton category (targeting *ZH*).

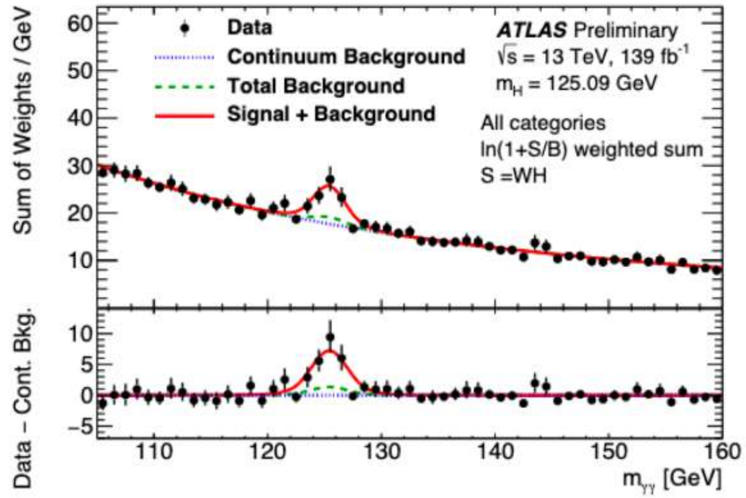


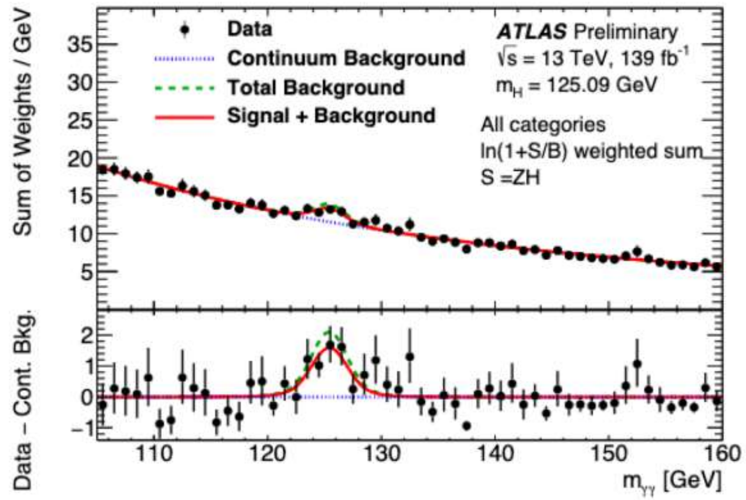
Measured *WH*+*ZH* cross-section:

$\sigma_{VH} \ = \ 5.9 \pm 1.4\,\text{fb}$

$\sigma_{VH,\text{expected}} = 4.53 \pm 0.12\,\text{fb}$

(p-value: 50%)





