Search for Higgs Boson decaying to $b\bar{b}$ and a new resonance decaying to $\gamma\gamma$ with the ATLAS Detector

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Overviews of the collaboration

- On the physics analysis
  - Search for H → $b\bar{b}$ in VH production mode (denoted as H → $b\bar{b}$)
  - Searches for diphoton resonances at low and high mass (denoted as Resonance)
- Involved in the related detector performance studies
  - B-jet tagging calibration *JHEP 08 (2018) 089*
  - Photon energy calibration *JINST 14 (2019) P03017*

LPNHE-Paris		
Kun LIU	Post-doc	H → $b\bar{b}$
Ilaria LUISE	PhD (3rd year)	H → $b\bar{b}$
Giovanni MARCHIORI	CRCN	H → $b\bar{b}$
Ioannis NOMIDIS	Post-doc	Resonance
Lydia ROOS	DR2	Resonance

USTC-Hefei		
Cheng CHEN	PhD (3rd year)	H → $b\bar{b}$
Asma HADEF	Post-doc	Resonance
Changqiao LI	Post-doc	H → $b\bar{b}$
Yanwen LIU	Professor	Both
Yufeng WANG	PhD (2nd year)	Resonance

VH, H→ b$\bar{b}$ Analysis

- H→ b$\bar{b}$:
  - Probe the Higgs coupling to bottom quarks
  - Largest branching ratio
  - Important to the total decay width
- VH production mode:
  - Lepton from W or Z to trigger
  - Better multi-jet background rejection
- Before Run-2
  - No observation of VH, H→ b$\bar{b}$

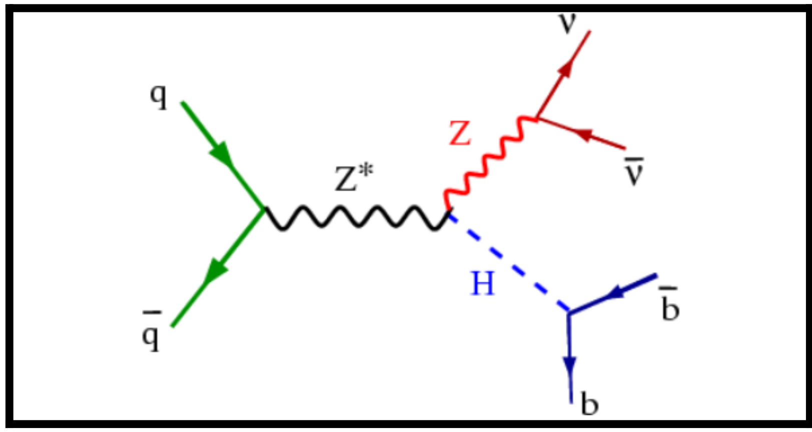
$$\mu = \frac{\sigma \cdot \mathrm{BR}}{\sigma_{\mathrm{SM}} \cdot \mathrm{BR}_{\mathrm{SM}}}$$

	Signal strength	Significance (expected)	Significance (observed)
CDF+DØ combination [1]	$1.9^{+0.8}_{-0.7}$	1.5σ	2.8σ (3.1σ global)
ATLAS Run-I [2]	$0.52^{+0.40}_{-0.37}$	2.6σ	1.4σ
CMS Run-I [3]	$0.89^{+0.47}_{-0.44}$	2.5σ	2.1σ
ATLAS+CMS Run-I* [4]	$0.70^{+0.29}_{-0.27}$	3.7σ	2.6σ

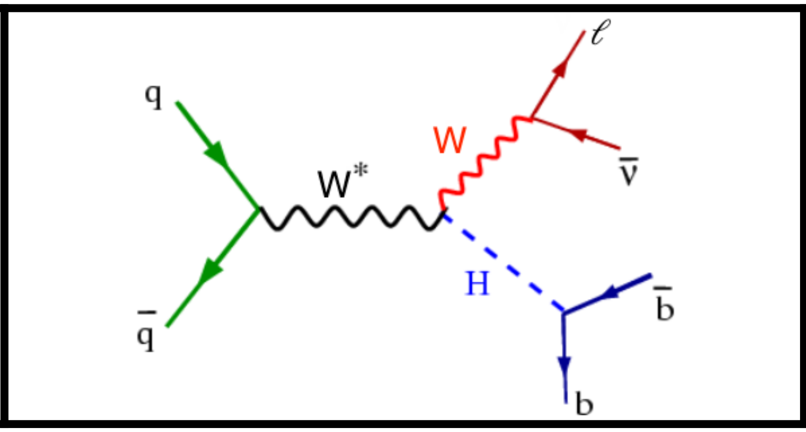
*with sub-leading contribution from ttH, H → bb

[1] Phys. Rev. Lett. **109** (2012) 071804
[2] JHEP01(2015)069
[3] Eur.Phys.J. C75(5), 212 (2015) + twiki
[4] JHEP08(2016)045

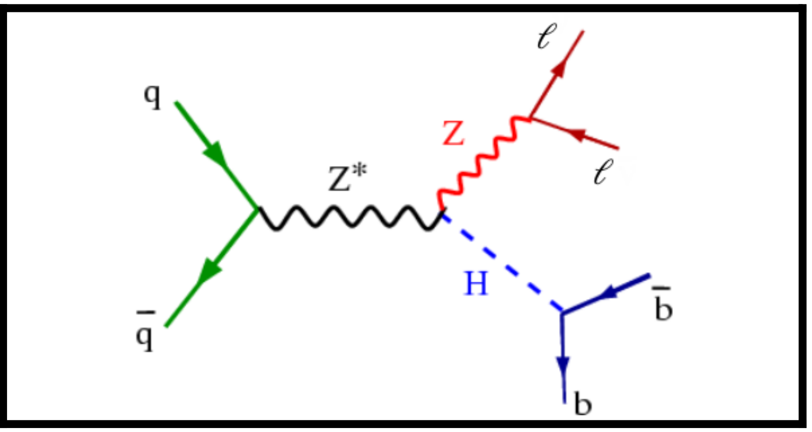
0-lepton



1-lepton



2-lepton



- This analysis performed in 0-/1-/2- lepton channel
- To separate VH signal from V+jets/ttbar/Diboson, Boosted Decision Trees (BDT) trained
- Fit on BDT scores to extract the signal yields

Status of VH, H→ $b\bar{b}$ searches in ATLAS

- *Evidence of VH, H → $b\bar{b}$ production with 36 fb^{-1} JHEP 12 (2017) 024*
- Observation of H → $b\bar{b}$ decays and VH production with 80 fb^{-1}
  - *Phys. Lett. B 786 (2018) 59*
  - H → $b\bar{b}$ decays observed
  - VH production mode observed
- Measurement of VH, H→ $b\bar{b}$ production as a function of the transverse momentum of the vector boson (*arXiv:1903.04618*, submitted to *JHEP*)
- Plan for the measurements with the full Run-2 dataset: 140 fb^{-1}
  - VH, H→ $b\bar{b}$ continued to have a more accurate measurement
  - VH, H→ $b\bar{b}$ in Boosted Regime
    ($b\bar{b}$ reconstructed as one fat-jet instead of two separated jets)
- Current responsibilities:
  - Resolved analysis co-convenor (Kun LIU)
  - HL-LHC prospects contact (Changqiao LI)

VH, $H \rightarrow b\bar{b}$ results with 80 fb^{-1} and from combination

Signal strength

$$\mu_{\mathrm{WH}} = 1.08^{+0.27}_{-0.27}(\mathrm{stat.})^{+0.38}_{-0.34}(\mathrm{syst.})$$

$$\mu_{\mathrm{ZH}} = 1.20^{+0.23}_{-0.23}(\mathrm{stat.})^{+0.23}_{-0.20}(\mathrm{syst.})$$

$$\mu_{\mathrm{VH}} = 1.16^{+0.16}_{-0.16}(\mathrm{stat.})^{+0.21}_{-0.19}(\mathrm{syst.})$$

- Expected significance: 4.3 σ
- Observed significance: 4.9 σ

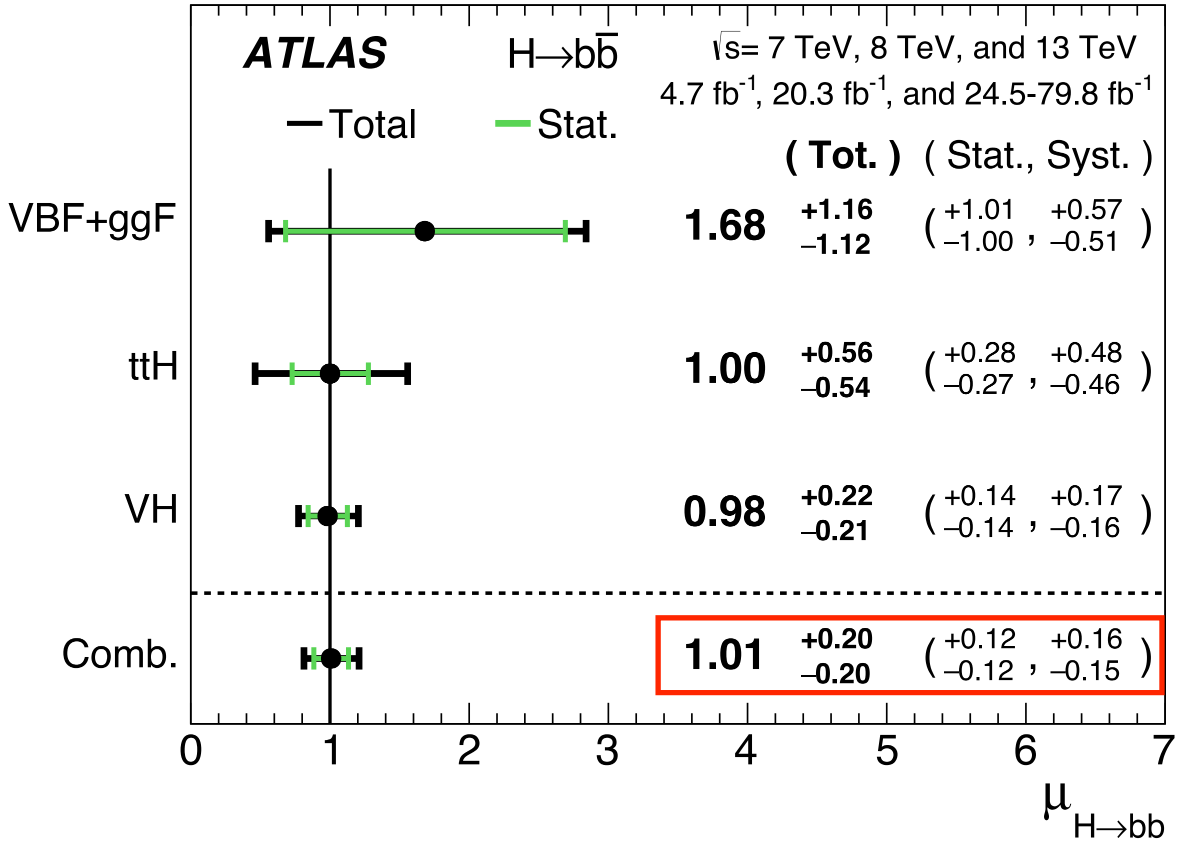
Combination with Run-1 Analysis:
(correlate signal theory and b-jets)

$$\mu_{\mathrm{WH}} = 1.08^{+0.24}_{-0.23}(\mathrm{stat.})^{+0.29}_{-0.27}(\mathrm{syst.})$$

