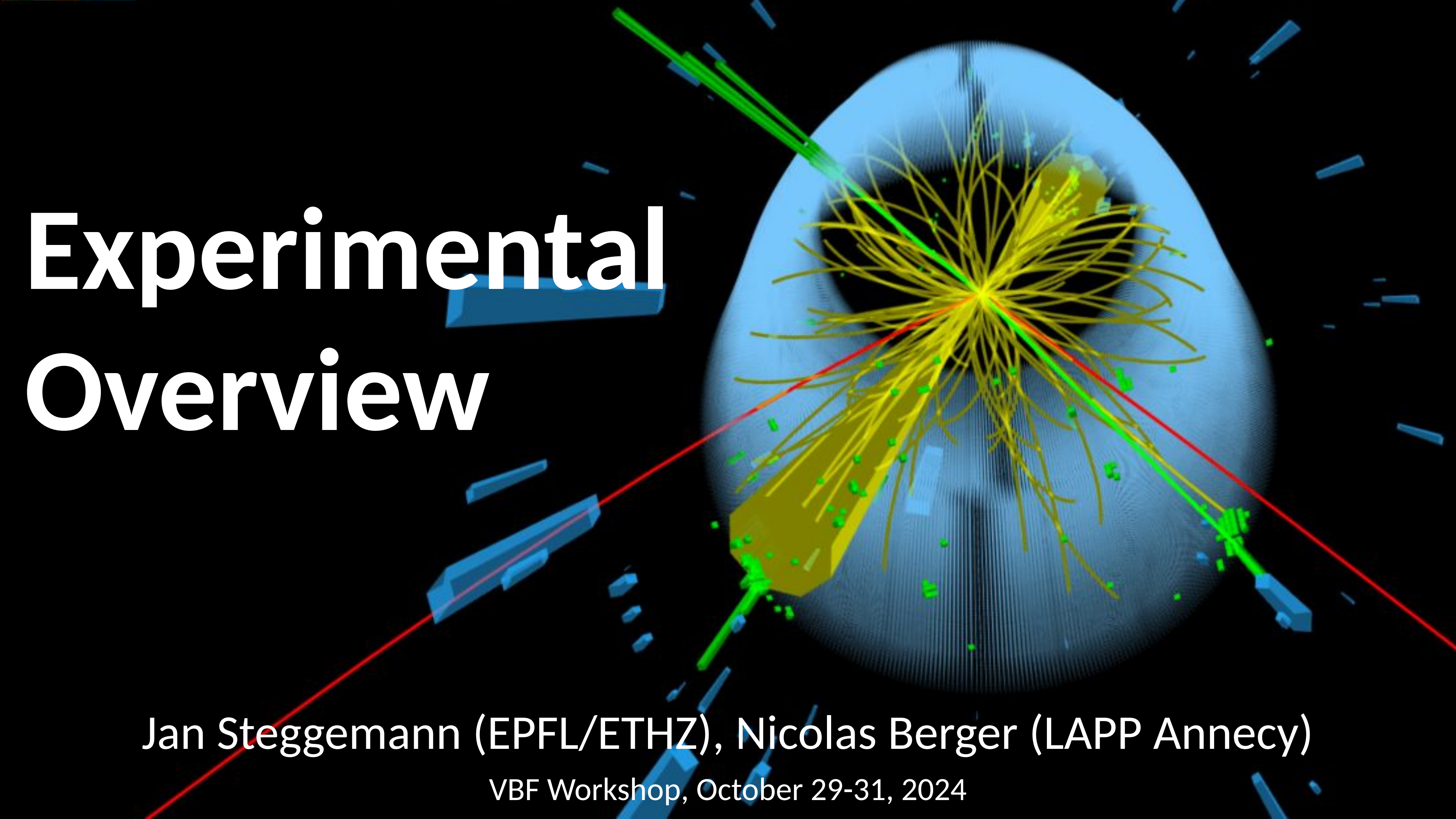


Experimental Overview

Jan Steggemann (EPFL/ETHZ), Nicolas Berger (LAPP Annecy)

VBF Workshop, October 29-31, 2024

VBF Production

Second-largest Higgs production mode (~7%)

Clean signature

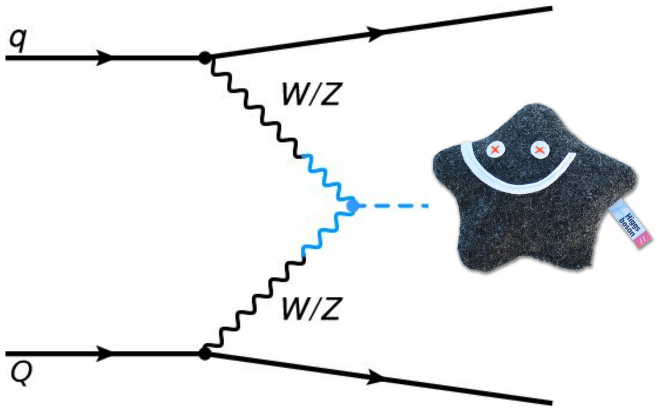
- Forward jets (large m_{jj}, large Δy_{jj})
- No color connection between jets
  ⇒ Low QCD activity in central region

⇒ Higher S/B than gg→H

⇒ Can access **H→ττ**, H→bb, as well as cleaner decays.

Key measurements:

- STXS, differential XS
- HVV couplings
- HVV CP
- Beyond single Higgs: HH, H→inv, …



Challenges

- QCD modeling (parton shower)
- Rejecting gg→H + jets
- Jet performance (JES, pileup, …)

Inclusive VBF Overview

	CMS	ATLAS	
H→γγ	μ = 1.04 ±0.30(stat) ±0.06(theo) ±0.10(exp) HIG-19-015	σ/σ_{SM} = 1.20 ±0.18(stat) ±0.19(syst) HIGG-2020-16	#3
H→4l	μ = 0.48 ±0.41(stat) ±0.12(syst) HIG-19-001	σ/σ_{SM} = 1.21 ±0.44(stat) ±0.06(theo) ±0.10(exp) HIGG-2018-28	
H→WW*	**μ = 0.71 ±0.26** **HIG-20-013**	**σ/σ_{SM} = 0.93 ±0.13(stat) ±0.16(syst)** **HIGG-2021-20**	#2
H→bb	μ = 1.01 ±0.50 HIG-22-009	μ = 0.99 ±0.35 HIGG-2019-04	
H→ττ	μ = **0.86 ±0.13(stat) ±0.05(theo) ±0.08(exp)** **HIG-19-010**	**σ/σ_{SM} = 0.93 ±0.12(stat) ±0.11(syst)** **HIGG-2022-07**	#1

General features

Reconstruction of the VBF system

- R=0.4 anti-kt jets
- ATLAS: use JVT, fJVT to reject pileup; CMS: PUPPI jets or pileup jet ID (for $p_T < 50$ GeV)
- Typically focus on $m_{jj} >$ ~350 GeV, $|\Delta\eta_{jj}| >$ ~3 region for the inclusive selection
- BDTs/NNs to further separate VBF from gg→H and non-Higgs backgrounds
  → Inputs: mainly jet kinematics
- Background estimation, signal reconstruction dependent on decay mode

MC Baseline

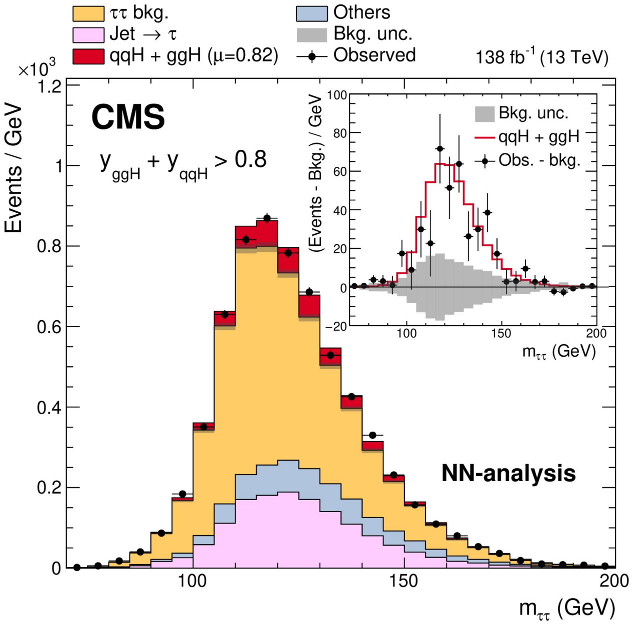
- Powheg Box v2 ⇒ Generation at NLO QCD, normalized to approx. NNLO QCD + NLO EW.
- Pythia 8 for UE/PS/hadronization
  → **CMS**: systematics from varying Pythia scales
  → **ATLAS**: Pythia scale variations + alternate samples with Herwig7 ⇒ Two-point systematics on UE/PS/Had

