

# Higgs physics

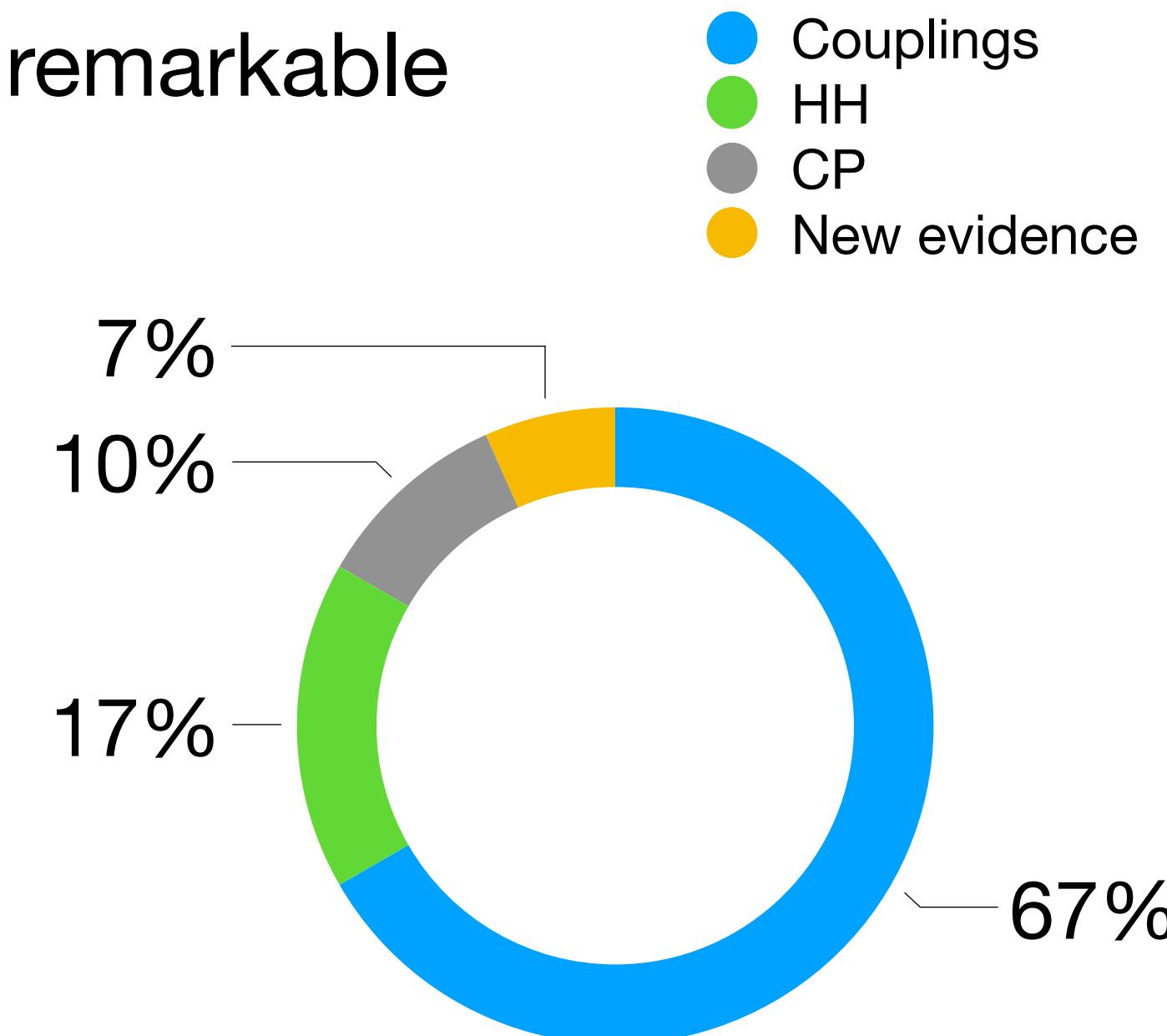
## Experimental talk

**LHCP 2021 - Plenary IV: Higgs Physics**  
Bortignon Pierluigi (INFN PD, UNICA)  
On behalf of the ATLAS and CMS collaborations

**LHCP2021, Paris**  
**Virtual World**  
**7-11 June 2021**

# HIGGS EXPERIMENTAL @LHCP

- The knowledge produced on the SM Higgs sector from last LHCP is remarkable showing it an extremely active and interesting topic
  - **31 new results since LHCP2020**
  - It is impossible to present them all in 24 minutes
  - Parallel Higgs sessions cover details of analyses
  - This review includes **only a selection of the most recent results**
  - Full list of results available in the experiments dedicated webpages ([ATLAS](#), [CMS](#))