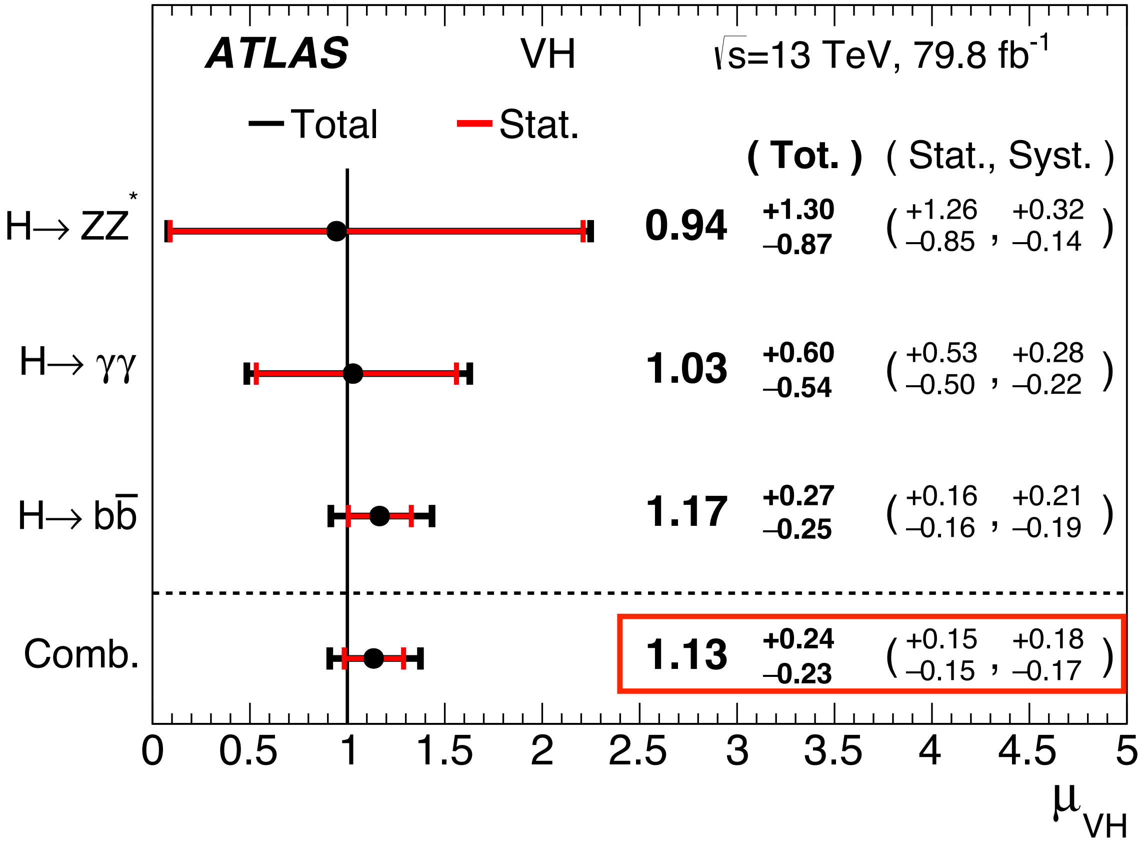
$$\mu_{\mathrm{ZH}} = 0.92^{+0.21}_{-0.20}(\mathrm{stat.})^{+0.19}_{-0.17}(\mathrm{syst.})$$

$$\mu_{\mathrm{VH}} = 0.98^{+0.14}_{-0.14}(\mathrm{stat.})^{+0.17}_{-0.16}(\mathrm{syst.})$$

- Expected significance: 5.1 σ
- Observed significance: 4.9 σ

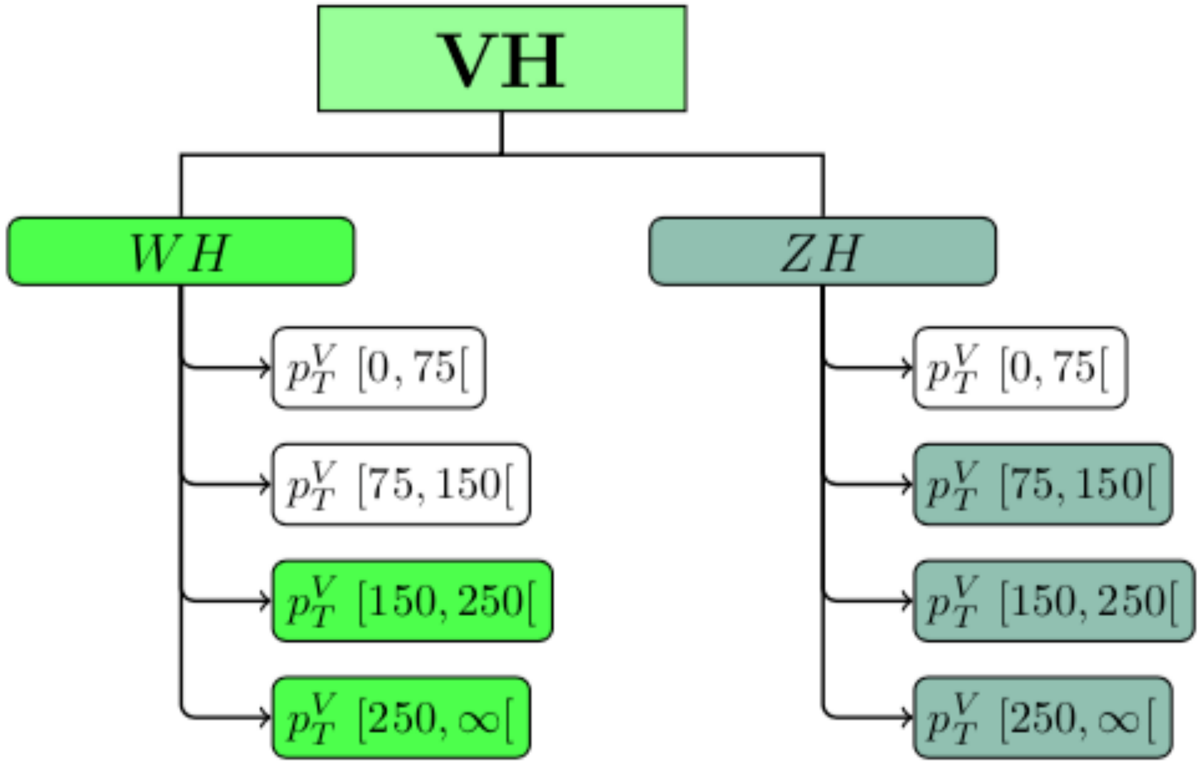


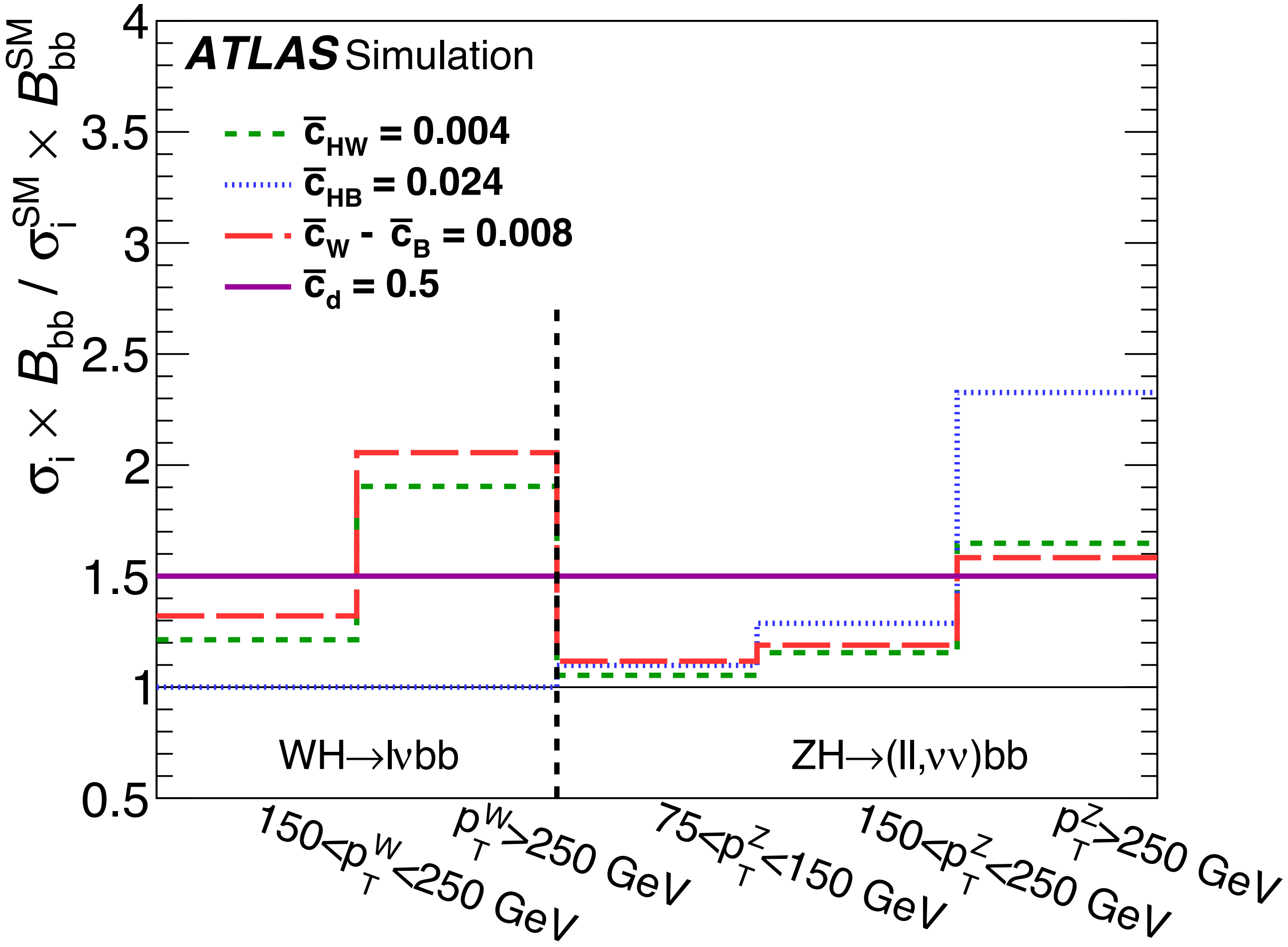
- Exp. significance = 5.5σ
- Obs. significance = 5.4σ
- $H \rightarrow b\bar{b}$ observed



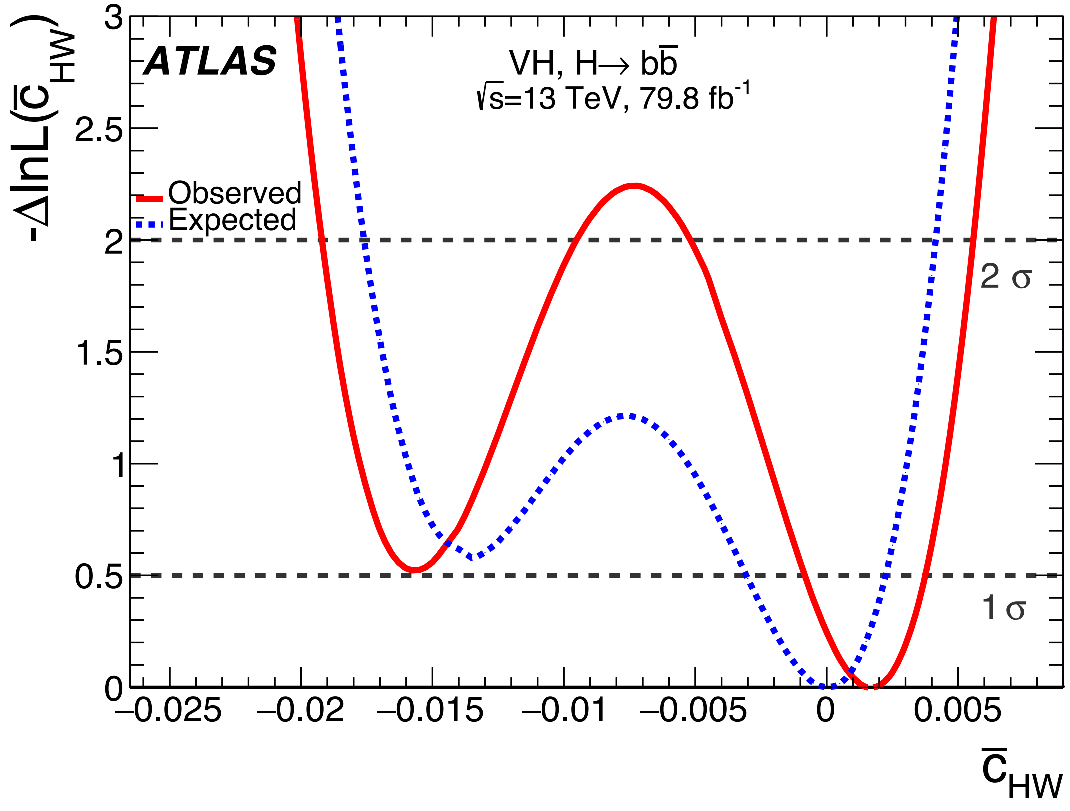
- Exp. significance = 4.8σ
- Obs. significance = 5.3σ
- VH observed