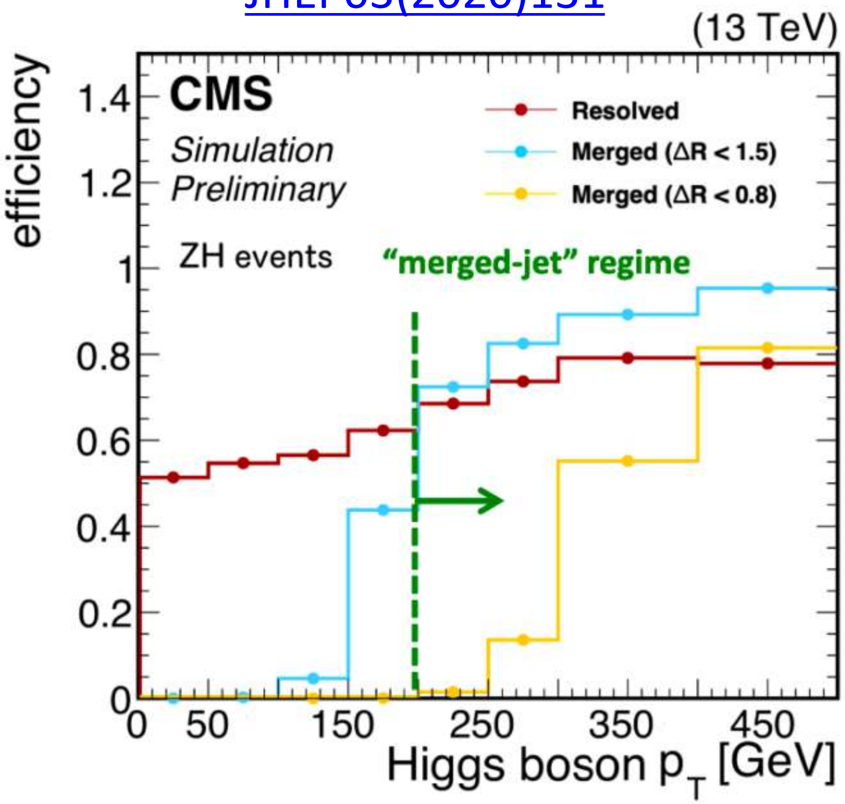
ATLAS - H→$\gamma\gamma$ Full Run2

- **Uncertainties**

	ggF+ $b\bar{b}H$	VBF	WH	ZH	$t\bar{t}H$+ tH
Uncertainty source	$\Delta\sigma$[%]	$\Delta\sigma$[%]	$\Delta\sigma$[%]	$\Delta\sigma$[%]	$\Delta\sigma$[%]
Underlying Event and Parton Shower (UEPS)	±2.3	±10	$< \pm1$	±9.6	±3.5
Modeling of Heavy Flavor Jets in non-$t\bar{t}H$ Processes	$< \pm1$	$< \pm1$	$< \pm1$	$< \pm1$	±1.3
Higher-Order QCD Terms (QCD)	±1.6	$< \pm1$	$< \pm1$	±1.9	$< \pm1$
Parton Distribution Function and α_S Scale (PDF+α_S)	$< \pm1$	±1.1	$< \pm1$	±1.9	$< \pm1$
Photon Energy Resolution (PER)	±2.9	±2.4	±2.0	±1.3	±4.9
Photon Energy Scale (PES)	$< \pm1$	$< \pm1$	$< \pm1$	±3.4	±2.2
Jet/$E_{\mathrm{T}}^{\mathrm{miss}}$	±1.6	±5.5	±1.2	±4.0	±3.0
Photon Efficiency	±2.5	±2.3	±2.4	±1.4	±2.4
Background Modeling	±4.1	±4.7	±2.8	±18	±2.4
Flavor Tagging	$< \pm1$	$< \pm1$	$< \pm1$	$< \pm1$	$< \pm1$
Leptons	$< \pm1$	$< \pm1$	$< \pm1$	$< \pm1$	$< \pm1$
Pileup	±1.8	±2.7	±2.1	±3.8	±1.1
Luminosity and Trigger	±2.1	±2.1	±2.3	±1.1	±2.3
Higgs Boson Mass	$< \pm1$	$< \pm1$	$< \pm1$	±3.7	±1.9

Searches: VH(cc) (2016)

JHEP03(2020)131



Channel	Resolved-jet	Merged-jet
$Z(\nu\nu)H(cc)$: 0L	$p_T(Z) > 170$ GeV	
$W(\ell\nu)H(cc)$: 1L	$p_T(W) > 100$ GeV	$p_T(V) > 200$ GeV
$Z(\ell\ell)H(cc)$: 2L	$p_T(Z) > 50$ GeV	

- **Resolved-jet topology**
  - Higgs decay products resolved in two AK4 (R=0.4) jets (di-jet)
  - Probe larger fraction of the available signal cross-section (95% of events have $p_T(V)<200$ GeV)
  - DeepCSV tagger (CvsL, CvsB)

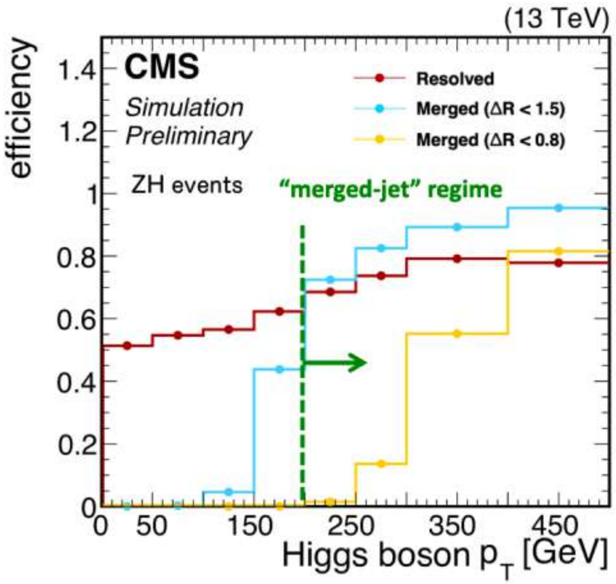
- **Merged-jet topology**
  - A single AK15 (R=1.5) jet to reconstruct the $H\rightarrow cc$ decay
  - Allows to better exploit the correlations between the two charms
  - DeepAK15 tagger