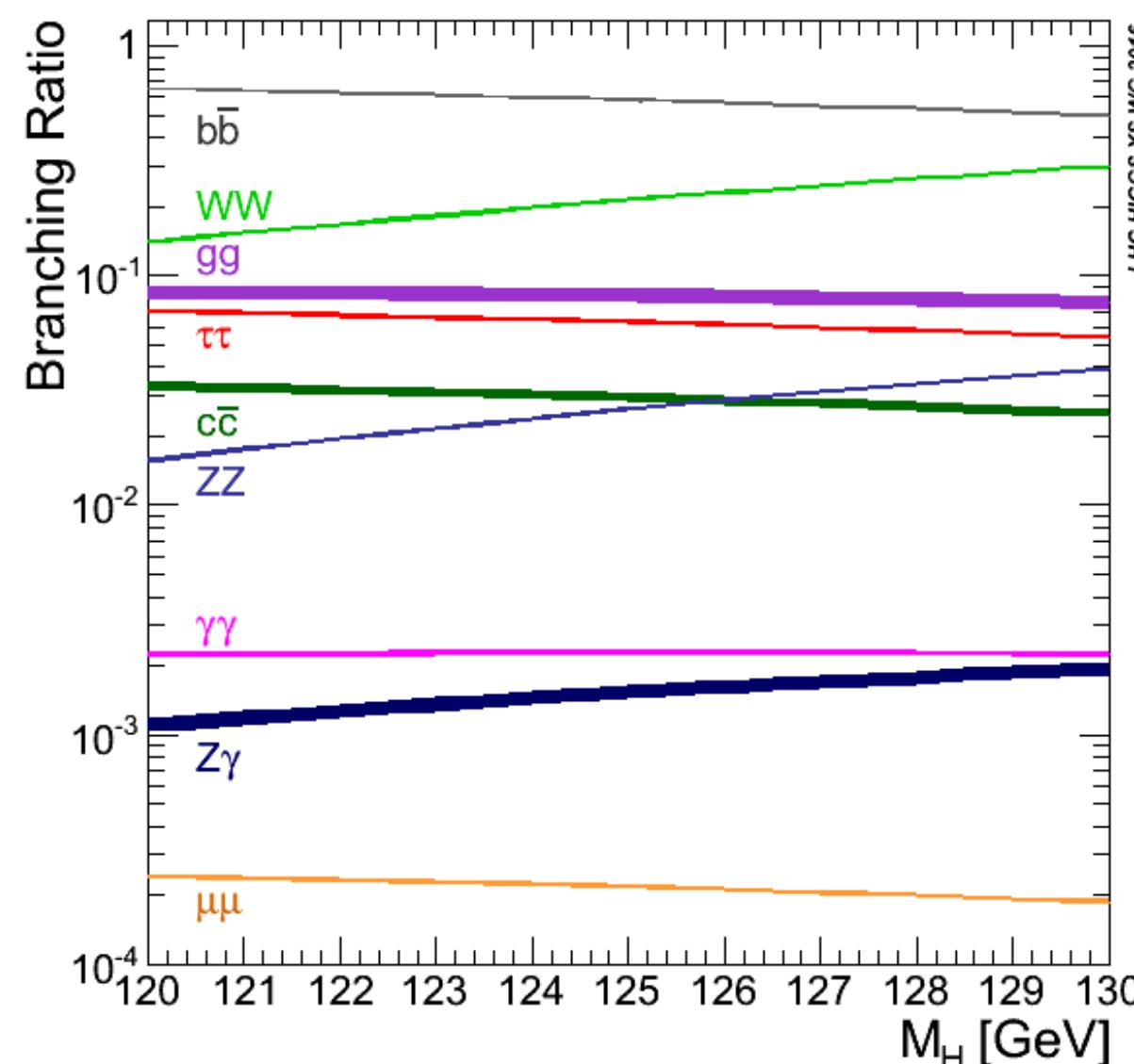
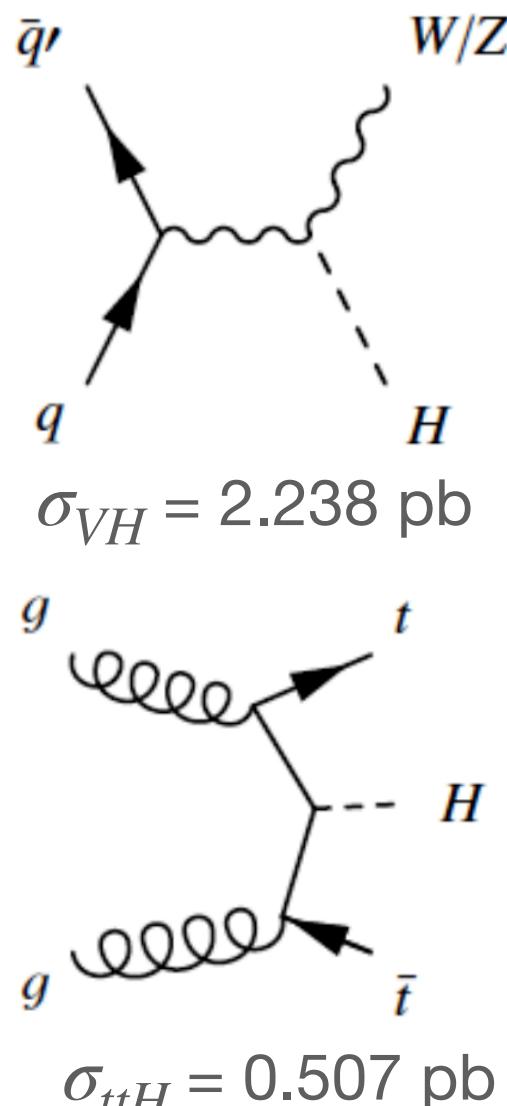
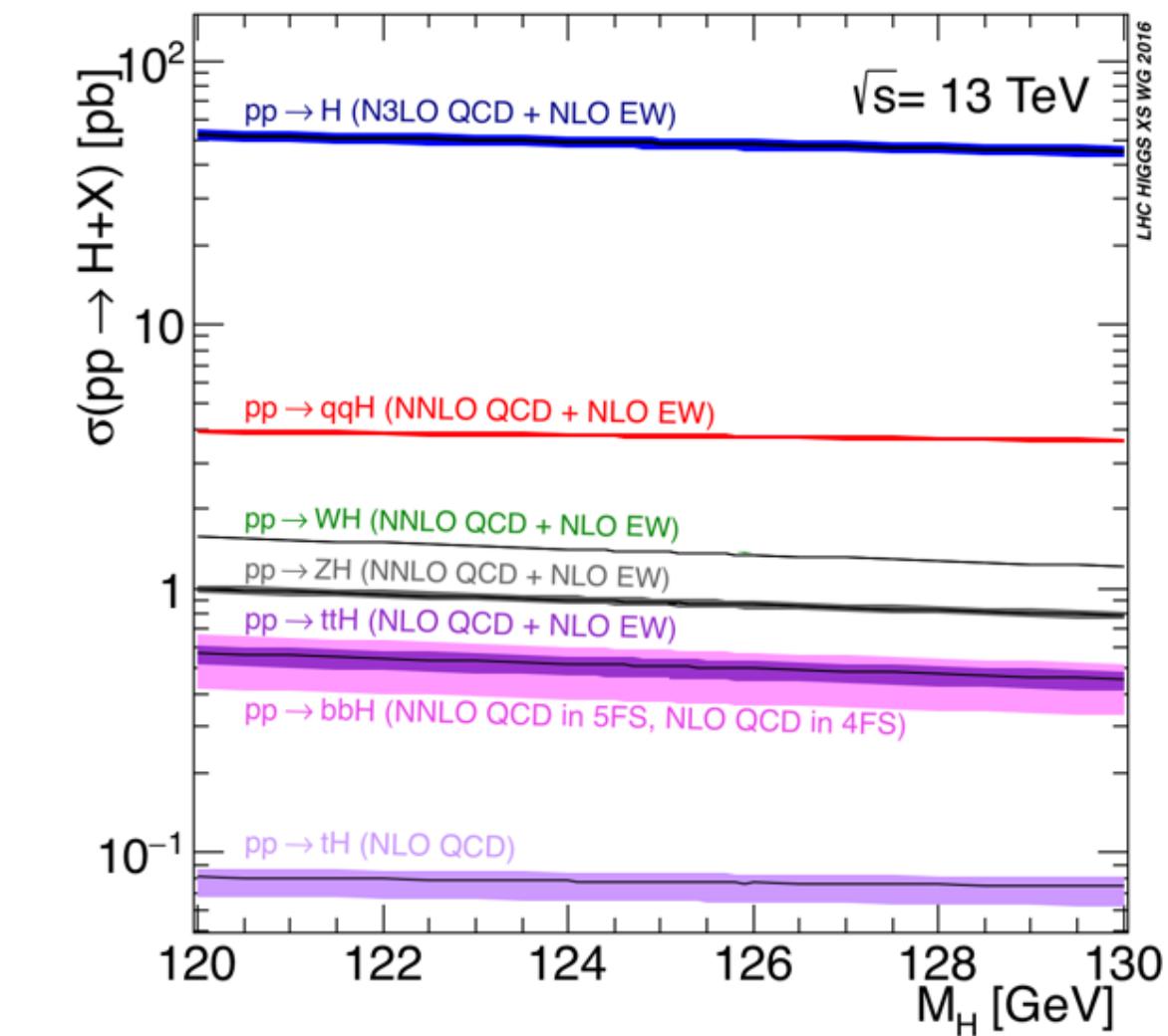
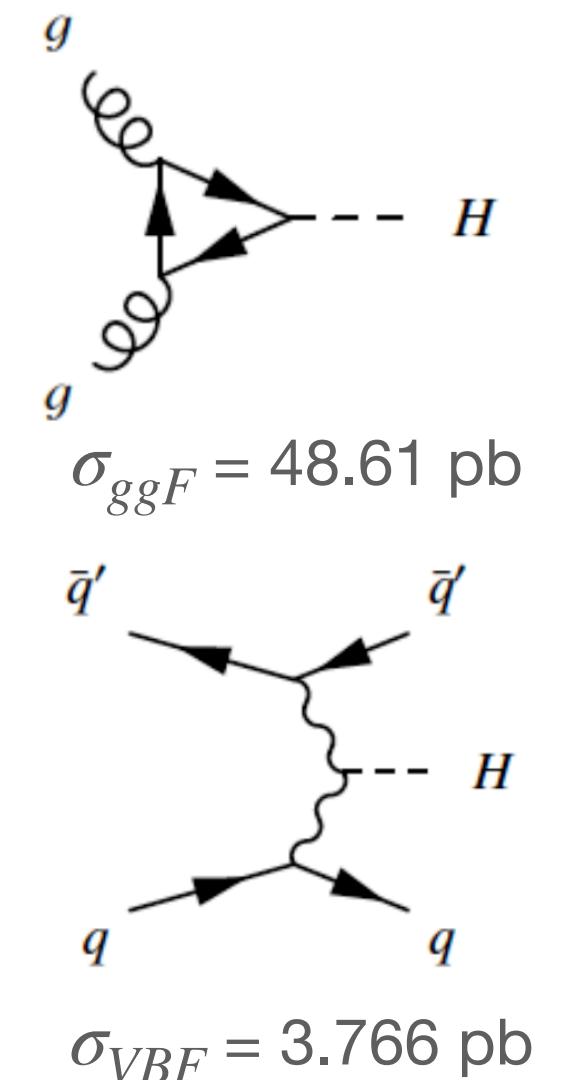


# OUTLINE

- Mass
  - Recent evidence for new decays
  - Higgs to fermions
  - Higgs to bosons
  - Combination
  - Di-Higgs
- 
- PARALLEL SESSIONS RELATED TALKS
- S. Katabchi (H decay to bosons) 7/6
  - M. M. Llacer (H CP studies) 7/6
  - C. Reissel (H to 3rd generation fermions) 7/6
  - K. Mazumdar (Rare H decays) 7/6
  - H. Abidi (Combination) 8/6
  - L. P. Sanchez (HH and self-coupling) 8/6
  - D.E. Boumediene (ttH) 9/6
  - R. Seidita (Fiducial and differential) 10/6