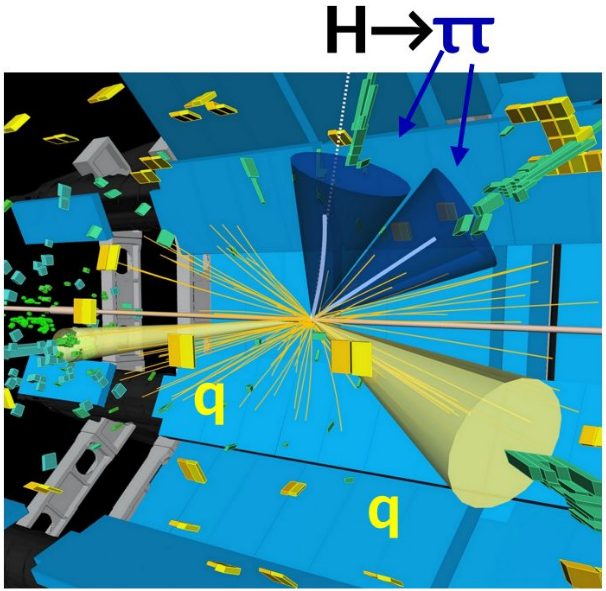
Cross-section measurements

ATLAS & CMS H→ττ

MVAs to reject backgrounds and separate Higgs production modes

Data-driven modeling of large Z→ττ contribution





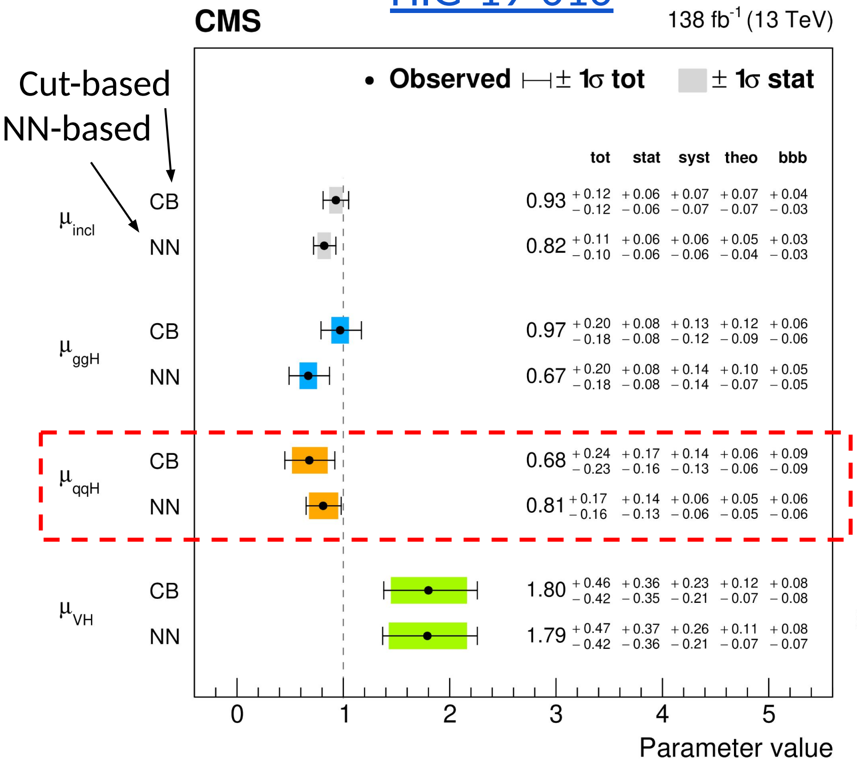
CMS ([HIG-19-010](HIG-19-010)): NN-based and cut-based analyses, VBF channel benefits most from NN (+30-40% sensitivity)

ATLAS (arXiv:2407.16320): “Second-wave” analysis out this Summer, with finer classification of VBF (→ STXS).