Differential cross-section of VH measurement with H → $b\bar{b}$

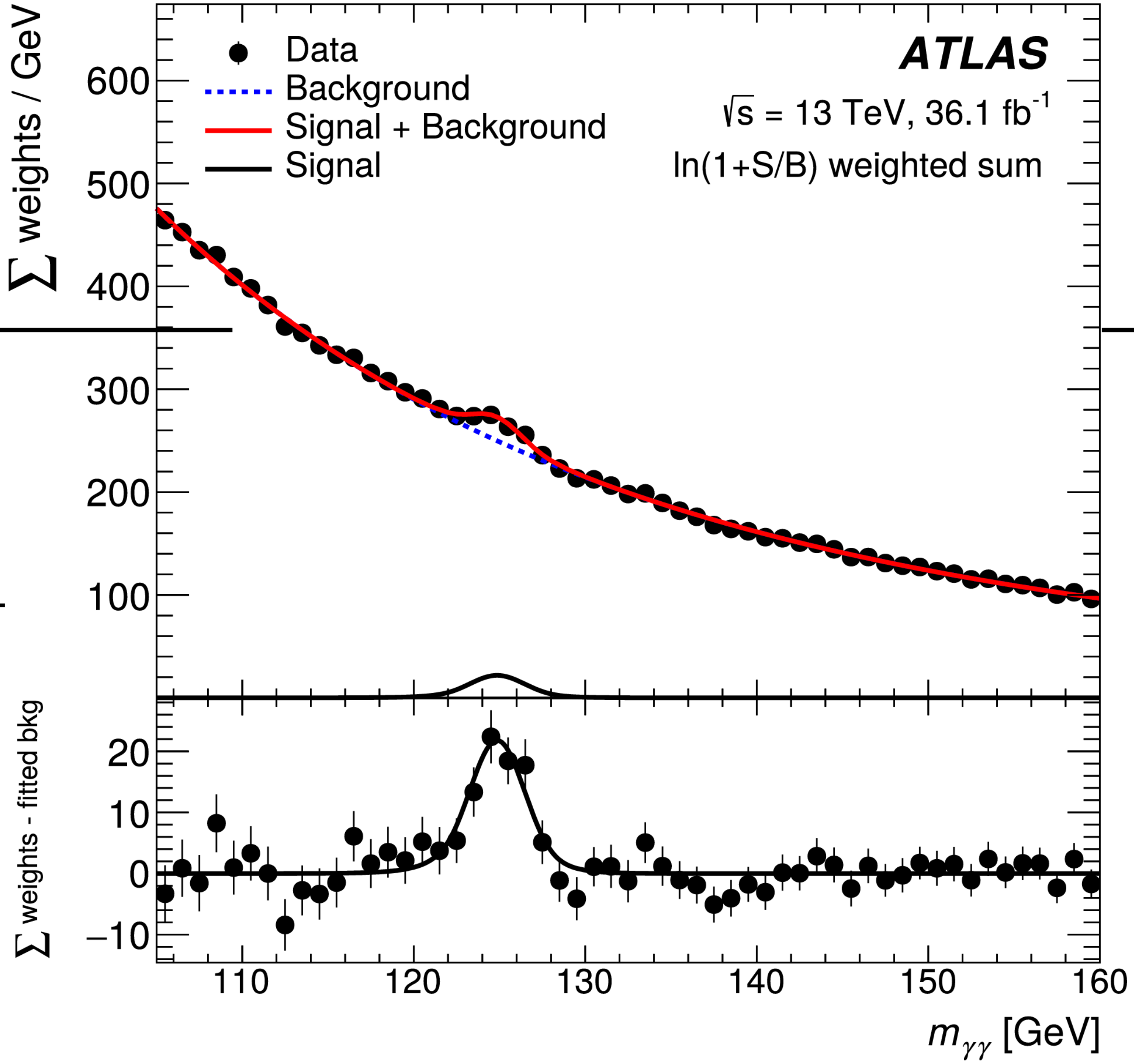




- Differential XS instead of inclusive signal strength
  - Providing more information for VH production
  - High pTV is more sensitive to new physics
- Same analysis strategy to VH, H → $b\bar{b}$:
  - Classification for the events
  - Same discriminant variables for fit
  - Signal theory uncertainties re-evaluated
- 5 XS measured: compatible with SM prediction
- Coefficients of the operators in the new physics are constrained



Search for new resonance decaying to $\gamma\gamma$ in low/high $m\gamma\gamma$



Low:

$m_{\gamma\gamma}$ <110 GeV

Motivated to search for axion-like particles (ALP) [1710.01743]
Simplified model used: ggF-scalar (low-mass SM-like Higgs)

High:

$m_{\gamma\gamma}$ > 160 GeV

Motivated to search for scalar and spin-2 particles [2HDM, R-S graviton, ...]
Narrow-/large-width scalar search
Simplified model used: ggF-scalar (high-mass SM-like Higgs), R-S graviton

- Low/high mass regions are studied separately because:
  - different event selections are used
    (e.g. looser cuts and more sophisticated background estimations needed at low mass)
  - different baseline models are used
    (e.g. no motivation for spin-2 graviton search at low mass)

Status of X→$\gamma\gamma$ searches in ATLAS

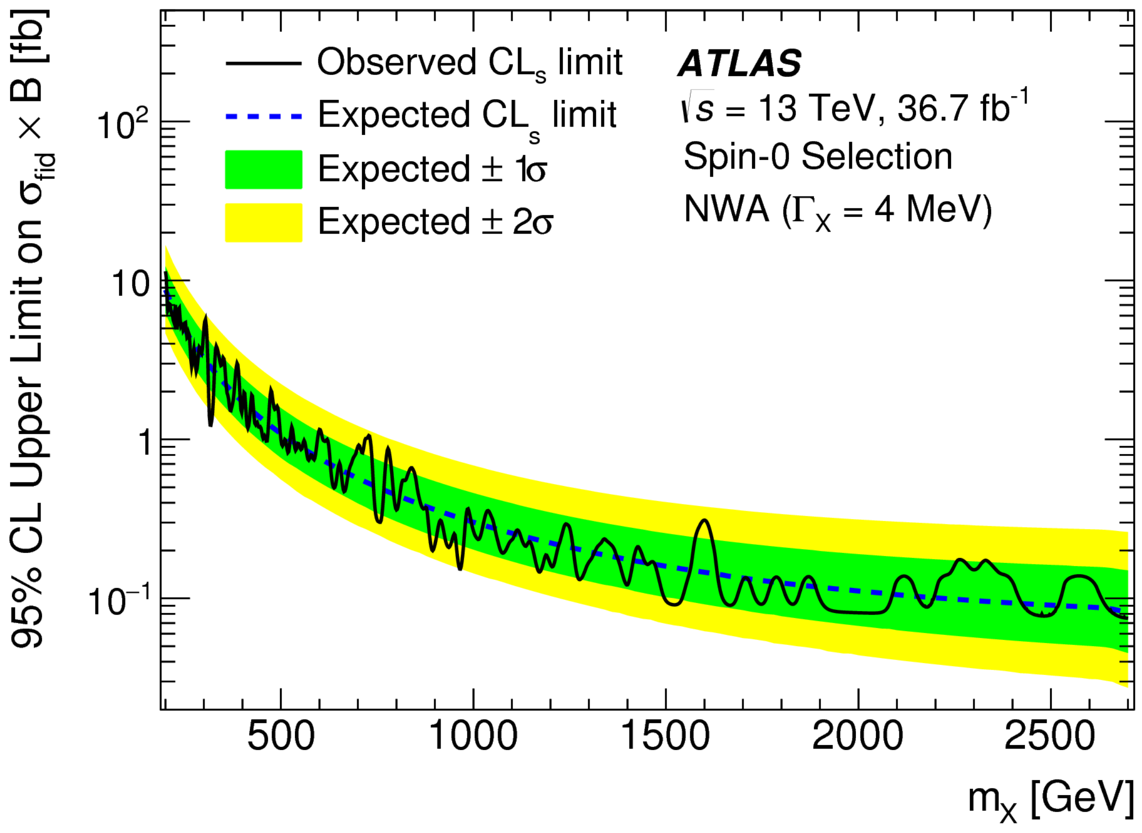
- Last published measurements: 36 fb^{-1}, Run-2
  - *High-mass research, Phys. Lett. B 775 (2017) 105*
- Last public measurements: 80 fb^{-1}
  - Low-mass research, ATLAS-CONF-2018-025
- Plan for the measurements with the full Run-2 dataset: 140 fb^{-1}
  - High mass search: Publication/CONF-conversion for summer conferences, targeting EPS (Mid July)
  - Low/very-low mass search: Publication to arrive in fall 2019
- Current responsibilities:
  - Analysis coordination of the resonance search group (Ioannis)
  - Software coordination of the framework for H→$\gamma\gamma$ analyses (Ioannis)

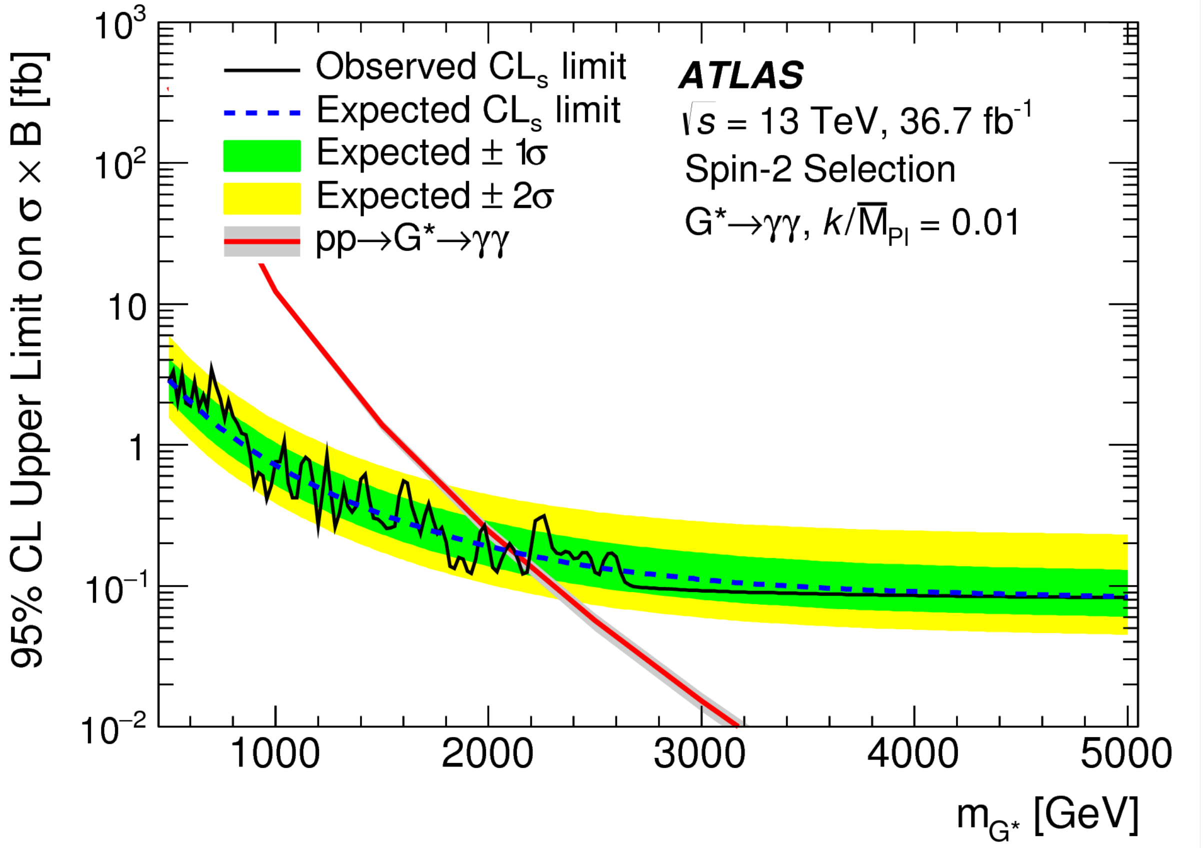
High mass search

- Lessons from the previous results: More data (usually) better than less data
  - The 3-4 σ excess seen by ATLAS+CMS in 2015 data proven to be a statistical fluctuation with x10 more data; last measurement with 36.7 fb-1

