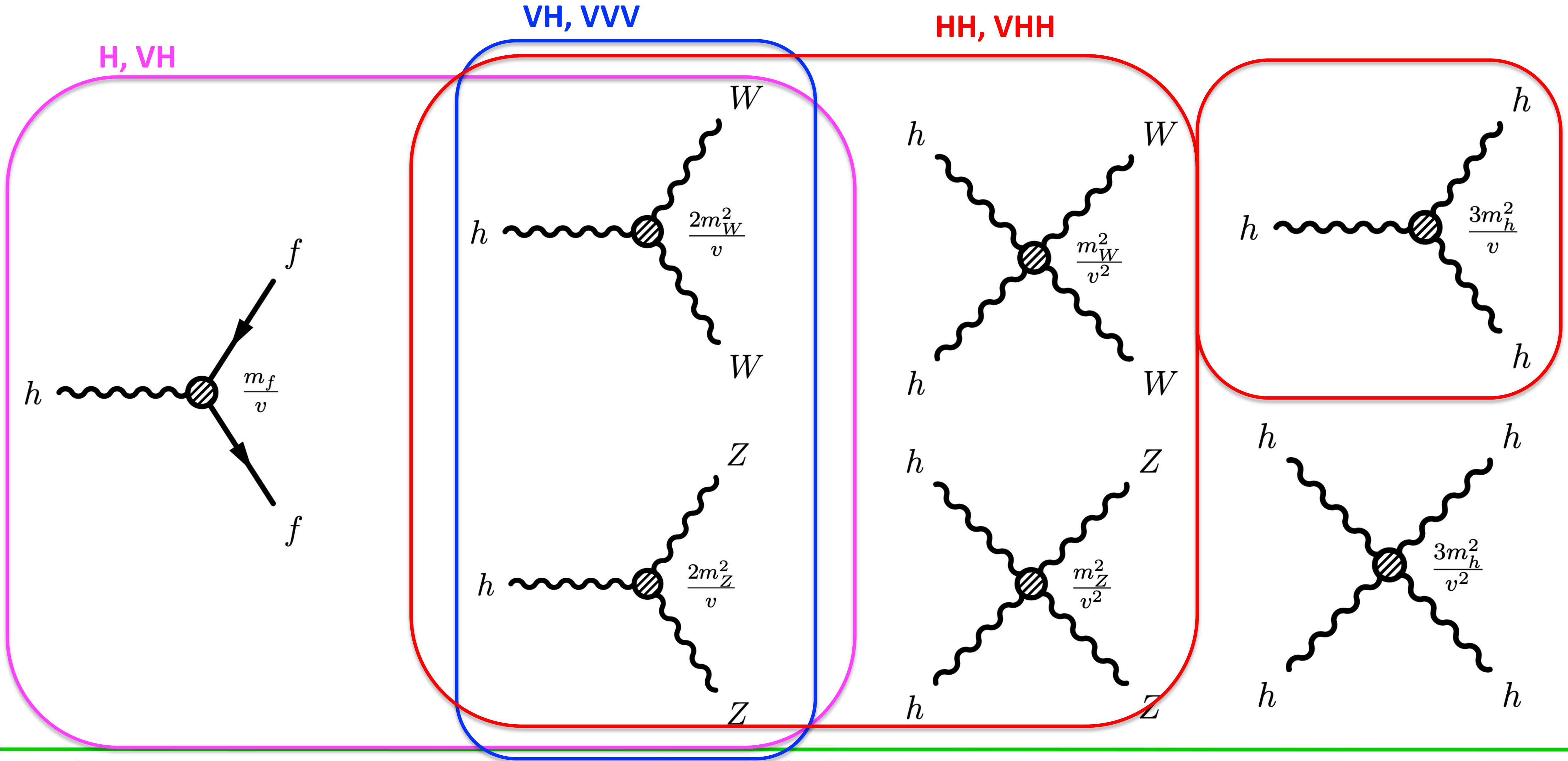
Multi-boson production involving the Higgs boson (ATLAS & CMS)

Lailin Xu
University of Sci. & Tech. of China
on behalf of ATLAS & CMS Collaborations

Multi-Boson Interactions 2022

2022.8.22-25, Shanghai

Introduction



H, VH

VH, VVV

HH, VHH

Outline

- Higgs production
- VH and VBF Higgs production
- HH production
- VHH production
- Triboson (WWV, ZZV)

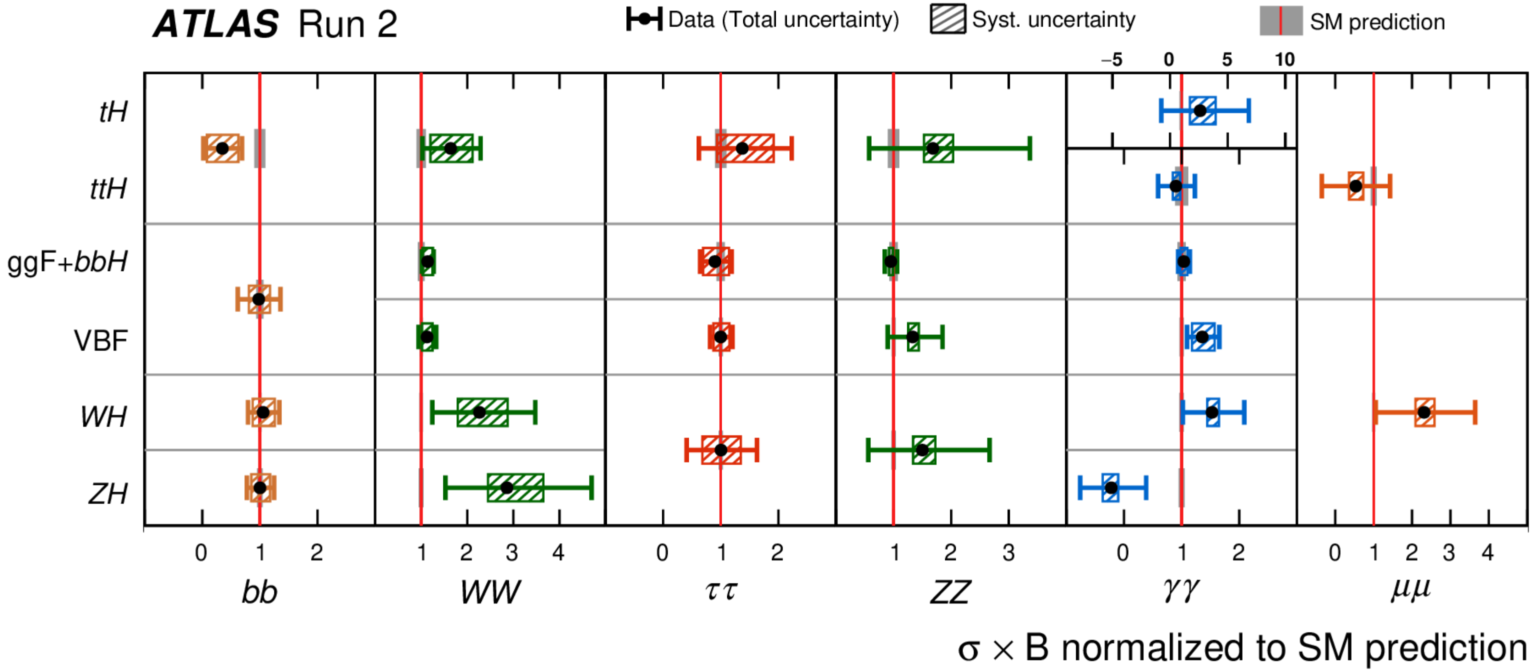
Inclusive Higgs production

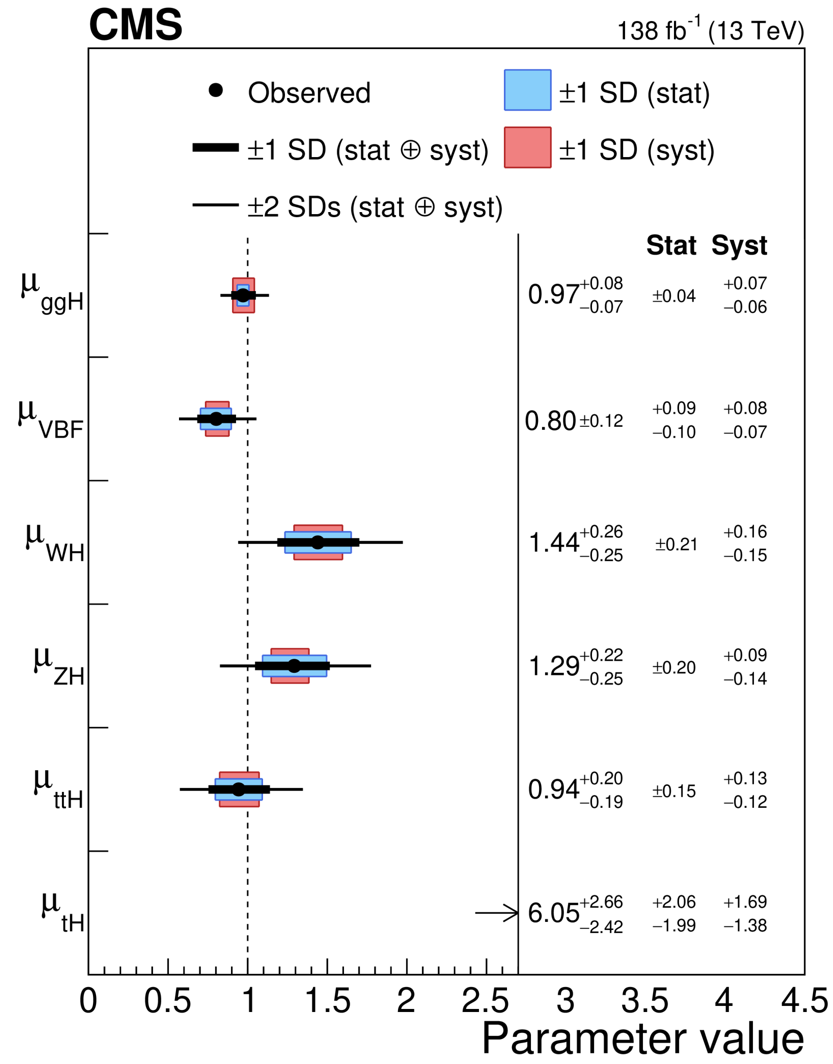
a few representative results

See more details in the dedicated talk by Changqiao

Higgs productions

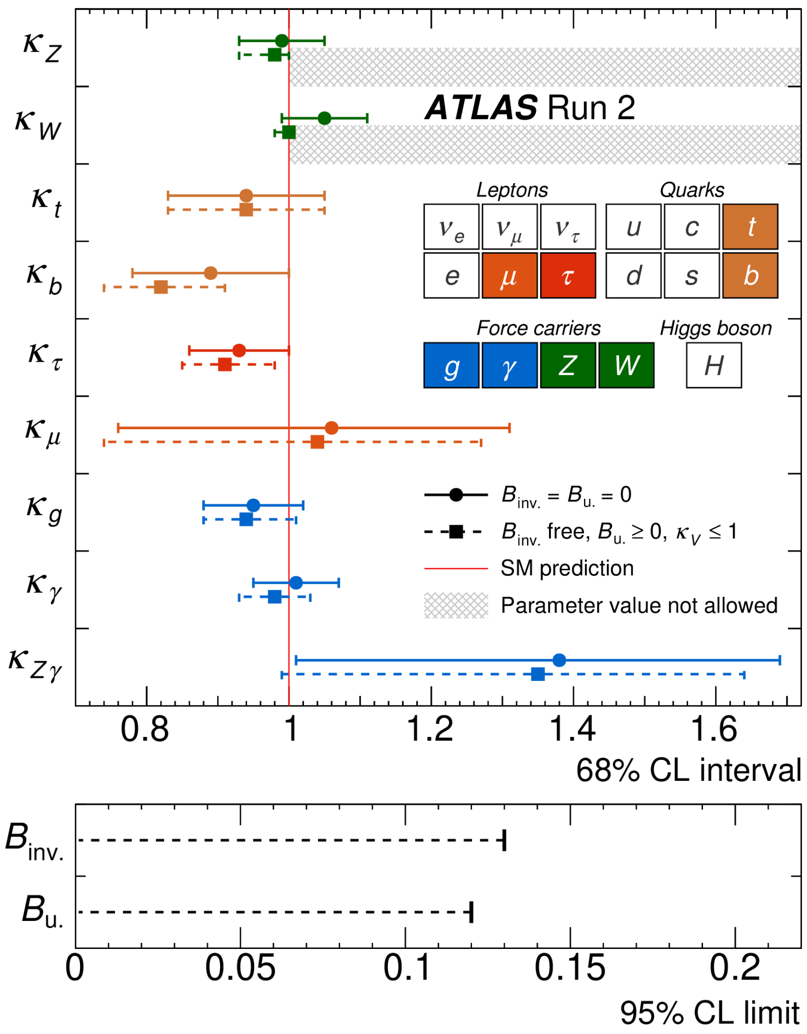
ATLAS: Nature 607 (2022) 52-59
CMS: Nature 607 (2022) 60-68

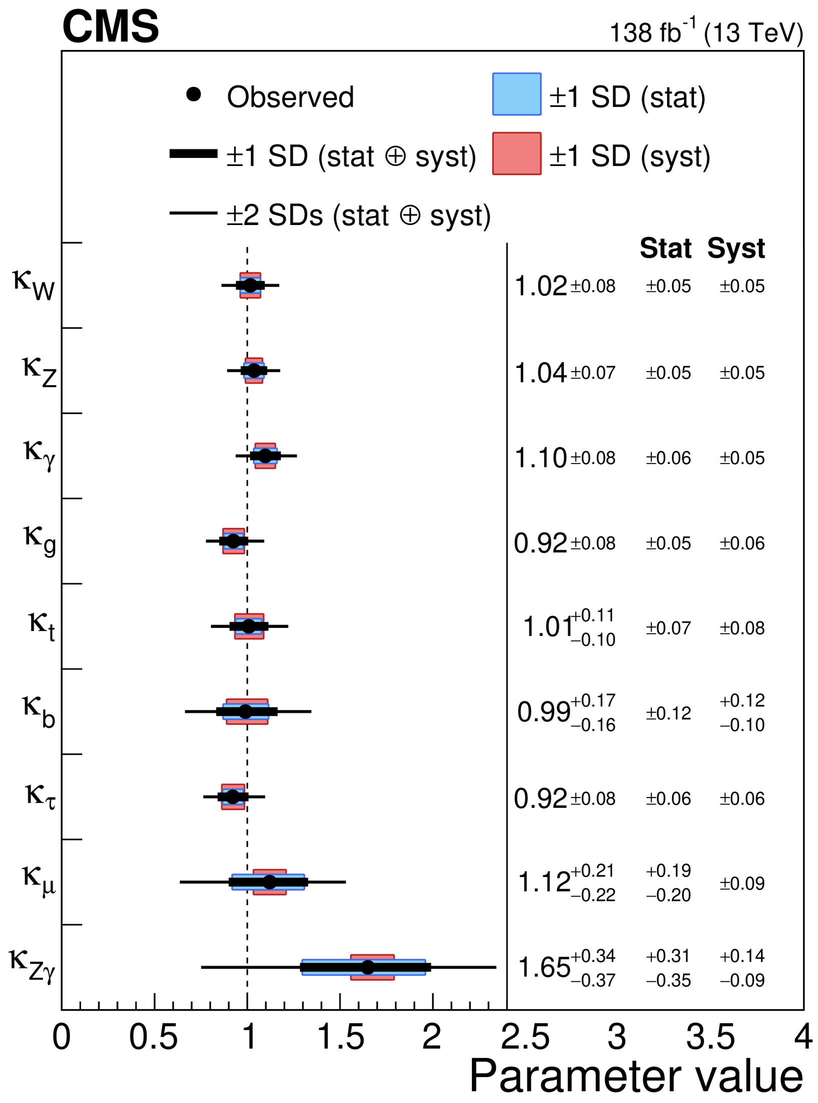




>5σ observation for all production modes except for tH
H→WW, ττ, ZZ, γγ now all at precisions ~10%
H→μμ, Zγ with a significance of ~2σ

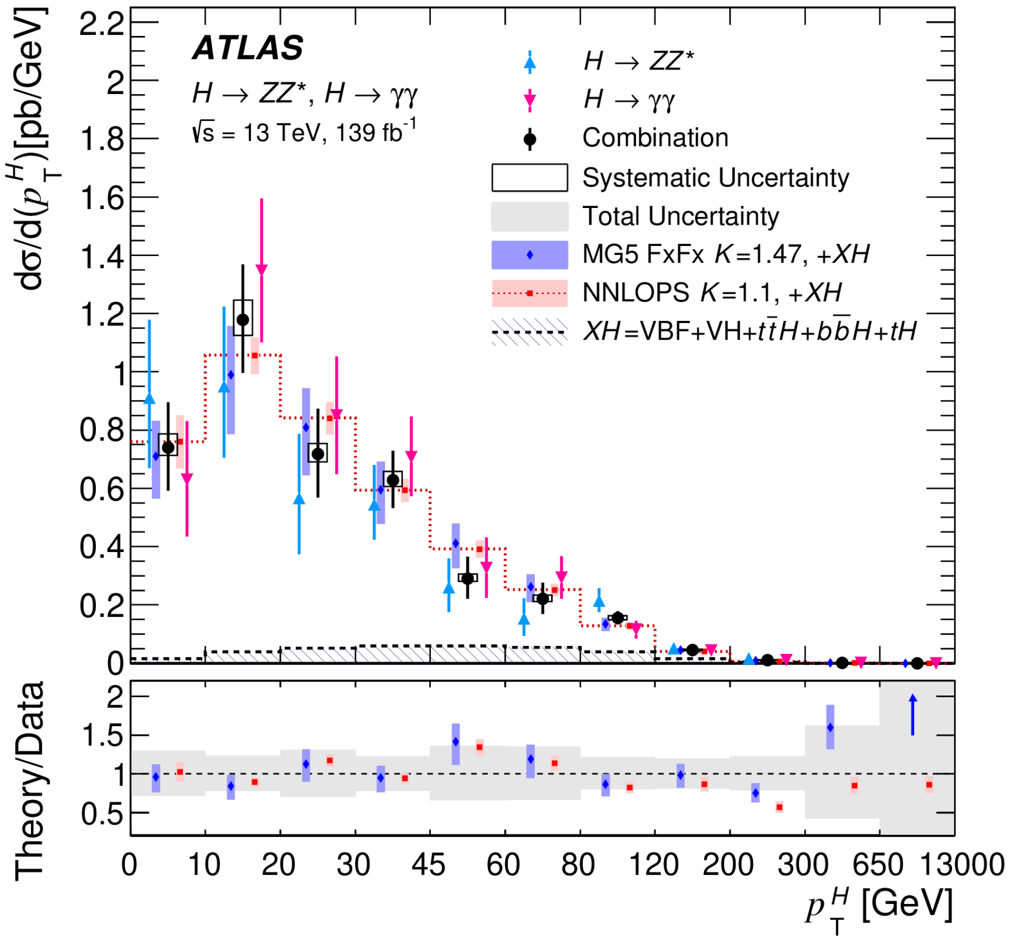
Higgs couplings

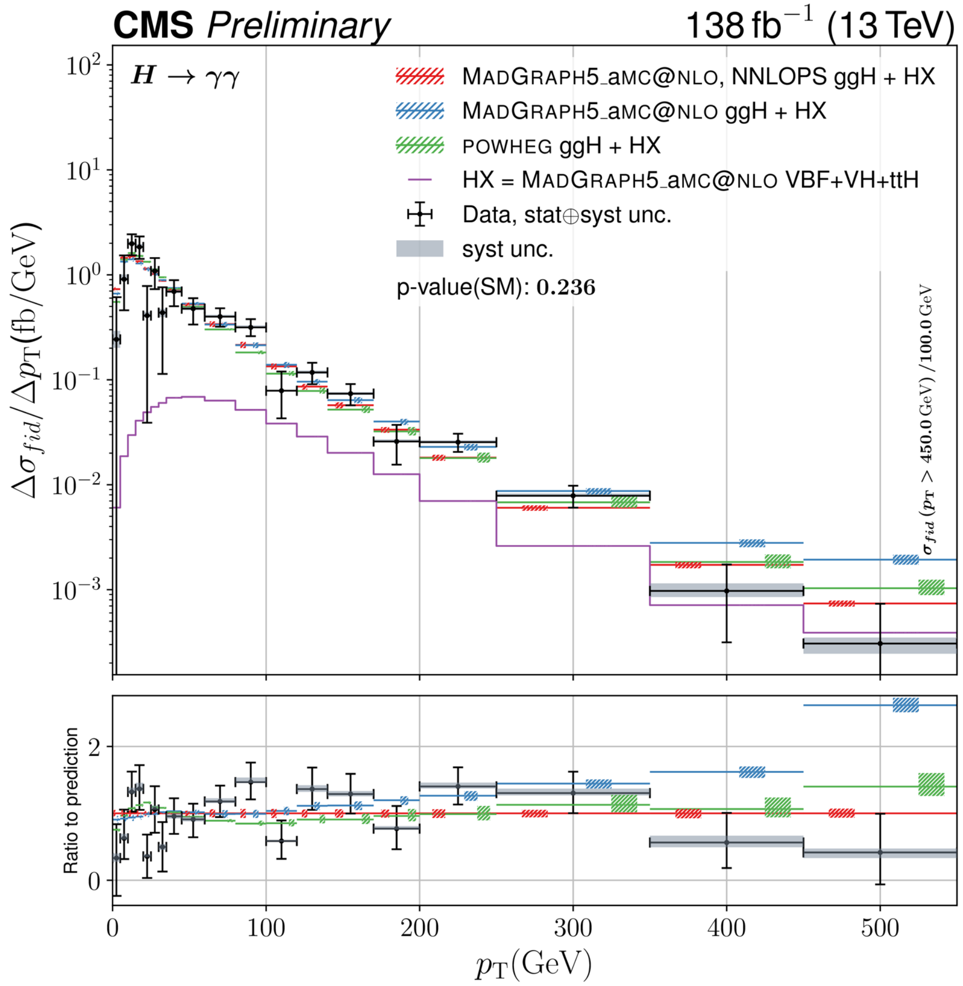




Differential cross-sections

ATLAS: arXiv:2207.08615
CMS: CMS-PAS-HIG-19-016





VH and VBF Higgs production

VH

- VH associated production:
  - Provides the best sensitivity to H→bb and H→cc decays and the VH production