# Higgs at the LHC

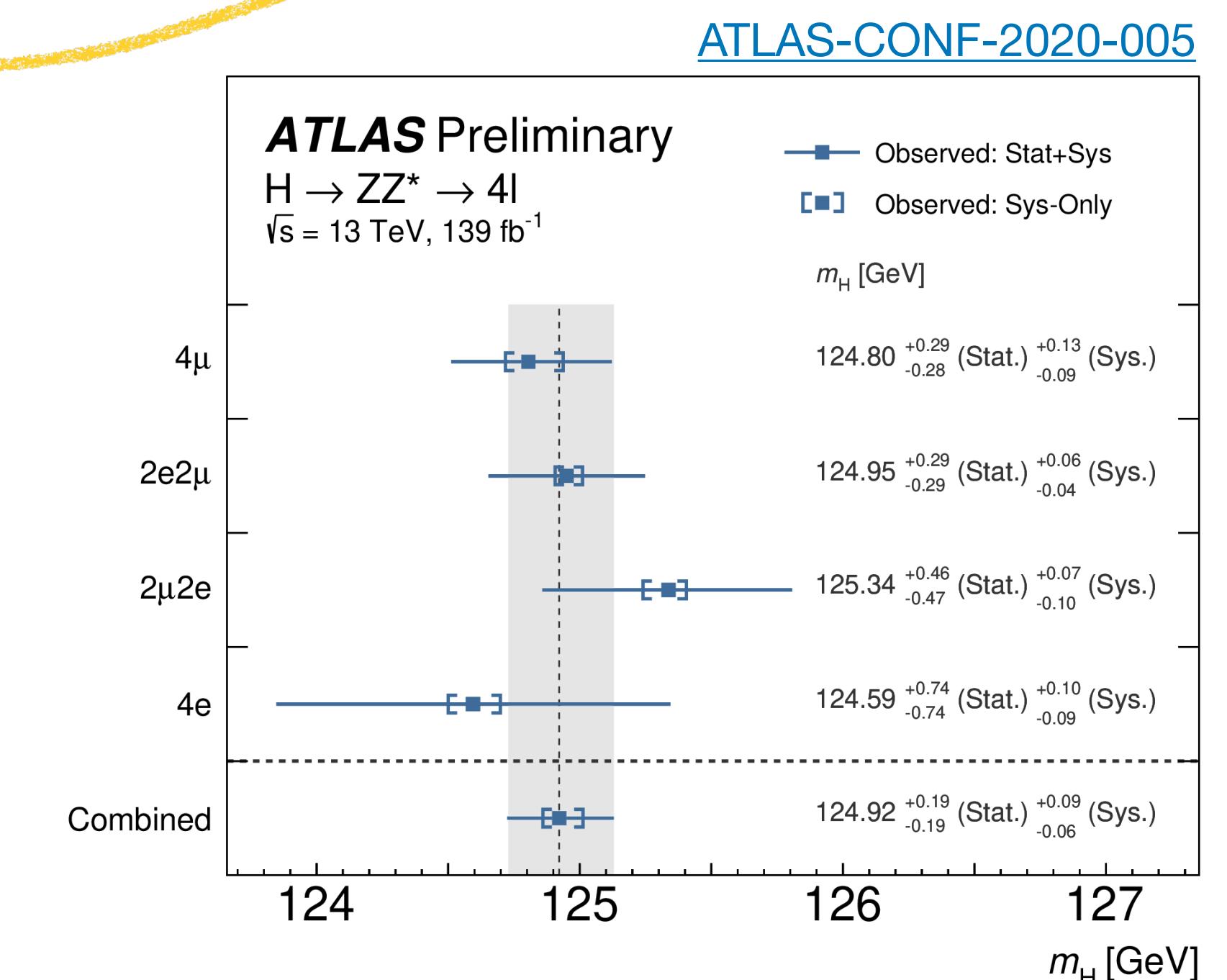
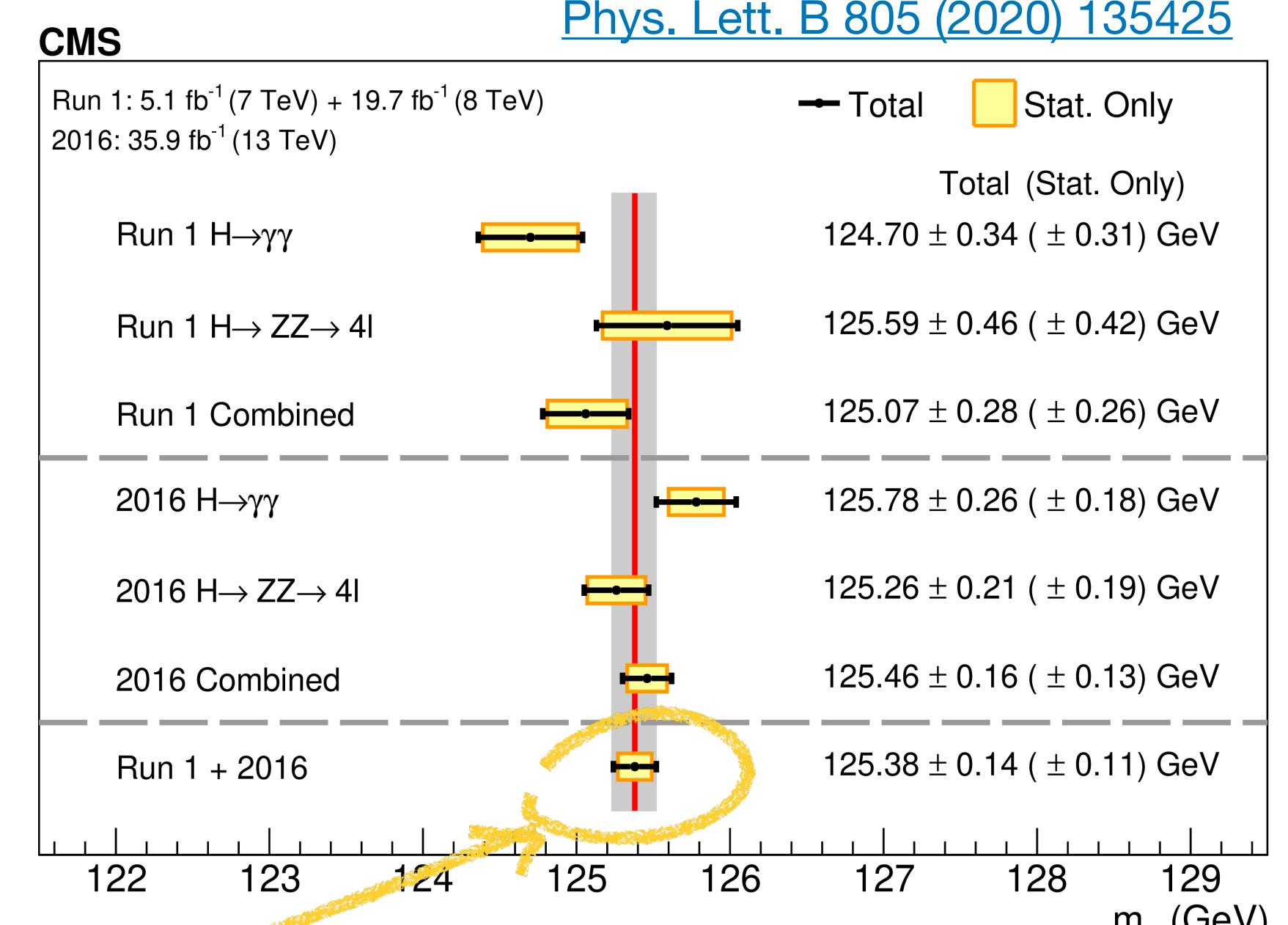
- ggF and VBF observed independently in Run1
- ttH, ZH, WH observed independently in Run2
- Decay rate are proportional to the decaying particles mass
  - Very large variation (for example 58% bb and 0.002%  $\mu\mu$ )