Planning to improve limits on spin-0/spin-2 resonances and push to higher masses with the full Run-2 data

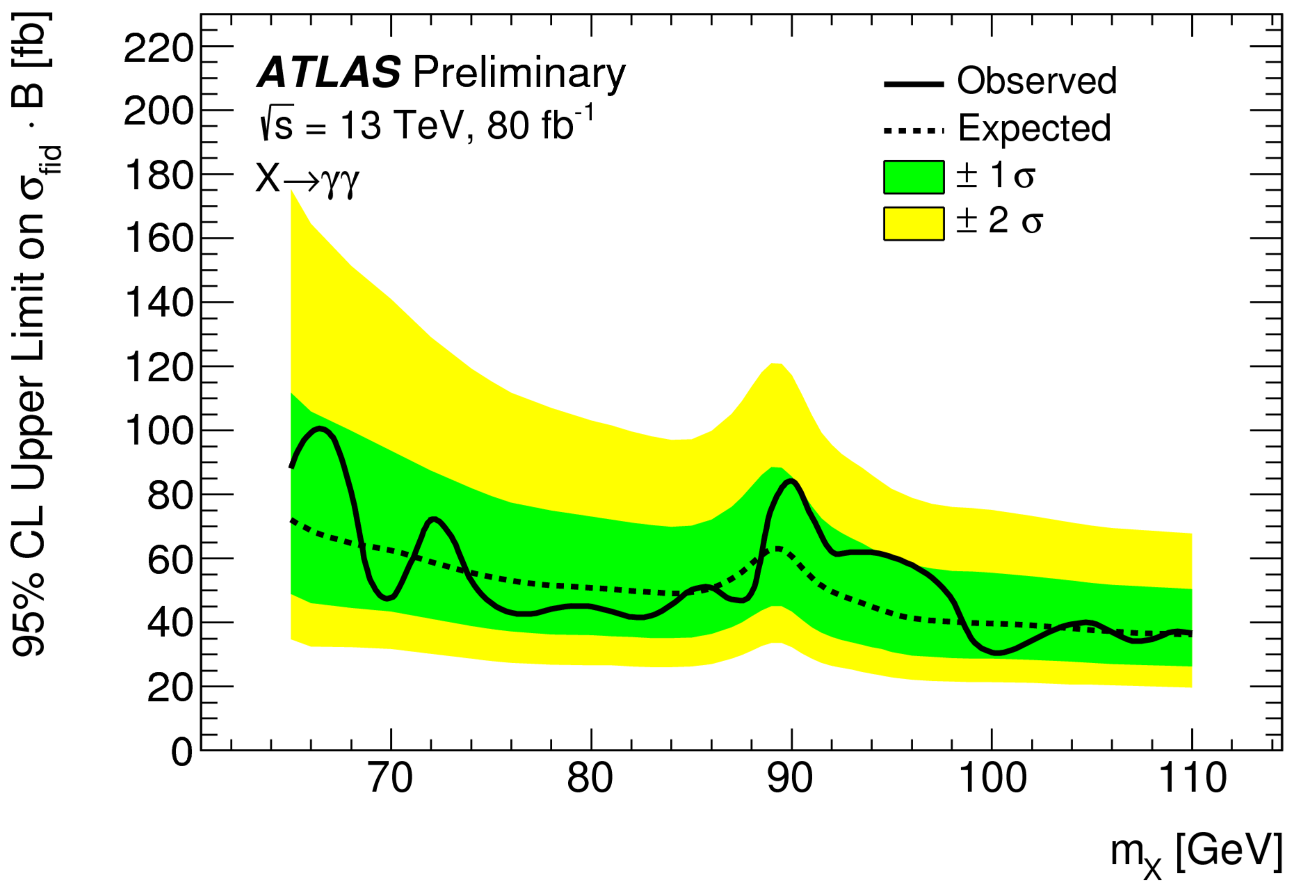
- Scalar search: the limits are on fiducial cross-section
  - model-independent, no assumption on the production mode
- Graviton search: the limits are on the total cross section
  - focus is on a simplified model

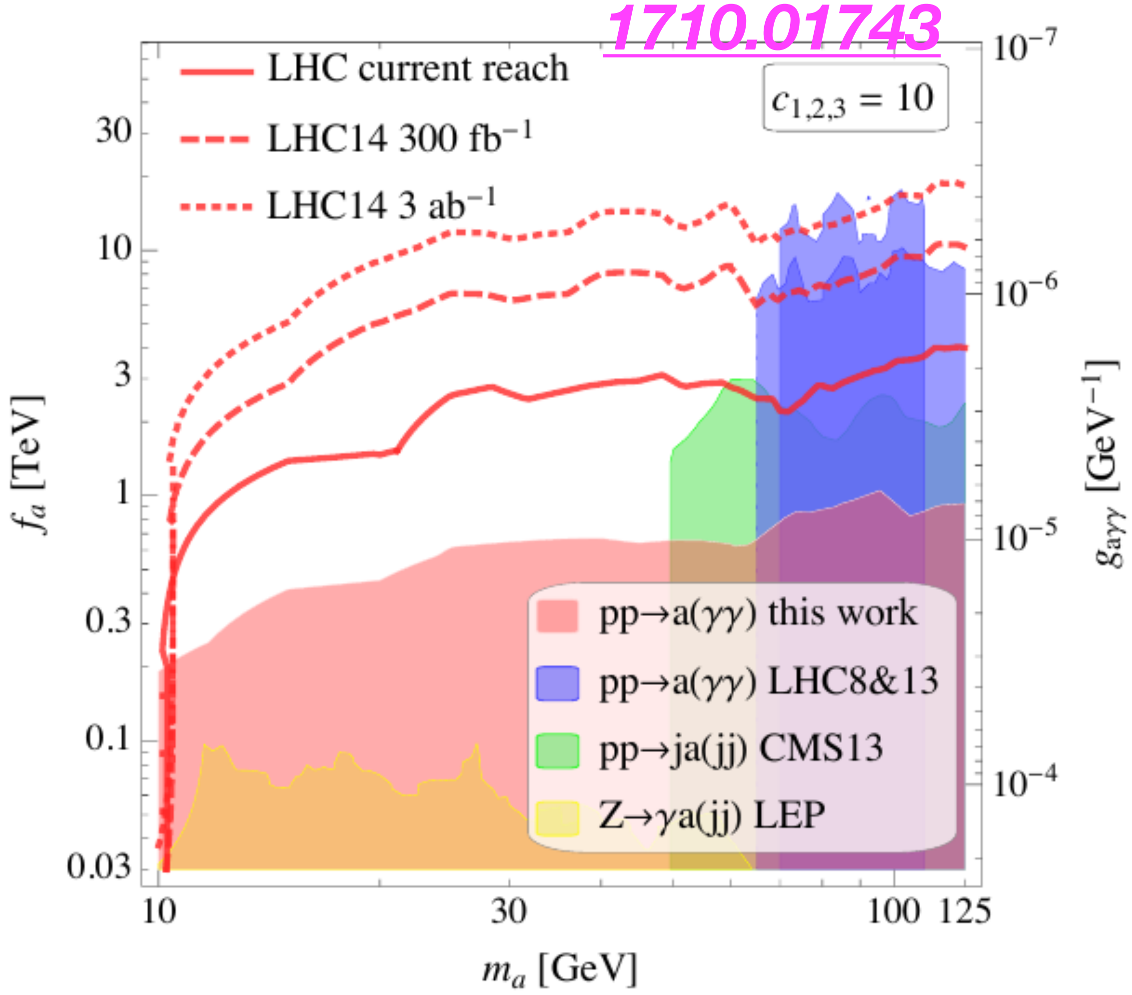




Low mass search

- Low mass search is as exciting and challenging as the high mass
  - CMS observes 3 σ excess at 95 GeV (PAS HIG-17-013),
  - No hints in ATLAS (though not excluded yet)
- Studied 65-110 GeV range; important to constrain background Z→ee→fake photons at ~ 90 GeV
- Preliminary result was limited by systematics from background modelling, aiming to reduce by a factor of two to publish
- Attempt to extend to very low mass (< 60 GeV); no direct searches in this region by any experiment
  - Trigger is a limitation; studying feasibility with Run-2 and potential strategies for Run-3