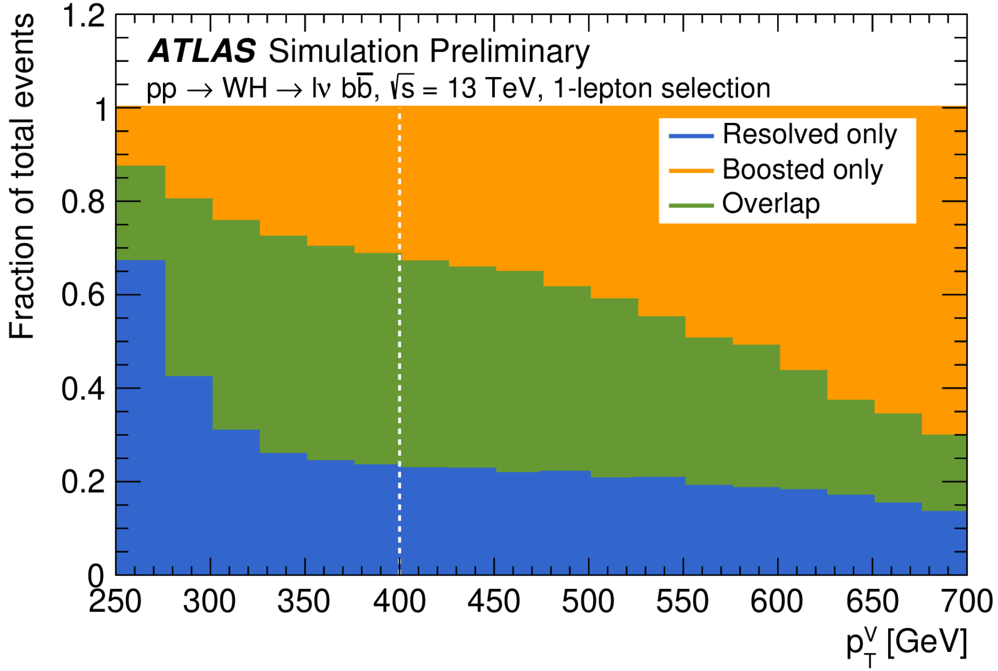
VH (full Run2)	ATLAS	CMS
VH(bb) resolved	EPJC 81 (2021) 178	
VH(bb) boosted	PLB 816 (2021) 136204	
VH(bb) boosted +resolved	ATLAS-CONF-2021-051	
VH(cc)	EPJC 82, 717 (2022)	arXiv:2205.05550
VH(WW*)		CMS-PAS-HIG-19-017

Not covered:
VH resonance searches, ATLAS arXiv:2207.00230

ATLAS VHbb combination

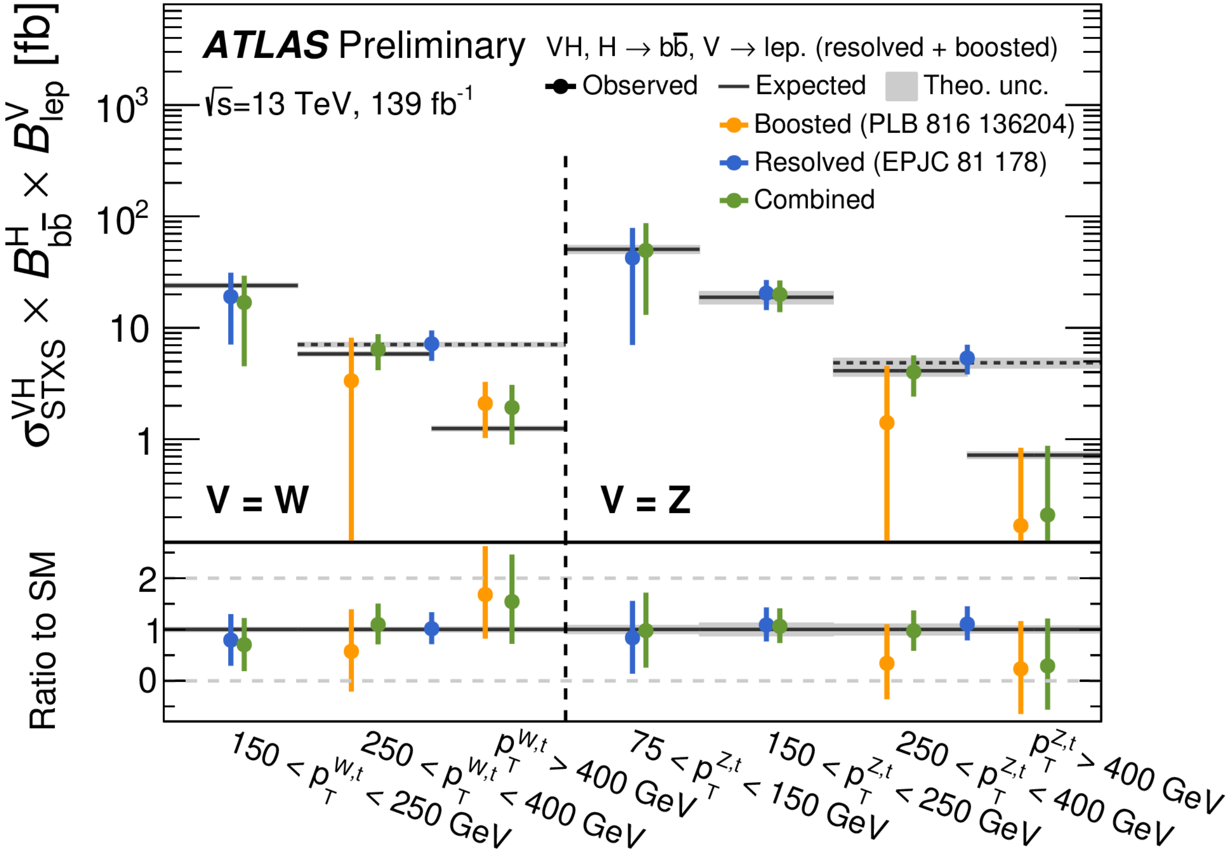
ATLAS-CONF-2021-051

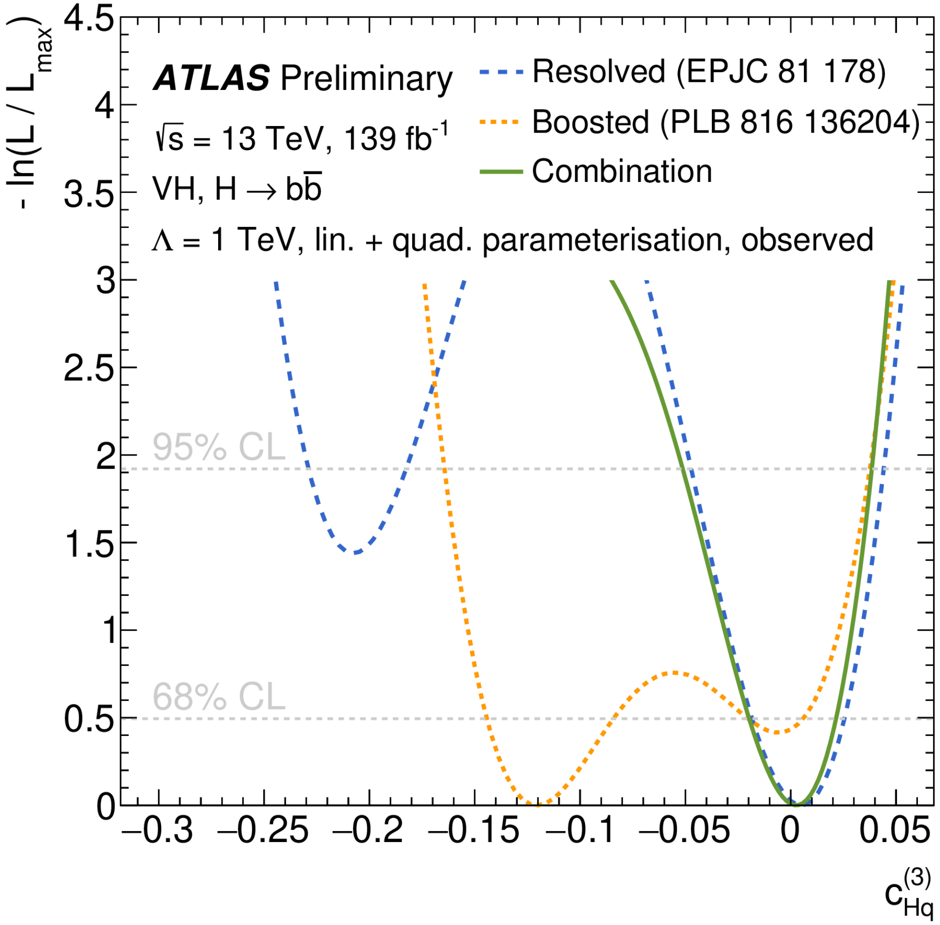
- ATLAS previously performed separate VHbb measurements in the resolved and boosted regimes
  - Both measurements define 3 channels: $ZH \rightarrow vvbb$(0-lep),$WH \rightarrow lvbb$(1-lep), $ZH \rightarrow llbb$(2-lep),
  - With significant overlapping events
- New combination aimed to make them orthogonal
  - $p_T^V < 400$ GeV: resolved; $p_T^V > 400$ GeV: boosted
- Statistical model adapted to obtain a coherent description of the common leading background contributions and systematic uncertainties



ATLAS VHbb combination

- Combined measurements
  - Consistent with previous measurements, but with improved EFT sensitivities





VH(cc)

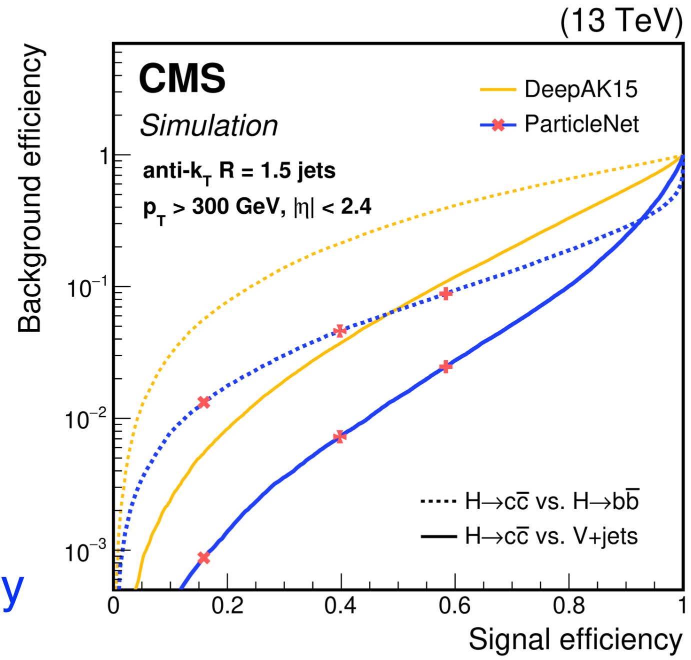
ATLAS: EPJC 82, 717 (2022)
CMS: arXiv:2205.05550

- Three lepton channels: $ZH \to \nu\nu cc$(0-lep),$WH \to l\nu cc$(1-lep), $ZH \to llcc$(2-lep)

VH (full Run2)	ATLAS	CMS	
$H \to cc$ reconstruction	resolved	boosted	resolved
c-tagging	DL1, a deep neural network	ParticleNet, a graph neural network	DeepJet
Categorization	2 p_T^V bins x (1-c-tag and 2-c-tag)	BDT x 3 cc-tagging regions	
Fitting discriminants	m_{Hcc}	m_{Hcc}	BDT

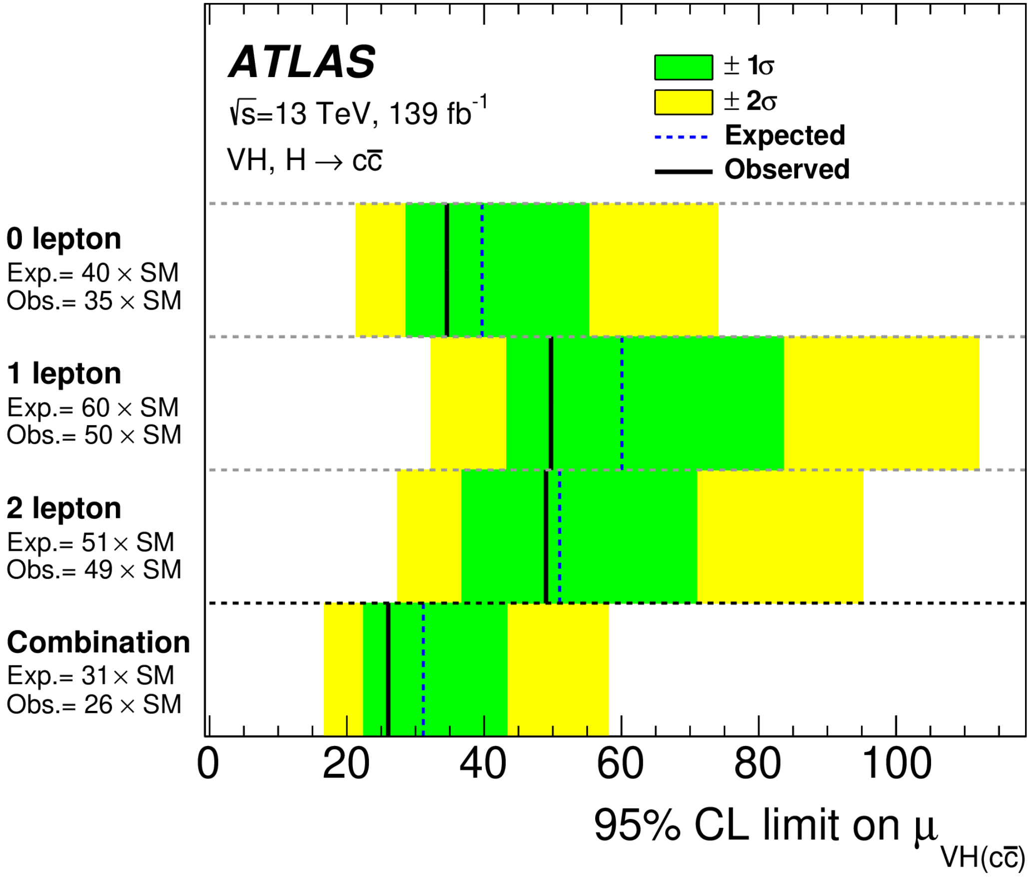
ATLAS uses a c-tagger that includes a b-tag veto on MV2c10@70% to establish orthogonality with VH(bb) and allows the combination

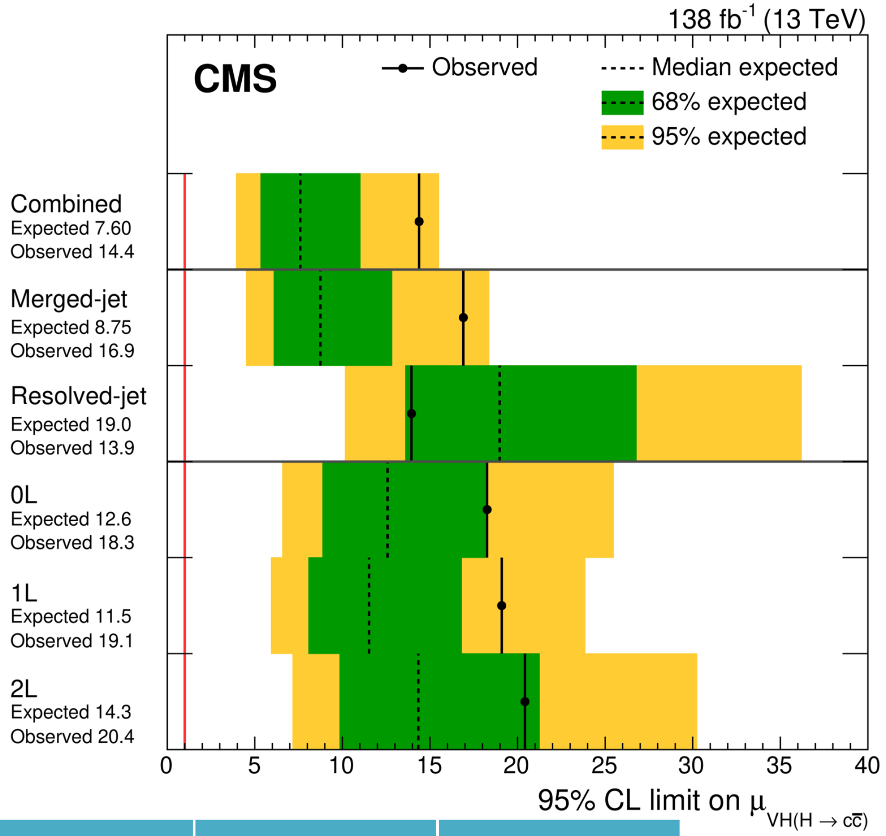
CMS ParticleNet tagger:
~5x better H→bb rejection
~5x better V+jet rejection
>2x improvement in the final sensitivity



VH(cc)

- Constraints on $\mu_{VH(cc)}$

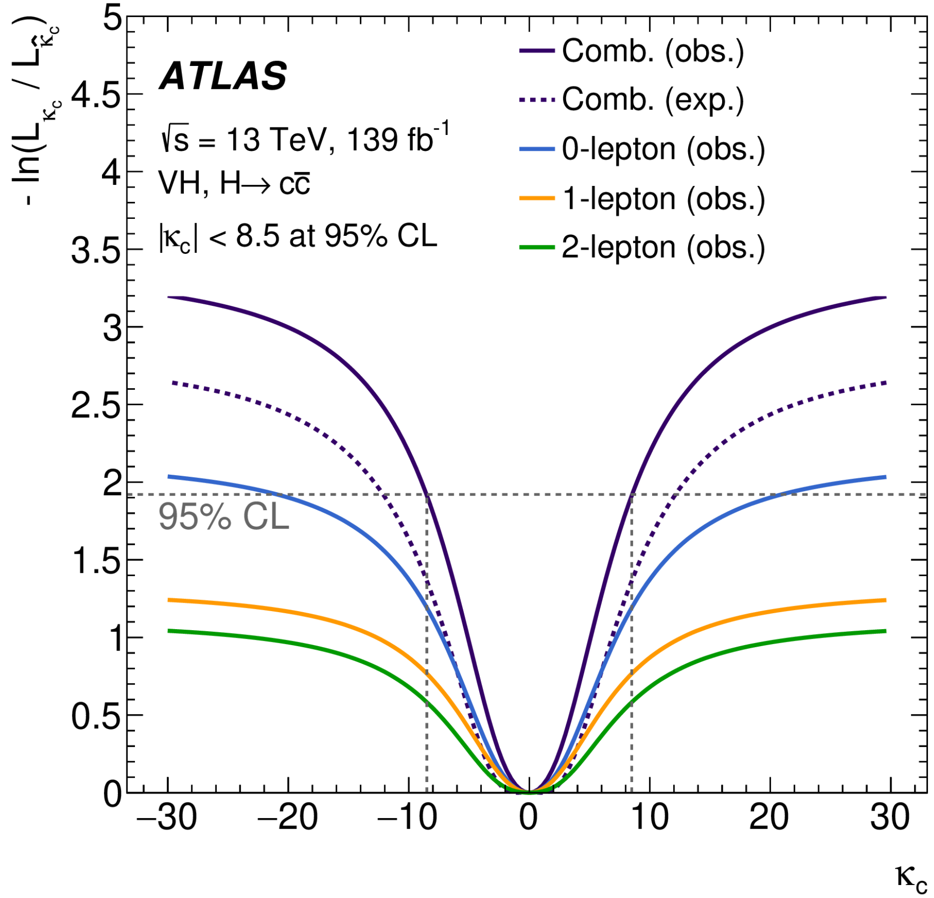


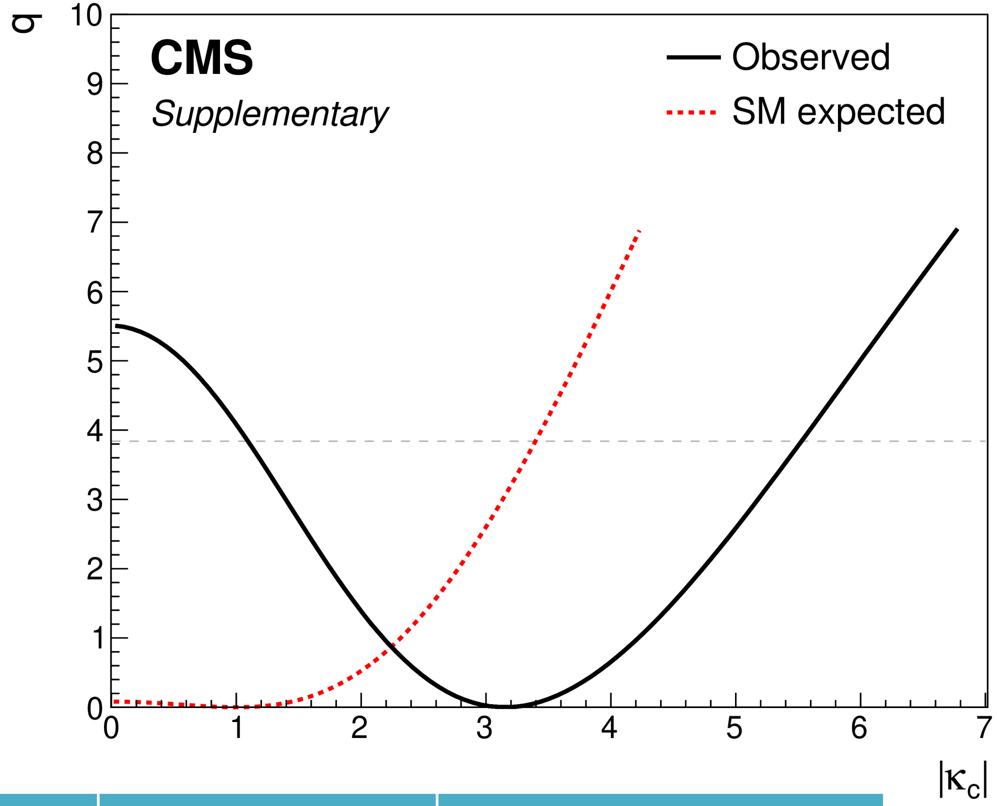


$\mu_{VH(cc)}$	ATLAS	CMS
Obs.	35	14.4
Exp.	40	7.60

VH(cc)