# Mass

# MASS

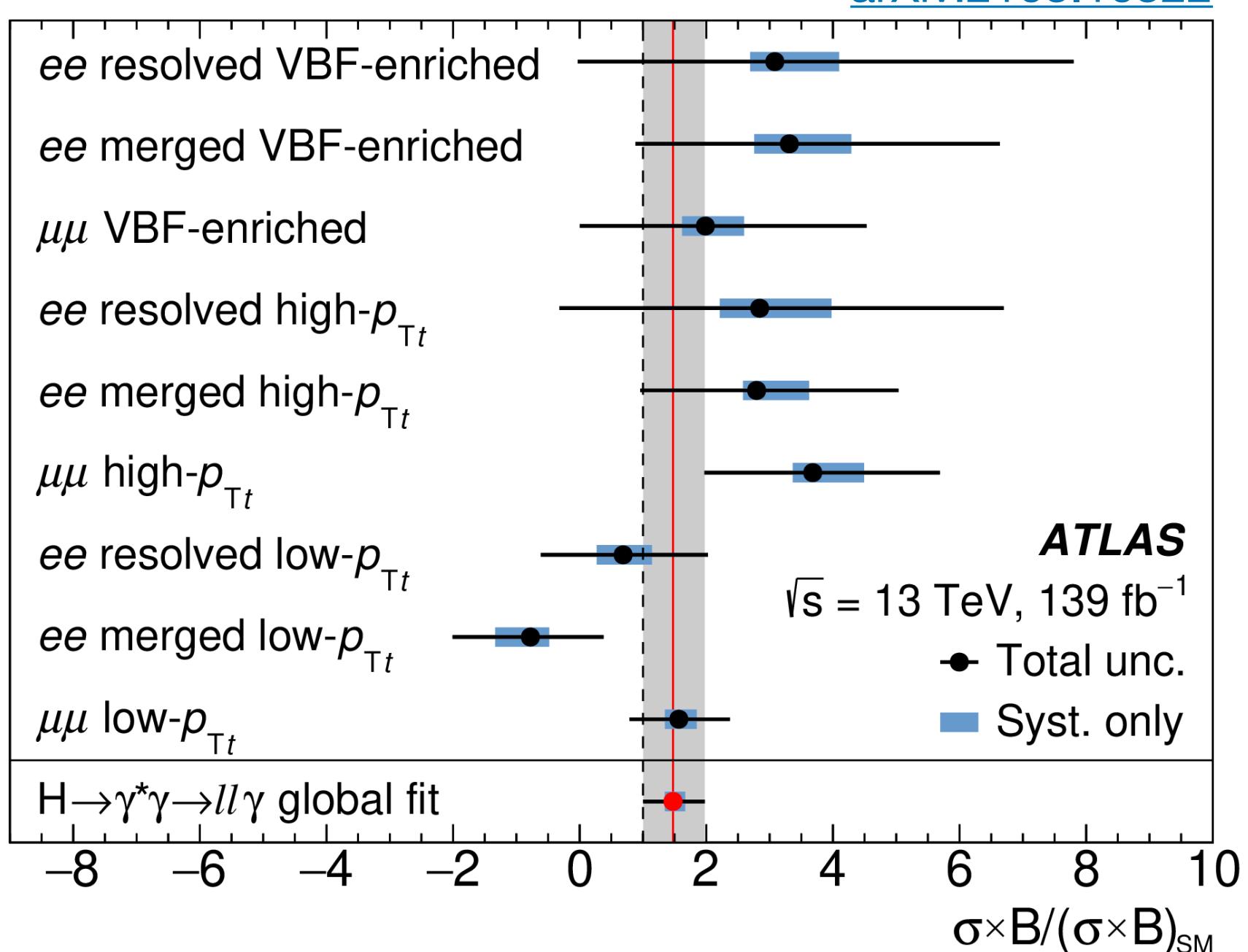
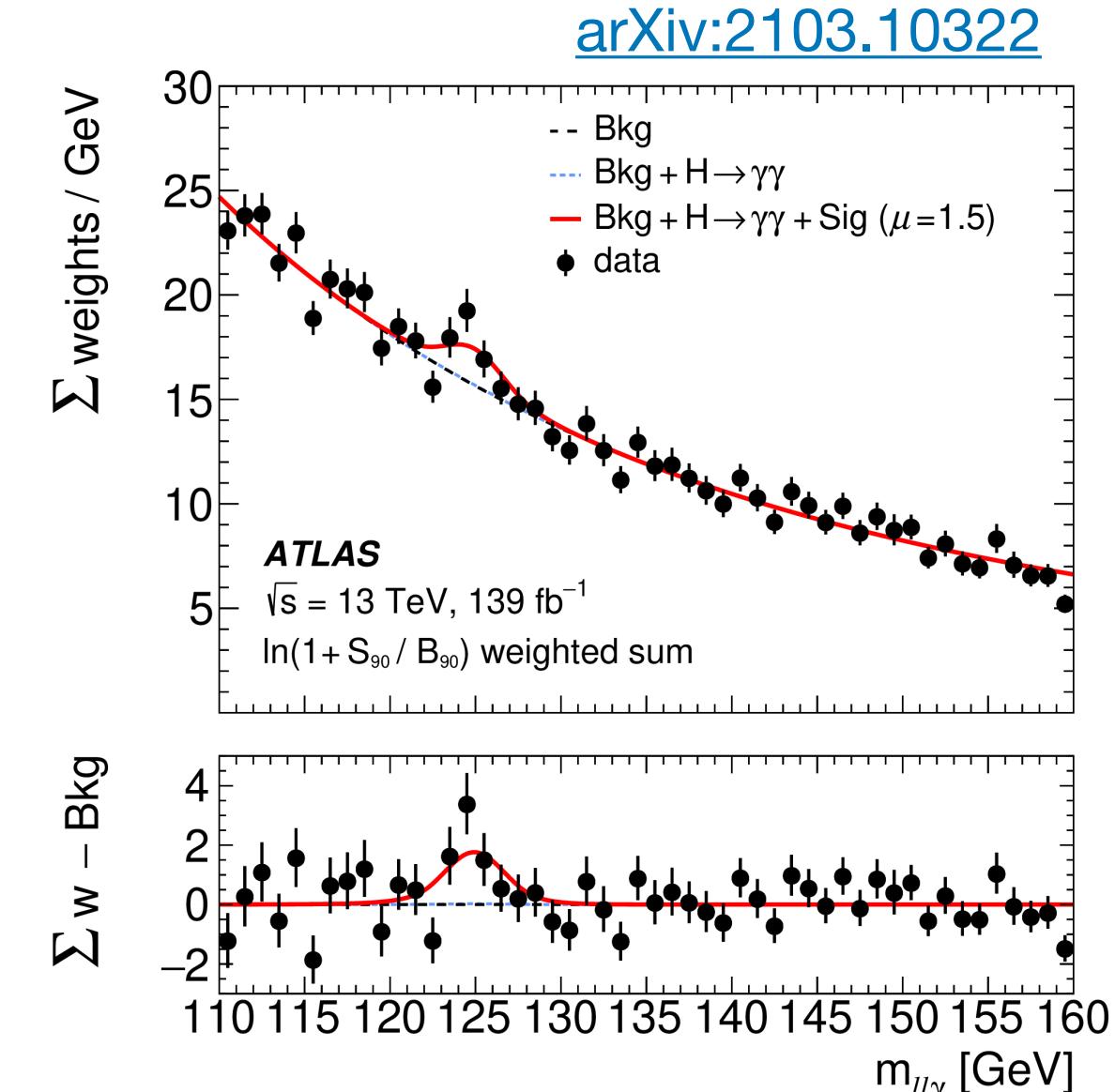
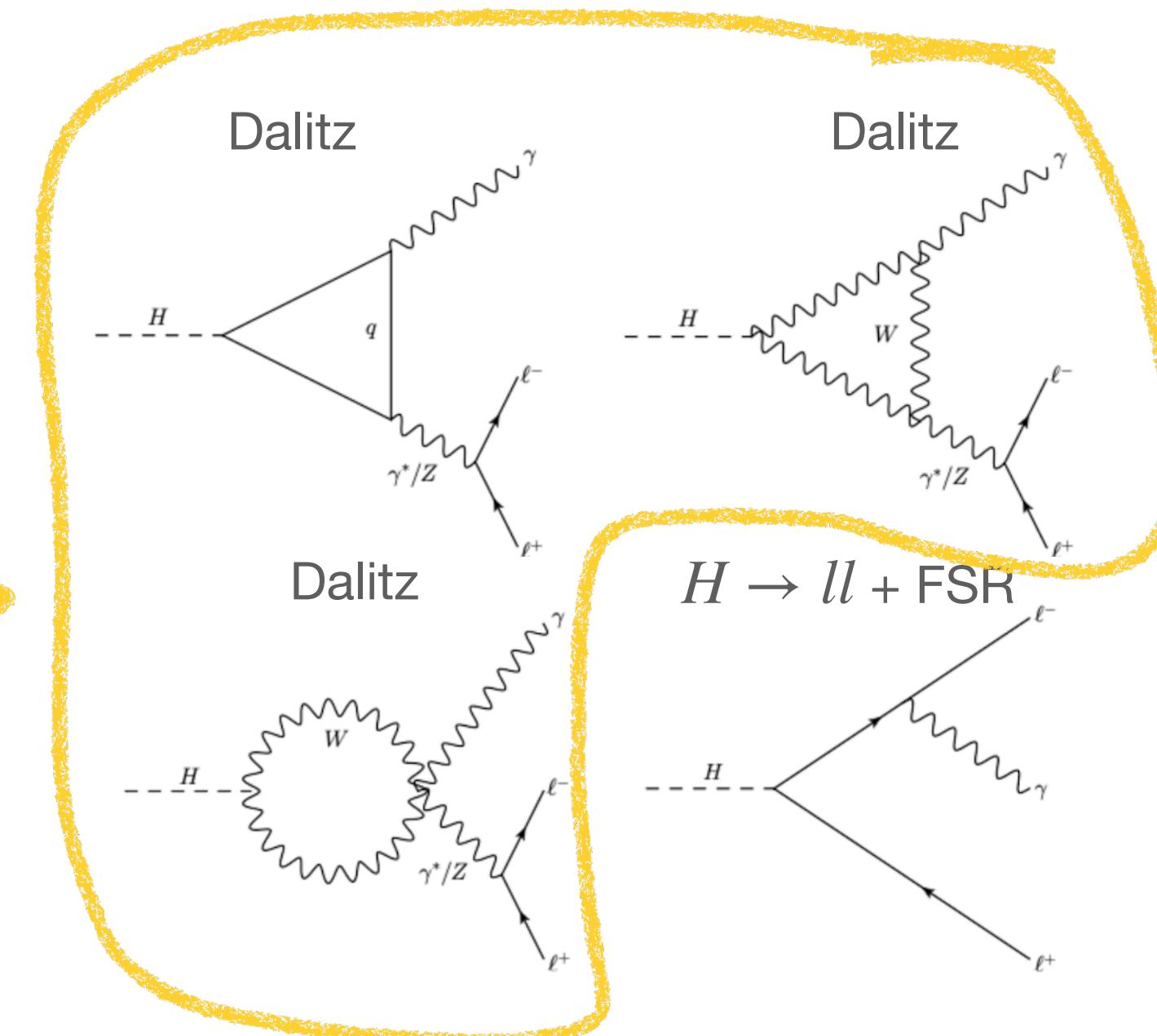
- Measuring the Higgs mass fixes all other predictions in the H sector
- Most sensitive channels are  $H \rightarrow \gamma\gamma$  and  $H \rightarrow ZZ \rightarrow 4l$
- CMS+ATLAS Run1 combination  $m_H = 125.09 \pm 0.24$  GeV
- CMS combines  $H \rightarrow \gamma\gamma$  and  $H \rightarrow ZZ \rightarrow 4l$  with Run1 and 2016
  - $m_H = 125.38 \pm 0.14 (\pm 0.11 \text{ stat. only})$  GeV (MOST PRECISE TO DATE)
- ATLAS full statistics of the  $H \rightarrow ZZ \rightarrow 4l$  channel
  - $m_H = 124.92 \pm 0.19 \text{ (stat)} {}^{+0.09}_{-0.06} \text{ (sys)}$  GeV
  - One of the most precise measurements in the EW sector (with a hadron machine not designed for precision!)
  - More precise measurements are expected soon using full Run1-Run2 dataset