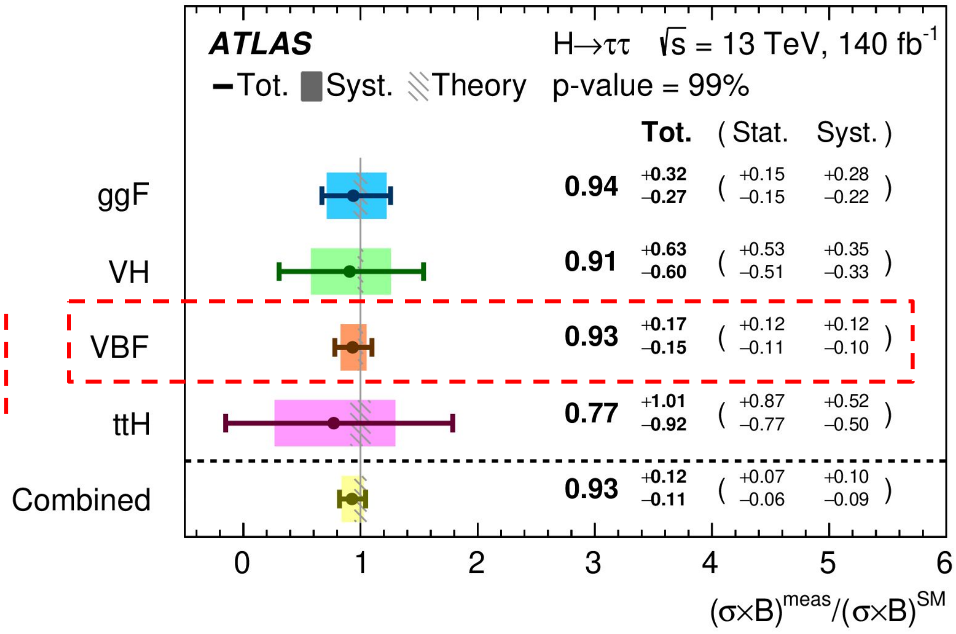
ATLAS & CMS H→ττ

Similar inclusive uncertainties, but quite different uncertainty breakdown

HIG-19-010

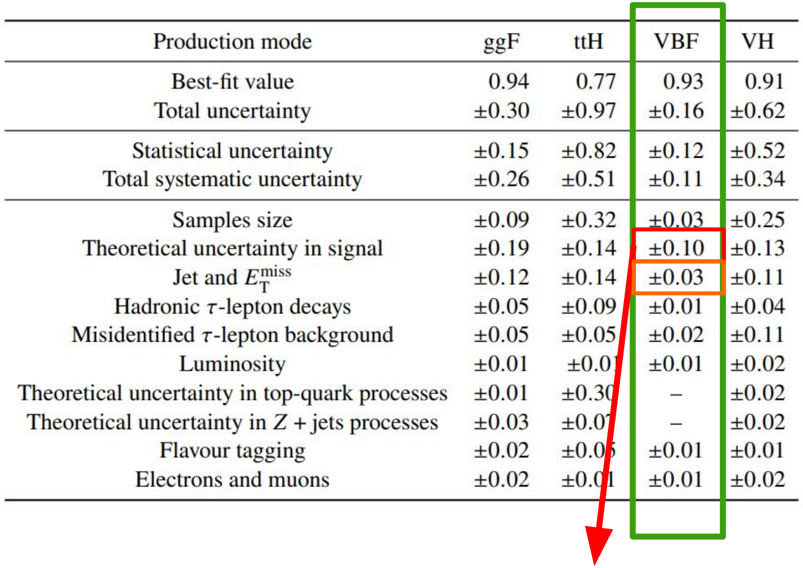


arXiv:2407.16320



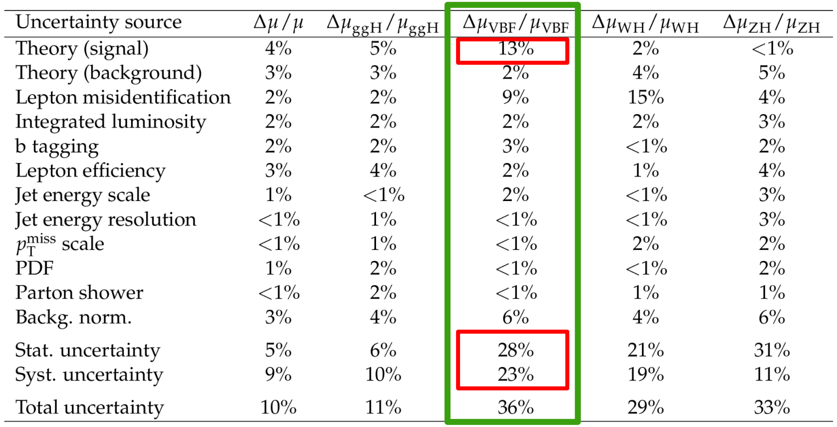
Uncertainties

ATLAS H→ττ



Production mode	ggF	ttH	VBF	VH
Best-fit value	0.94	0.77	0.93	0.91
Total uncertainty	±0.30	±0.97	±0.16	±0.62
Statistical uncertainty	±0.15	±0.82	±0.12	±0.52
Total systematic uncertainty	±0.26	±0.51	±0.11	±0.34
Samples size	±0.09	±0.32	±0.03	±0.25
Theoretical uncertainty in signal	±0.19	±0.14	±0.10	±0.13
Jet and E_T^{miss}	±0.12	±0.14	±0.03	±0.11
Hadronic τ-lepton decays	±0.05	±0.09	±0.01	±0.04
Misidentified τ-lepton background	±0.05	±0.05	±0.02	±0.11
Luminosity	±0.01	±0.01	±0.01	±0.02
Theoretical uncertainty in top-quark processes	±0.01	±0.30	–	±0.02
Theoretical uncertainty in Z + jets processes	±0.03	±0.07	–	±0.02
Flavour tagging	±0.02	±0.05	±0.01	±0.01
Electrons and muons	±0.02	±0.01	±0.01	±0.02

CMS H→WW



Uncertainty source	$\Delta\mu/\mu$	$\Delta\mu_{ggH}/\mu_{ggH}$	$\Delta\mu_{VBF}/\mu_{VBF}$	$\Delta\mu_{WH}/\mu_{WH}$	$\Delta\mu_{ZH}/\mu_{ZH}$
Theory (signal)	4%	5%	13%	2%	<1%
Theory (background)	3%	3%	2%	4%	5%
Lepton misidentification	2%	2%	9%	15%	4%
Integrated luminosity	2%	2%	2%	2%	3%
b tagging	2%	2%	3%	<1%	2%
Lepton efficiency	3%	4%	2%	1%	4%
Jet energy scale	1%	<1%	2%	<1%	3%
Jet energy resolution	<1%	1%	<1%	<1%	3%
p_T^{miss} scale	<1%	1%	<1%	2%	2%
PDF	1%	2%	<1%	<1%	2%
Parton shower	<1%	2%	<1%	1%	1%
Backg. norm.	3%	4%	6%	4%	6%
Stat. uncertainty	5%	6%	28%	21%	31%
Syst. uncertainty	9%	10%	23%	19%	11%
Total uncertainty	10%	11%	36%	29%	33%

Mainly UE/PS (Pythia8 vs. Herwig7), both for VBF, and ggF in VBF phase space

\+ QCD μ_R/μ_F
\+ gg→H jet-bin migrations
\+ VBF ME (Powheg vs. MG)

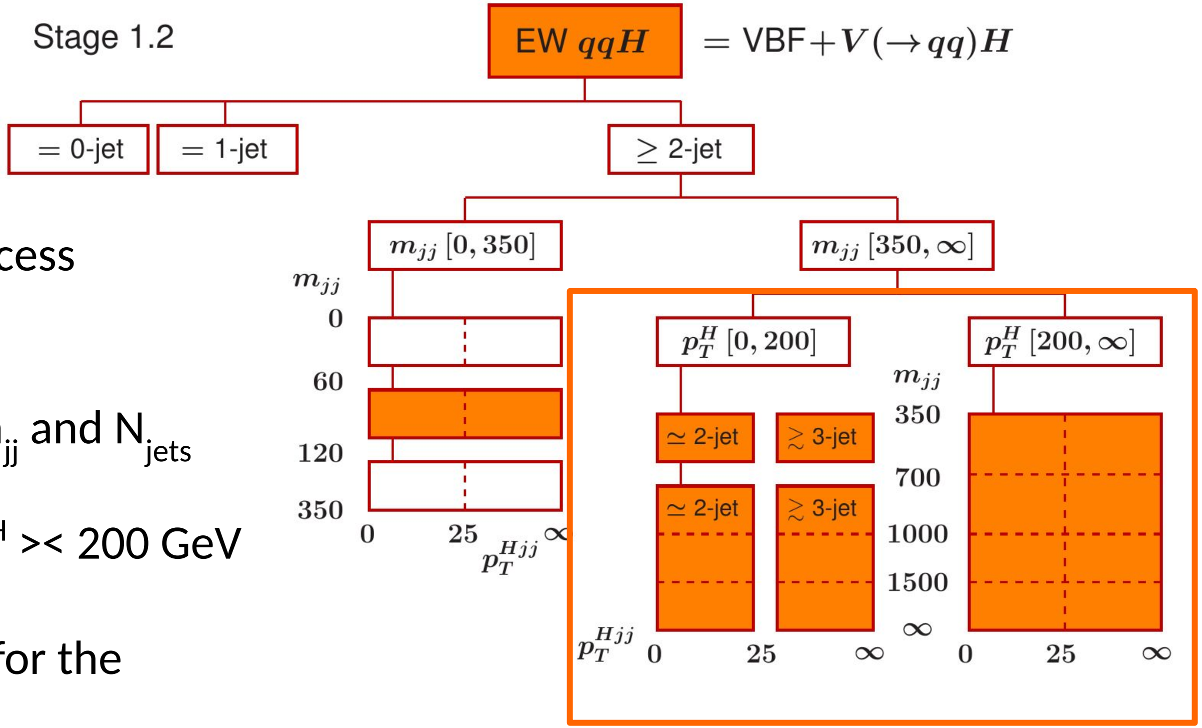
Main differences w.r.t. ATLAS:

- PS uncertainties from varying Pythia PS weights (also dominant)
- Some of the analyses don't use the recommended dipole shower yet, to be improved for future measurements

Raffaele's talk has a nice discussion of the CMS uncertainty model

Cross-section measurements: STXS

qq→Hqq STXS



VBF-dominated regions

VBF part of the qq→Hqq process (along with qq→(V→qq)H)

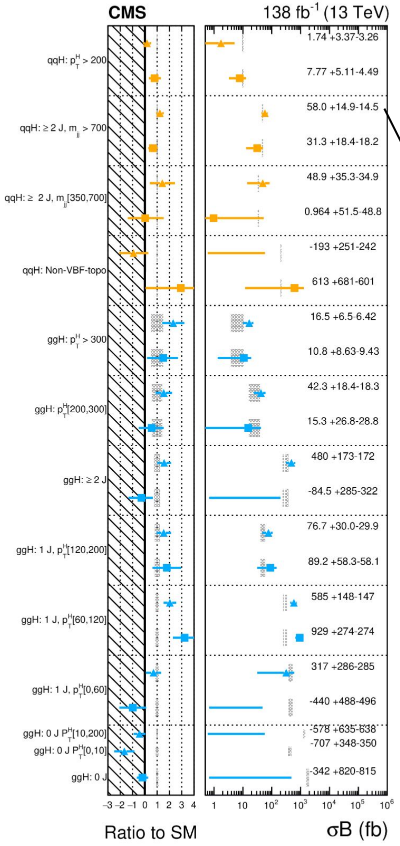
Bins split mainly along p_T^H, m_{jj} and N_{jets}

Main focus on m_{jj} bins for p_T^H >< 200 GeV

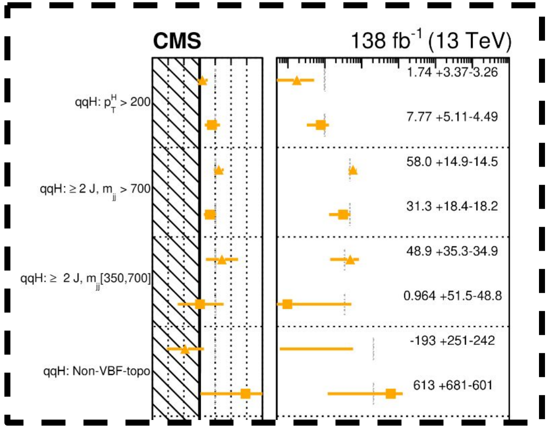
Use p_T^{Hjj} >< 25 GeV as proxy for the presence of a 3rd jet