- Constraints on κ_c



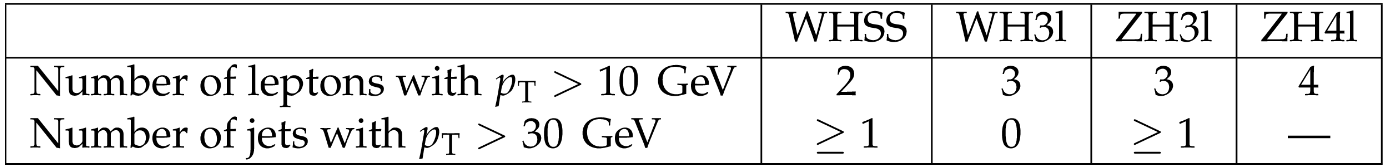


κ_c	ATLAS	CMS
Obs.	$|\kappa_c| < 8.5$	$1.1 < |\kappa_c| < 5.5$
Exp.	$|\kappa_c| < 12.4$	$|\kappa_c| < 3.4$

CMS VH(WW*)

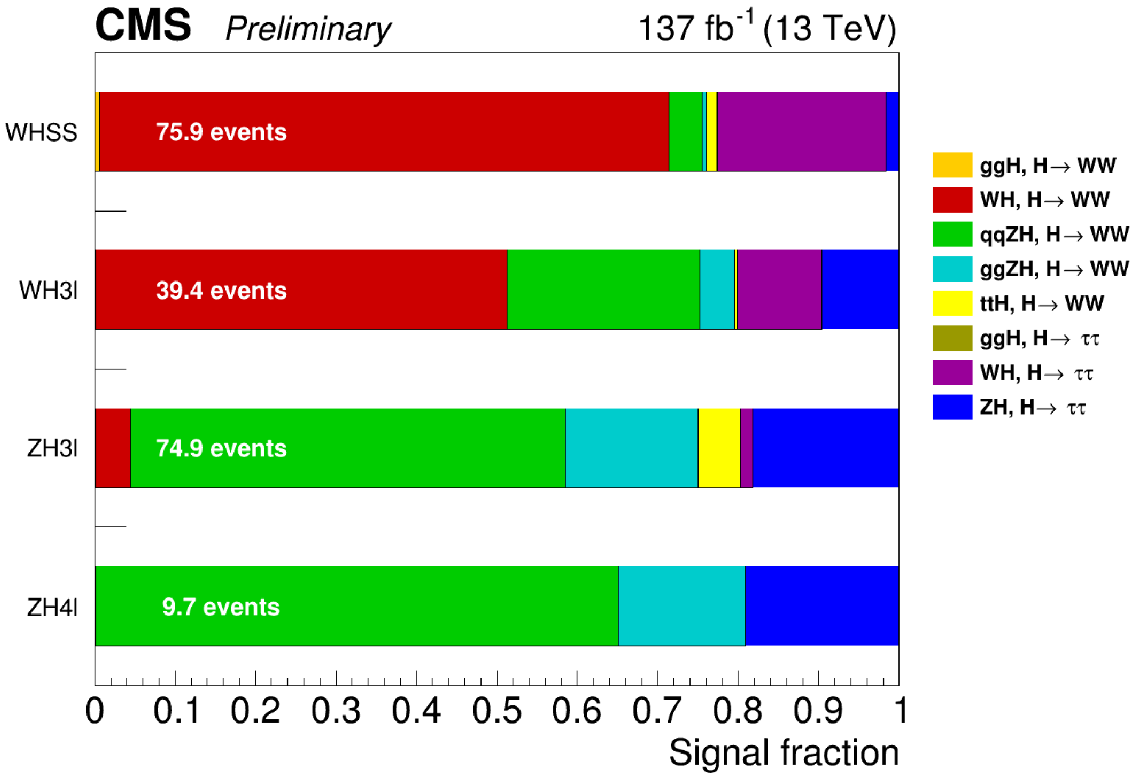
CMS-PAS-HIG-19-017

- Experimental signatures:
  - $W \rightarrow l\nu, Z \rightarrow ll$ and $\mathrm{H} \rightarrow WW^* \rightarrow l\nu l\nu / l\nu qq$
  - Four final states: $WH \rightarrow 2l2\nu qq$ (WHSS), $WH \rightarrow 3l3\nu$(WH3l), $ZH \rightarrow 3l\nu qq$ (ZH3l), and $ZH \rightarrow 4l2\nu$(ZH4l)



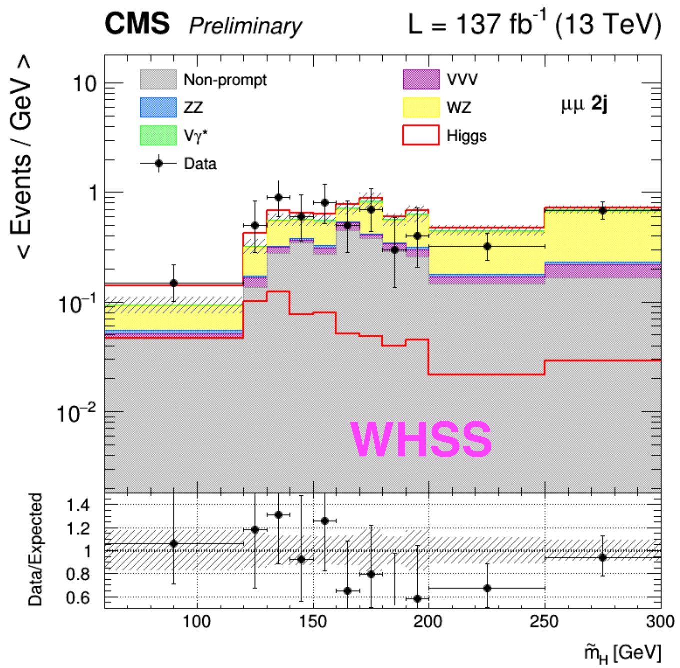
	WHSS	WH3l	ZH3l	ZH4l
Number of leptons with $p_{\mathrm{T}} > 10$ GeV	2	3	3	4
Number of jets with $p_{\mathrm{T}} > 30$ GeV	≥ 1	0	≥ 1	—

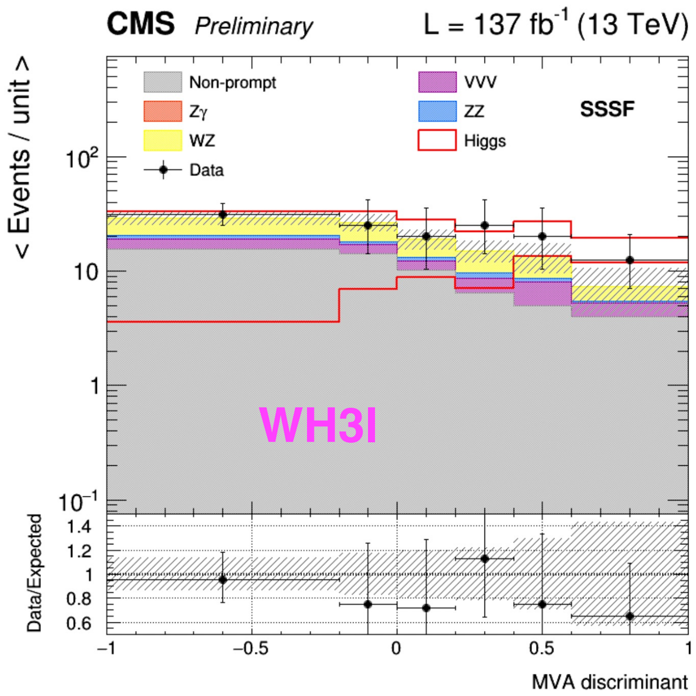
- Non-negligible contribution from $\mathrm{H} \rightarrow \tau\tau$ is also considered as the signal

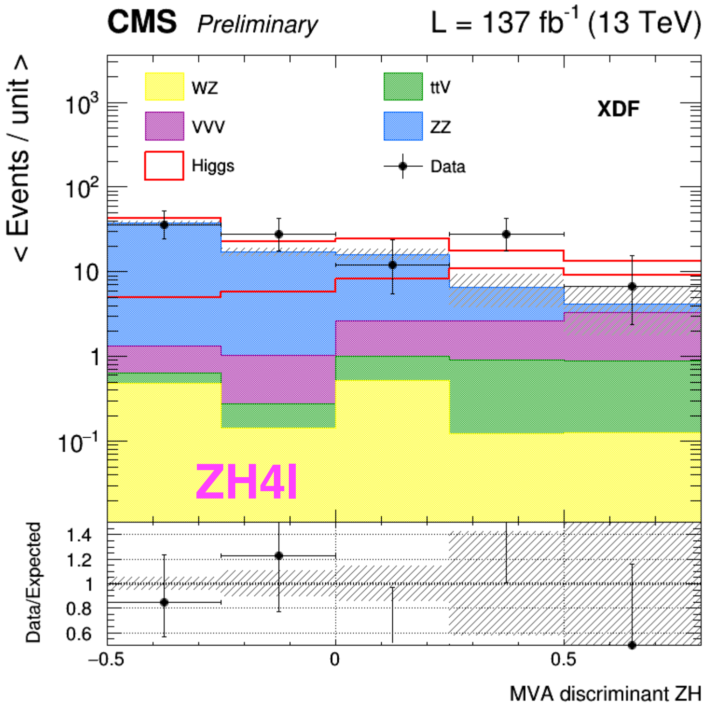


CMS VH(WW*)

- Main backgrounds: WZ, ZZ, $Z\gamma^*$
  - Dedicated control regions to constrain WZ, $Z\gamma^*$ and ZZ respectively
- Signal extraction:
  - mH for WHSS and ZH3l
  - BDT discriminants for WH3l and ZH4l

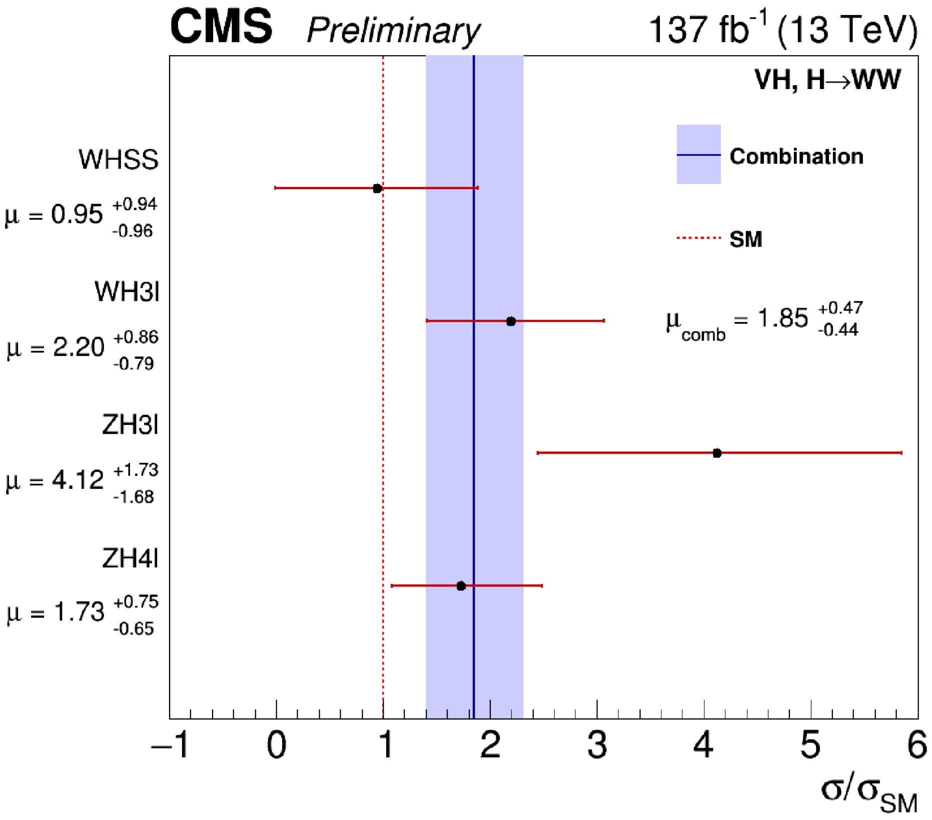






CMS VH(WW*)

- Signal strengths measurements:
  - For inclusive VH production: observed(expected) 4.7(2.8) σ
  - Also in two p_T^V bins: $p_T^V < 150\ GeV$ and $p_T^V > 150\ GeV$



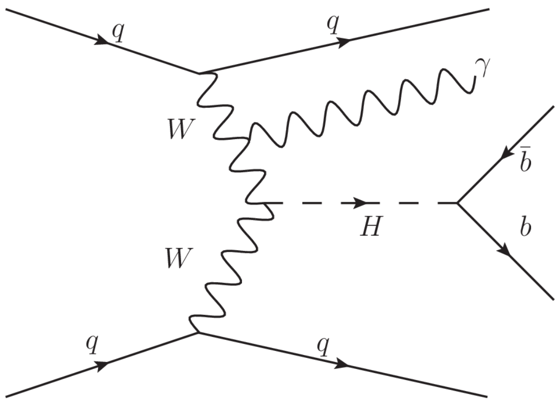
Category	μ	Significance
WHSS	$0.95^{+0.94}_{-0.96}$	1.0 σ (1.1 σ expected)
WH3l	$2.20^{+0.86}_{-0.79}$	3.0 σ (1.6 σ expected)
ZH3l	$4.12^{+1.73}_{-1.68}$	2.5 σ (0.6 σ expected)
ZH4l	$1.73^{+0.75}_{-0.65}$	3.1 σ (2.1 σ expected)
Combination	$1.85^{+0.47}_{-0.44}$	4.7 σ (2.8 σ expected)

	μ	Significance
$WH\ p_T^V < 150$ GeV	$1.5^{+1.0}_{-0.9}$	1.64 σ (1.24 σ expected)
$WH\ p_T^V > 150$ GeV	$3.6^{+1.8}_{-1.6}$	2.23 σ (0.83 σ expected)
$ZH\ p_T^V < 150$ GeV	$3.4^{+1.1}_{-1.0}$	4.37 σ (1.59 σ expected)
$ZH\ p_T^V > 150$ GeV	$0.8^{+1.2}_{-0.9}$	0.83 σ (1.18 σ expected)

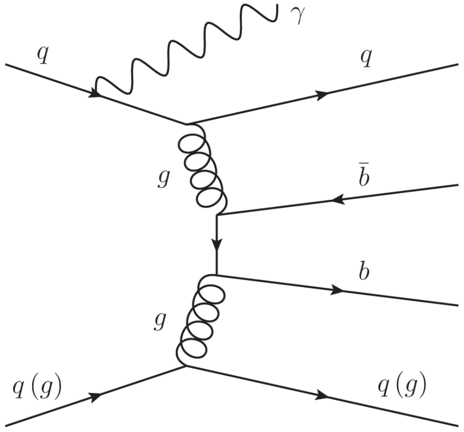
ATLAS VBF Hγ

JHEP 03 (2021) 268

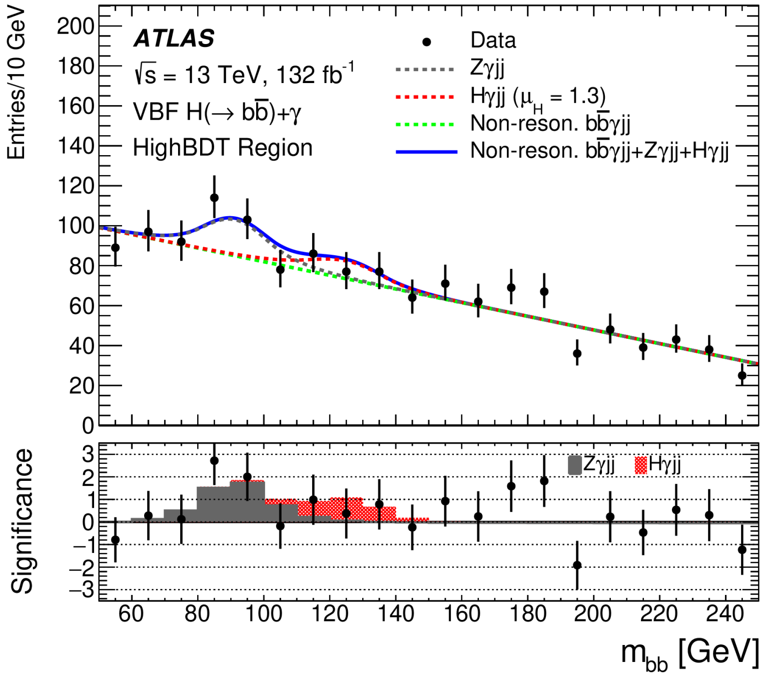
- A unique Higgs production mode to be explored
- The presence of an isolated high-energy γ helps suppress the background



Z boson fusion suppressed

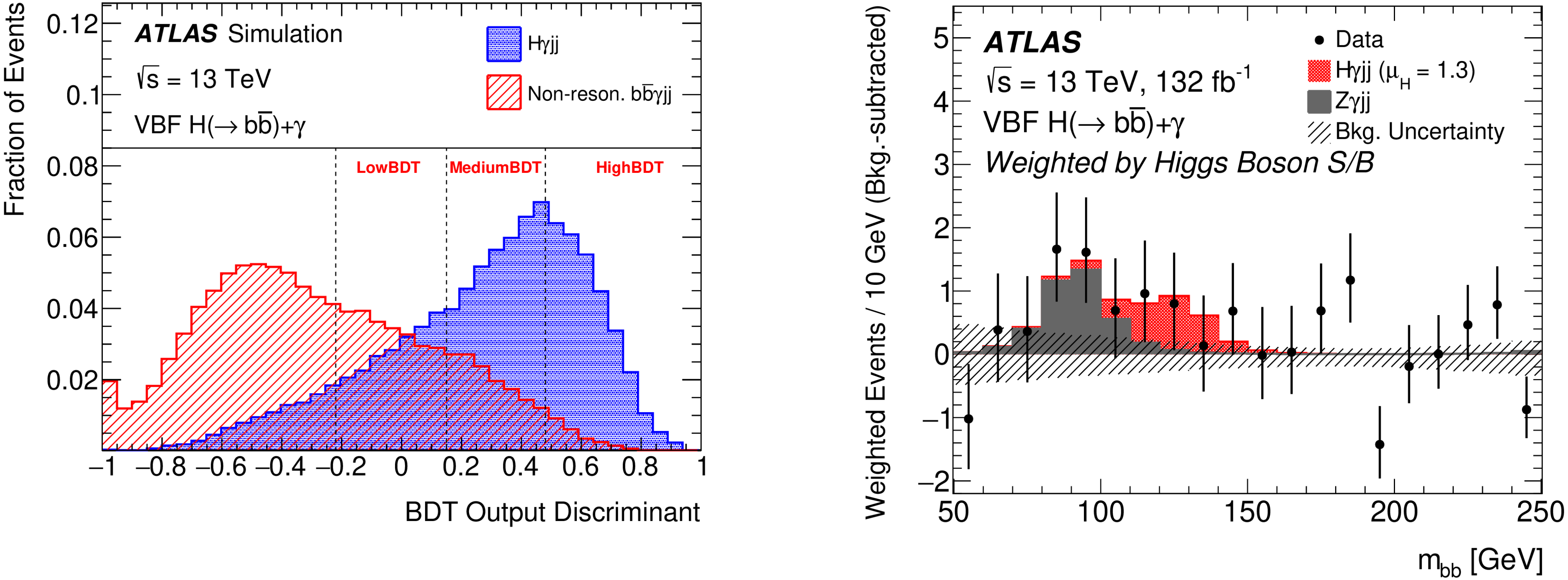


- Main background: non-resonant $bb\gamma jj$ production and resonant $Z(\rightarrow bb)\gamma jj$ production
  - parameterized with analytic functions derived from simulated events or data sideband regions



ATLAS VBF Hγ

- BDT is used to discriminate the signal from the background
- Signal extraction: fit to m_{bb} distributions in 3 BDT bins
  - Observed: $\mu_H = 1.3 \pm 1.0$, 1σ significance



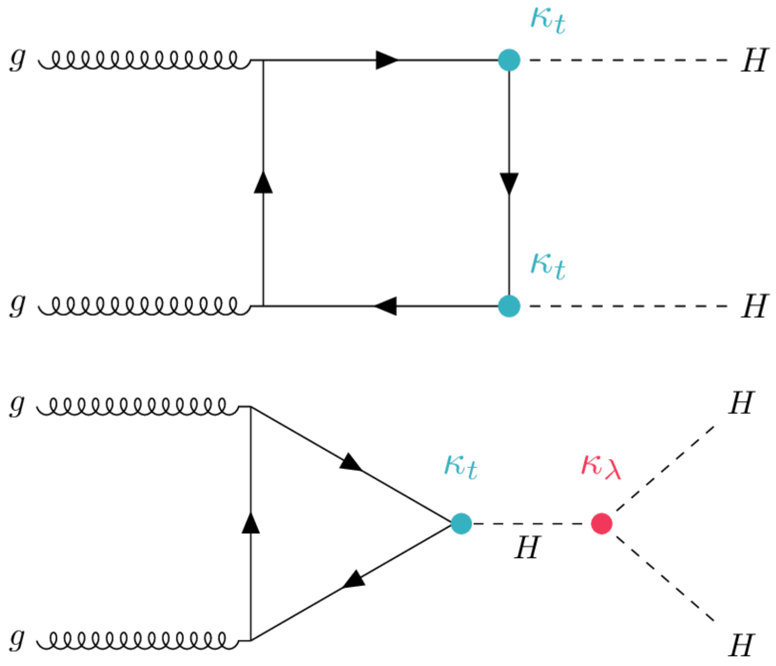
HH production

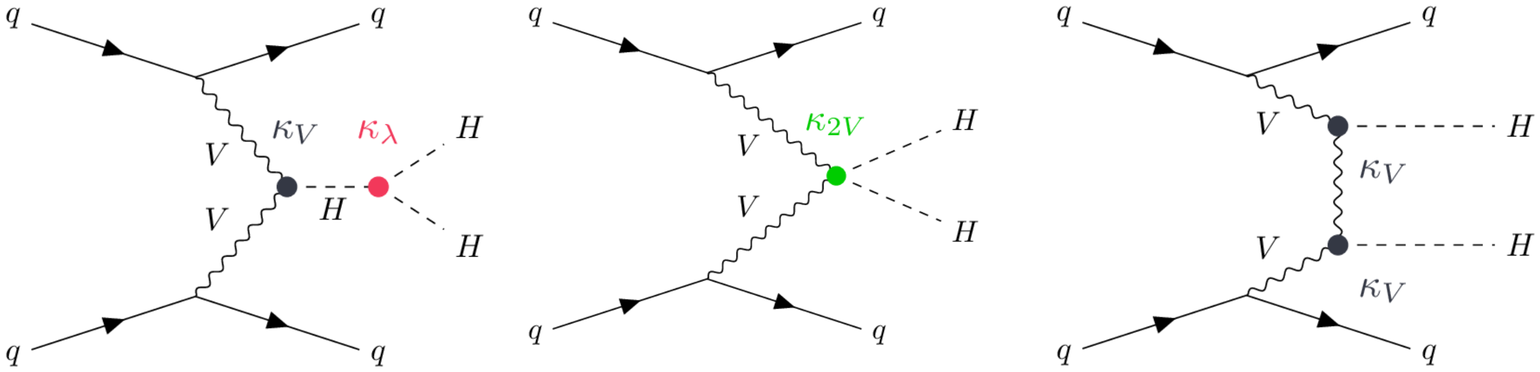
Non-resonant hh production

- Direct probe of the trilinear Higgs self-coupling κ_λ
- Main production processes: ggF and VBF

$$\sigma^{GGF}_{HH} = 31.05 \text{ fb } \pm 3\%(\text{PDF} + \alpha_S) \, {}^{+2.2\%}_{-5\%} \, (\text{scale}) \, \pm 2.6\%(m_t) \text{ @ } 13 \; TeV$$