A light start...  
Fermions

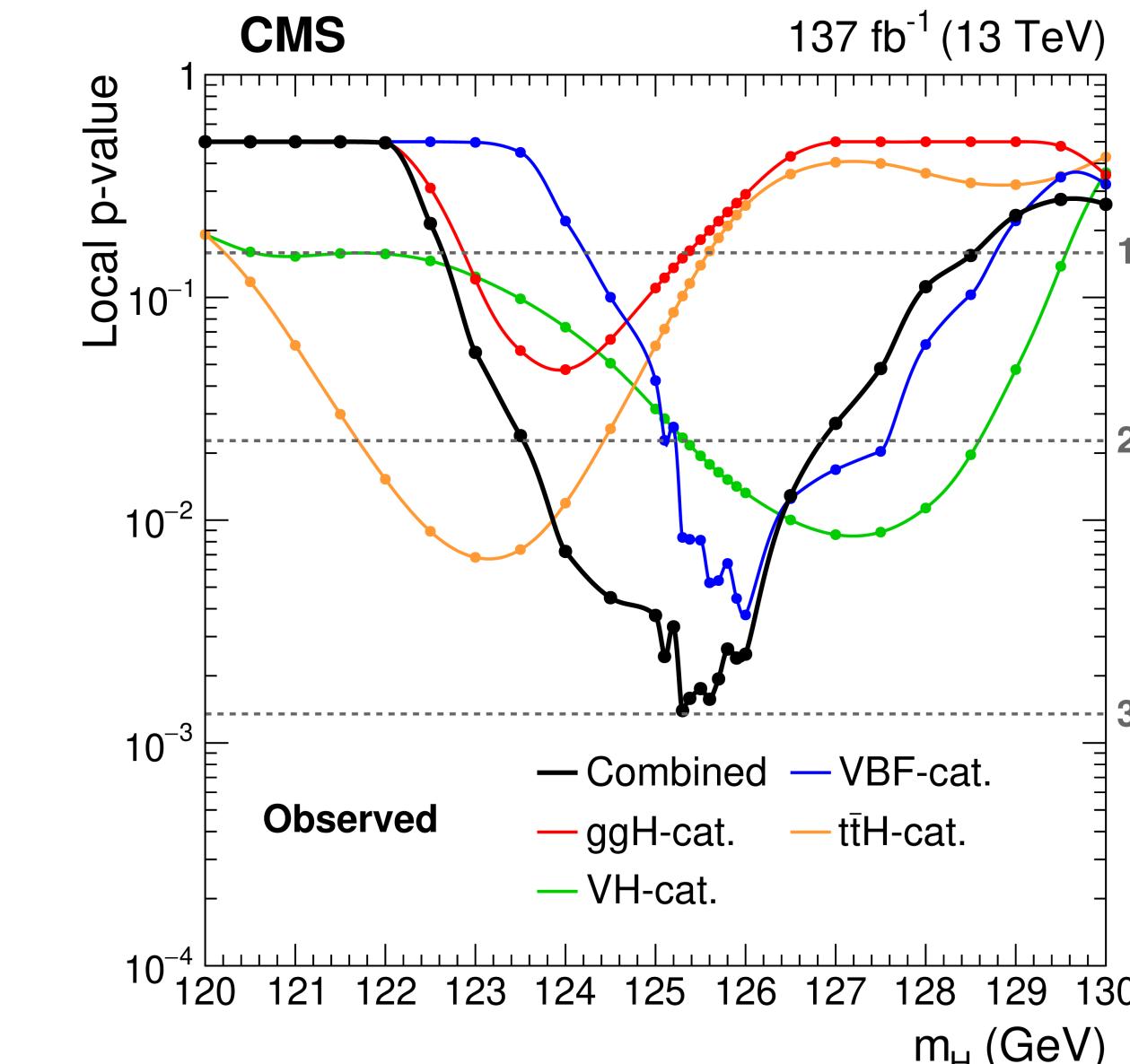
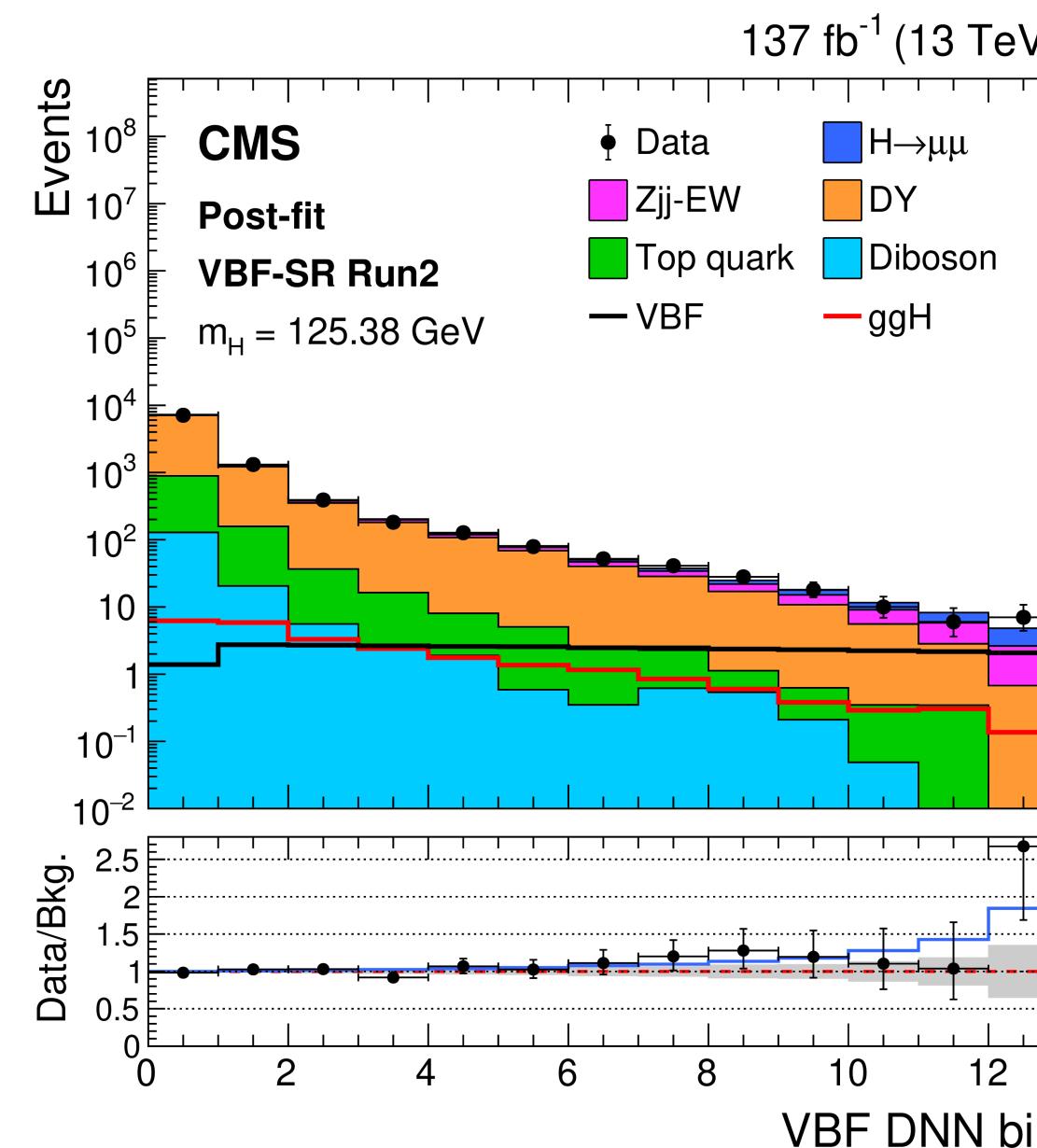