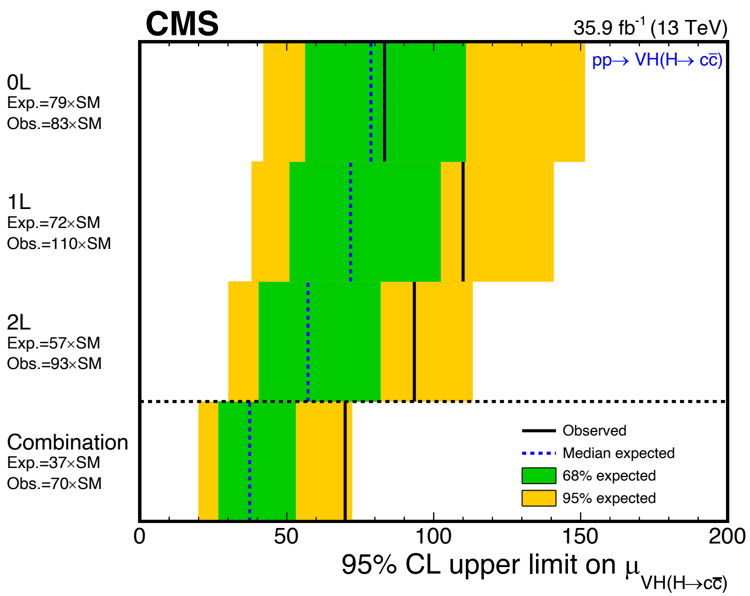
Final results: combination of the two topologies to maximise the sensitivity

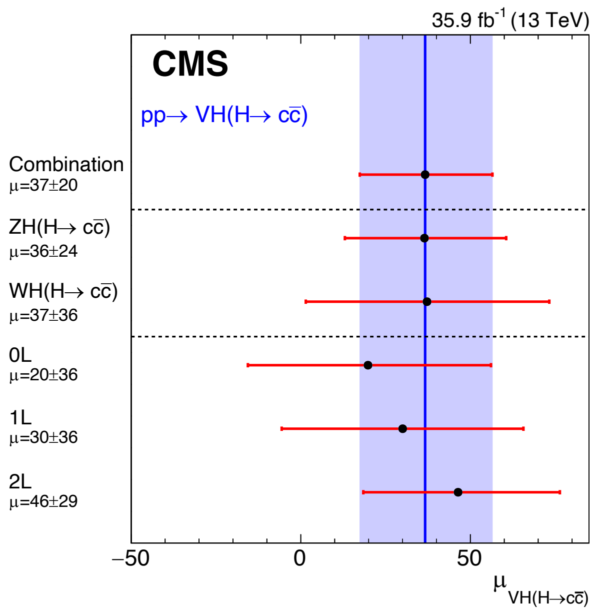
Searches: VH(cc) (2016)

- Combination: resolved-jet: $p_T(V) < 300$ GeV / merged-jet: $p_T(V) > 300$ GeV
  - Systematics: correlated, but: c/cc-tagging efficiency & PDF, μR, μF for V+jets
- Validation with VZ(Z→cc) : $\mu_{VZ(Z\to cc)} = 0.55^{+0.86}_{-0.84}$ with 0.7σ obs. (1.3σ exp.)