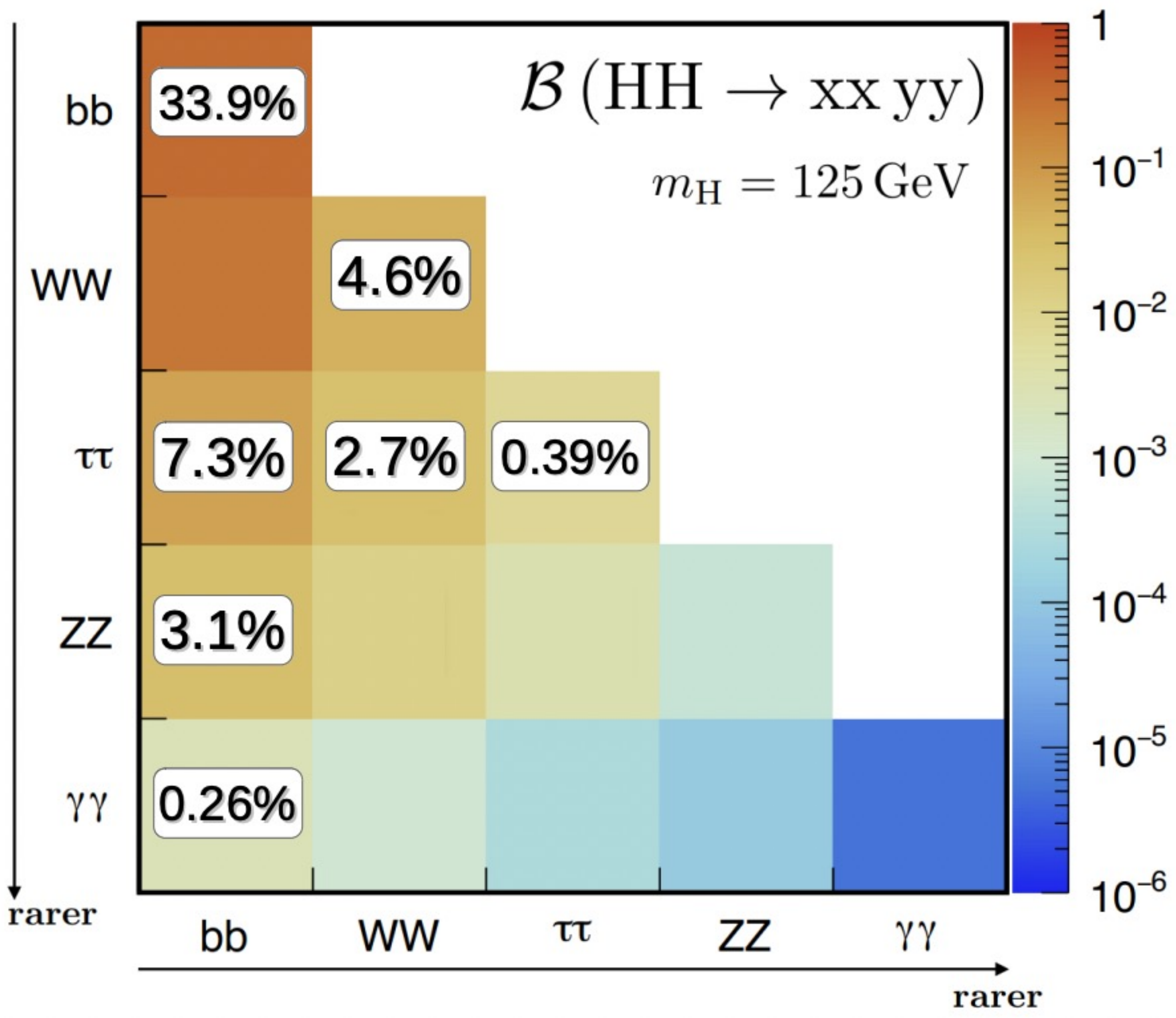
$$\sigma^{VBF}_{HH} = 1.73 \text{ fb } \pm 2.1\%(\text{PDF} + \alpha_S) \, {}^{+0.03\%}_{-0.04\%} \, (\text{scale}) \text{ @ } 13 \; TeV$$





The VBF production has unique sensitivity to $\kappa_{2\text{v}}$

Search channels



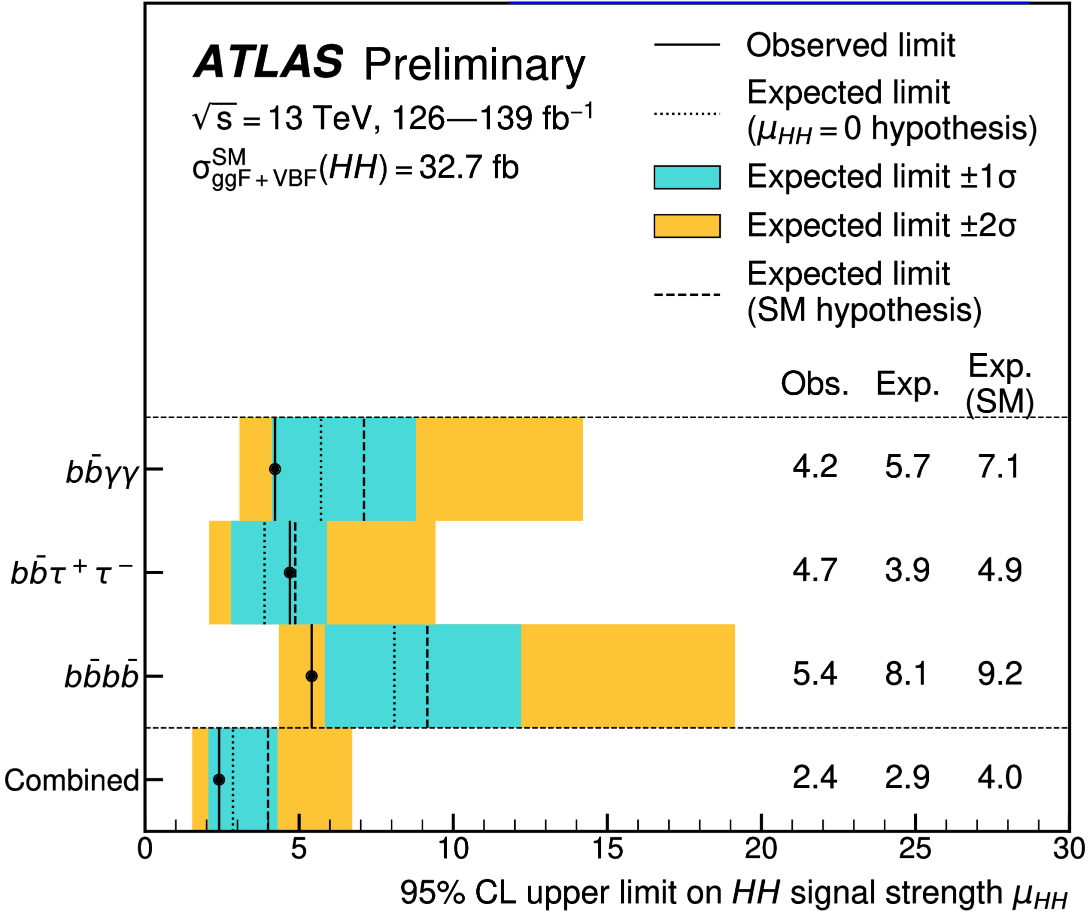
- No Golden channels
- Decay channels with large Br's may lead to challenging signatures
- Exploring a mixture of different Higgs decay channels to increase the sensitivity

Search channels

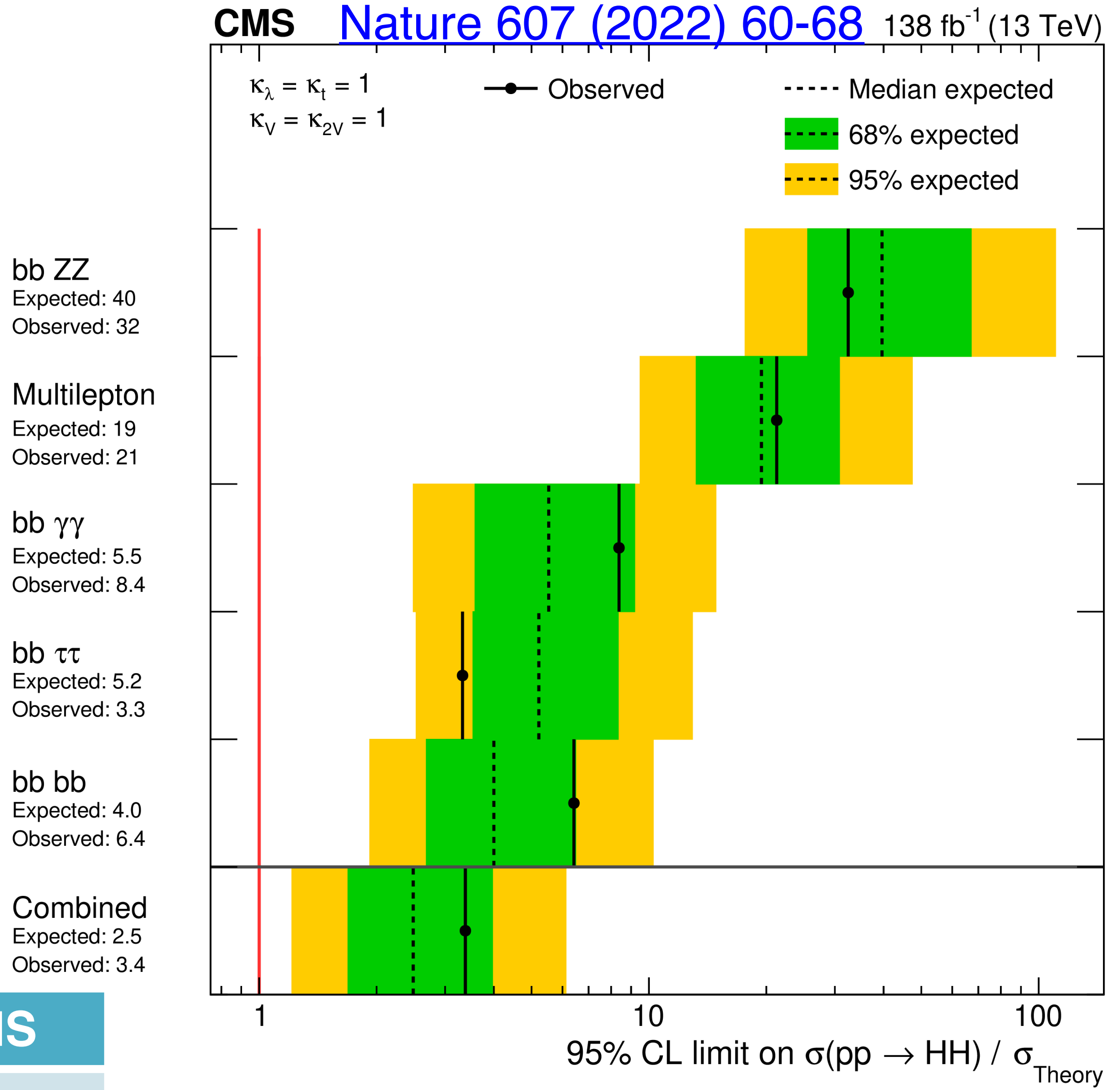
	ATLAS	**CMS**	
4b (resolved)	ATLAS-CONF-2022-035	arXiv:2202.09617	both ggF and VBF
4b (boosted)		arXiv:2205.06667	both ggF and VBF
VBF 4b resolved	JHEP 07 (2020) 108		
$bb\tau\tau$	ATLAS-CONF-2021-030	arXiv:2206.09401	
$bb\gamma\gamma$	arXiv:2112.11876	JHEP03(2021)257	
$bbZZ(4l)$		arXiv:2206.10657	
$bb + WW/ZZ/\tau\tau(l\nu l\nu)$	PLB 801 (2020) 135145		
$4W, WW\tau\tau, 4\tau$		arXiv:2206.10268	
Combination	ATLAS-CONF-2022-050	Nature 607 (2022) 60-68	