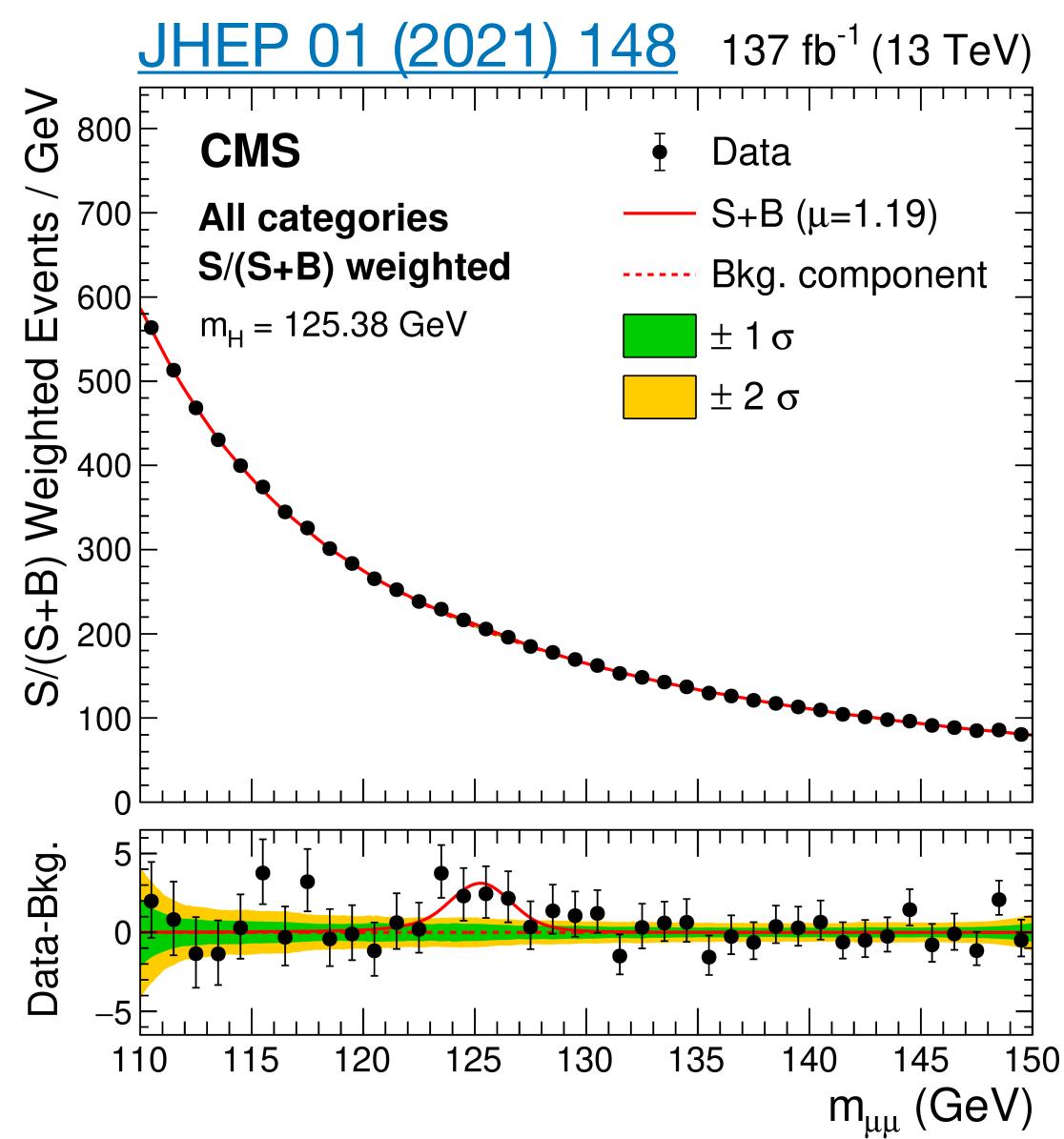
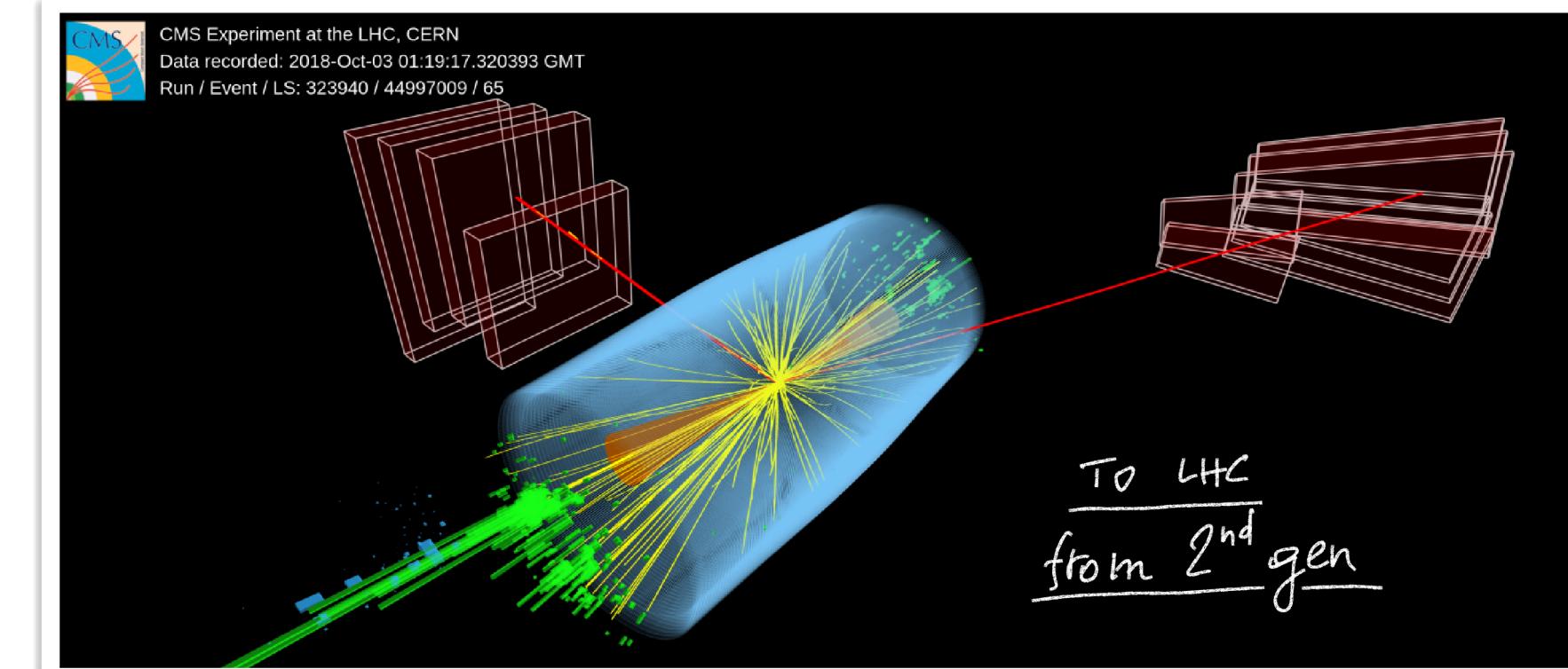
# $H \rightarrow ll\gamma$ evidence