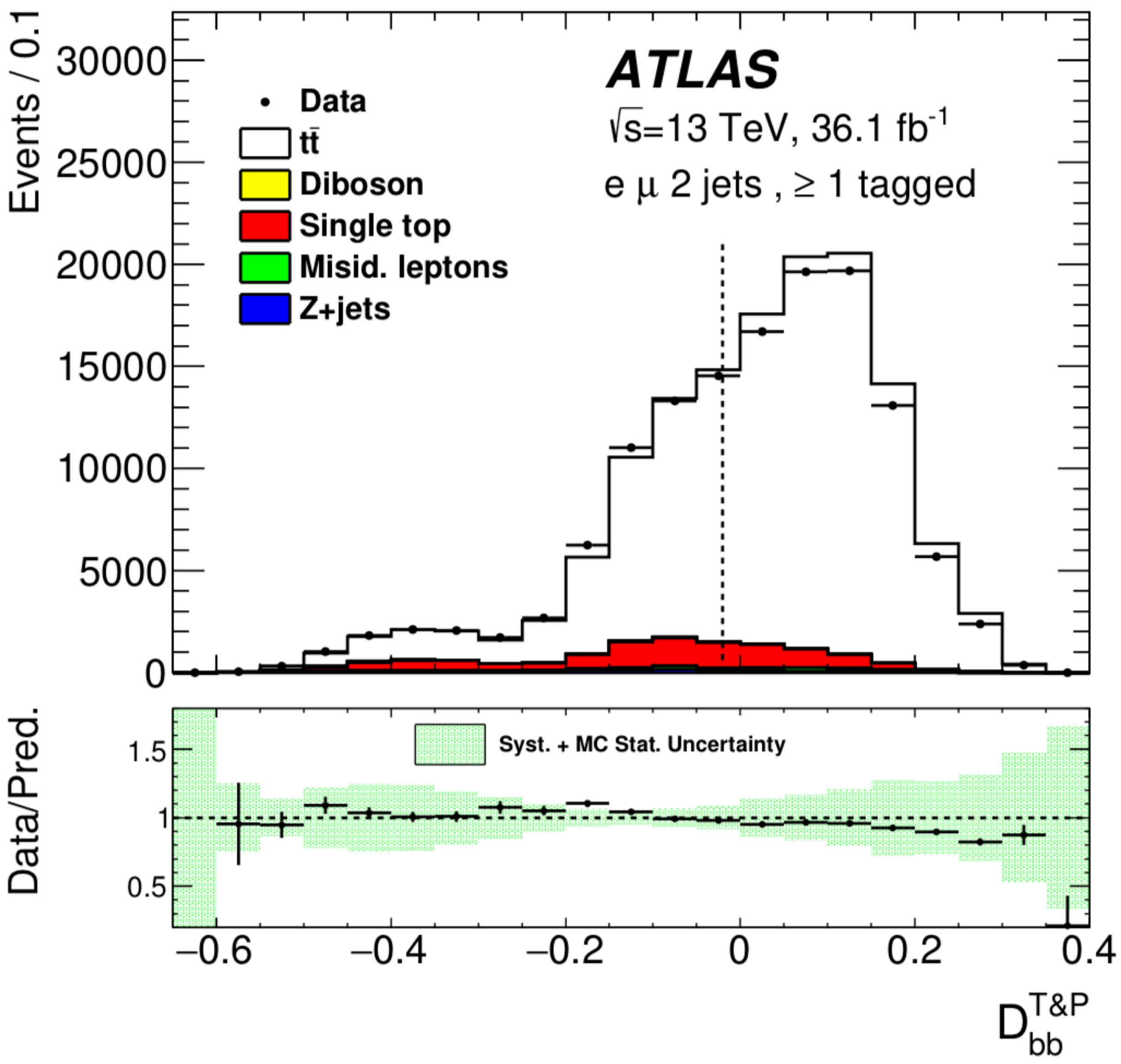
1710.01743

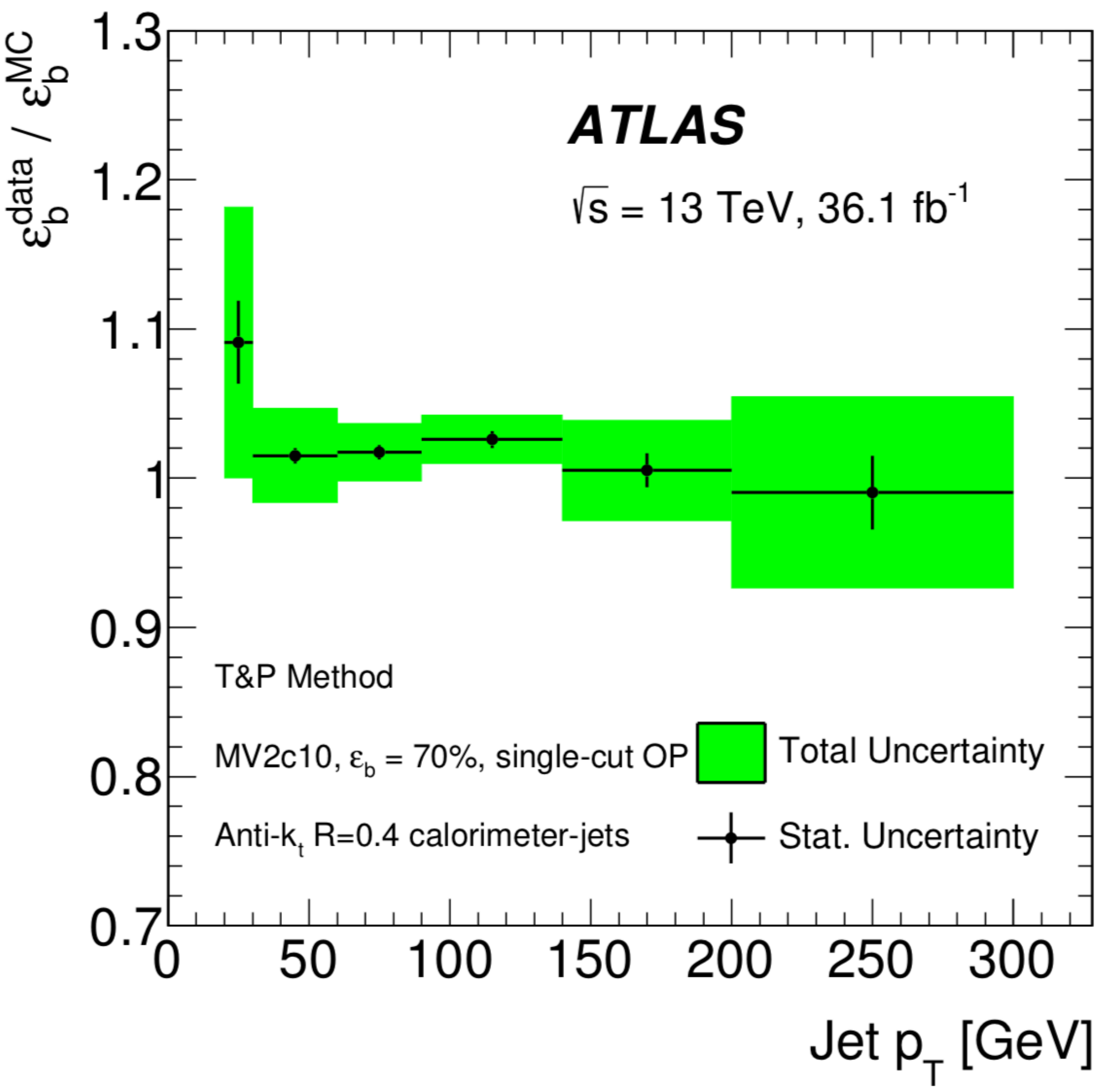
Summary

- LPNHE-Paris and USTC-Hefei have successful collaborations in
  - Search for $H \rightarrow b\bar{b}$ in VH production mode
    - one paper in 2017 and one paper in 2018
    - 1/2 paper/conference-note in preparation for 2019 fall
  - Searches for diphoton resonances at low and high mass
    - High mass research: Publication/CONF-conversion for summer conferences, targeting EPS (Mid July)
    - Low/very-low mass: Publication to arrive in fall 2019

Backup

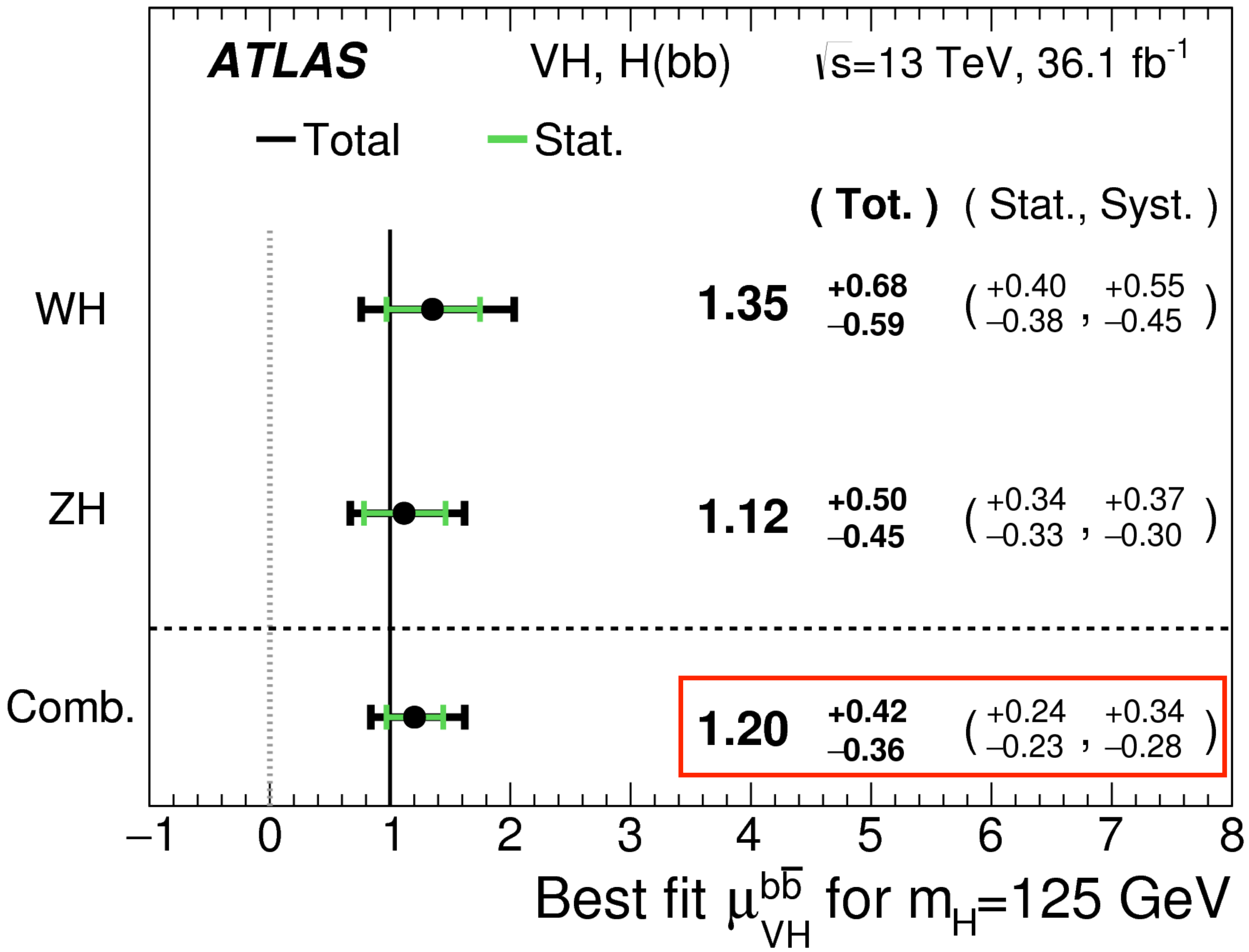
Measurements of b-jet tagging efficiency

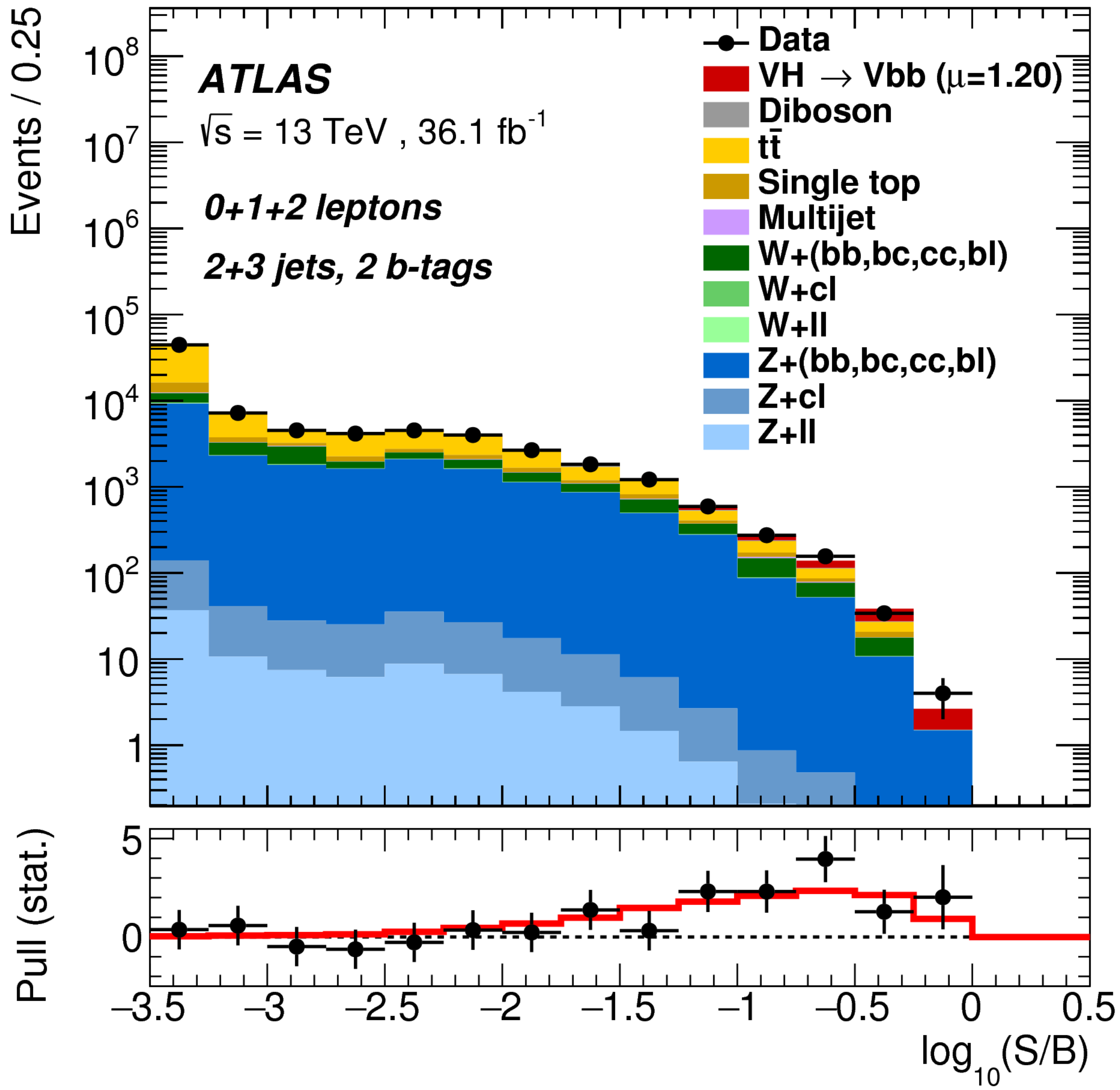




- Left: so-called Purity BDT is used to separate events with two b-jets from the events with other jet combinations, cut on output of Purity BDT can further improve the b-jet purity
- Right: calibration results as the ratio of the efficiency in measured in MC over the one measured in data, shown with the uncertainties