	95% C.L. Exclusion Limits					
	Resolved-jet	Boosted-jet	Combination			
	$p_T(V)<300$ GeV	$p_T(V)>300$ GeV	0L	1L	2L	**All. Ch.**
Exp.	45^{+18}_{-13}	73^{+34}_{-22}	79^{+32}_{-22}	72^{+31}_{-21}	57^{+25}_{-17}	**$37^{+16\,(+35)}_{-11\,(-17)}$**
Obs.	86	75	83	**110**	93	**70**







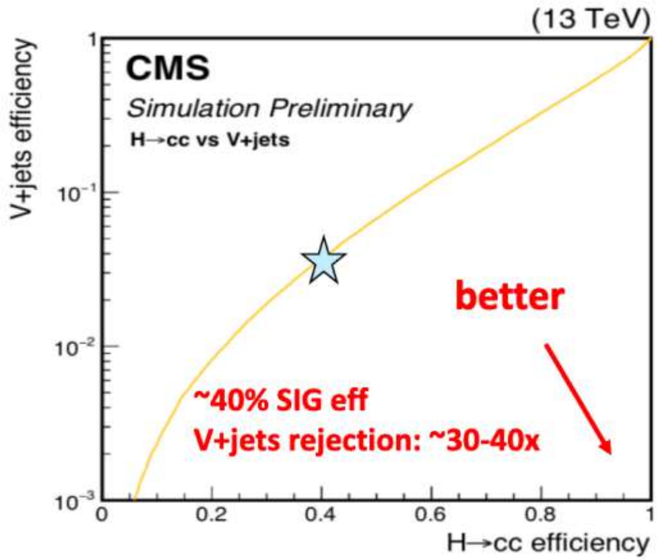
Heavy flavour tagger for AK15: DeepAK15

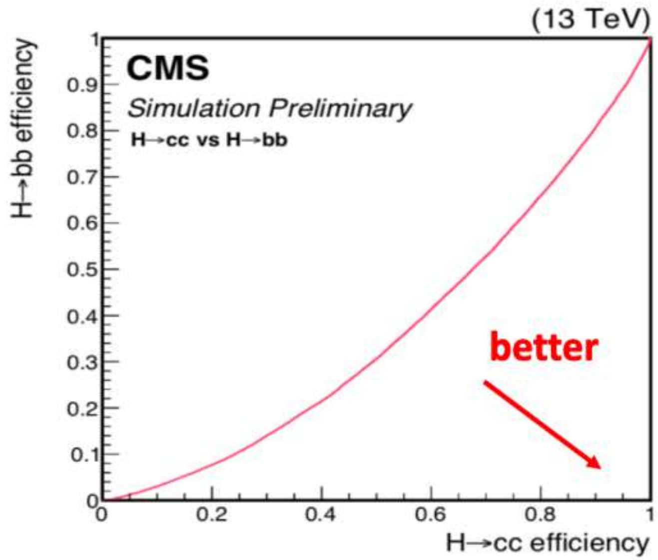
- **DeepAK15 tagger – cornerstone of the boosted VHcc analysis**
  - Reconstruction of moderately to largely boosted Higgs
  - DeepAK15: good compromise between signal purity and acceptance p_T>200 GeV

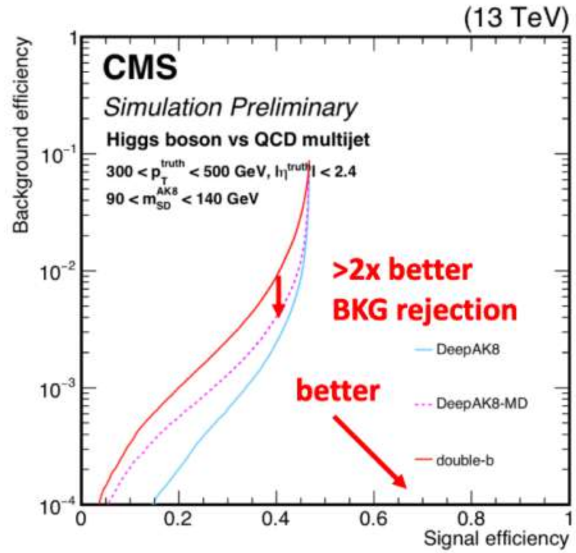
More information → Huilin talk

- **Boosted jet tagger "DeepAK8" adapted on AK15 jets**
  - DNN multiclassifier for top, W, Z, Higgs, and QCD jets
  - Mass decorrelation techniques to mitigate mass sculpting
  - Validation in data using proxy jets from g→cc