- SM Higgs can decay in  $ll\gamma$  in different ways
- Low mass ( $m_{ll} < 30$  GeV) targets Dalitz
- First evidence of  $H \rightarrow ll\gamma$  with  $l = e$  or  $\mu$ 
  - Includes all main production (ggF, VBF, VH, ttH)
  - Dedicated reconstruction for merged electrons
  - Categorisation based on lepton flavour ( $ee, \mu\mu$ ) and event topology (VBF-like,  $p_T^{ll}$ , merged/resolved)
  - Signal extraction via simultaneous fit of parametric functions of  $m_{ll\gamma}$  in all categories
  - Observed (expected) significance is  $3.2$  ( $2.1$ )  $\sigma$
  - Signal strength  $\mu = 1.5 \pm 0.5$



# $H \rightarrow \mu\mu$ - Welcome 2nd gen!

- Direct evidence of the Higgs decaying to second generation fermions
- Included all main production modes (ggF, VBF, VH, ttH)
  - BDT are used to improve signal classification
  - Analytical fit to the invariant mass for signal extraction
  - CMS VBF category uses a template based approach directly on the DNN output for signal extraction



[Phys. Lett. B 812 \(2021\) 135980](#)

**ATLAS**

Significance of  $2.0$  ( $1.7$ )  $\sigma$   
 $\mu = 1.2 \pm 0.6$

[JHEP 01 \(2021\) 148](#)

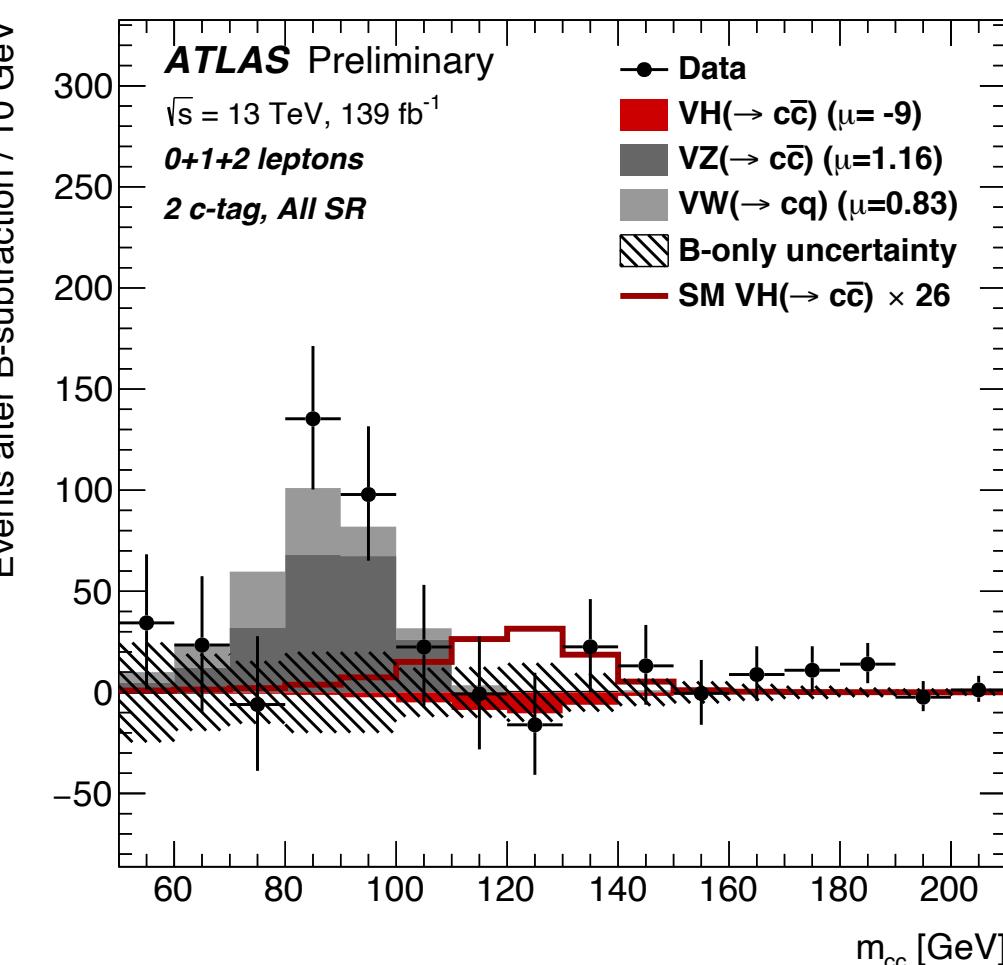
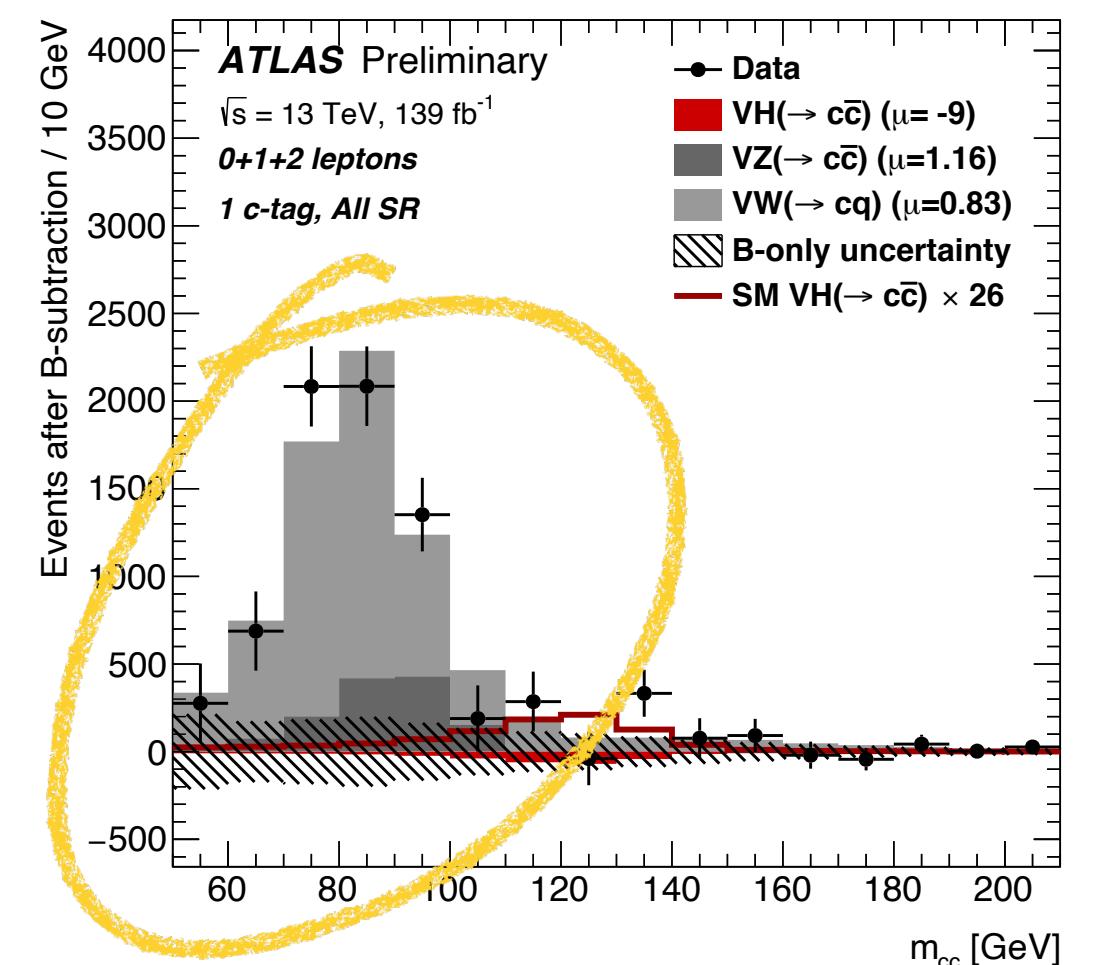
**CMS**