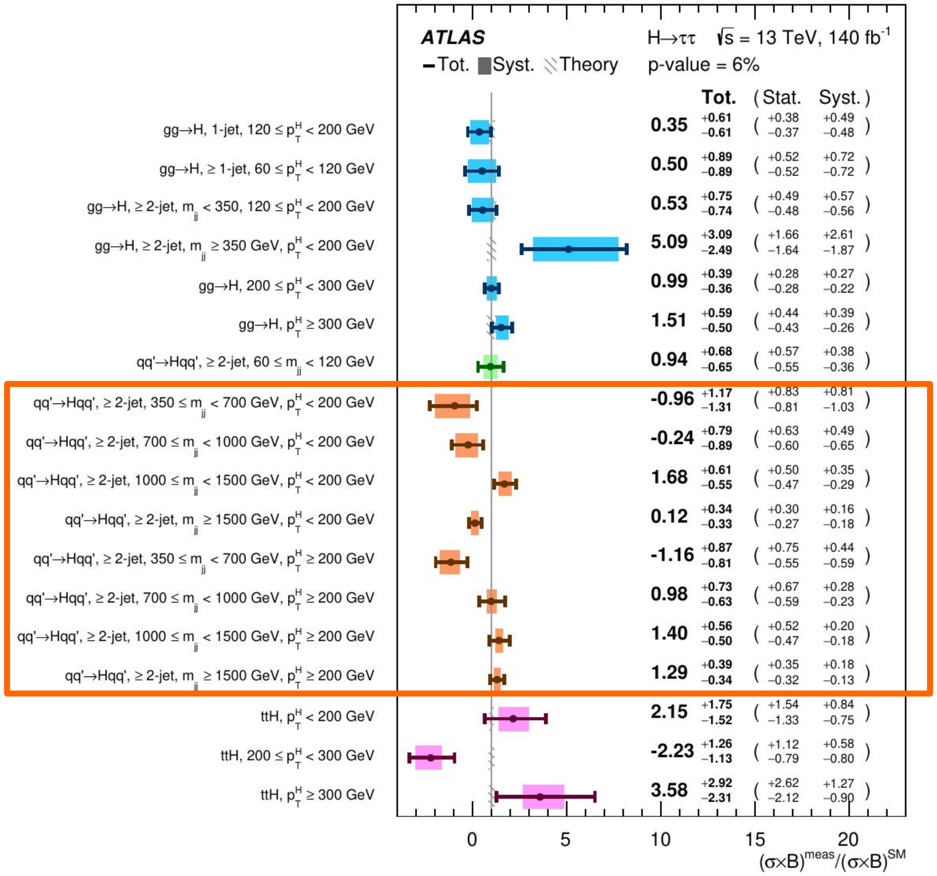
Discussions ongoing on Stage 1.3 updates, in particular interplay with (V→qq)H
→ More in Robin's talk tomorrow!

H→ττ STXS



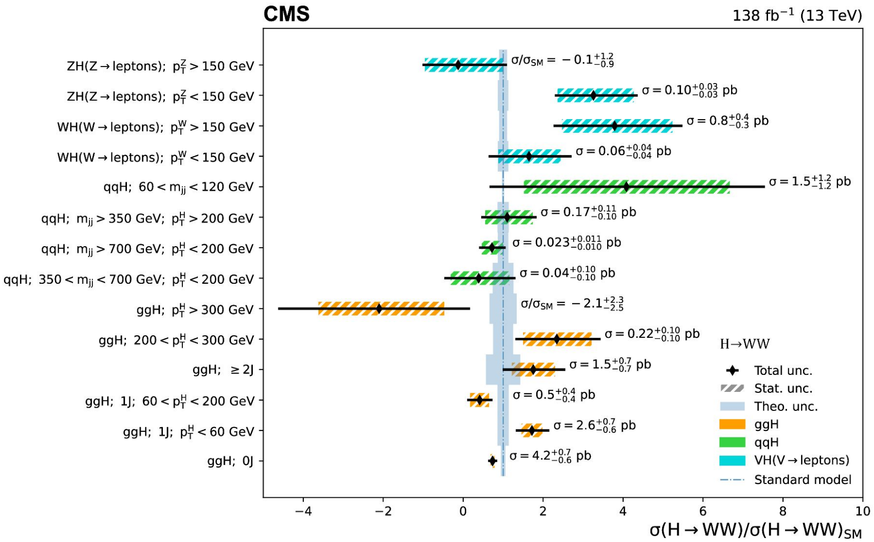
CMS VBF H→ττ: Reduced STXS 1.2 scheme

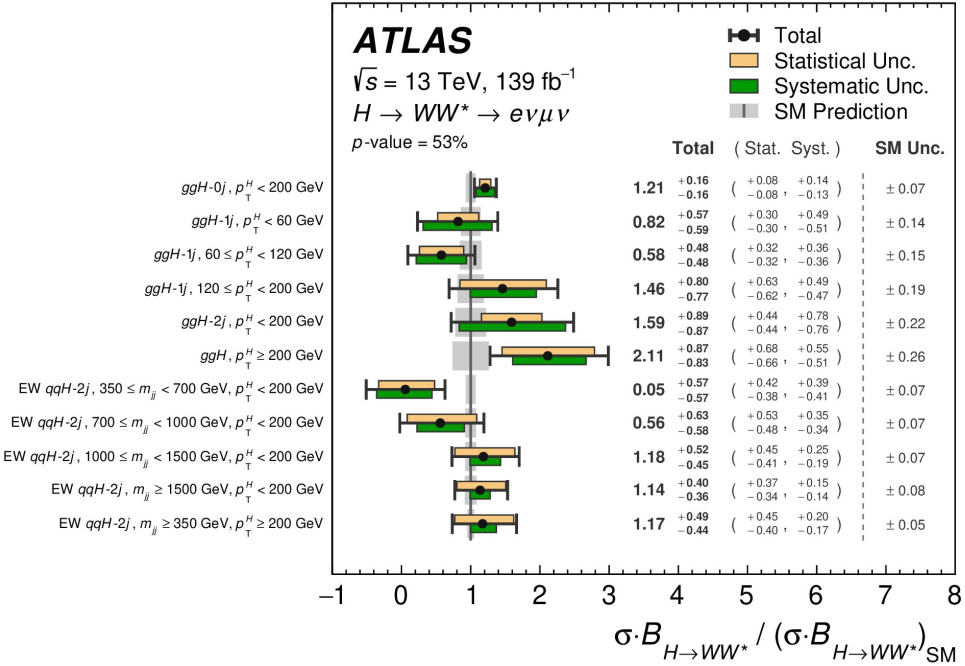


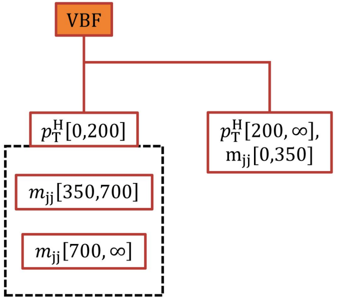


ATLAS H→ττ: finer binning in 2nd wave analysis, probes m_{jj} > 1500, p_T^H > 200 GeV

H→WW*







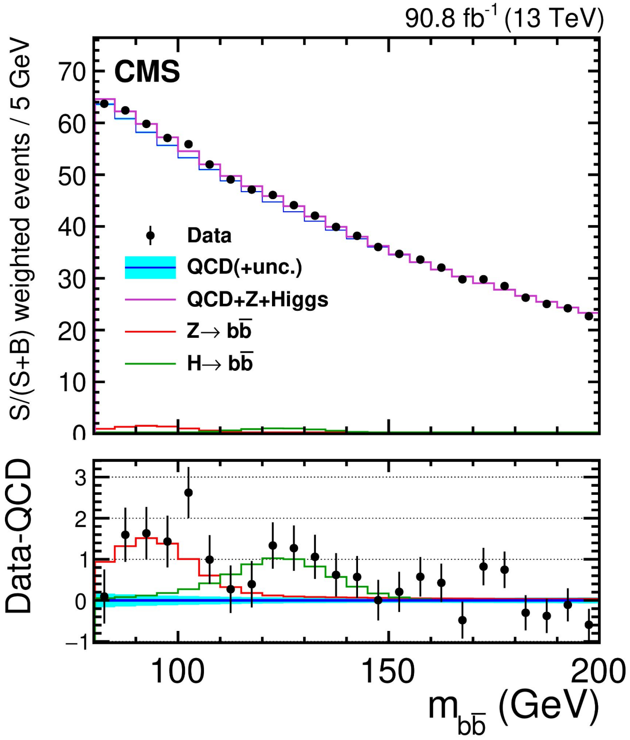
CMS VBF:
Reduced STXS
1.2 scheme

Probing $m_{jj} > 1500$, in the $p_T^H < 200$ GeV region

Cross-section measurements: Beyond STXS

VBF H→bb

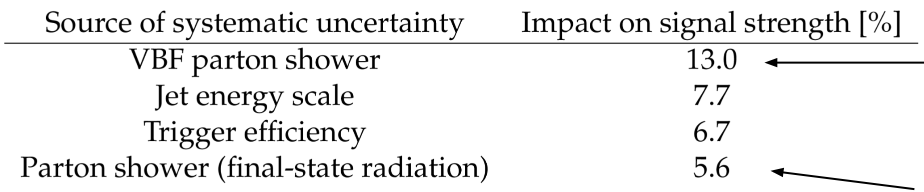
HIGG-2019-04



Similar ATLAS/CMS strategy:

- Fit m_{bb} distribution in MVA categories (smooth QCD background)
- Use b-jet triggers (3-4 jets + 1-2 b-jets)
  - ○ *Not available in CMS in 2017*
- Overall $\varepsilon \sim 1\%$ but large event yields

CMS: $\mu = 1.01 \pm 0.39$ (stat) $+0.39$ -0.24 (syst)



Source of systematic uncertainty	Impact on signal strength [%]
VBF parton shower	13.0
Jet energy scale	7.7
Trigger efficiency	6.7
Parton shower (final-state radiation)	5.6

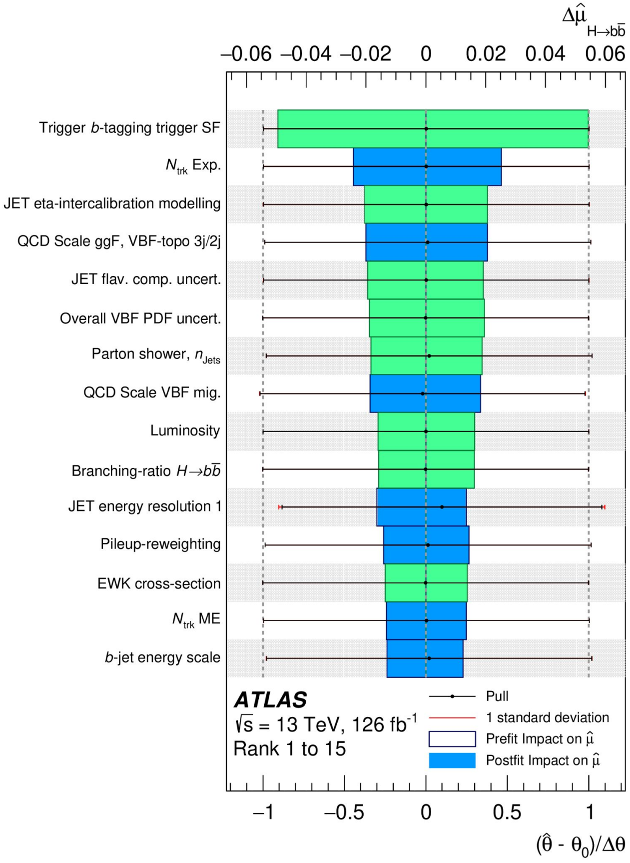
Pythia dipole shower vs. Herwig

Pythia shower scales

ATLAS: $\mu = 0.95 \pm 0.32$ (stat) $+0.20$ -0.17 (syst)

VBF H→bb

HIGG-2019-04



Similar ATLAS/CMS strategy:

- Fit m_{bb} distribution in MVA categories (smooth QCD background)
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- Overall ε~1% but large event yields

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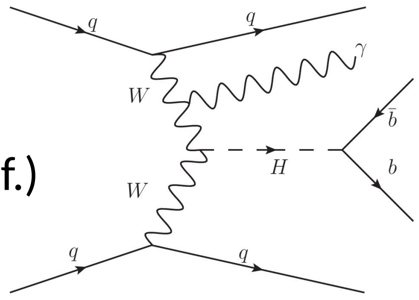
Pythia dipole shower vs. Herwig

Pythia shower scales

ATLAS: μ=0.95 ± 0.32 (stat) +0.20 -0.17 (syst)

ATLAS VBF+γ H→bb

HIGG-2020-14

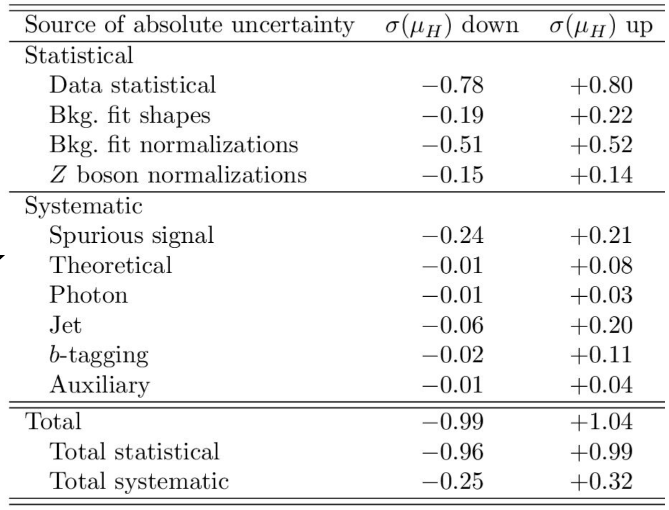


- Require addition γ (p_T^H > 30 GeV) in final state
- Mainly sensitive to κ_W (κ_Z contribution suppressed by ISR/FSR interf.)
- Similar data-driven approach as VBF H→bb
- Use Herwig7 PS due to issues with Pythia8

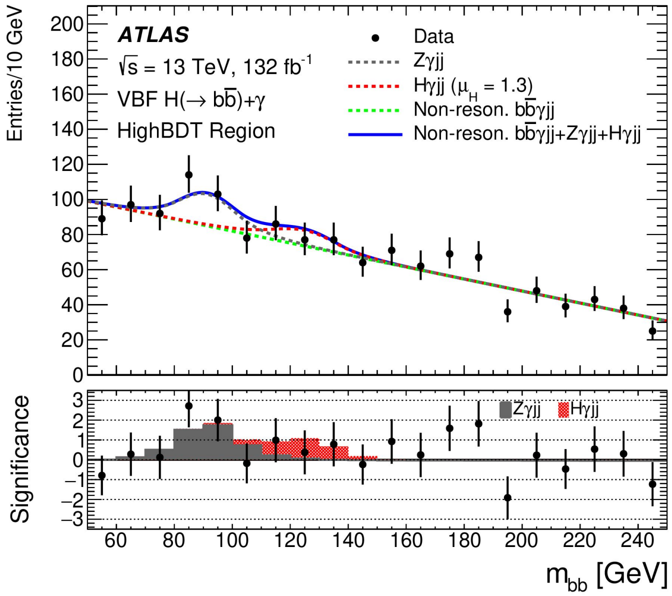
Inclusive **μ = 1.3 ± 1.0**

Ongoing discussions on implementation of STXS binning

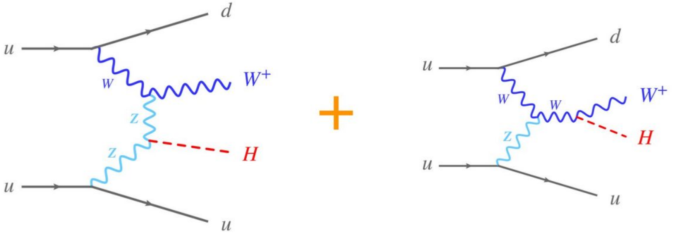
Limited impact from theory uncertainties



Source of absolute uncertainty	$\sigma(\mu_H)$ down	$\sigma(\mu_H)$ up
Statistical		
Data statistical	−0.78	+0.80
Bkg. fit shapes	−0.19	+0.22
Bkg. fit normalizations	−0.51	+0.52
Z boson normalizations	−0.15	+0.14
Systematic		
Spurious signal	−0.24	+0.21
Theoretical	−0.01	+0.08
Photon	−0.01	+0.03
Jet	−0.06	+0.20
b-tagging	−0.02	+0.11
Auxiliary	−0.01	+0.04
Total	−0.99	+1.04
Total statistical	−0.96	+0.99
Total systematic	−0.25	+0.32