VH, H → $b\bar{b}$ results with 36 fb^{-1}





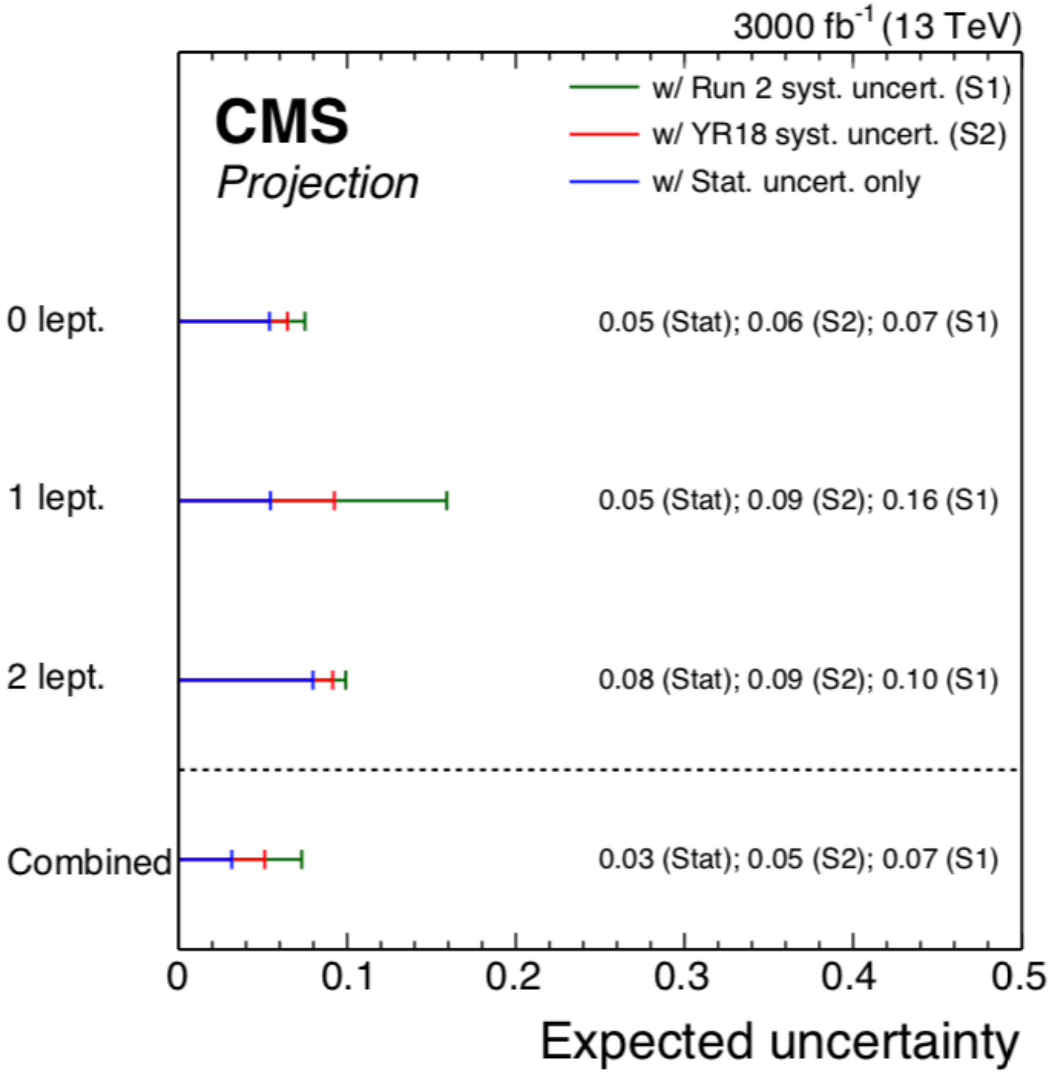
2 signal strengths (μ $_{WH,}$ μ $_{ZH}$) and the inclusive signal strength μ $_{VH}$

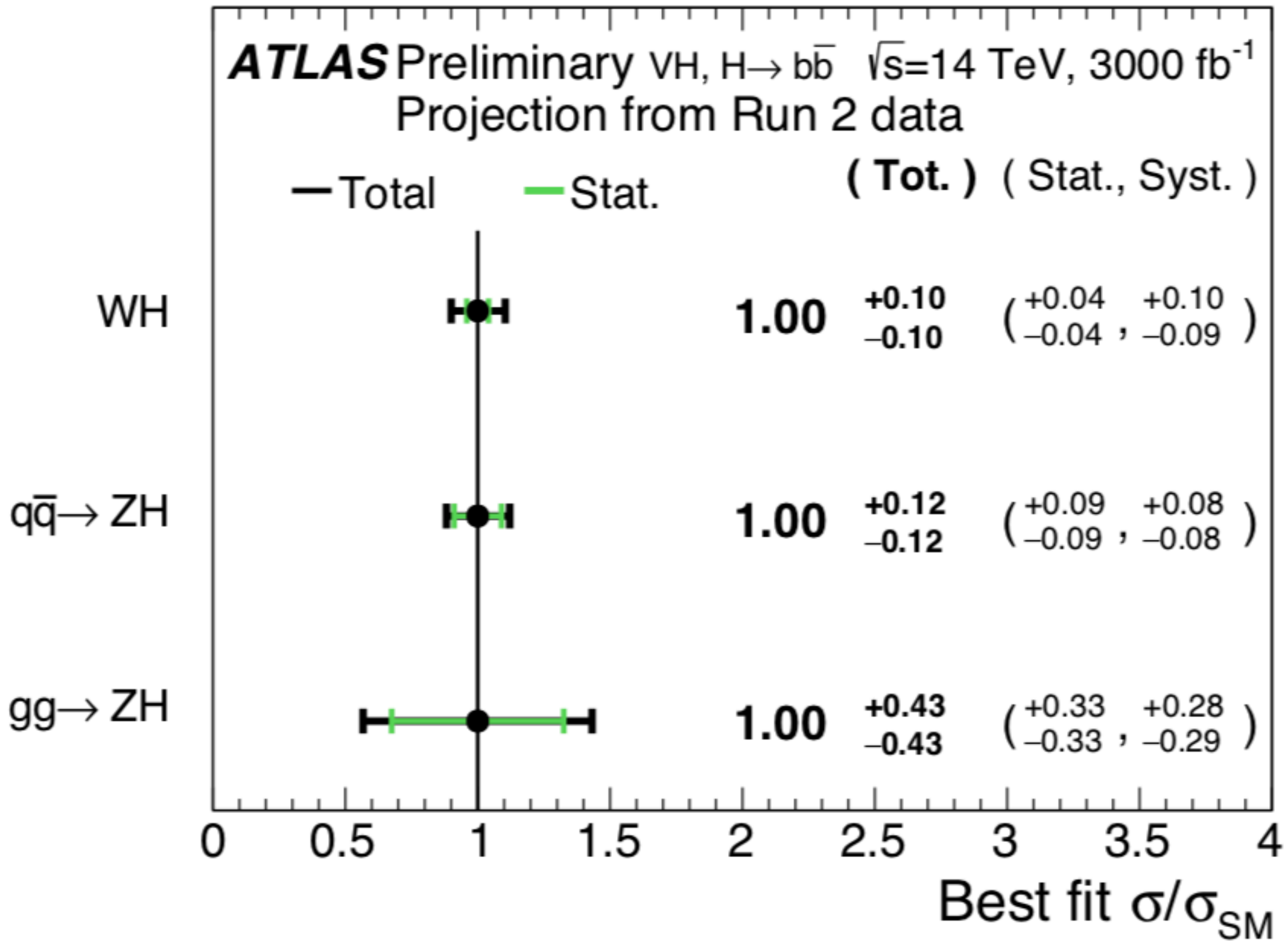
- Expected significance: 3.0σ
- Observed significance: 3.5σ

HL-LHC prospects

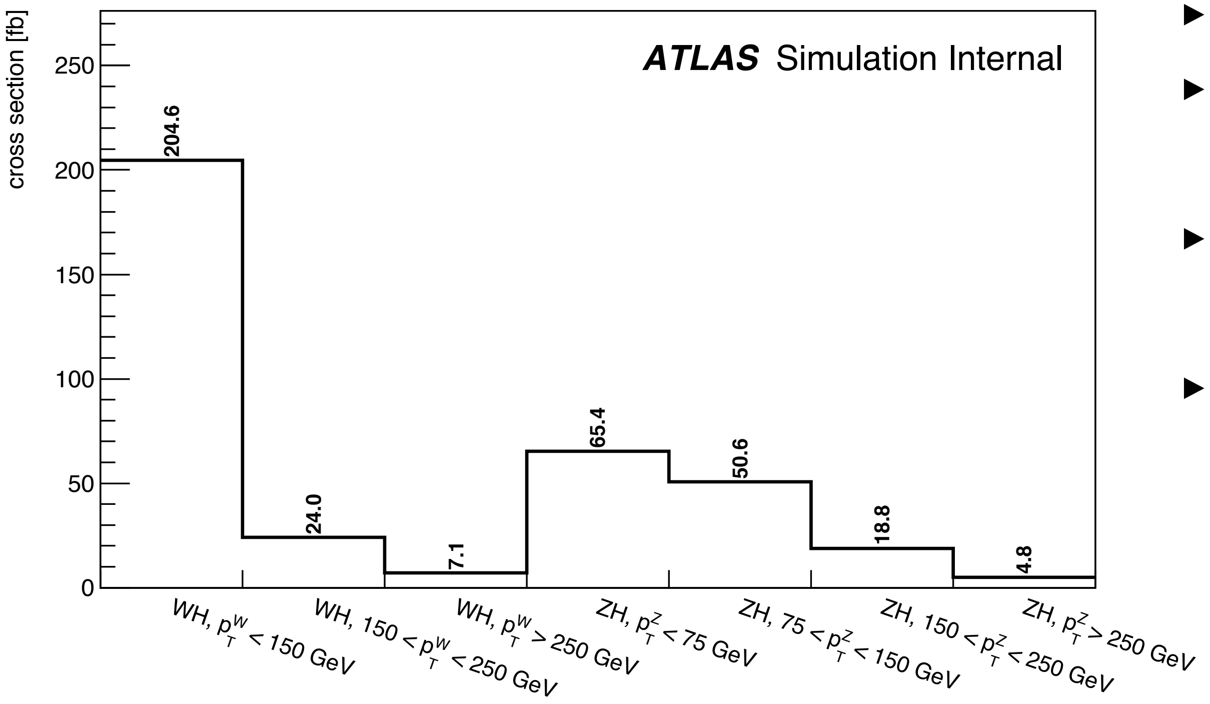
- “Yellow Report” in preparation for input to European Update of Particle Physics Strategy
- VH, H→$b\bar{b}$ extrapolation based on the 80 fb^{-1} analysis, luminosity: 80 fb^{-1} → 3000 fb^{-1}
- Object reconstruction performance assumed similar in Run-2 and HL-LHC
- For the systematic uncertainties, two scenarios are considered:
  - Scenario-1 (S1): same values as “observation” analysis
  - Scenario-2 (S2): reduction according to potential improvements