Combined limits on μ_{hh}

ATLAS-CONF-2022-050

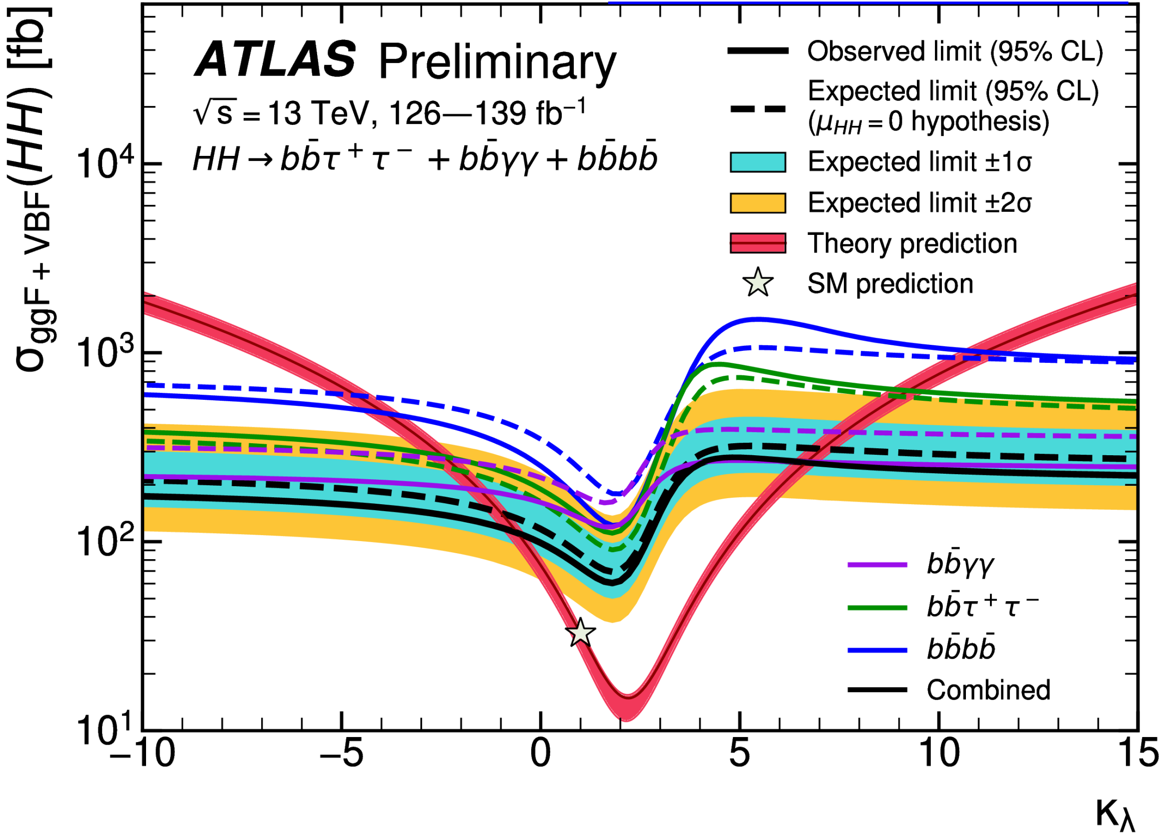


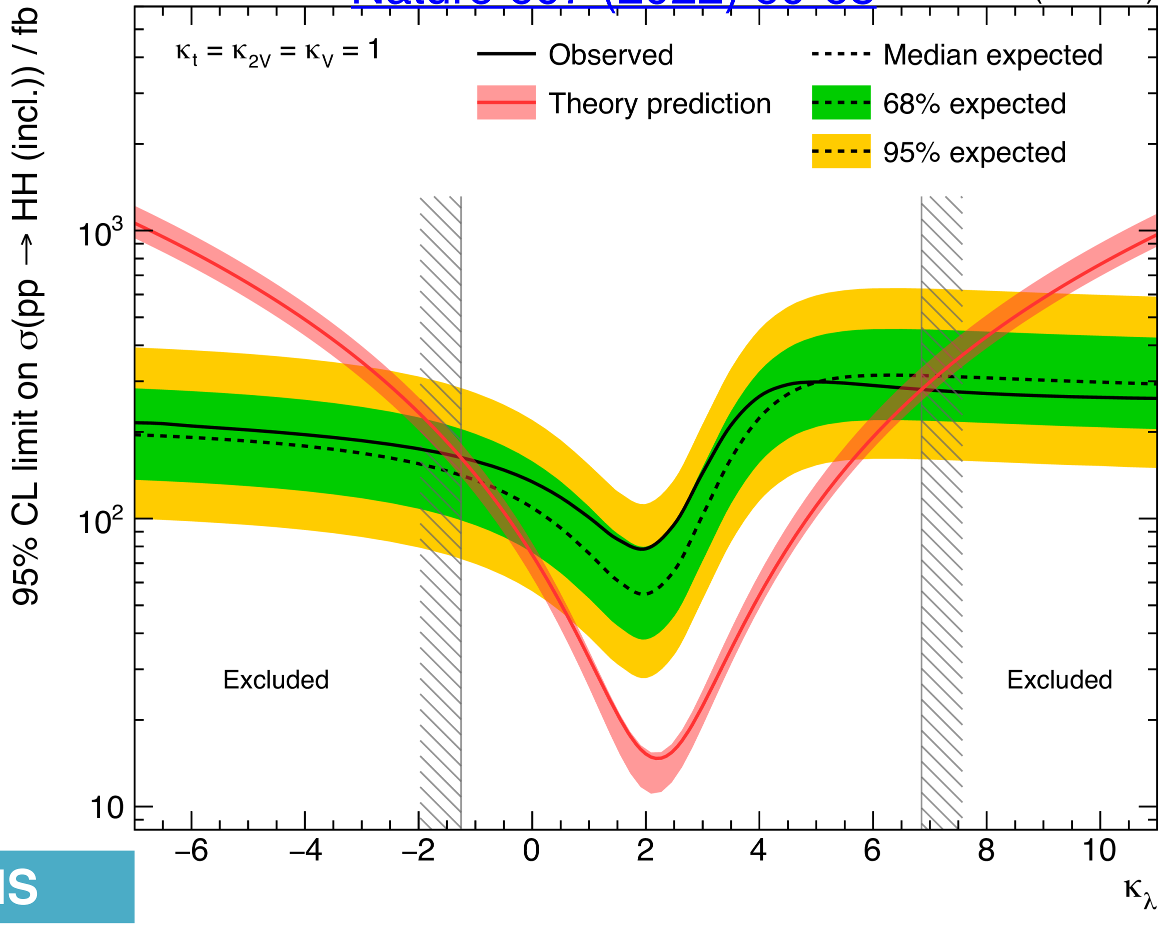
CMS Nature 607 (2022) 60-68



μ_{hh}	ATLAS	CMS
Obs.	2.4	3.4
Exp.	2.9	2.5

Combined limits on κ_λ

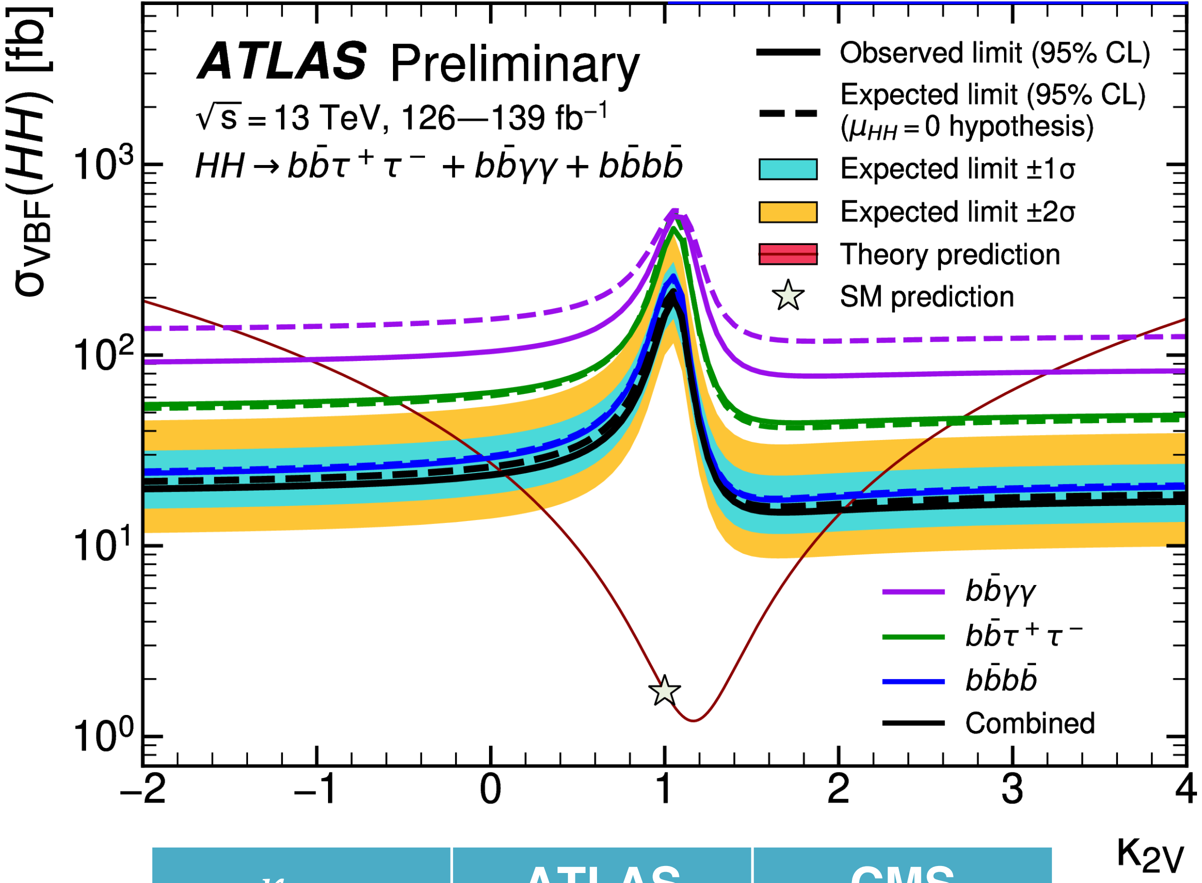

ATLAS-CONF-2022-050


Nature 607 (2022) 60-68

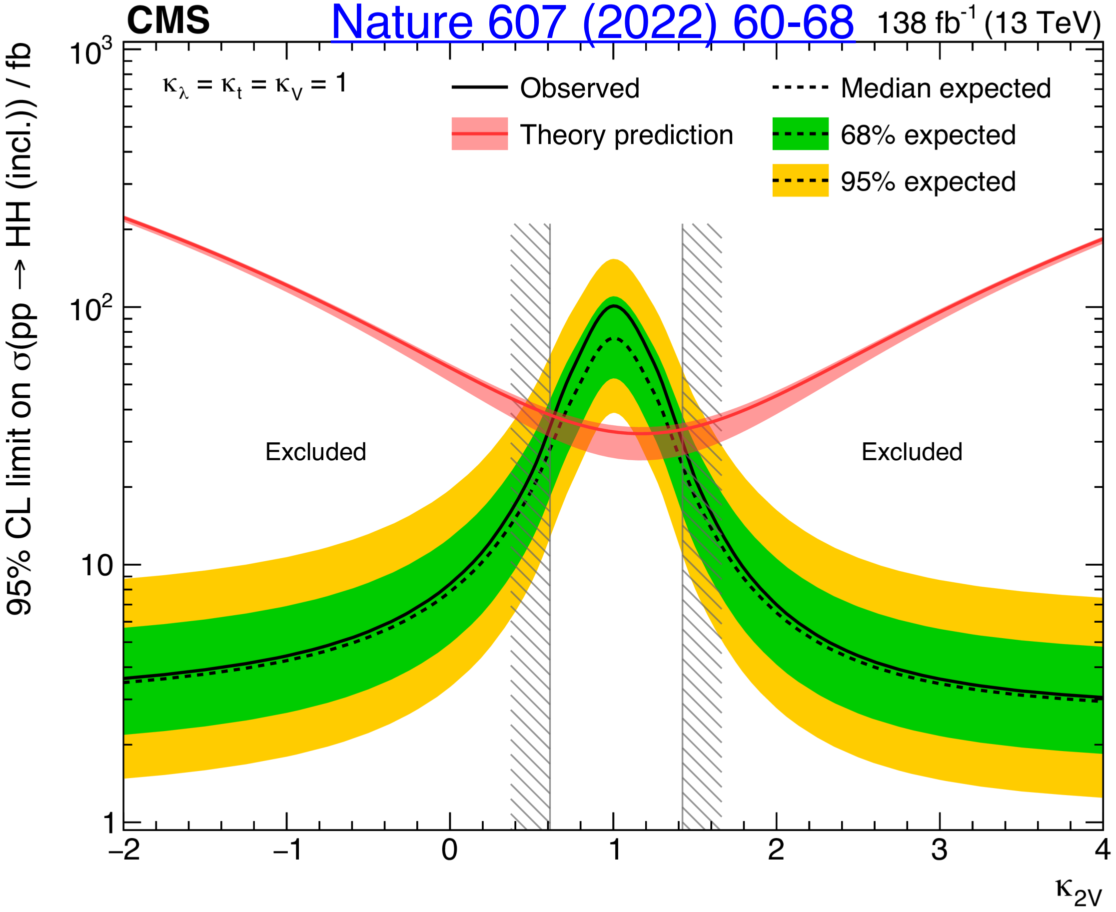
κ_λ	ATLAS	CMS
Obs.	(-0.6, 6.6)	(-1.24, 6.49)
Exp.	(-2.1, 7.8)	

Combined limits on κ_{2V}

ATLAS-CONF-2022-050



Nature 607 (2022) 60-68



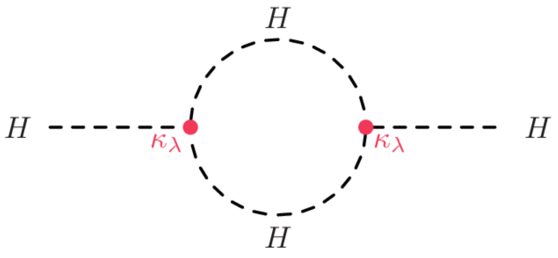
κ_{2V}	ATLAS	CMS
Obs.	(0.1, 2.0)	(0.67, 1.38)
Exp.	(0.0, 2.1)	

Single + Double-Higgs combination

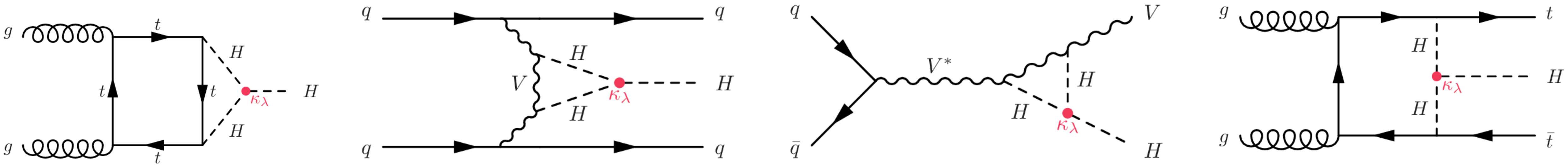
ATLAS-CONF-2022-050

- Single-Higgs processes are indirectly sensitive to κ_λ via NLO EW corrections:

Universal correction $\boldsymbol{O}(\kappa_\lambda^2)$: Higgs loops



Linear correction $\boldsymbol{O}(\kappa_\lambda)$: both process and kinematics dependent



- Simplified template cross-section (STXS) results are parametrized as a function of $(\kappa_\lambda, \kappa_m)$

$$n_{i,f}^{\text{signal}}(\kappa_\lambda, \kappa_m) \propto \mu_i(\kappa_\lambda, \kappa_m) \times \mu_f(\kappa_\lambda, \kappa_m) \times \sigma_{\text{SM},i} \times \text{BR}_{\text{SM},f} \times (\epsilon \times A)_{if}$$

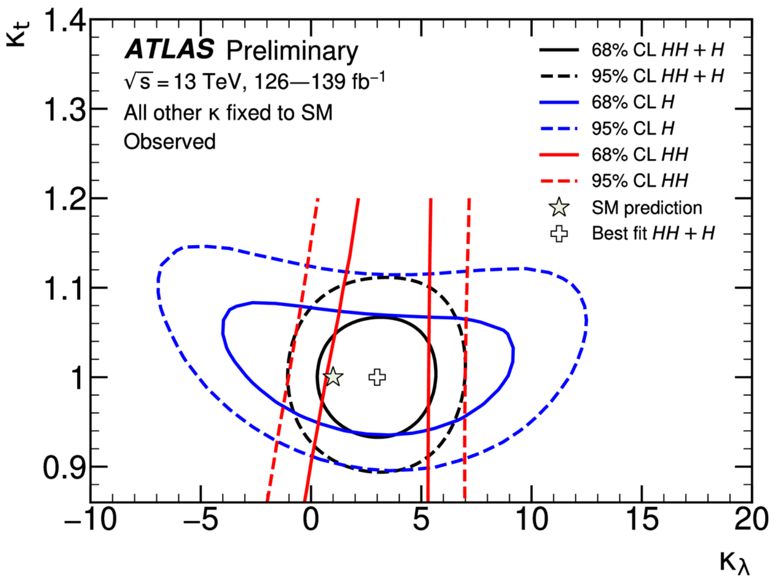
κ_m: the other couplings modifier

Single + Double-Higgs combination

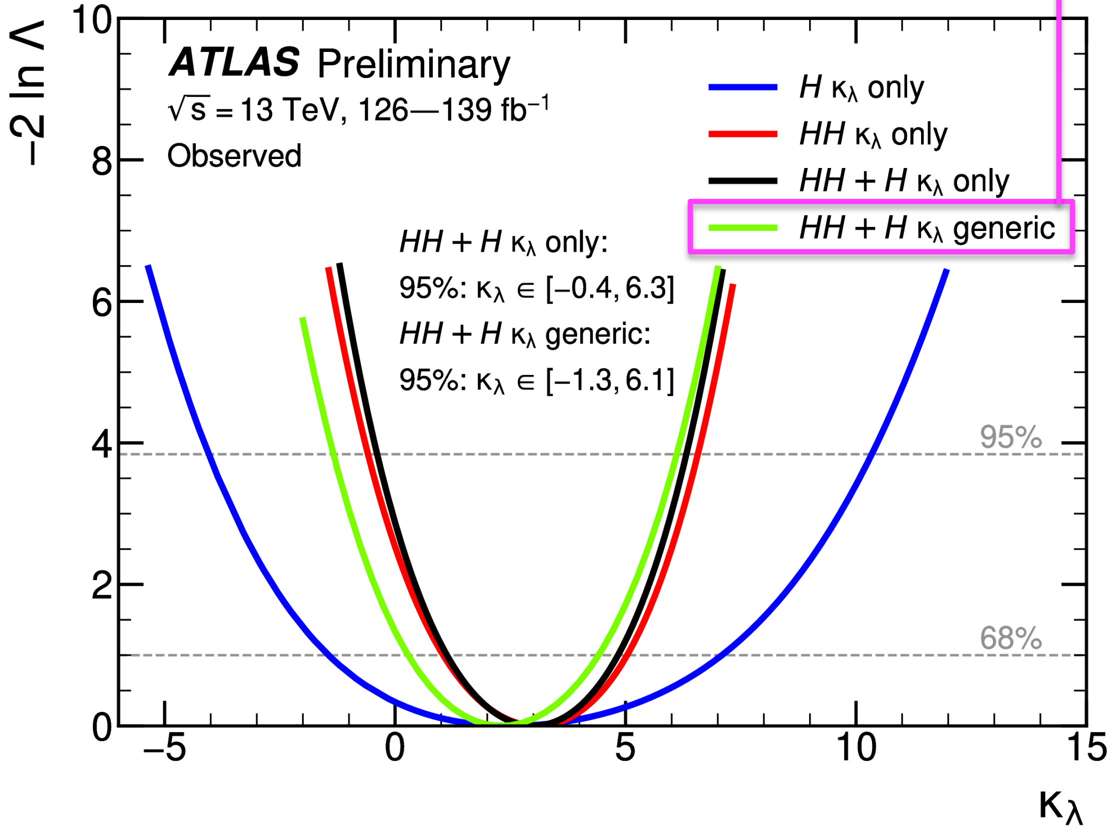
Channel	Integrated luminosity (fb^{-1})	Ref.
$HH \rightarrow b\bar{b}\gamma\gamma$	139	
$HH \rightarrow b\bar{b}\tau\bar{\tau}$	139	
$HH \rightarrow b\bar{b}b\bar{b}$	126	
$H \rightarrow \gamma\gamma$	139	
$H \rightarrow ZZ^* \rightarrow 4\ell$	139	
$H \rightarrow \tau^+\tau^-$	139	
$H \rightarrow WW^* \rightarrow e\nu\mu\nu$ (ggF,VBF)	139	
$H \rightarrow b\bar{b}$ (VH)	139	
$H \rightarrow b\bar{b}$ (VBF)	126	
$H \rightarrow b\bar{b}$ $(t\bar{t}H)$	139	

3 most sensitive hh analyses

STXS results



$\kappa_\lambda, \kappa_t, \kappa_b, \kappa_\tau, \kappa_V$ floating with $\kappa_{2V} = 1$



VHH production

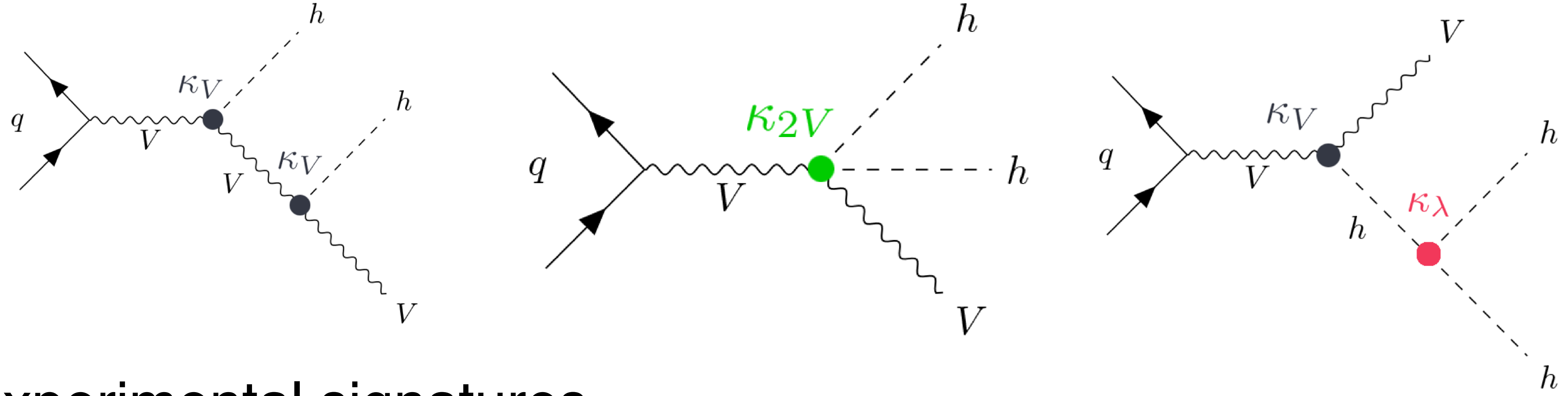
ATLAS Vhh search

ATLAS-CONF-2022-043

- First search for Vhh production at the LHC
- Rare process:
  - 0.50 ± 0.01 fb for Whh, 0.36 ± 0.01 fb for Zhh (@NNLO QCD)
  - Sensitive to 3 distinct Higgs couplings: $\kappa_{\mathrm{V}}, \kappa_{2\mathrm{V}}, \kappa_{\lambda}$
  - Also sensitive to resonances VH→Vhh

$\sigma_{ggF} = 31.05\text{fb}$

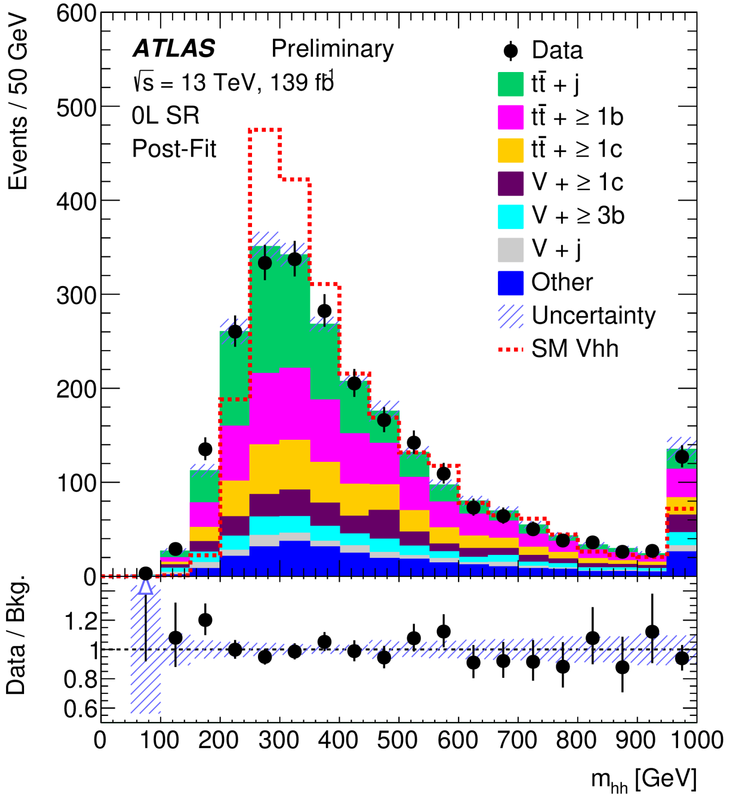
$\sigma_{VBF} = 1.73\text{fb}$

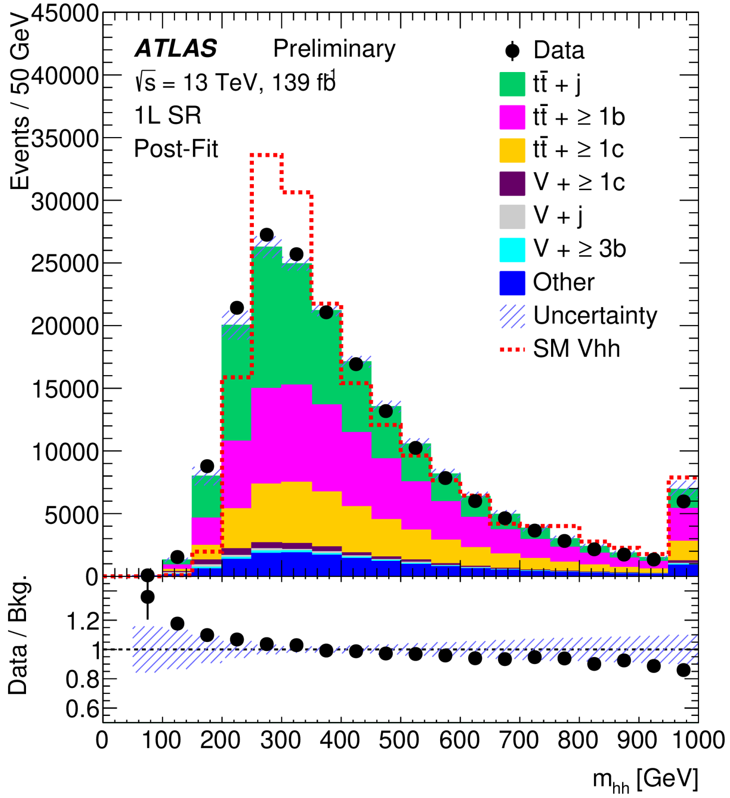


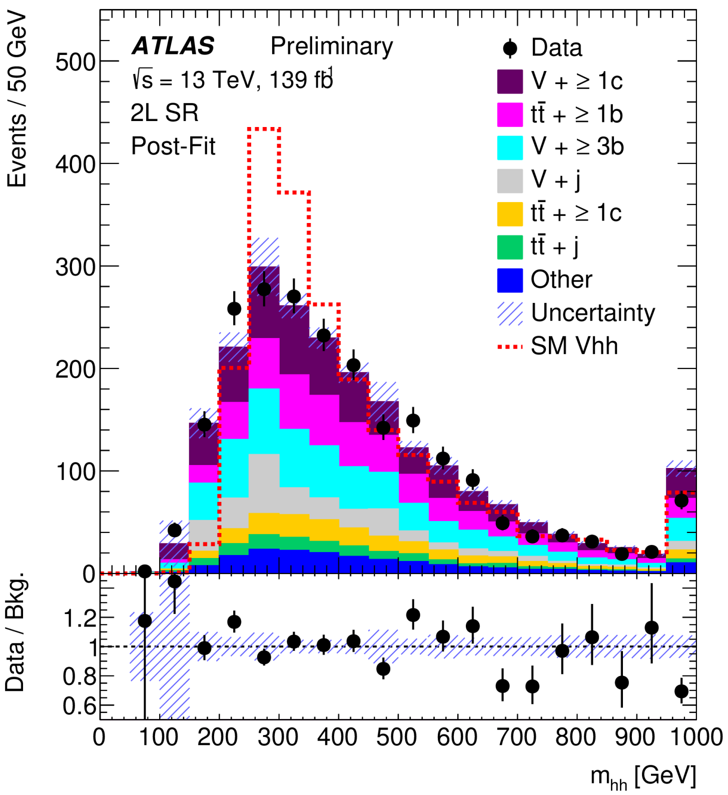
- Experimental signatures
  - $Zhh \rightarrow \nu\nu 4b$ (0L), $Whh \rightarrow l\nu 4b$ (denoted by 1L), $Zhh \rightarrow ll4b$ (denoted by 2L)

ATLAS Vhh search

- Event selection:
  - A leptonic W or Z candidate
  - Two $h \rightarrow bb$ candidates by minimising the value of $|m_{h1} - 120| + |m_{h2} - 120|$ GeV
- Main backgrounds: $t\bar{t}$, V+jets, constrained using data CRs