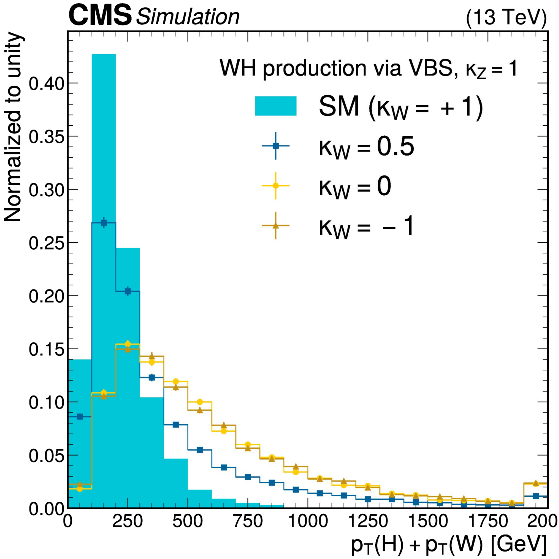


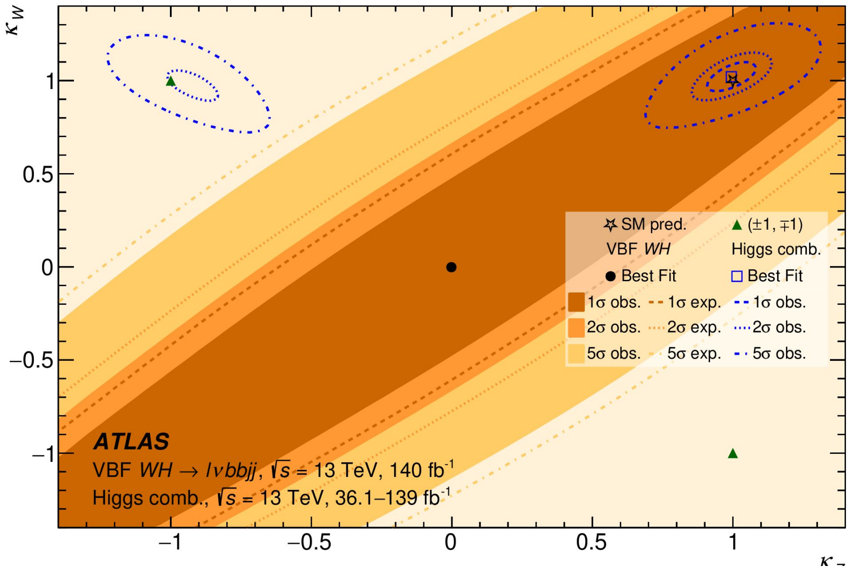
VBF WH→ bb (ATLAS+CMS)



Search for WH→bb with VBF-produced W: very small SM rate due to interference between κ_W & κ_Z diagrams

⇒ Flipping the relative sign of κ_W & κ_Z ⇒ large enhancement + different kinematics !





CMS: μ = 3.0 +5.9 -5.7

CMS/ATLAS: Exclude sign(κ_W κ_Z) = -1 at >>5σ

VBF production at high p_T

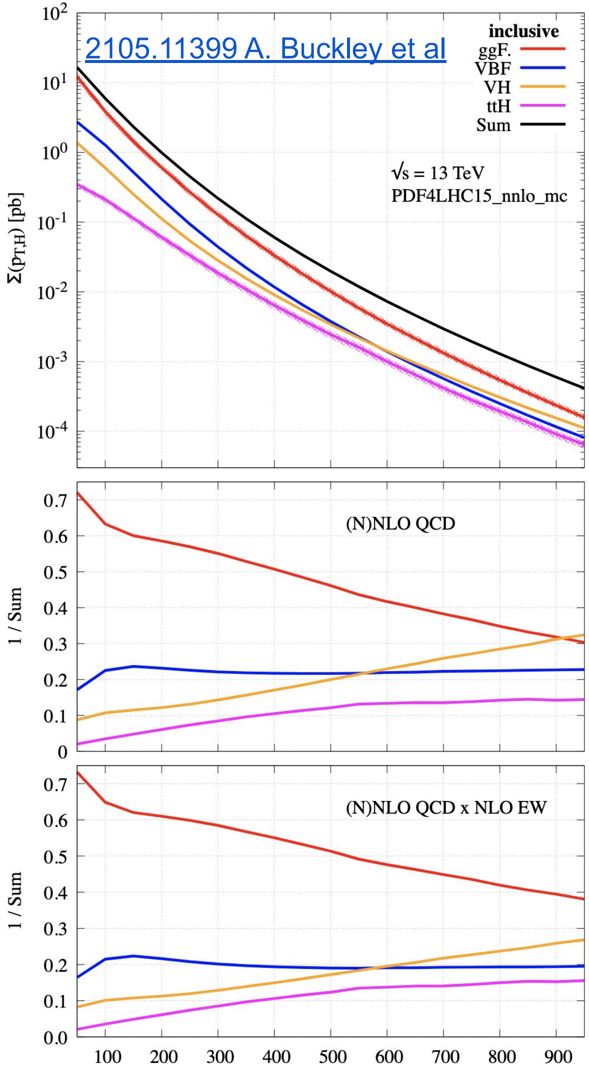
VBF/ggH ratio rises vs Higgs p_T:

Inclusively: VBF/total ~ 7%

p_T^H > 100 GeV: VBF/total ~ 20%

VBF jets provide additional handle against background i important at high p_T):

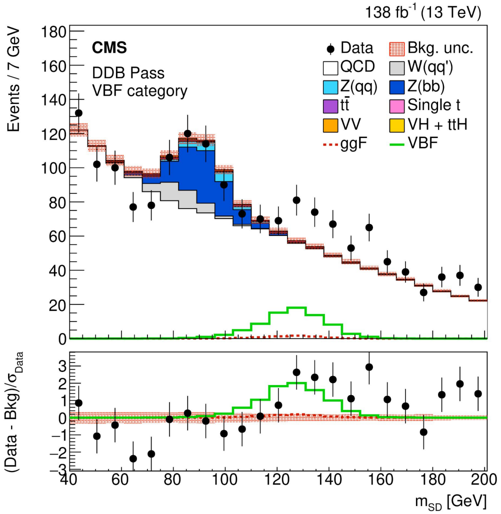
- Expect similar sensitivity as ggH
- Also probes different BSM models

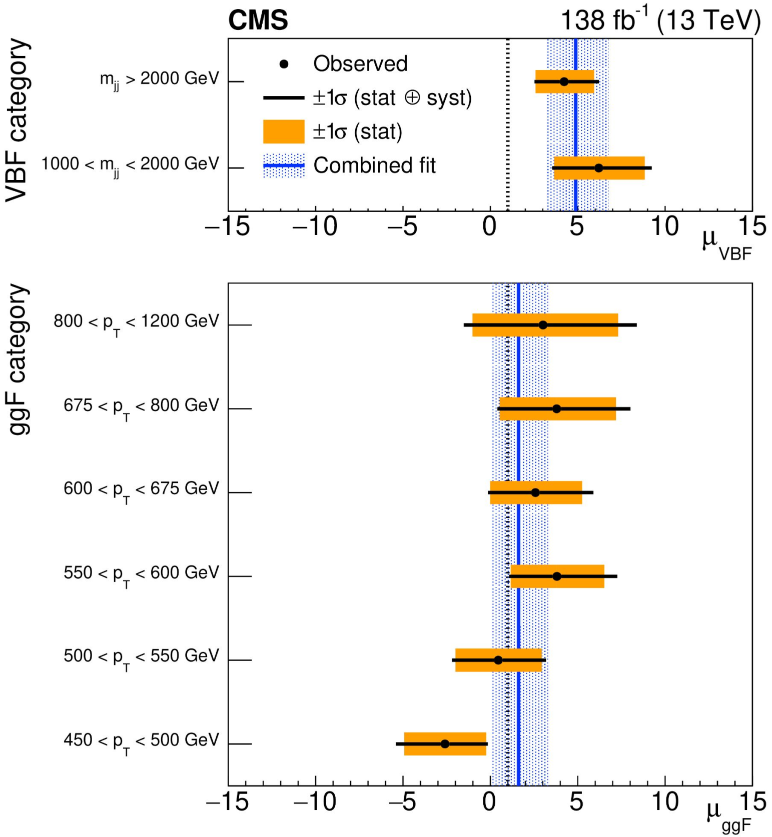


2105.11399 A. Buckley et al

VBF H→bb at high p_T

Some excess at high p_T, driven by VBF channel (μ = 4.9 ± 1.8)





Leading systematic uncertainty: VBF parton shower (13% impact on signal strength)

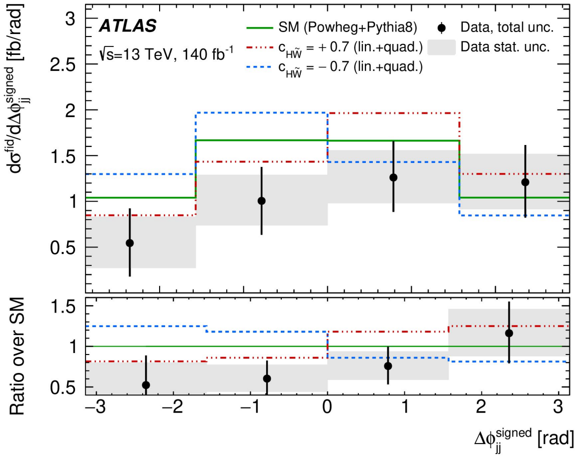
HIG-21-020, Jennet Dickinson's talk at last year's LHC H WG meeting