CMS-DP-2017-049
NIPS 2017 paper,
CMS-JME-18-002







$$\frac{\mathrm{score}(Z \to c\bar{c}) + \mathrm{score}(H \to c\bar{c})}{\mathrm{score}(Z \to c\bar{c}) + \mathrm{score}(H \to c\bar{c}) + \mathrm{score}(QCD)}$$

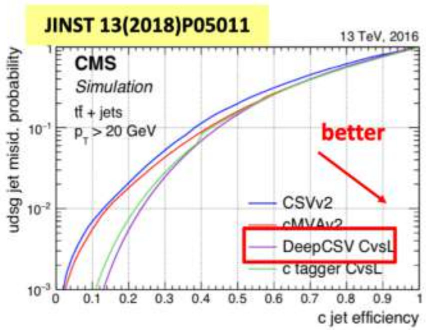
Significant gain in performance
[Even larger @high p_T]

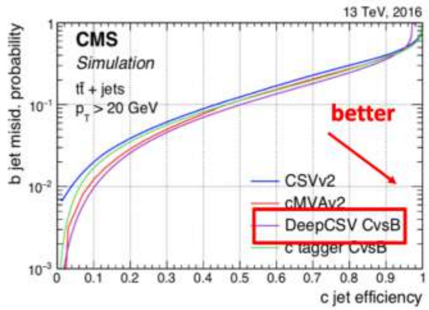
Heavy flavour tagger for AK4: DeepCSV

- **Define two discriminants to separate c-jets from light and b-jets**

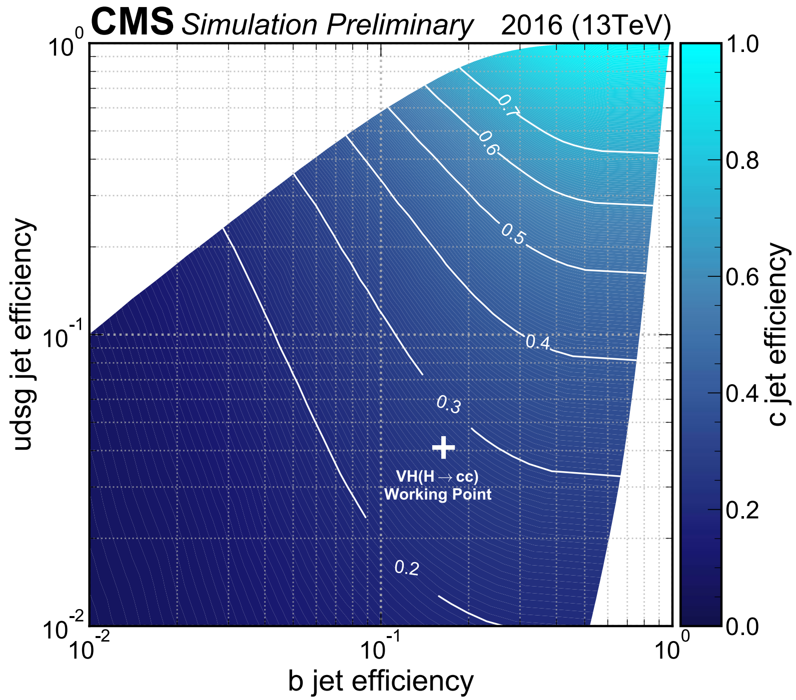
$$CvsL = \frac{p(c)}{p(c) + p(light)}$$