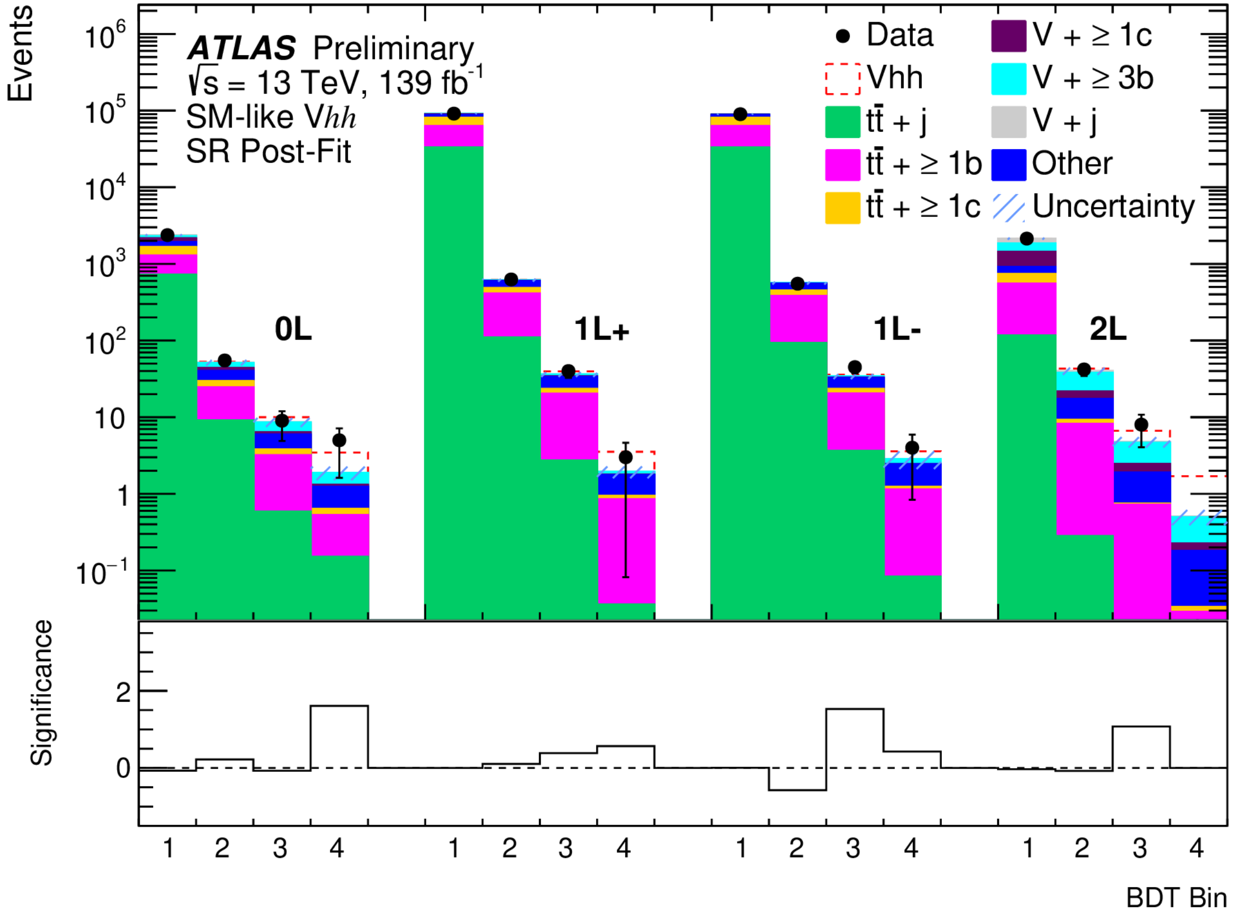






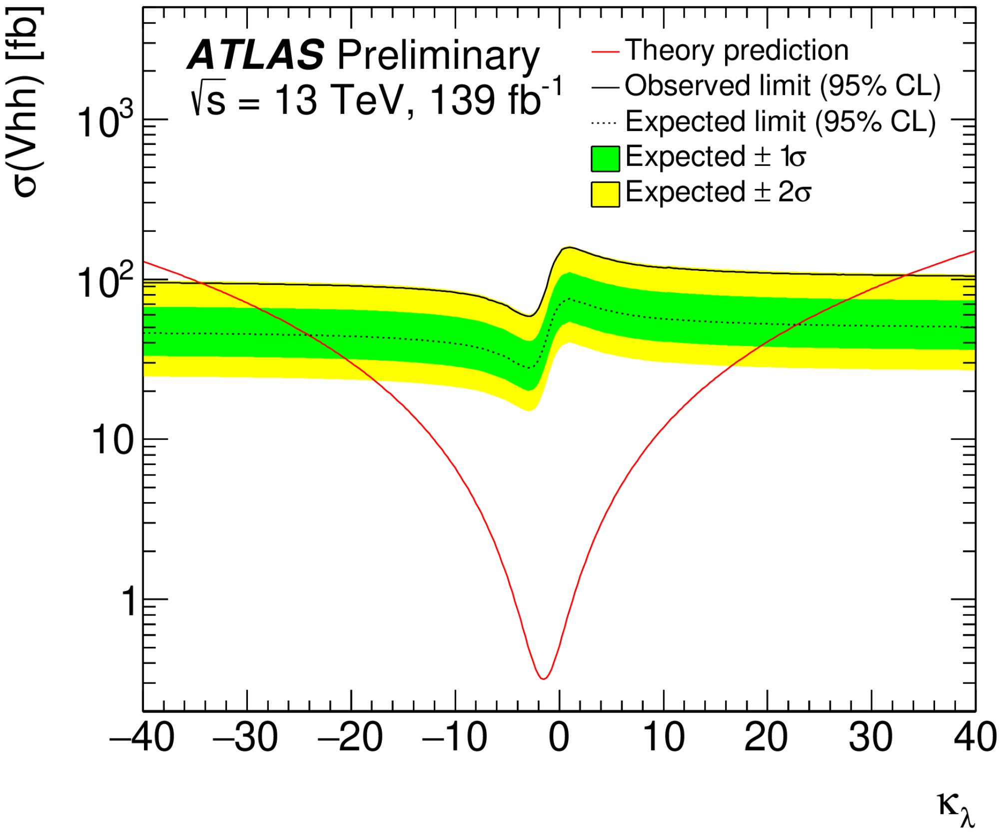
ATLAS Vhh search

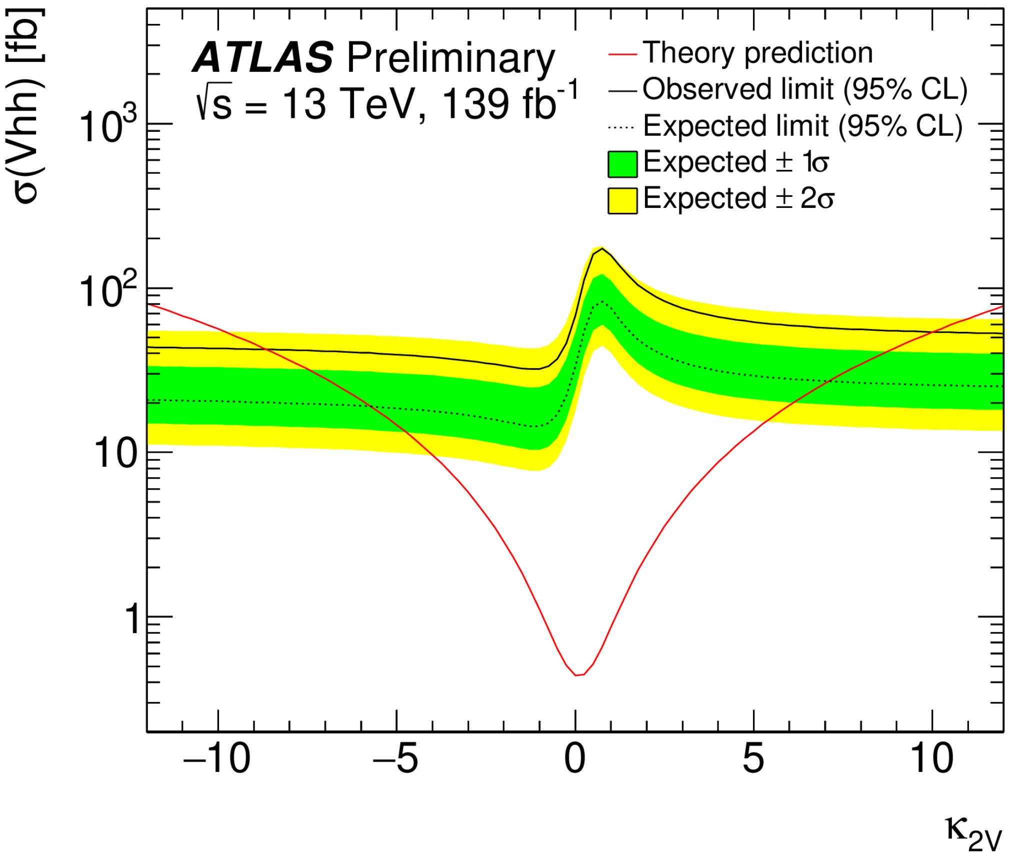
- BDTs are used to improve the signal/background separation
  - One for each channel (0/1/2-L)



ATLAS Vhh search

- Constraints on $\kappa_{2V}, \kappa_{\lambda}$
  - Weaker sensitivity than ggF and VBF processes





Triboson production

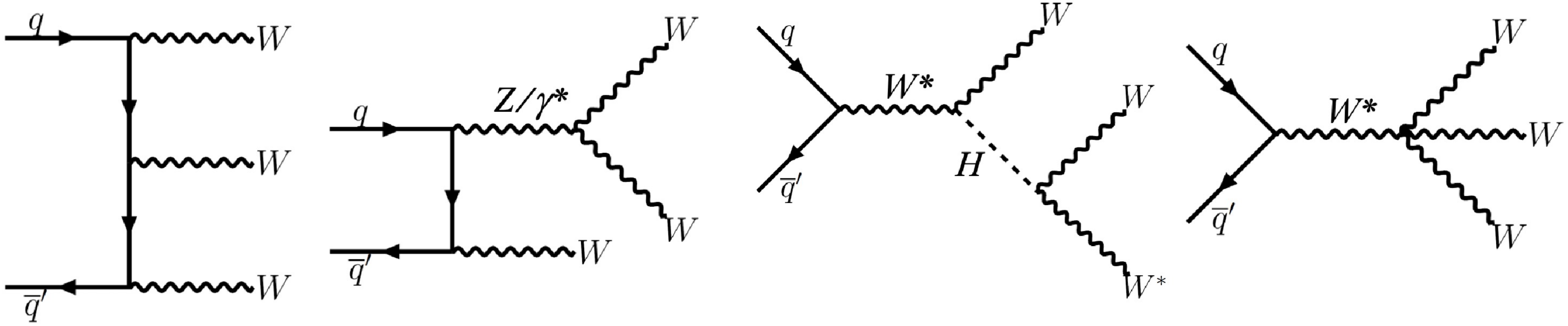
focused on WWW

See other triboson(VVγ, V$\gamma\gamma$) results in talks by:

Bing Li, Andrew Gilbert, Andrew Michael Levin

WWW observation

- Direct measurement of gauge boson self-coupling
  - Finely balanced cancellations between QGC, TGC, Higgs amplitudes needed to preserve unitarity at high CM energies



- First evidence for WWW and WWZ at ATLAS in 2019 (PLB 798 (2019) 134913)
  - Partial Run 2 dataset 80 fb^{-1}
  - Observed: WVV 4.1σ, WWW 3.2σ
- First observation of VVV (V=W,Z) at CMS in 2020 (PRL125(2020)151802)
  - Full Run-2 with 139 fb^{-1}
  - Observed: 5.7σ (3.3σ for WWW and 3.4σ for WWZ)

ATLAS WWW observation

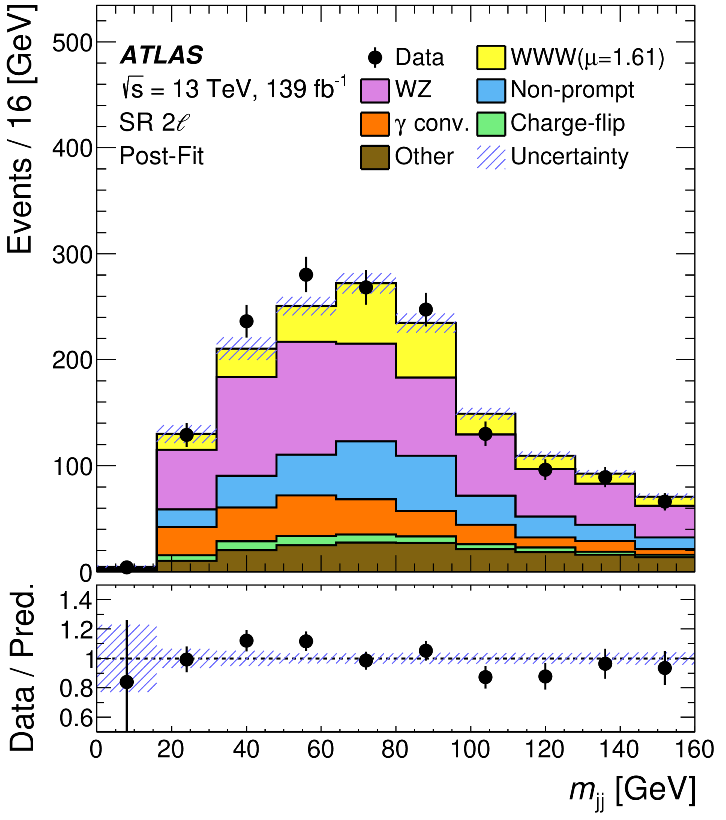
PRL 129 (2022) 061803

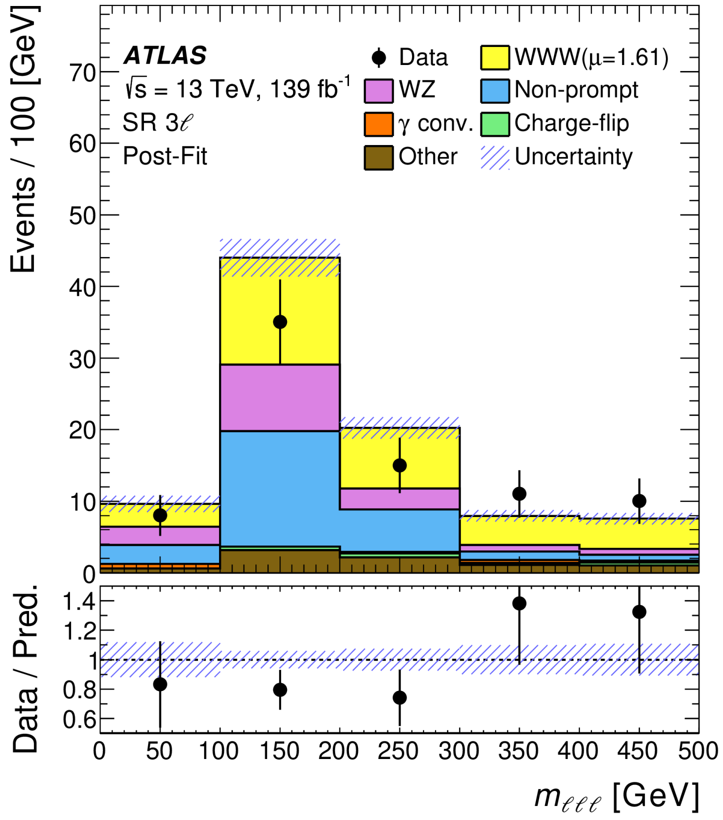
- New measurements
  - Full Run-2 with 139 fb^{-1}
  - Final states considered: WWW→2l2νjj, 3l3ν with l=e, μ

Channel	Detector Signatures
$W^{\pm}W^{\pm}W^{\mp} \rightarrow 2l2\nu jj$	$e^{\pm}e^{\pm}jj + E_T^{miss}$ $e^{\pm}\mu^{\pm}jj + E_T^{miss}$ $\mu^{\pm}\mu^{\pm}jj + E_T^{miss}$
$W^{\pm}W^{\pm}W^{\mp} \rightarrow 3l3\nu$	$e^{\pm}e^{\pm}\mu^{\mp} + E_T^{miss}$ $\mu^{\pm}\mu^{\pm}e^{\mp} + E_T^{miss}$

ATLAS WWW observation

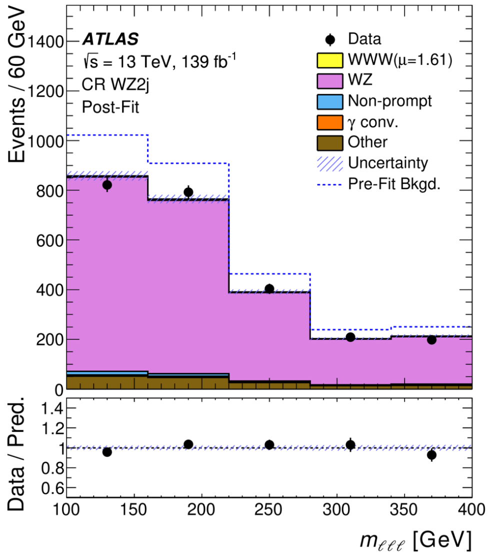
- For 2l2j: m_{jj} < 160 GeV, $|\Delta\eta_{jj}|$ < 1.5 required to reject same-sign WWjj
- Main Backgrounds :
  - 2l2j: WZ+2jets, non-prompt leptons (mainly ttbar), γ conversions
  - 3l: WZ+0jets, non-prompt





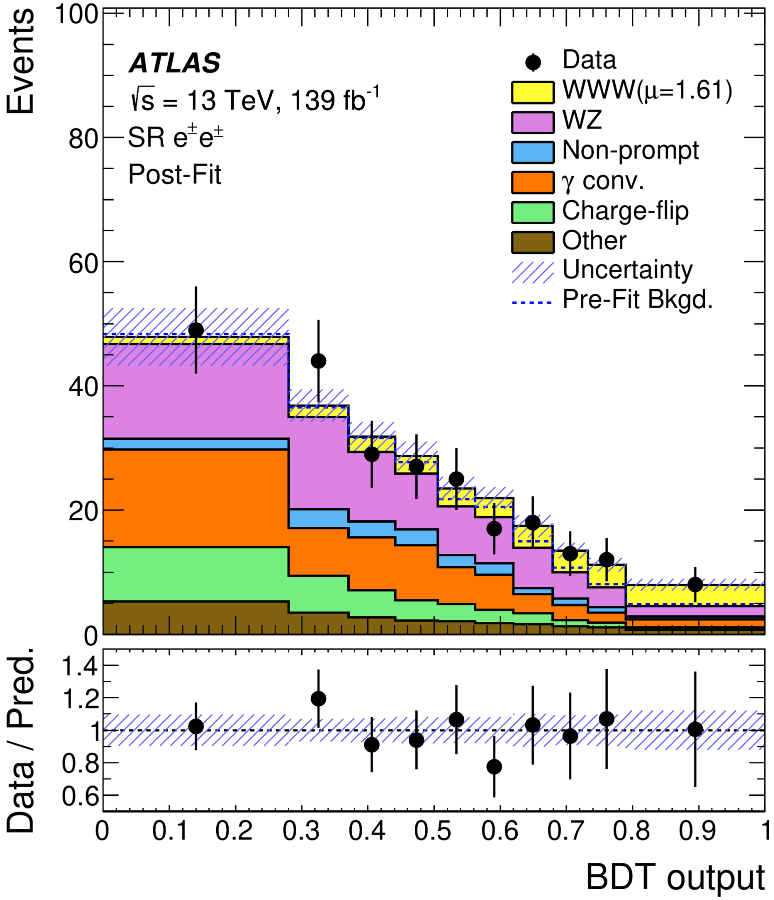
Background estimation:

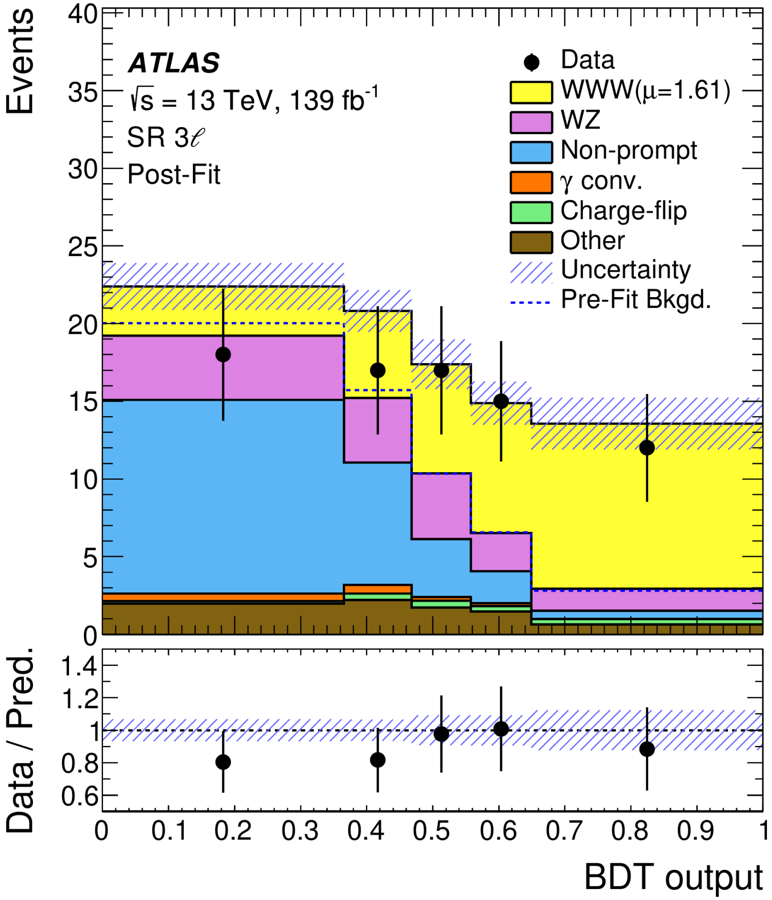
- WZ: three control regions defined, 0/1/2-jets
- non-prompt leptons and γ conversions: fake-factor methods



ATLAS WWW observation

- Two BDTs used to improve signal to background separation in 2l2j and 3l SRs
  - Using XGBoost





ATLAS WWW observation

- Signal extraction: binned likelihood fit to BDT distributions in SRs and m_{lll} in WZ CRs
  - Observed (expected) significance of 8.0(5.4)σ
- The inclusive $pp \rightarrow WWW$ production cross section is measured
  - $\sigma^{meas.} = \sigma^{pred.} \cdot \mu^{meas.}$

	Measured	**Predicted**
σ(pp→WWW)	820 ± 100 (stat.) ± 80 (syst.) fb	511 ± 18 (syst.) fb

SM prediction: NLO QCD + LO EW
- Sherpa 2.2.2 for on-shell WWW: 209 ± 17 fb
- PowhegBox v2 for WH→WWW*: 302 ± 8 fb

~2.6σ discrepancy

Fit	$\mu(WWW)$	Significance observed (expected)
$e^{\pm}e^{\pm}$	1.54 ± 0.76	2.2 (1.4) σ
$e^{\pm}\mu^{\pm}$	1.44 ± 0.39	4.1 (3.0) σ
$\mu^{\pm}\mu^{\pm}$	2.23 ± 0.46	5.6 (2.7) σ
2ℓ	1.75 ± 0.30	6.6 (4.0) σ
3ℓ	1.32 ± 0.37	4.8 (3.8) σ
Combined	**1.61 ± 0.25**	**8.0 (5.4) σ**

Uncertainty source	$\Delta\sigma/\sigma$ [%]
Data-driven background	6.0
Prompt-lepton-background modeling	3.0
Jets and $E_{\mathrm{T}}^{\mathrm{miss}}$	2.6
MC statistics	2.5
Lepton	2.2
Luminosity	1.9
Signal modeling	1.5
Pile-up modeling	1.0
Total systematic uncertainty	9.9
Data statistics	11.6
WZ normalizations	3.1
Total statistical uncertainty	12.0

CMS VVV observation

PRL125(2020)151802

- Combined production of VVV (V=W,Z) with full Run2 data

Process	Theoretical cross section (NLO)	σ_{TOT} x BR
WWW	509 fb	54.0 fb
WWZ	354 fb	4.12 fb
WZZ	91.6 fb	0.36 fb
ZZZ	37.1 fb	0.05 fb