CP Measurements

HVV CP measurement

VBF jet kinematics sensitive to HVV interaction structure, in particular CP-even vs. CP-odd

→ Probes possible CP-odd admixture in H(125) and CP violation in the Higgs sector



Observables:

- “Hand-crafted” CP-sensitive variables, e.g. (signed) $\boldsymbol{\Delta\varphi_{jj}}$.
- **Optimal Observables**, using the full ME information to separate CP-even from CP-odd

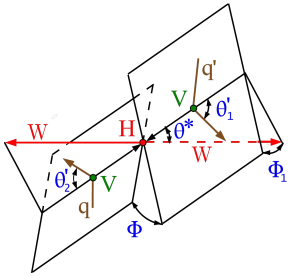
$$OO_1 = \frac{2\Re\left(M_{\mathrm{SM}}^{*} M_{\mathrm{BSM}}\right)}{\left|M_{\mathrm{SM}}\right|^{2}}$$

Results presented as:

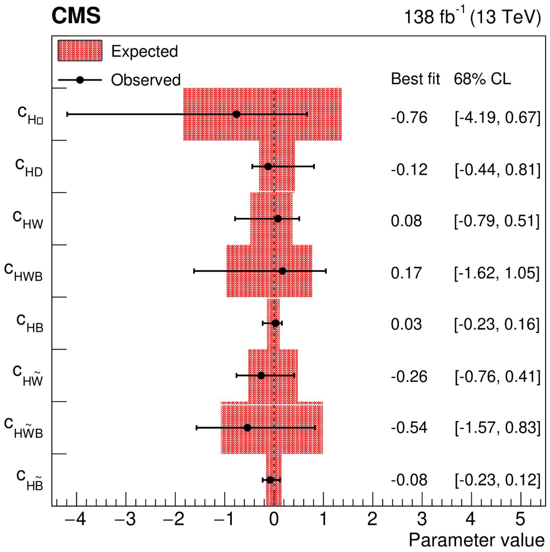
- SMEFT Warsaw basis ($\boldsymbol{\tilde{c}_{HW}}$, $\tilde{c}_{HB}$, $\tilde{c}_{HWB}$) → ATLAS, CMS
- SMEFT Higgs basis ($\boldsymbol{\tilde{c}_{zz}}$, $\tilde{c}_{Z\gamma}$, $\tilde{c}_{\gamma\gamma}$) → CMS
- Amplitude coefficients (f_{a2}, $\boldsymbol{f_{a3}}$, $f_{\Lambda1}$) → CMS

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2} O_i^{(6)}$$

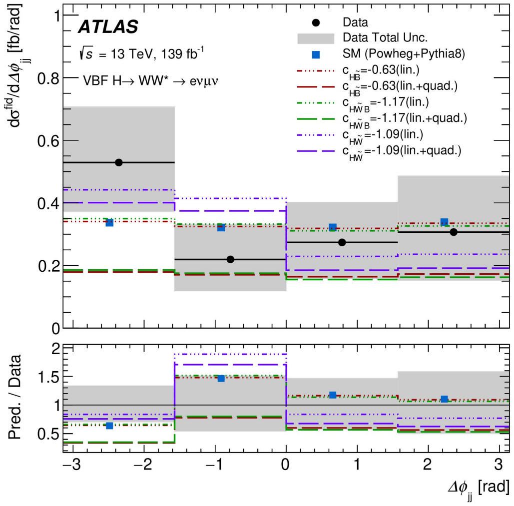
H→WW* CP

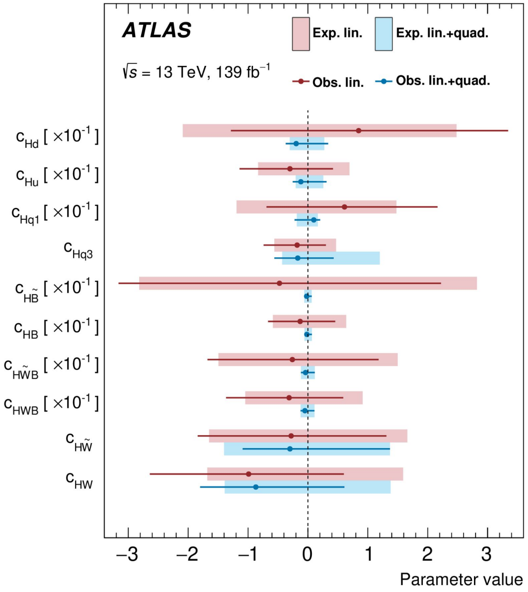


CMS (HIG-22-008): Apply ME method to the qq→qq(H→WW*) process (also VH, ggH)
→ Results in Warsaw, Higgs and f_{ai} bases.



ATLAS (HIGG-2020-25): measure diffXS of the Δφjj variable, SMEFT interpretation in the unfolded distribution



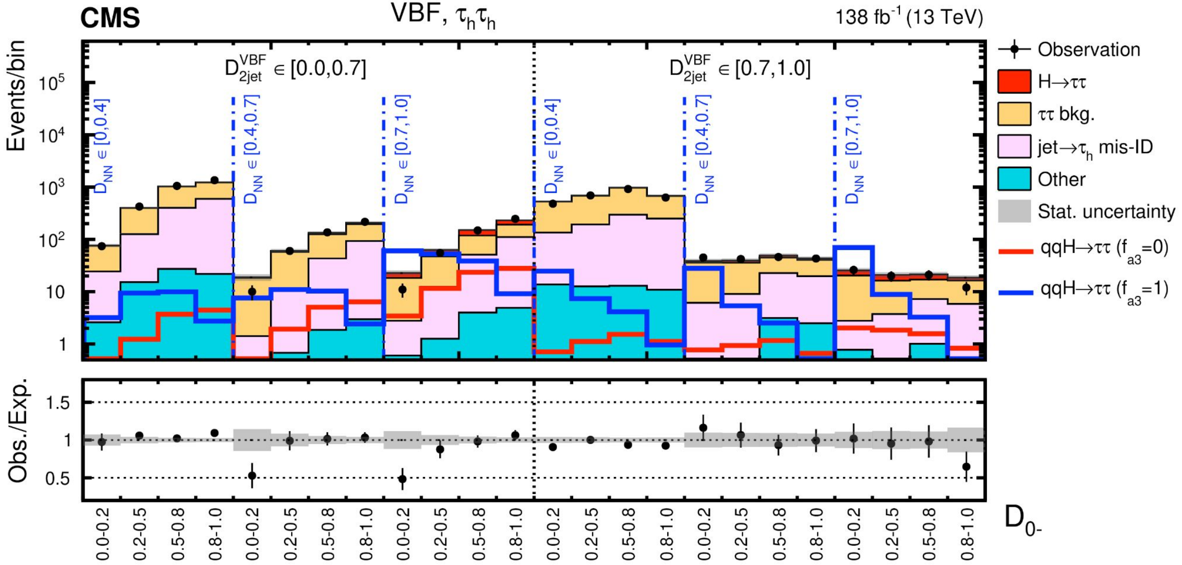


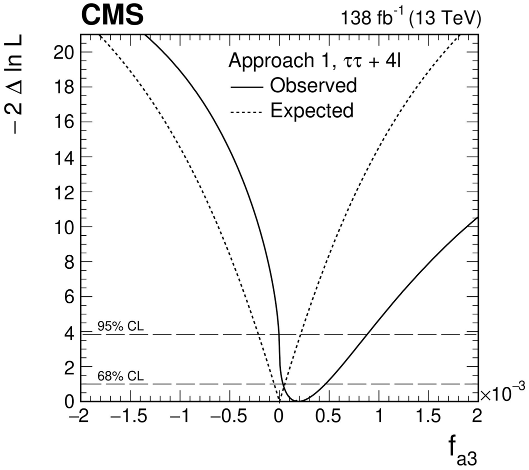
- Better sensitivity for CMS thanks to ME approach and use of H→WW* decay and other production modes
- EFT validity seems good from lin/quad comparison
- Uncertainties mainly statistical (PS/modeling < 10%σ_{tot})

H→ττ CP

CMS (2205.05120):