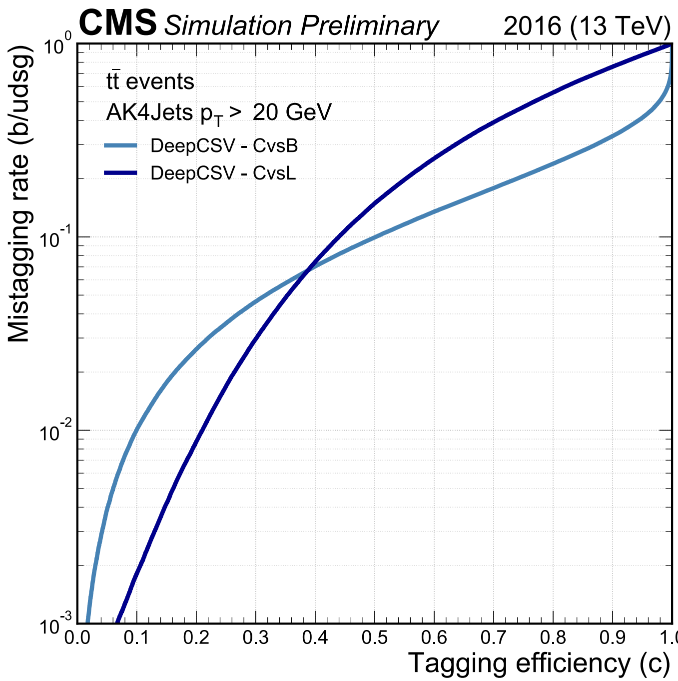
$$CvsB = \frac{p(c)}{p(c) + p(b)}$$





More information
→ Spandan talk

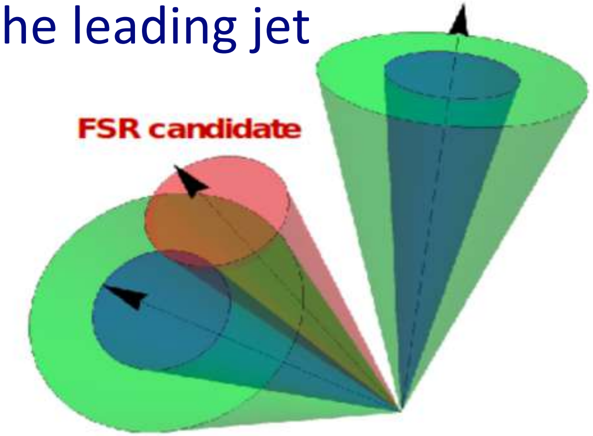




- Taggers working point used in the analysis allow for **~28%** efficiency for **charm** jet while keeping the rate from **b-jet ~15%** and from **light ~4%**

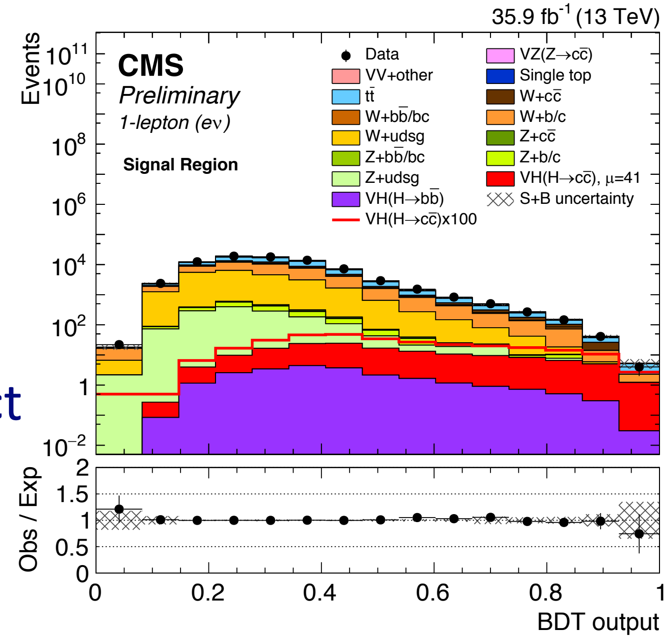
Resolved-jet: Search Strategy

- **Higgs boson reconstruction**
  - Pair of jets with the highest CvsL-score ➔ build Higgs candidate 4-vector
  - Further require: CvsL(max) >0.4 & CvsB(min)>0.2 for the leading jet