Production	Decay channels
WWW	$W^{\pm}W^{\pm}W^{\mp} \rightarrow 2l2vjj$
	$W^{\pm}W^{\pm}W^{\mp} \rightarrow 3l3v$
WWZ	$W^{\pm}W^{\mp}Z \rightarrow 4l2v$
WZZ	$W^{\pm}ZZ \rightarrow 5l1v$
ZZZ	$ZZZ \rightarrow 6l$

- BDTs used in 2l, 3l and 4l channels, cut-based for the others
  - The 2l channel is subdivided into 3 categories: 1-jets, m_{jj}-in($65 < m_{jj} < 95$ GeV), m_{jj}-out
  - The 3l channel is subdivided based on the number of SFOS lepton pairs: 0/1/2-SFOS

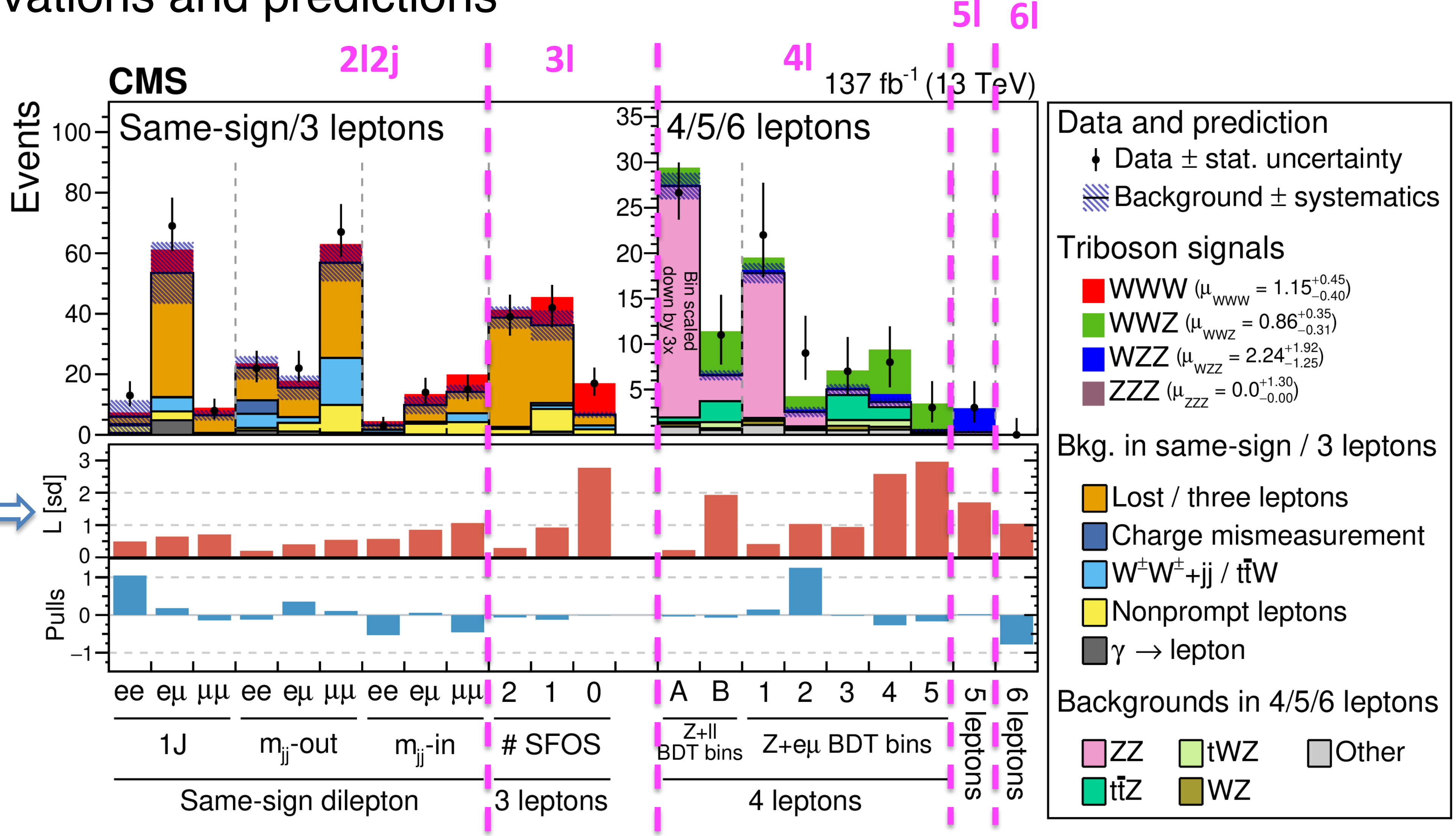
CMS VVV observation

PRL125(2020)151802

- Summary of observations and predictions

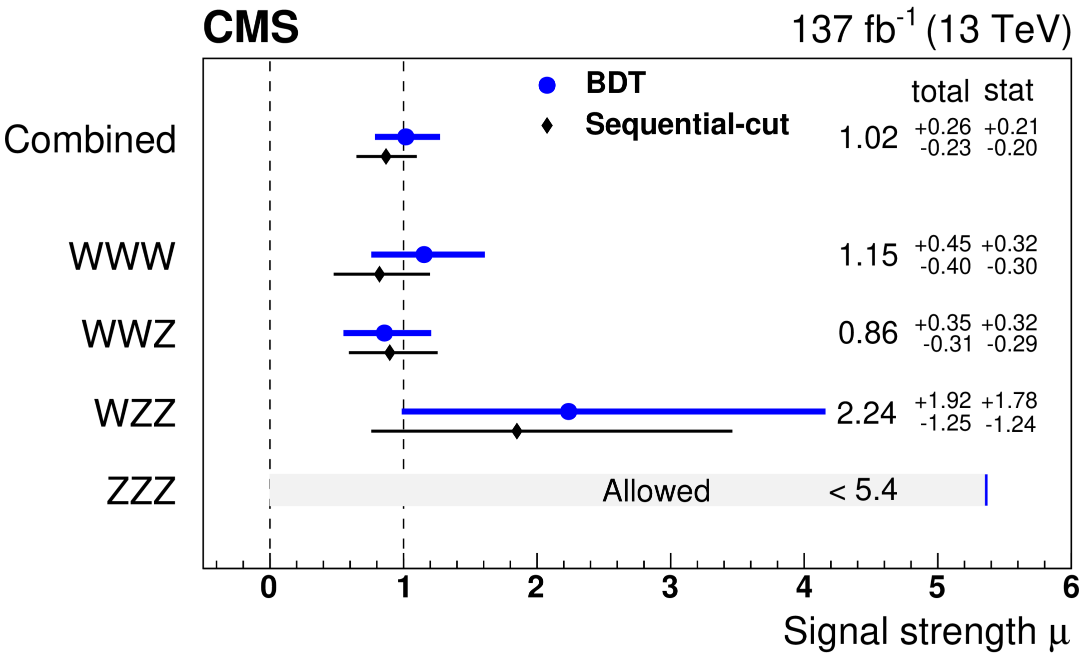
In the most sensitive signal regions, approximately 1/3 of the VVV events come from VH production.

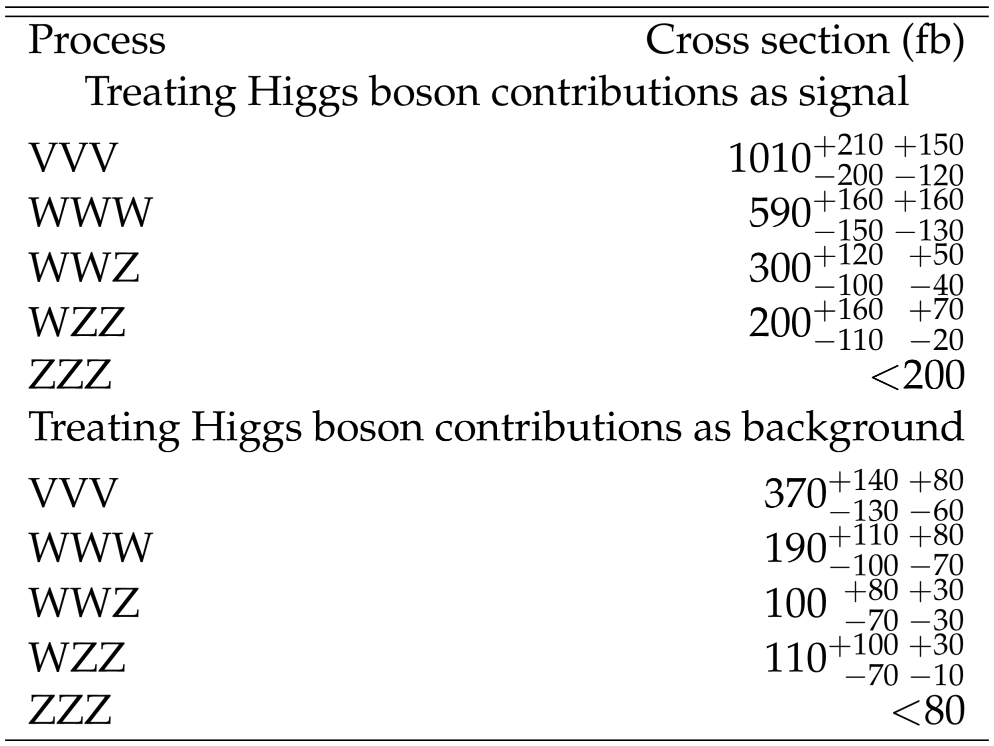
Signal significance



CMS VVV observation

- Signal strength and cross-section measurements
  - Observed: 5.7σ (3.3σ for WWW and 3.4σ for WWZ)





Process	Cross section (fb)
Treating Higgs boson contributions as signal	
VVV	$1010^{+210}_{-200}\,^{+150}_{-120}$
WWW	$590^{+160}_{-150}\,^{+160}_{-130}$
WWZ	$300^{+120}_{-100}\,^{+50}_{-40}$
WZZ	$200^{+160}_{-110}\,^{+70}_{-20}$
ZZZ	<200
Treating Higgs boson contributions as background	
VVV	$370^{+140}_{-130}\,^{+80}_{-60}$
WWW	$190^{+110}_{-100}\,^{+80}_{-70}$
WWZ	$100\,^{+80}_{-70}\,^{+30}_{-30}$
WZZ	$110^{+100}_{-70}\,^{+30}_{-10}$
ZZZ	<80

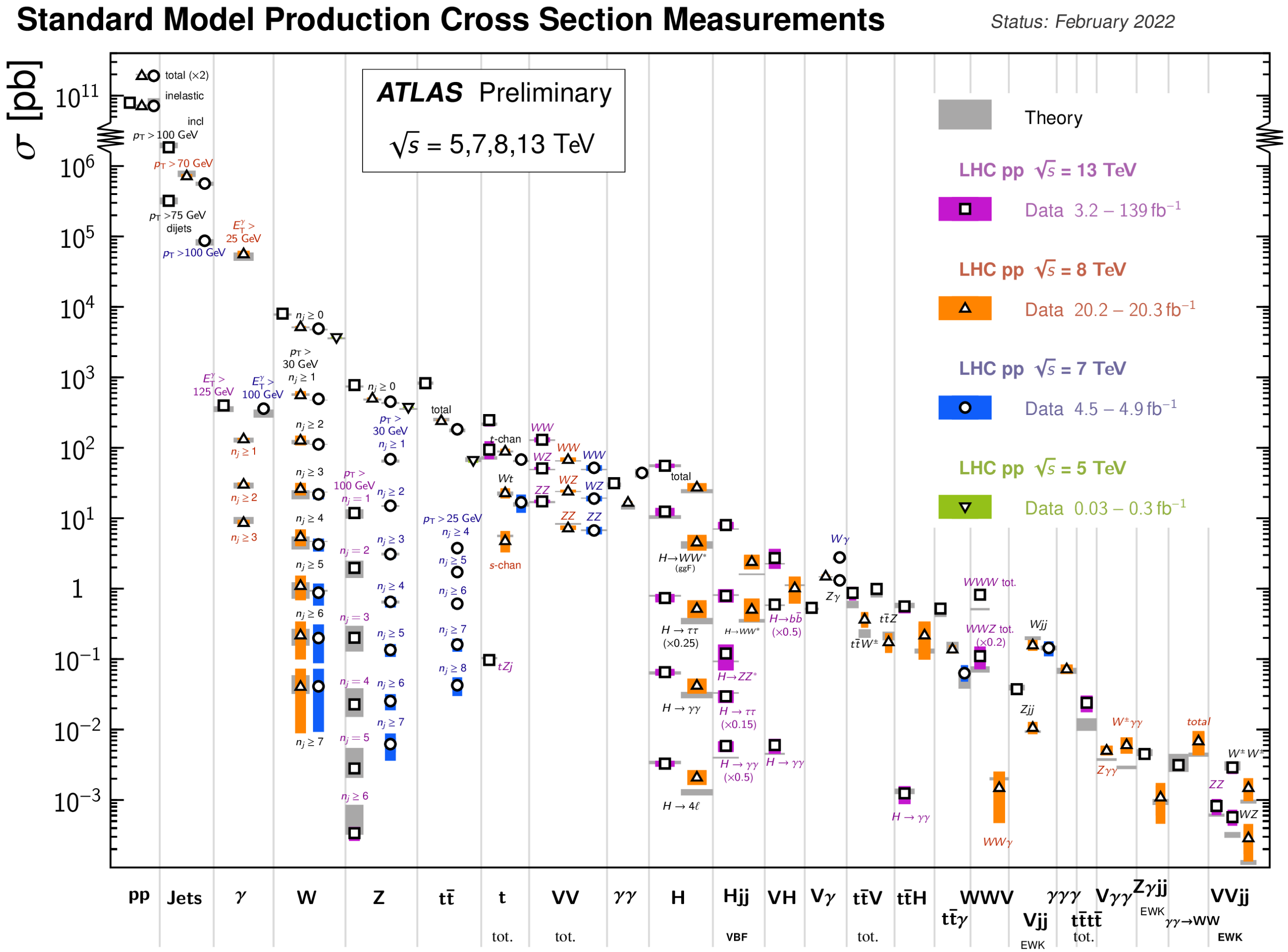
	μ_{WWW}	σ(pp→WWW) Measured	Predicted
ATLAS	1.61 ± 0.25	820 ± 100 (stat.) ± 80 (syst.) fb	511 ± 18 (syst.) fb
CMS	$1.15^{+0.45}_{-0.40}(stat.)^{+0.32}_{-0.30}(syst.)$	$590^{+160}_{-150}(stat.)^{+160}_{-130}(syst.)\mathrm{fb}$	509 (± ~10%) fb

Summary

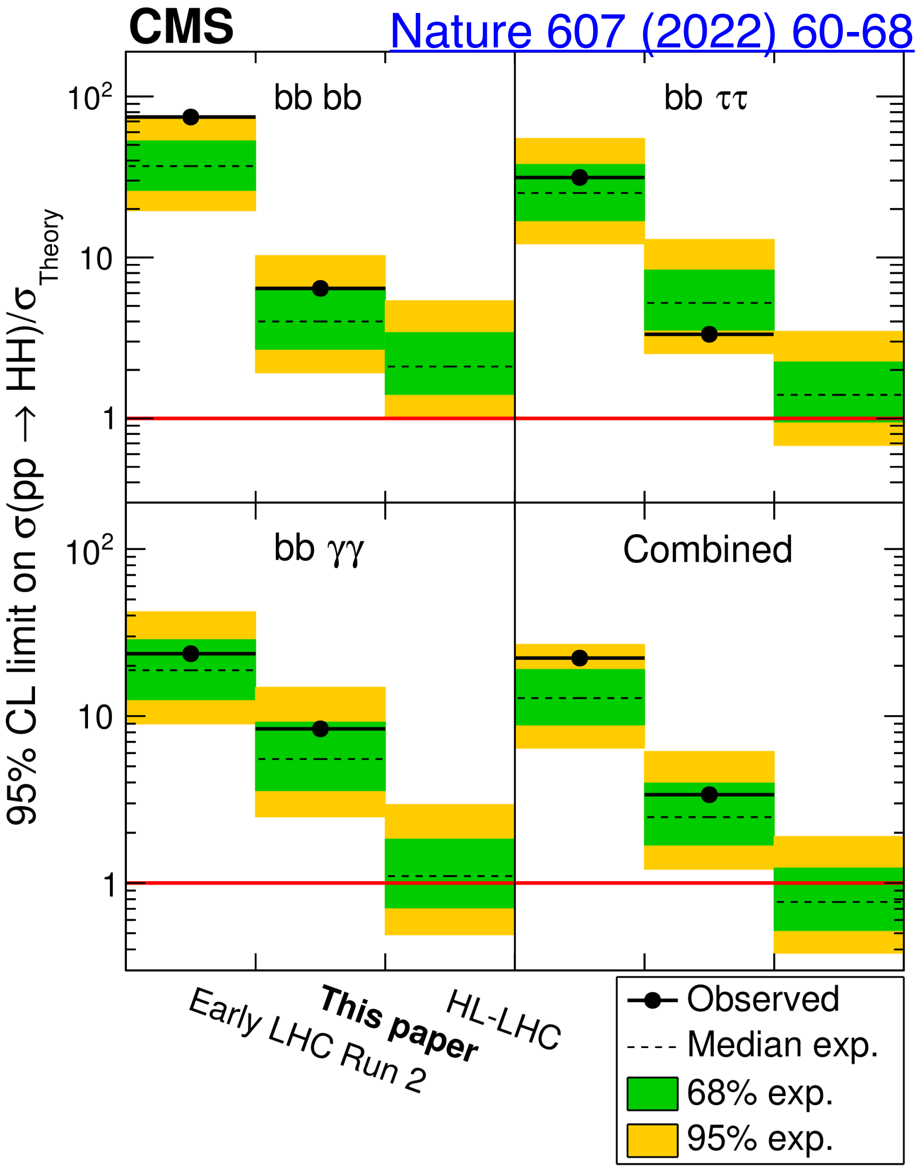
- Multi-boson production involving the Higgs boson covers vibrant Higgs/DiHiggs and EWK physics programs
  - Higgs couplings: HVV, Higgs self-couplings, HHVV
  - Gauge couplings: triple- and quartic-gauge couplings
  - Essential to probe the nature of the EWSB
- Measurements provide invaluable test of the SM and also a unique window to BSM physics
- Looking forward to Run-3 and beyond: a long and exciting journey ahead of us