- Use matrix-element-based discriminators to distinguish between different production mechanisms, background, and anomalous couplings/CP admixtures
- Set constraints on Higgs-V anomalous couplings with 2 different approaches
- Combine with previous results in H→ZZ decays

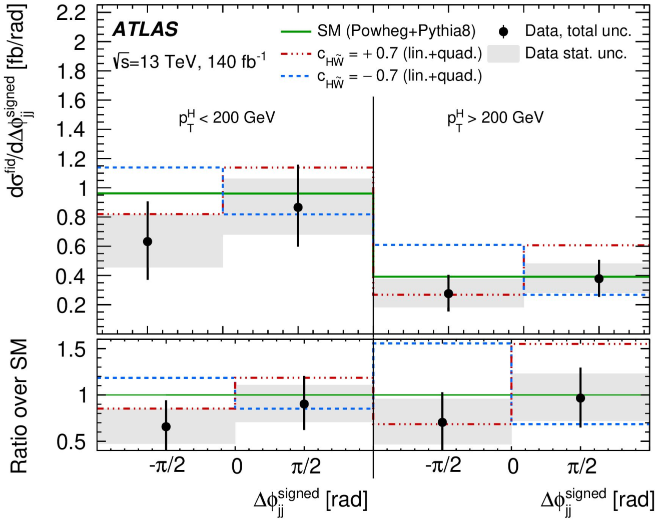


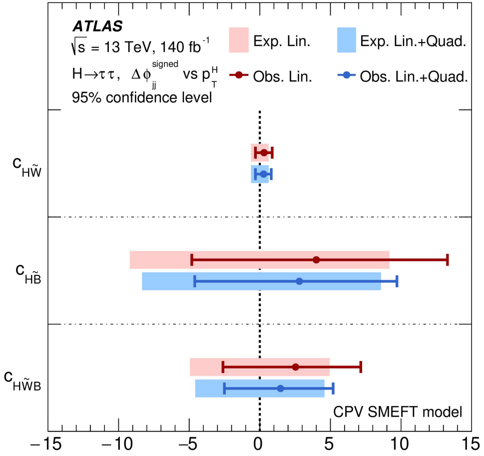


H→ττ CP

ATLAS (2407.16320):

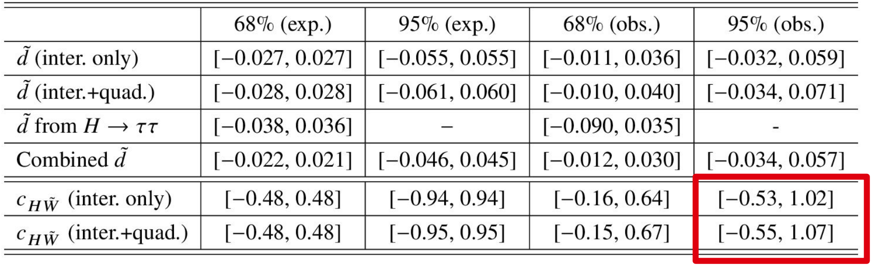
- Measure H→ττ diffXS, in particular $\Delta\varphi_{jj}$.
- Use $\Delta\varphi_{jj}$ vs p_T^H distribution (2 x 2 bins) to set constraints on Warsaw basis SMEFT parameters
- Best current constraint on $\tilde{c}_{HW}$: $\mathbf{-0.31 < \tilde{c}_{HW} < 0.88}$
- Mainly stat-dominated, leading uncertainties are exp.
- Could get even better with OO ?...





H→γγ (HIGG-2020-08):

- Categorization in BDTs for VBF/ggF and VBF/bkg
- Extract signal from $m_{\gamma\gamma}$ fit in each OO bin.

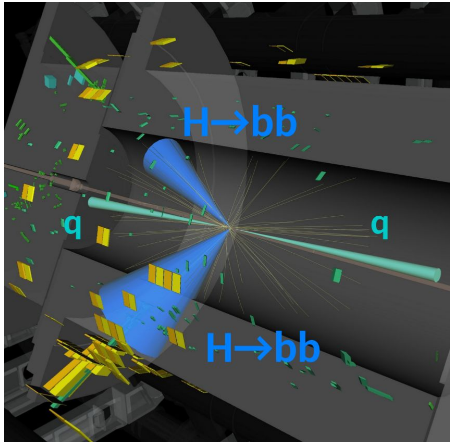


	68% (exp.)	95% (exp.)	68% (obs.)	95% (obs.)
$\tilde{d}$ (inter. only)	[−0.027, 0.027]	[−0.055, 0.055]	[−0.011, 0.036]	[−0.032, 0.059]
$\tilde{d}$ (inter.+quad.)	[−0.028, 0.028]	[−0.061, 0.060]	[−0.010, 0.040]	[−0.034, 0.071]
$\tilde{d}$ from $H \to \tau\tau$	[−0.038, 0.036]	–	[−0.090, 0.035]	-
Combined $\tilde{d}$	[−0.022, 0.021]	[−0.046, 0.045]	[−0.012, 0.030]	[−0.034, 0.057]
$c_{H\tilde{W}}$ (inter. only)	[−0.48, 0.48]	[−0.94, 0.94]	[−0.16, 0.64]	[−0.53, 1.02]
$c_{H\tilde{W}}$ (inter.+quad.)	[−0.48, 0.48]	[−0.95, 0.95]	[−0.15, 0.67]	[−0.55, 1.07]

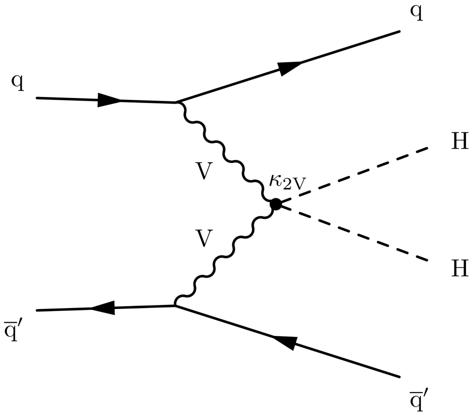
Beyond single Higgs

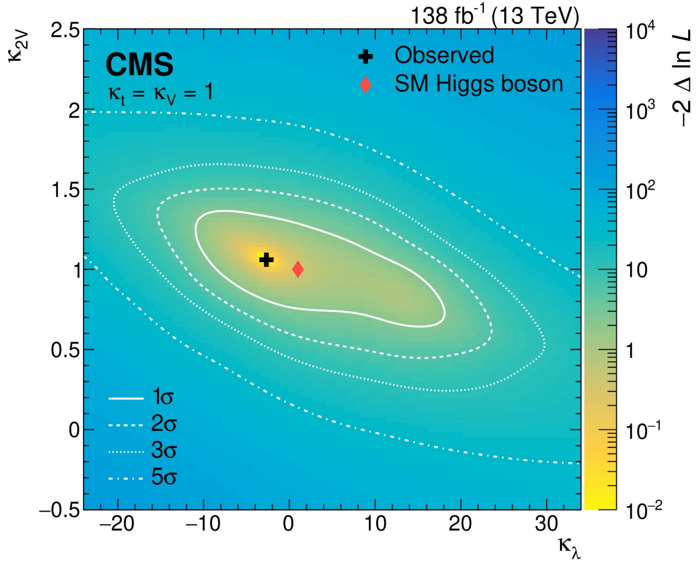
VBF HH production

κ_{2V} = 0 would lead to strong enhancement of VBF HH at high m_{HH}.
➔ VBF HH→4b with highly boosted H→bb decays excellent probe



CMS (B2G-22-003): $0.67 < \kappa_{2V} < 1.38$ @ 95% CL
⇒ exclude $\kappa_{2V} = 0$ at > 5σ





ATLAS (HDBS-2022-02): $0.55 < \kappa_{2V} < 1.49$ @ 95% CL

Summary

- VBF is a critical tool for the measurement of Higgs boson properties
- Main current directions:
  - ✔ Probe H(H)VV couplings – strong constraints on κ_{2V} !
  - ✔ Probe for new physics in corners of phase space (high p_T^H, high m_{jj} …)
  - ✔ Test Higgs boson CP
- Challenges and limitations (More in Alessandro’s talk after this one!)
  - ✔ Parton shower! (known since a while now…)
  - ✔ ggF modeling and separation from VBF (see Stephen’s talk tomorrow)

    → Sensitivity increasing with use of ML
  - ✔ Other theory issues (Missing HO, gg→H Njets distribution, ME, …)
  - ✔ Experimental: jet energy scale, pileup rejection, …
  - ✔ Can we target less VBF-like VBF ? (central jets, 0/1 jets, etc…)
- Much more to come in Run 3 and beyond!