arxiv.1902.00134

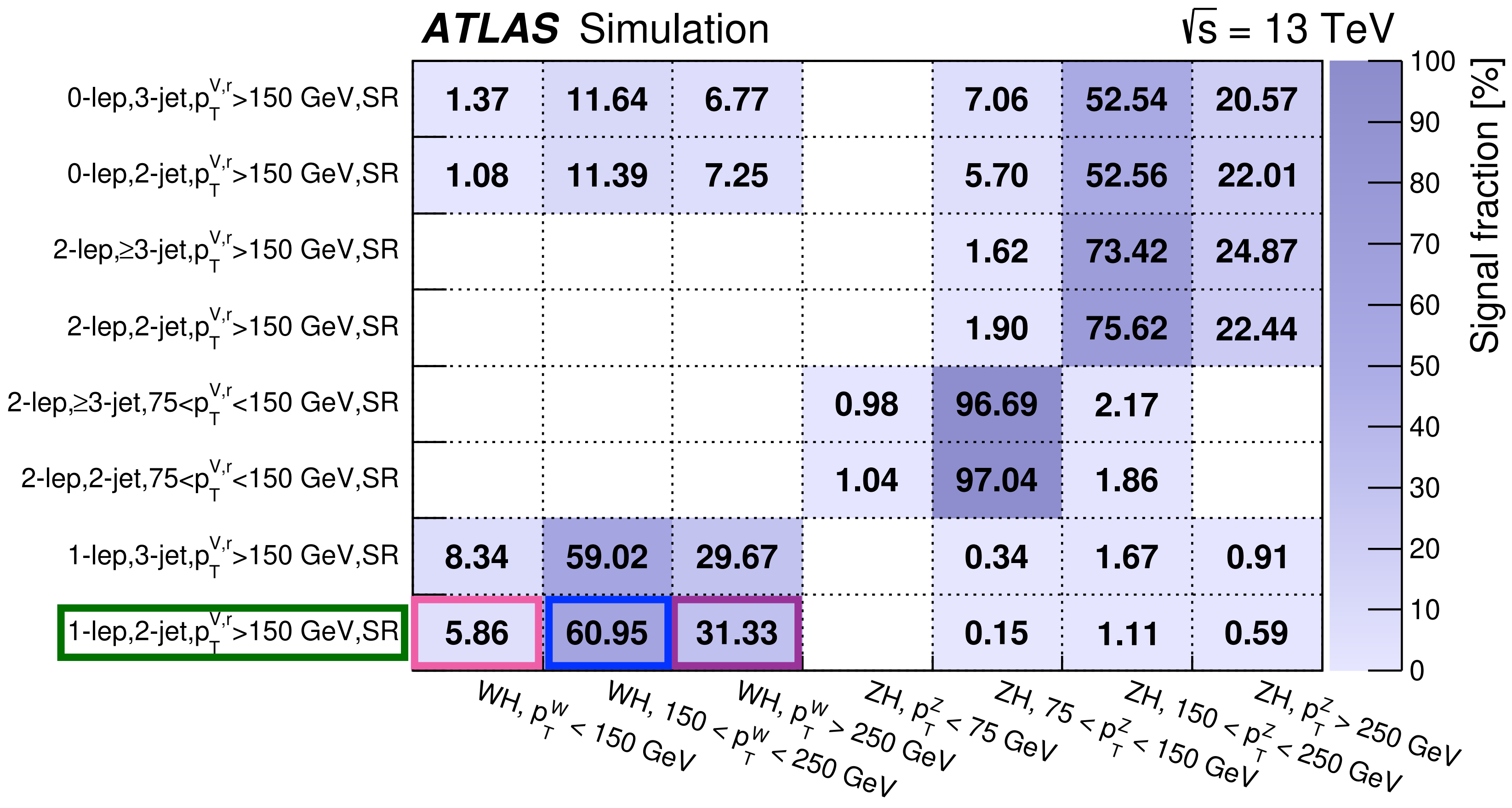




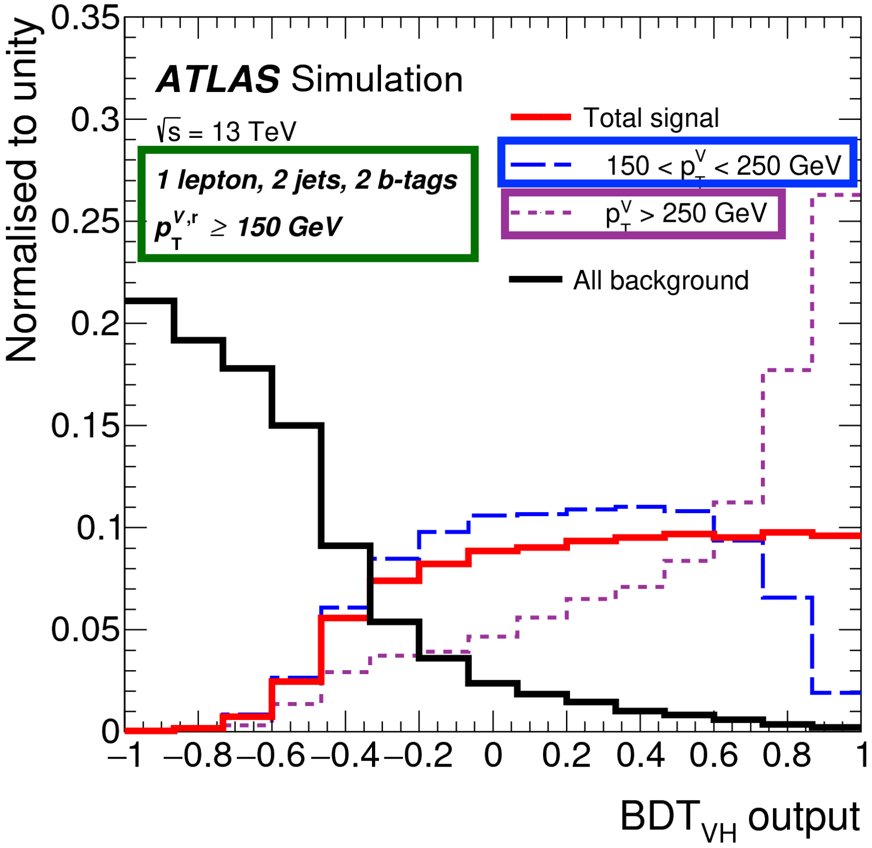
Expected signal yield in each SR



- XS for template bins predicted by SM
- Signal with different p_T^V survived mainly in the corresponding $p_T^{V,r}$ region
- **Small migration** with p_T^V to $p_T^{V,r}$ due to the resolution
- **p_T^V 150-250** and **>250** survived in the same region **$p_T^{V,r}$ >150**
  - Separated by BDT classifier ($p_T^{V,r}$ used in training)



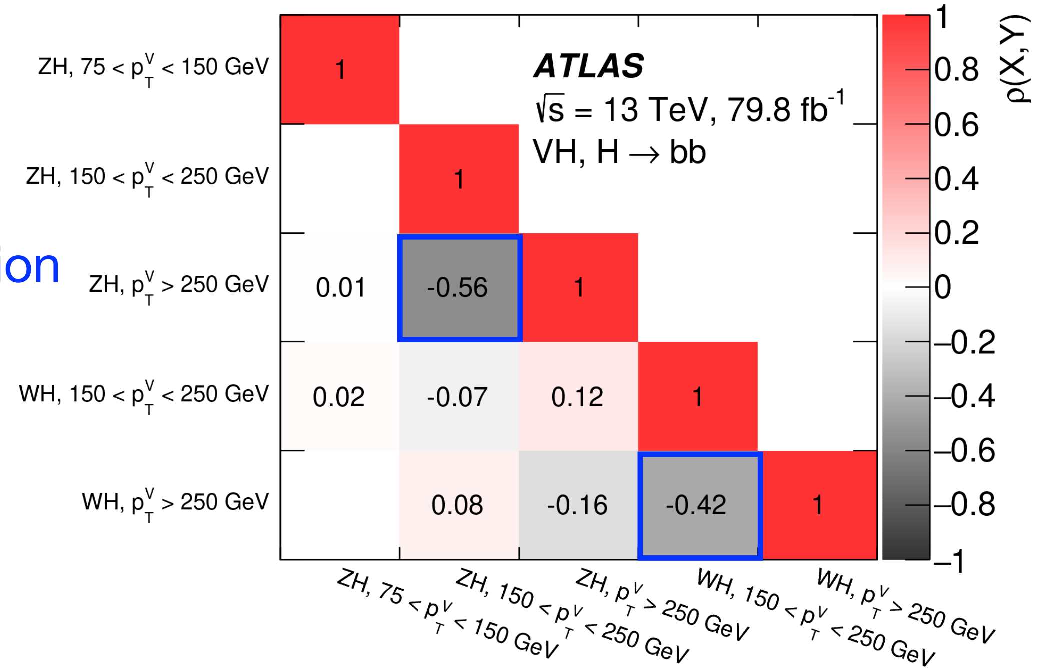
	WH, $p_T^W < 150$ GeV	WH, $150 < p_T^W < 250$ GeV	WH, $p_T^W > 250$ GeV	ZH, $p_T^Z < 75$ GeV	ZH, $75 < p_T^Z < 150$ GeV	ZH, $150 < p_T^Z < 250$ GeV	ZH, $p_T^Z > 250$ GeV
0-lep,3-jet,$p_T^{V,r}$>150 GeV,SR	1.37	11.64	6.77		7.06	52.54	20.57
0-lep,2-jet,$p_T^{V,r}$>150 GeV,SR	1.08	11.39	7.25		5.70	52.56	22.01
2-lep,≥3-jet,$p_T^{V,r}$>150 GeV,SR					1.62	73.42	24.87
2-lep,2-jet,$p_T^{V,r}$>150 GeV,SR					1.90	75.62	22.44
2-lep,≥3-jet,75<$p_T^{V,r}$<150 GeV,SR				0.98	96.69	2.17	
2-lep,2-jet,75<$p_T^{V,r}$<150 GeV,SR				1.04	97.04	1.86	
1-lep,3-jet,$p_T^{V,r}$>150 GeV,SR	8.34	59.02	29.67		0.34	1.67	0.91
1-lep,2-jet,$p_T^{V,r}$>150 GeV,SR	5.86	60.95	31.33		0.15	1.11	0.59

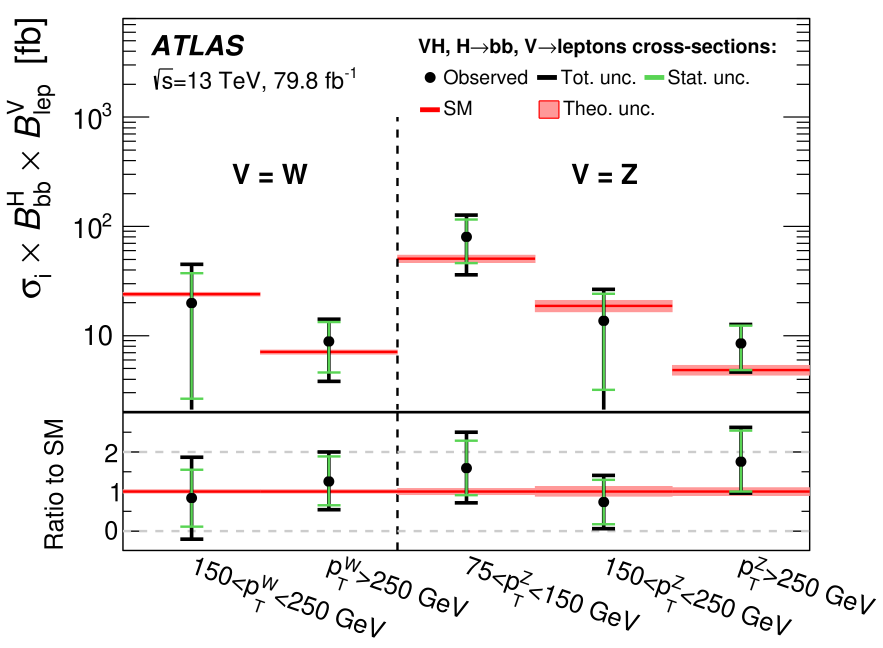


Measurement of 5XS

- Theory prediction uncertainty on XS of measure bins removed
- Systematics from high-granularity regions merged to 5-POI
- 5-POI (each XS normalised to SM prediction) simultaneous measured