Summary

ATL-PHYS-PUB-2022-009

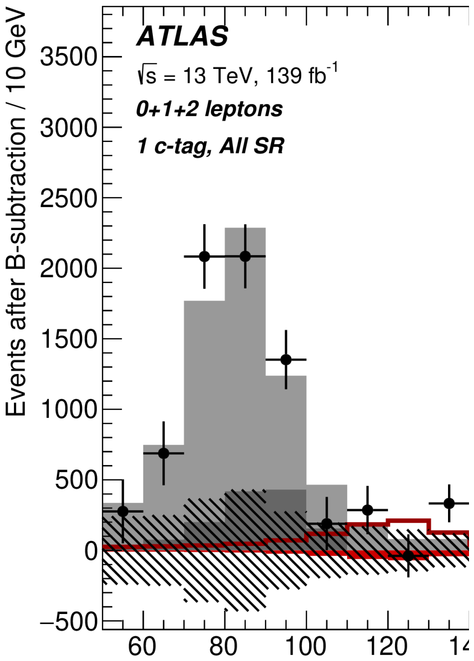


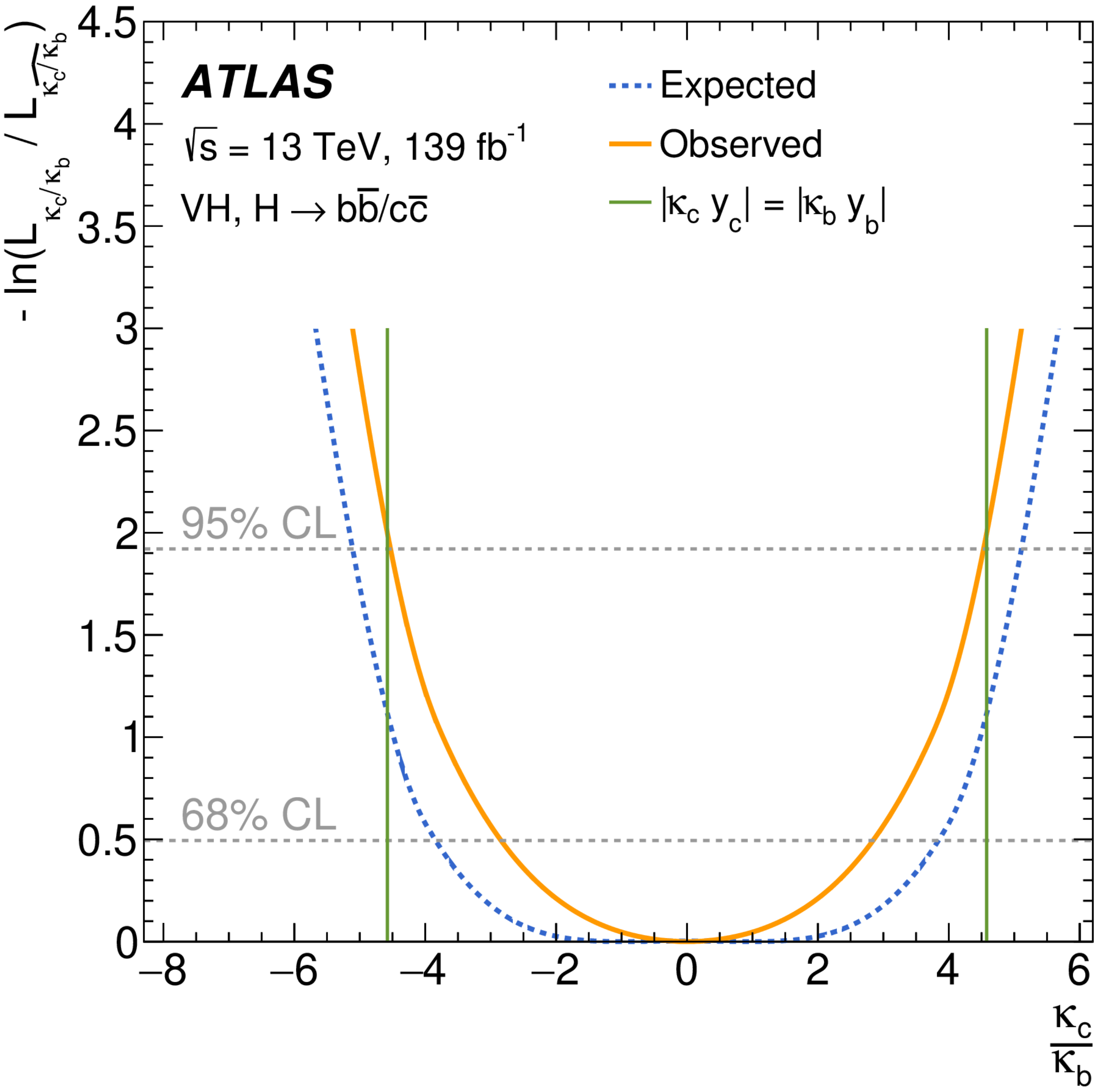
CMS Nature 607 (2022) 60-68



Backup

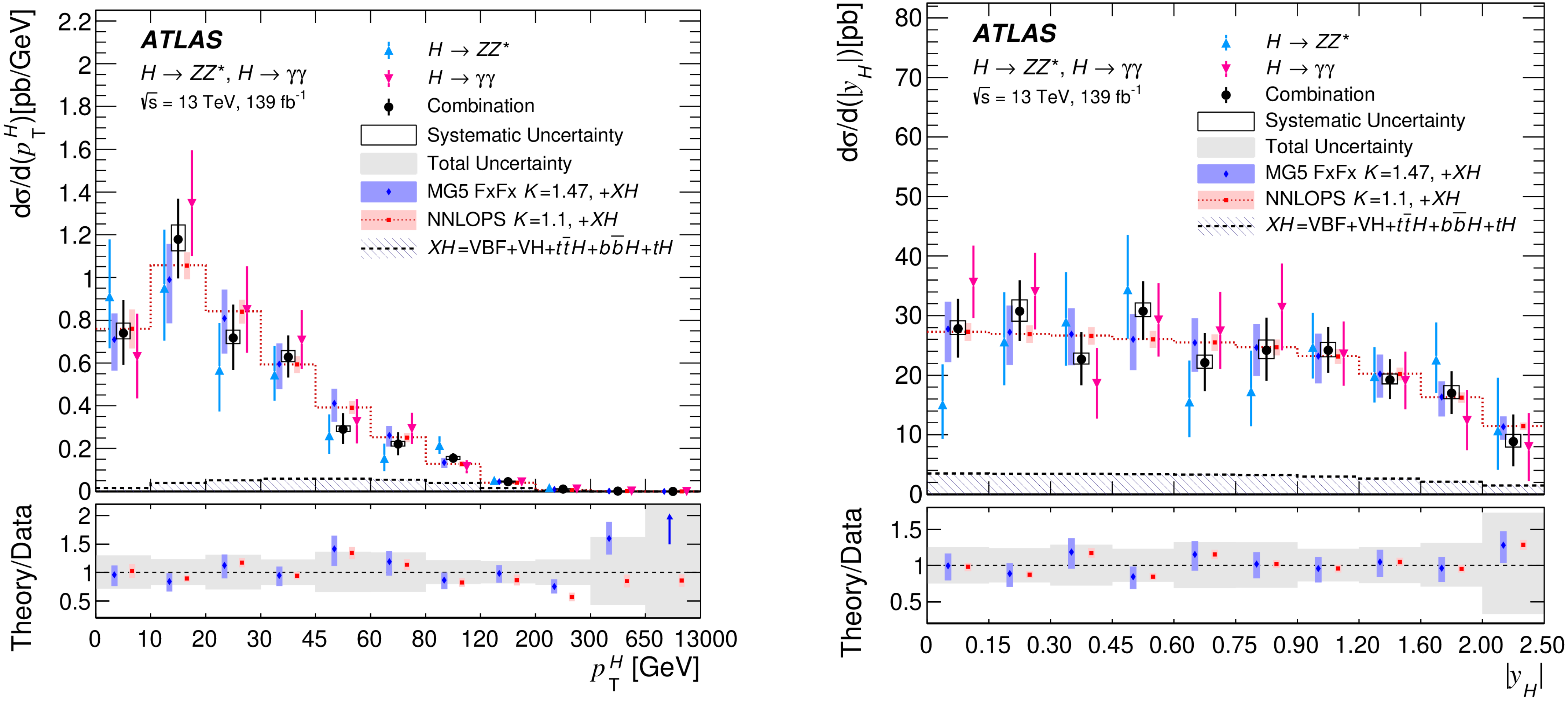
: [arXiv:2201.11428](https://arxiv.org/abs/2201.11428)
[arXiv:2205.05550](https://arxiv.org/abs/2205.05550)





Differential cross-sections

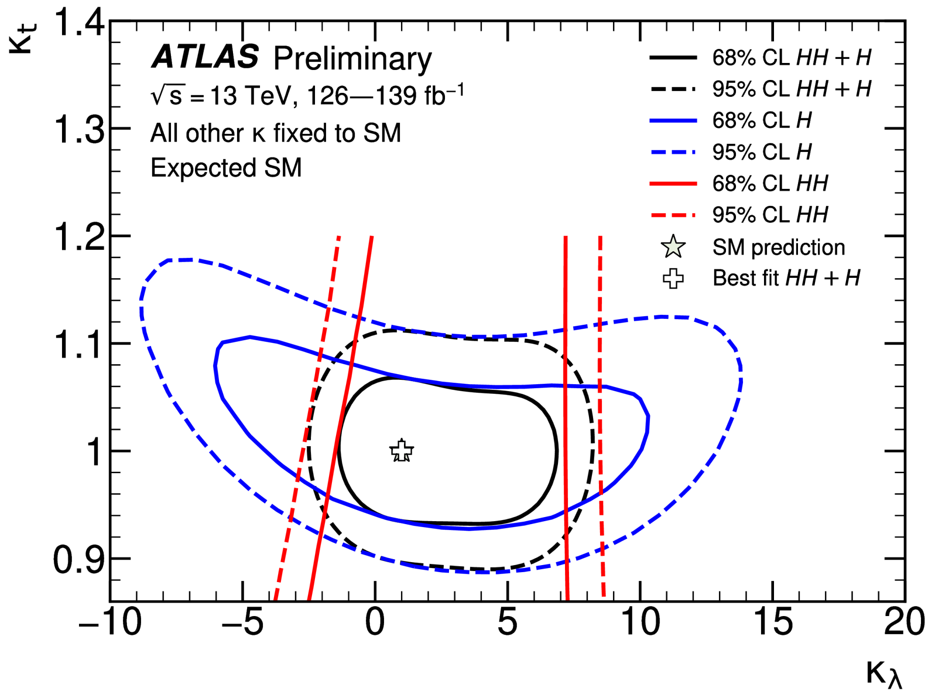
ATLAS: [arXiv:2207.08615](https://arxiv.org/abs/2207.08615)

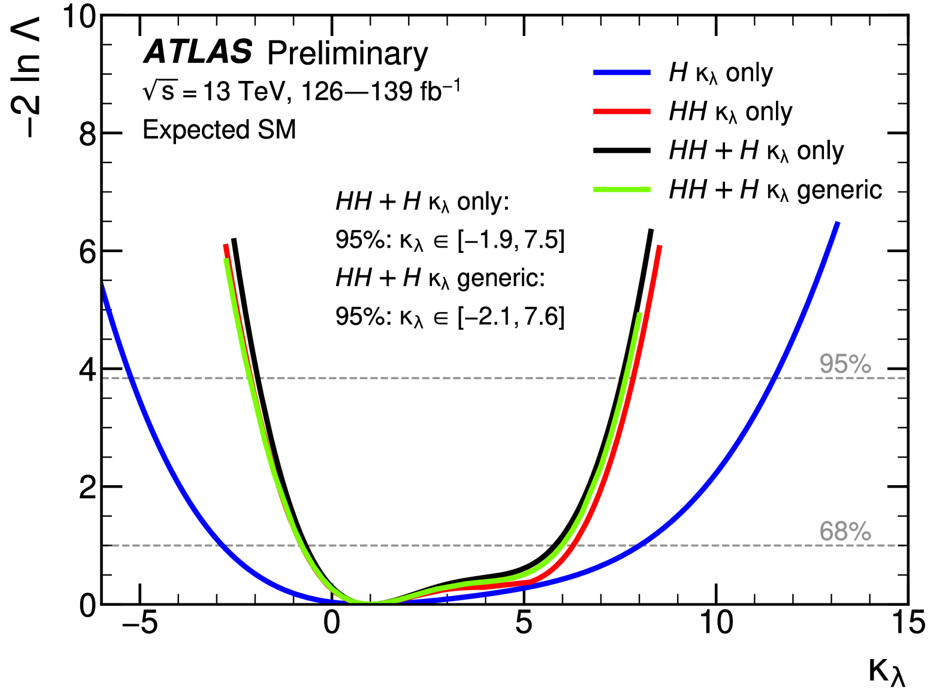


ATLAS H+HH combination

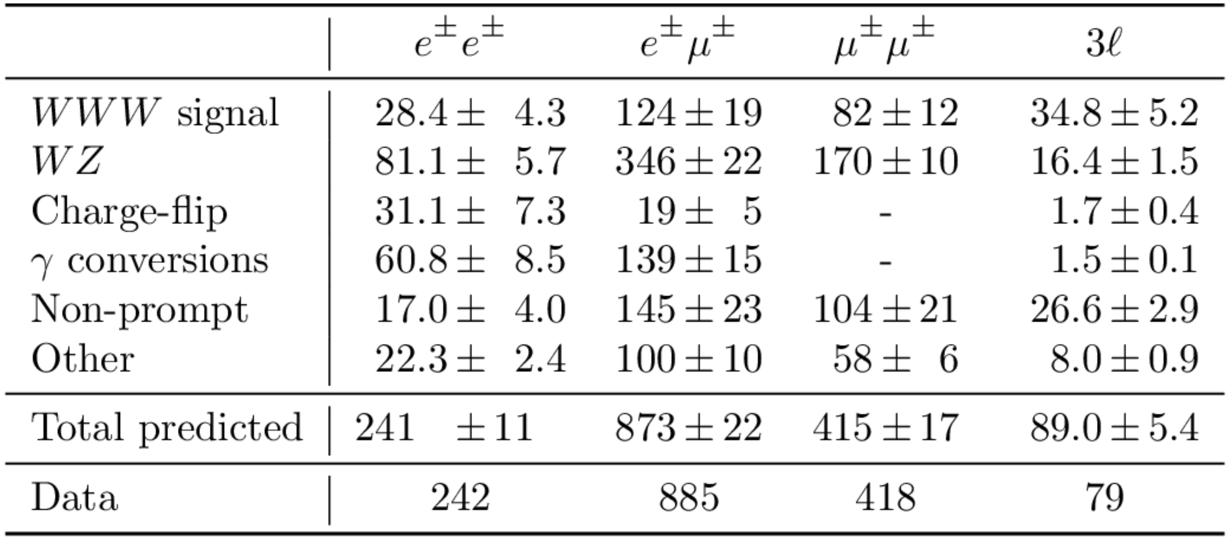
ATLAS-CONF-2022-050

Combination assumption	Obs. 95% CL	Exp. 95% CL	Obs. value$^{+1\sigma}_{-1\sigma}$
HH combination	$-0.6 < \kappa_\lambda < 6.6$	$-2.1 < \kappa_\lambda < 7.8$	$\kappa_\lambda = 3.1^{+1.9}_{-2.0}$
Single-H combination	$-4.0 < \kappa_\lambda < 10.3$	$-5.2 < \kappa_\lambda < 11.5$	$\kappa_\lambda = 2.5^{+4.6}_{-3.9}$
HH+H combination	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.5$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
HH+H combination, κ_t floating	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
HH+H combination, κ_t, κ_V, κ_b, κ_τ floating	$-1.3 < \kappa_\lambda < 6.1$	$-2.1 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 2.3^{+2.1}_{-2.0}$

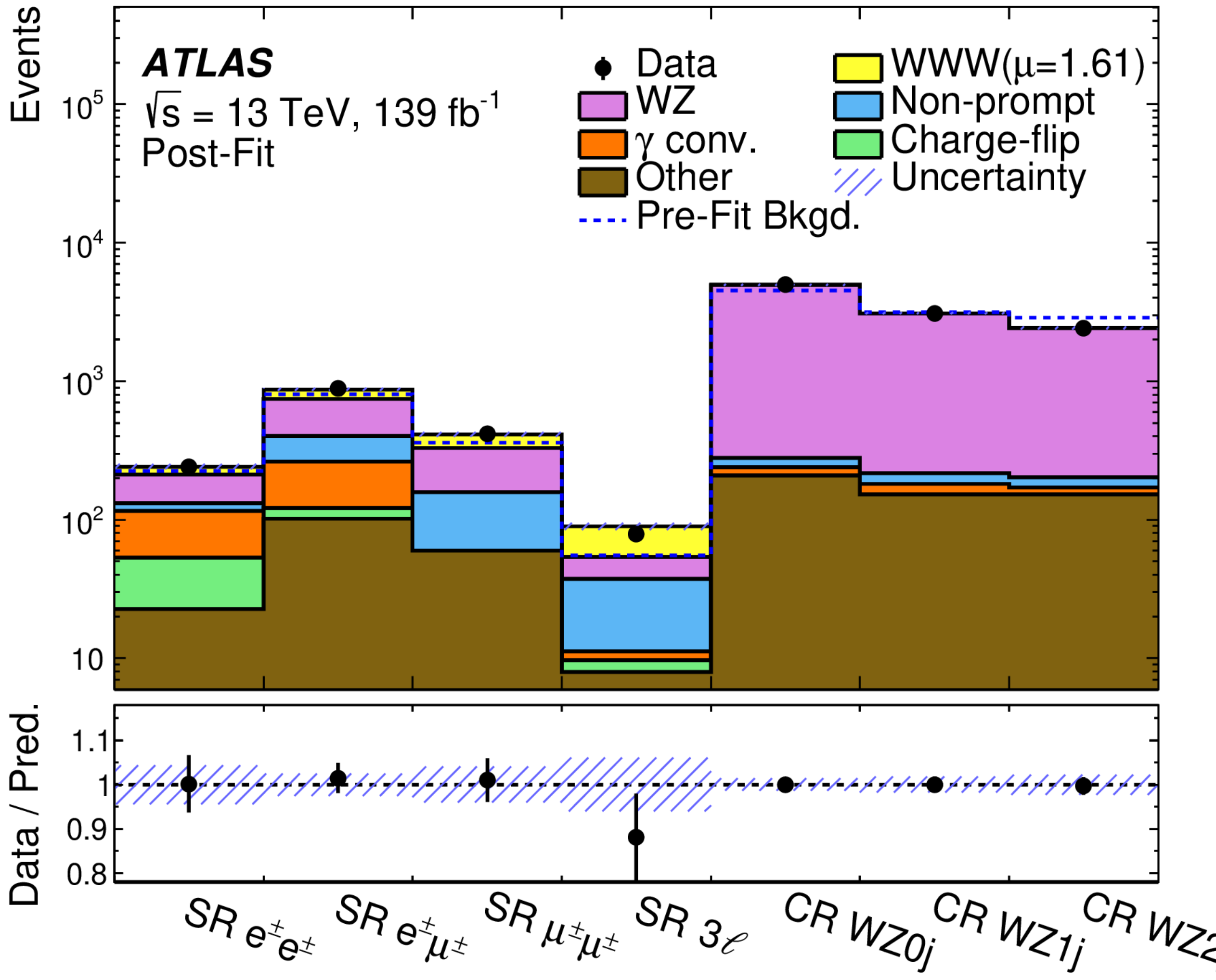




ATLAS WWW observation



	$e^\pm e^\pm$	$e^\pm \mu^\pm$	$\mu^\pm \mu^\pm$	3ℓ
WWW signal	28.4 ± 4.3	124 ± 19	82 ± 12	34.8 ± 5.2
WZ	81.1 ± 5.7	346 ± 22	170 ± 10	16.4 ± 1.5
Charge-flip	31.1 ± 7.3	19 ± 5	-	1.7 ± 0.4
γ conversions	60.8 ± 8.5	139 ± 15	-	1.5 ± 0.1
Non-prompt	17.0 ± 4.0	145 ± 23	104 ± 21	26.6 ± 2.9
Other	22.3 ± 2.4	100 ± 10	58 ± 6	8.0 ± 0.9
Total predicted	241 ± 11	873 ± 22	415 ± 17	89.0 ± 5.4
Data	242	885	418	79



ATLAS WWW

2l2j signal region

2l2v2j Signal Region		
$e^\pm e^\pm$	$e^\pm \mu^\pm$	$\mu^\pm \mu^\pm$
No SFOS pairs, no 3rd lepton		
Leading lepton pT > 27 GeV		
$40 < m_{ll} < 400$ GeV		
$m_{ee} < 80$GeV || $100 \text{ GeV} < m_{ee}$		
≥ 2 jets, $m_{jj} < 160$ GeV, $\lvert\Delta\eta_{jj}\rvert < 1.5$		
no b quark jet		
E_T^{miss} significance > 3		

Rejects non-prompt bkg from J/ψ, ϒ, γ* + jets

Rejects Charge Flip Electrons from Z → ee

Rejects WW VBS

Rejects non-prompt lepton from b-decays (tt, wt etc)

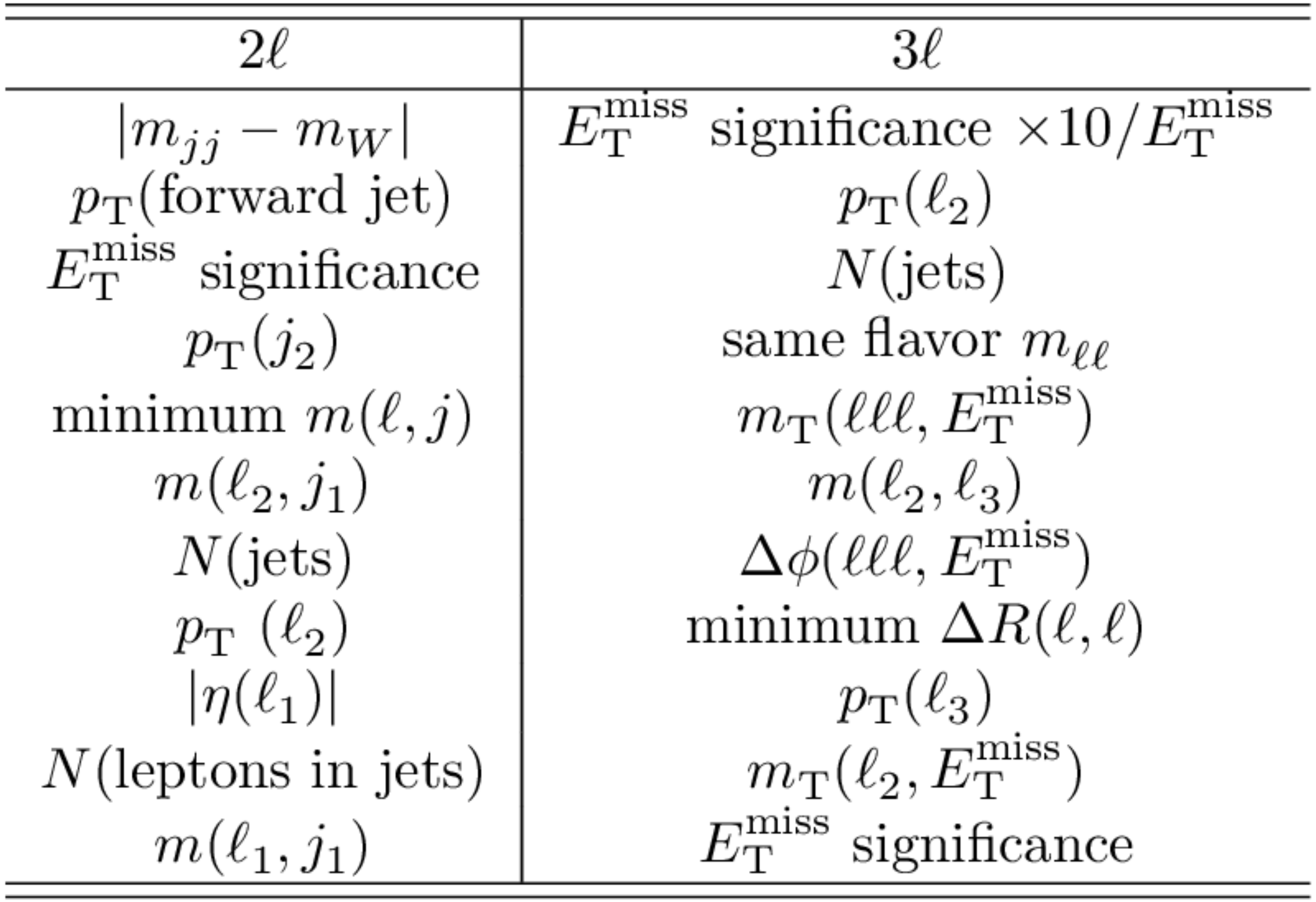
3l signal region

3l3v Signal Region
$e^\pm e^\pm \mu^\mp$ or $e^\mp \mu^\pm \mu^\pm$
No OSSF pairs
No 4th lepton
Leading lepton pT > 27 GeV
Sum of lepton charge = 1 (++ − or −− +)
no b-jets

Rejects non-prompt lepton from b-decays (tt, wt etc)

ATLAS WWW

Boosted Decision Tree Variables



2ℓ	3ℓ
$\lvert m_{jj} - m_W \rvert$	$E_{\mathrm{T}}^{\mathrm{miss}}$ significance $\times 10/E_{\mathrm{T}}^{\mathrm{miss}}$
p_{T}(forward jet)	$p_{\mathrm{T}}(\ell_2)$
$E_{\mathrm{T}}^{\mathrm{miss}}$ significance	N(jets)
$p_{\mathrm{T}}(j_2)$	same flavor $m_{\ell\ell}$
minimum $m(\ell, j)$	$m_{\mathrm{T}}(\ell\ell\ell, E_{\mathrm{T}}^{\mathrm{miss}})$
$m(\ell_2, j_1)$	$m(\ell_2, \ell_3)$
N(jets)	$\Delta\phi(\ell\ell\ell, E_{\mathrm{T}}^{\mathrm{miss}})$
$p_{\mathrm{T}}\ (\ell_2)$	minimum $\Delta R(\ell, \ell)$
$\lvert\eta(\ell_1)\rvert$	$p_{\mathrm{T}}(\ell_3)$
N(leptons in jets)	$m_{\mathrm{T}}(\ell_2, E_{\mathrm{T}}^{\mathrm{miss}})$
$m(\ell_1, j_1)$	$E_{\mathrm{T}}^{\mathrm{miss}}$ significance