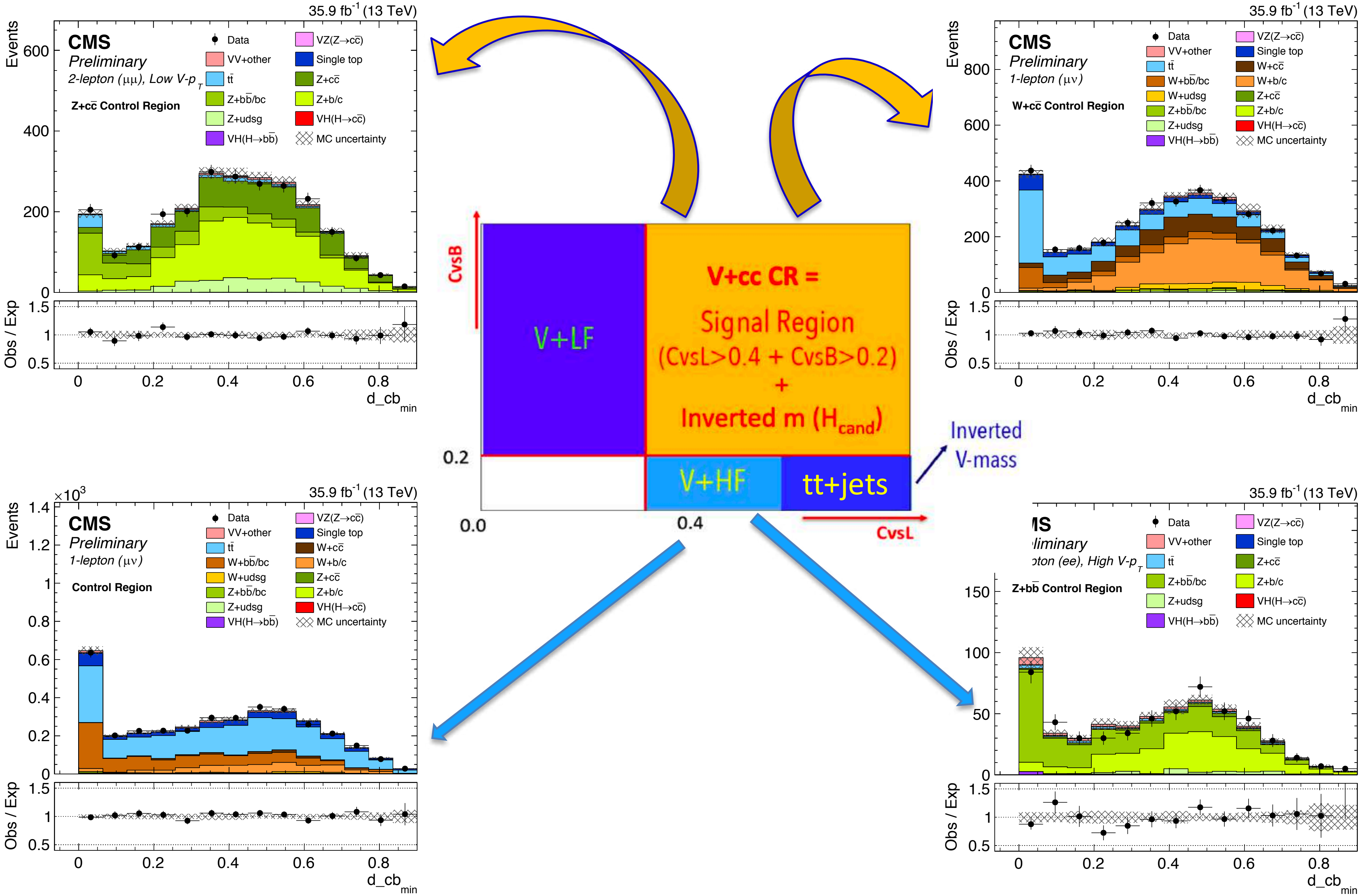


- **Final State Radiation (FSR) recovery**
  - Improve dijet invariant mass resolution by a few %

- **Multivariate analysis for final signal extraction**
  - BDT to further discriminate signal from backgrounds
  - Dedicated training in each channel
  - Input variables: H properties, V boson properties, c-tagging discriminants, event kinematics & object correlations



Resolved-jet: Background estimation (II)



Resolved-jet: Background estimation (II)

Combination: https://cds.cern.ch/record/2725733

Results Included in Combination

✓ Included, will full Run 2 dataset (139 fb^{-1})

(✓) Included with 2015-2016 data only

	ZZ→4l	γγ	bb	μμ	ττ	WW	multi-lep	inv
ggF	✓	✓		✓	(✓)	(✓)		
VBF	✓	✓	(✓)	✓	(✓)	(✓)		✓
WH	✓	✓	✓	✓				
ZH	✓	✓	✓	✓				
ttH	✓	✓	(✓)	✓			(✓)	
tH		✓						