Strong anti-correlation
p_T^V in [150,250]
p_T^V > 250





Measurement region ($\lvert y_H\rvert < 2.5$, $H \to b\bar{b}$)	SM prediction [fb]			Result [fb]			Stat. Unc. [fb]		Syst. Unc. [fb] Th. Sig.		Th. Bkg.		Exp.	
$W \to l\nu$, $150 < p_T^V < 250$ GeV	24.00	±	1.06	19.9	±	25.0	±	17.3	±	1.6	±	13.2	±	9.4
$W \to l\nu$, $p_T^V > 250$ GeV	7.08	±	0.34	8.8	±	5.2	±	4.4	±	0.5	±	2.5	±	0.9
$Z \to ll, \nu\nu$, $75 < p_T^V < 150$ GeV	50.61	±	4.09	80.5	±	45.2	±	34.7	±	10.1	±	20.8	±	19.3
$Z \to ll, \nu\nu$, $150 < p_T^V < 250$ GeV	18.80	±	2.37	13.7	±	12.7	±	10.6	±	1.4	±	6.1	±	3.3
$Z \to ll, \nu\nu$, $p_T^V > 250$ GeV	4.85	±	0.50	8.5	±	4.0	±	3.7	±	0.8	±	1.2	±	0.6

- Most of measurement limited by statistics

EFT interpretation

- Beyond Standard Model (BSM) prediction constrained by the STXS measurement
- Effective Field Theory (EFT) parametrising the effects from BSM
- Leading effect on BSM from Dimension 6 operators

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i c_i^{(6)} O_i^{(6)} / \Lambda^2$$

- Focus on four operators affecting Higgs interaction with W (O_{HW}, O_W) and Z (all four)

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

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

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

$$O_B = \tfrac{i}{2}\left(H^\dagger \overset{\leftrightarrow}{D^\mu} H\right) D^\nu B_{\mu\nu},$$

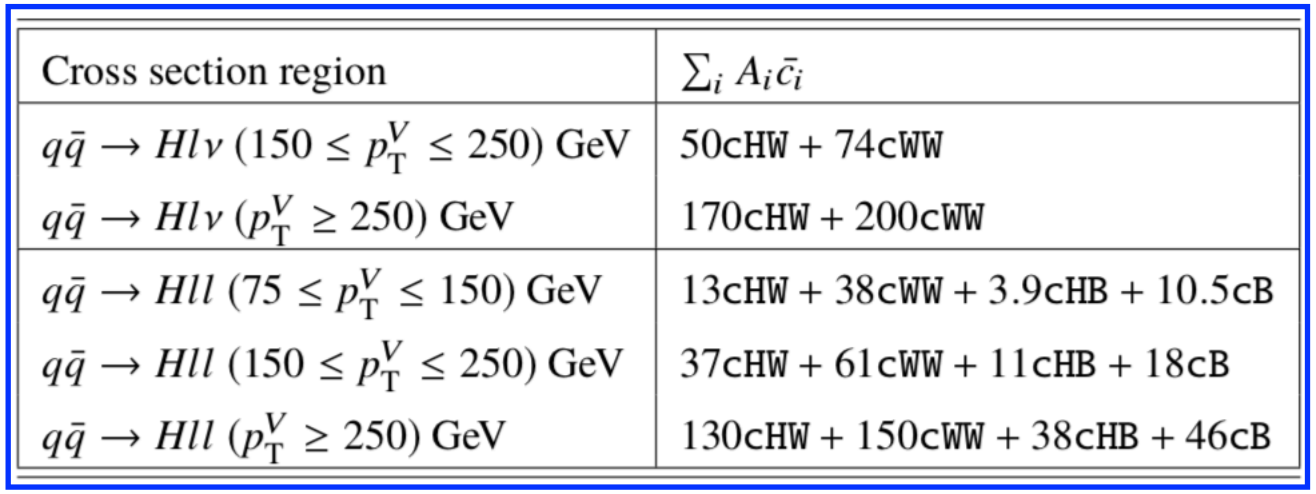
Dimensionless coefficients

$$\mathrm{cHW} = \frac{m_W^2}{g}\frac{c_{HW}}{\Lambda^2}, \quad \mathrm{cHB} = \frac{m_W^2}{g'}\frac{c_{HB}}{\Lambda^2}, \quad \mathrm{cWW} = \frac{m_W^2}{g}\frac{c_W}{\Lambda^2}, \quad \mathrm{cB} = \frac{m_W^2}{g'}\frac{c_B}{\Lambda^2},$$

- The impact on the XS include
  - Interference between SM and BSM (linear terms)
  - BSM only (quadratic terms)

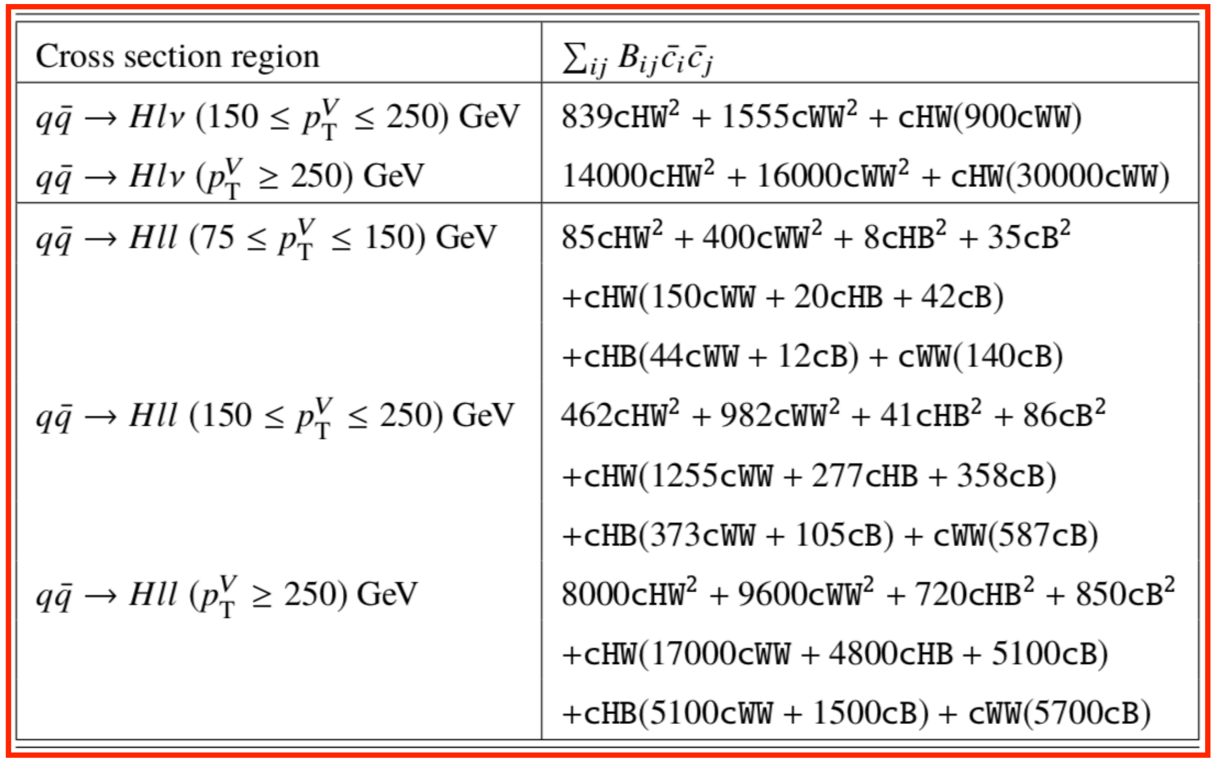
$$\frac{\sigma_{EFT}}{\sigma_{SM}} = 1 + \boxed{\sum_i A_i \bar{c}_i} + \boxed{\sum_{ij} B_{ij}\bar{c}_i\bar{c}_j}$$

- Relationship between 5 XS and coefficients



Cross section region	$\sum_i A_i\bar{c}_i$
$q\bar{q} \to Hl\nu$ ($150 \le p_T^V \le 250$) GeV	$50\mathrm{cHW} + 74\mathrm{cWW}$
$q\bar{q} \to Hl\nu$ ($p_T^V \ge 250$) GeV	$170\mathrm{cHW} + 200\mathrm{cWW}$
$q\bar{q} \to Hll$ ($75 \le p_T^V \le 150$) GeV	$13\mathrm{cHW} + 38\mathrm{cWW} + 3.9\mathrm{cHB} + 10.5\mathrm{cB}$
$q\bar{q} \to Hll$ ($150 \le p_T^V \le 250$) GeV	$37\mathrm{cHW} + 61\mathrm{cWW} + 11\mathrm{cHB} + 18\mathrm{cB}$
$q\bar{q} \to Hll$ ($p_T^V \ge 250$) GeV	$130\mathrm{cHW} + 150\mathrm{cWW} + 38\mathrm{cHB} + 46\mathrm{cB}$

Strongly Interacting Light Higgs formulation



Cross section region	$\sum_{ij} B_{ij}\bar{c}_i\bar{c}_j$
$q\bar{q} \to Hl\nu$ ($150 \le p_T^V \le 250$) GeV	$839\mathrm{cHW}^2 + 1555\mathrm{cWW}^2 + \mathrm{cHW}(900\mathrm{cWW})$
$q\bar{q} \to Hl\nu$ ($p_T^V \ge 250$) GeV	$14000\mathrm{cHW}^2 + 16000\mathrm{cWW}^2 + \mathrm{cHW}(30000\mathrm{cWW})$
$q\bar{q} \to Hll$ ($75 \le p_T^V \le 150$) GeV	$85\mathrm{cHW}^2 + 400\mathrm{cWW}^2 + 8\mathrm{cHB}^2 + 35\mathrm{cB}^2$ $+\mathrm{cHW}(150\mathrm{cWW} + 20\mathrm{cHB} + 42\mathrm{cB})$ $+\mathrm{cHB}(44\mathrm{cWW} + 12\mathrm{cB}) + \mathrm{cWW}(140\mathrm{cB})$
$q\bar{q} \to Hll$ ($150 \le p_T^V \le 250$) GeV	$462\mathrm{cHW}^2 + 982\mathrm{cWW}^2 + 41\mathrm{cHB}^2 + 86\mathrm{cB}^2$ $+\mathrm{cHW}(1255\mathrm{cWW} + 277\mathrm{cHB} + 358\mathrm{cB})$ $+\mathrm{cHB}(373\mathrm{cWW} + 105\mathrm{cB}) + \mathrm{cWW}(587\mathrm{cB})$
$q\bar{q} \to Hll$ ($p_T^V \ge 250$) GeV	$8000\mathrm{cHW}^2 + 9600\mathrm{cWW}^2 + 720\mathrm{cHB}^2 + 850\mathrm{cB}^2$ $+\mathrm{cHW}(17000\mathrm{cWW} + 4800\mathrm{cHB} + 5100\mathrm{cB})$ $+\mathrm{cHB}(5100\mathrm{cWW} + 1500\mathrm{cB}) + \mathrm{cWW}(5700\mathrm{cB})$

“Higgs Effective Lagrangian” implementation

5-POI → coefficients

- Strong constrain on S = cWW + cB from precise electroweak data, S assumed as 0
- Thus constrain set on the coefficients: cHW, cHB, cWW-cB
- 5-POI parametrised with the above coefficients in linear and quadrature terms
- Maximum likelihood fits with POIs as cHW, cHB, cWW-cB
- One-dimensional fit performed