Significance of  $3.0$  ( $2.5$ )  $\sigma$   
 $\mu = 1.19^{+0.40}_{-0.39} (\text{stat})^{+0.15}_{-0.14} (\text{syst})$

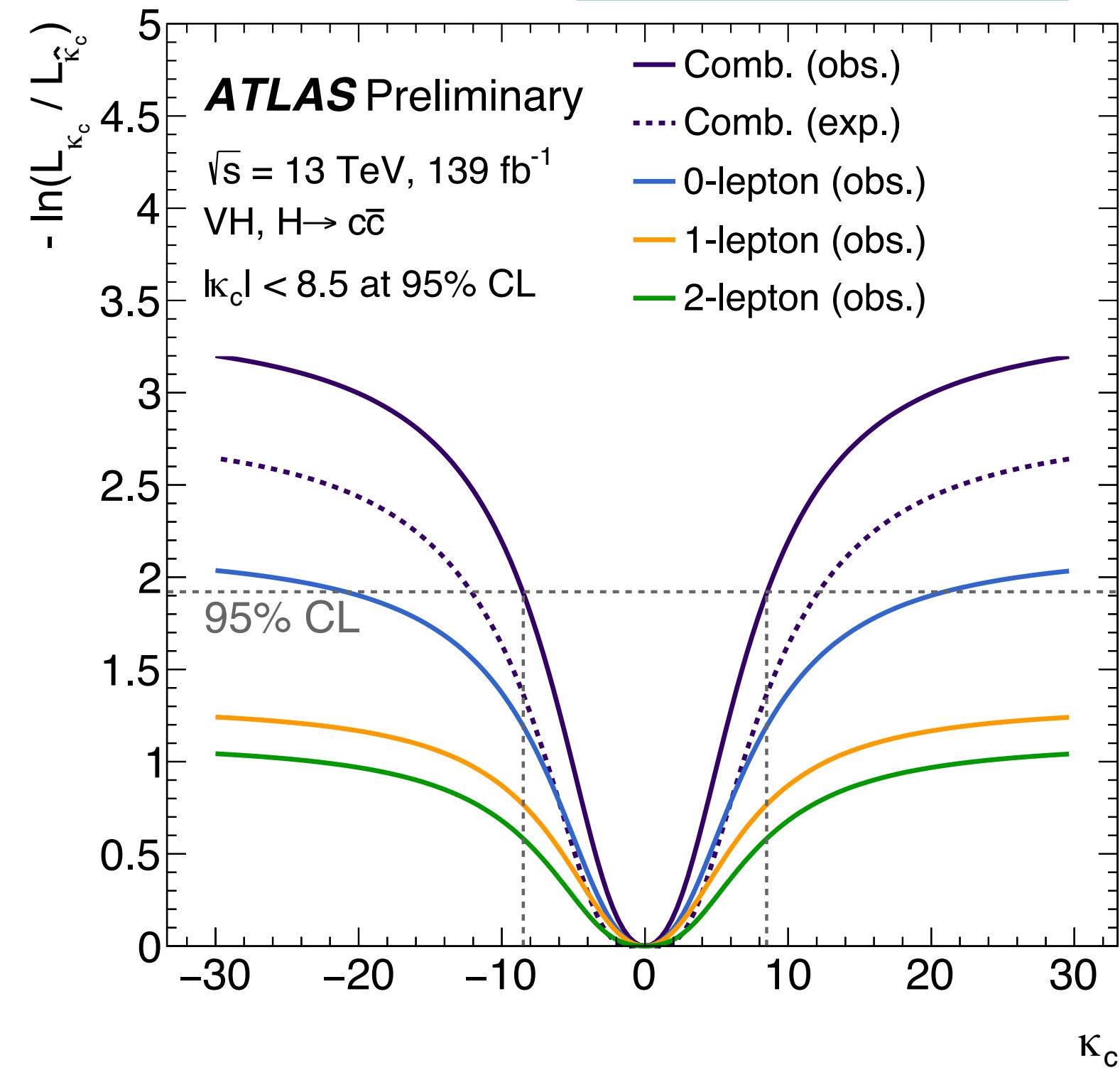
## NEW RESULTS FOR THIS CONFERENCE

$$H \rightarrow CC$$

- Hcc is the next milestone in the study of the second generation couplings
- ATLAS just released VHcc using the full Run2 data
- Three production modes  $Z(l\bar{l})H$ ,  $Z(\nu\bar{\nu})H$ ,  $W(l\nu)H$  **NEW!**
- Categorisation in  $p_T^V$ ,  $N_{jet}$ ,  $N_{c-tag}$  (16 signal regions)
- Signal extraction via simultaneous fit of  $m_{cc}$
- Validation using di-boson production with charm decay
  - VZ(cc) significance of 2.6 (2.2) sigma
  - VW(cq) significance 3.8 (4.6) sigma
- Observed (expected)  $\mu_{VHcc} < 26$  (31) @95%CL
- Observed (expected)  $|\kappa_c| < 8.4$  (12.4) @95%CL



[ATLAS-CONF-2021-027](#)



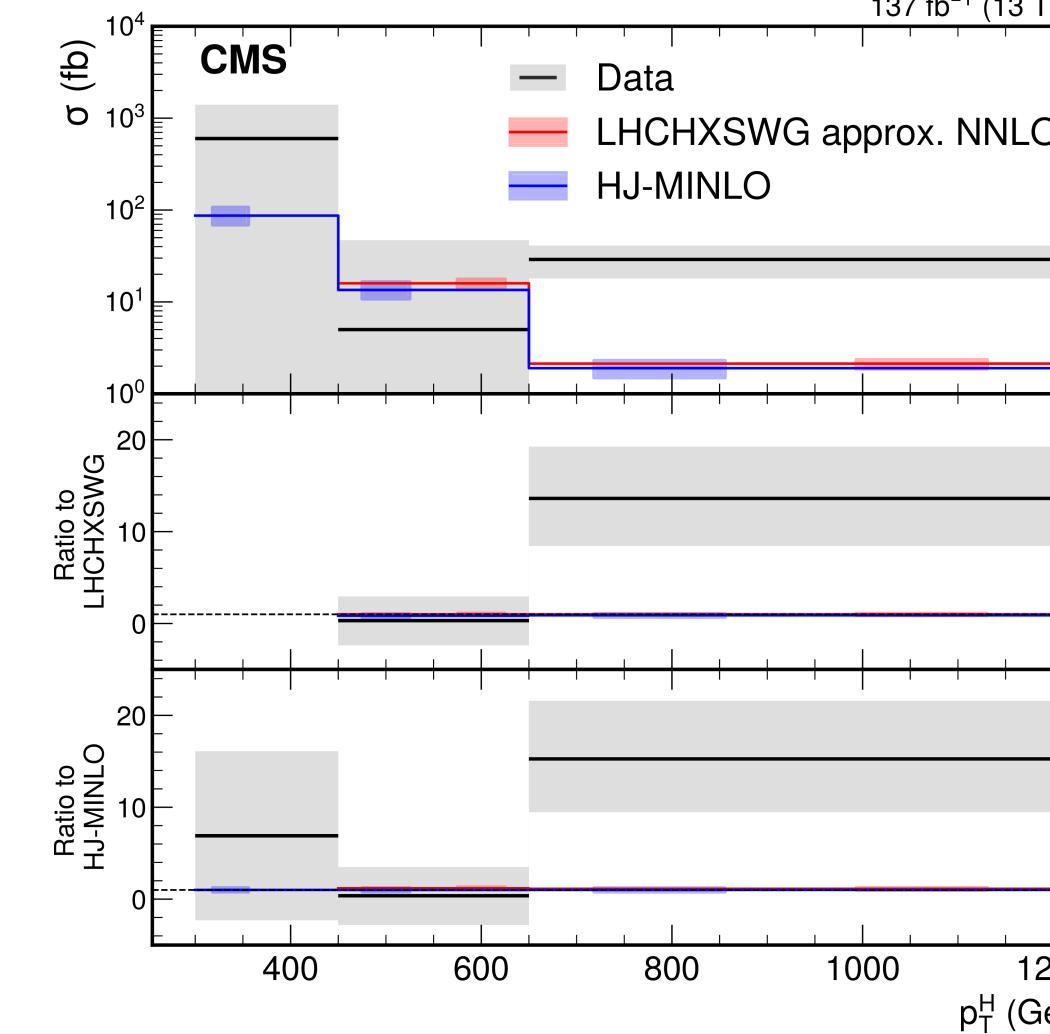
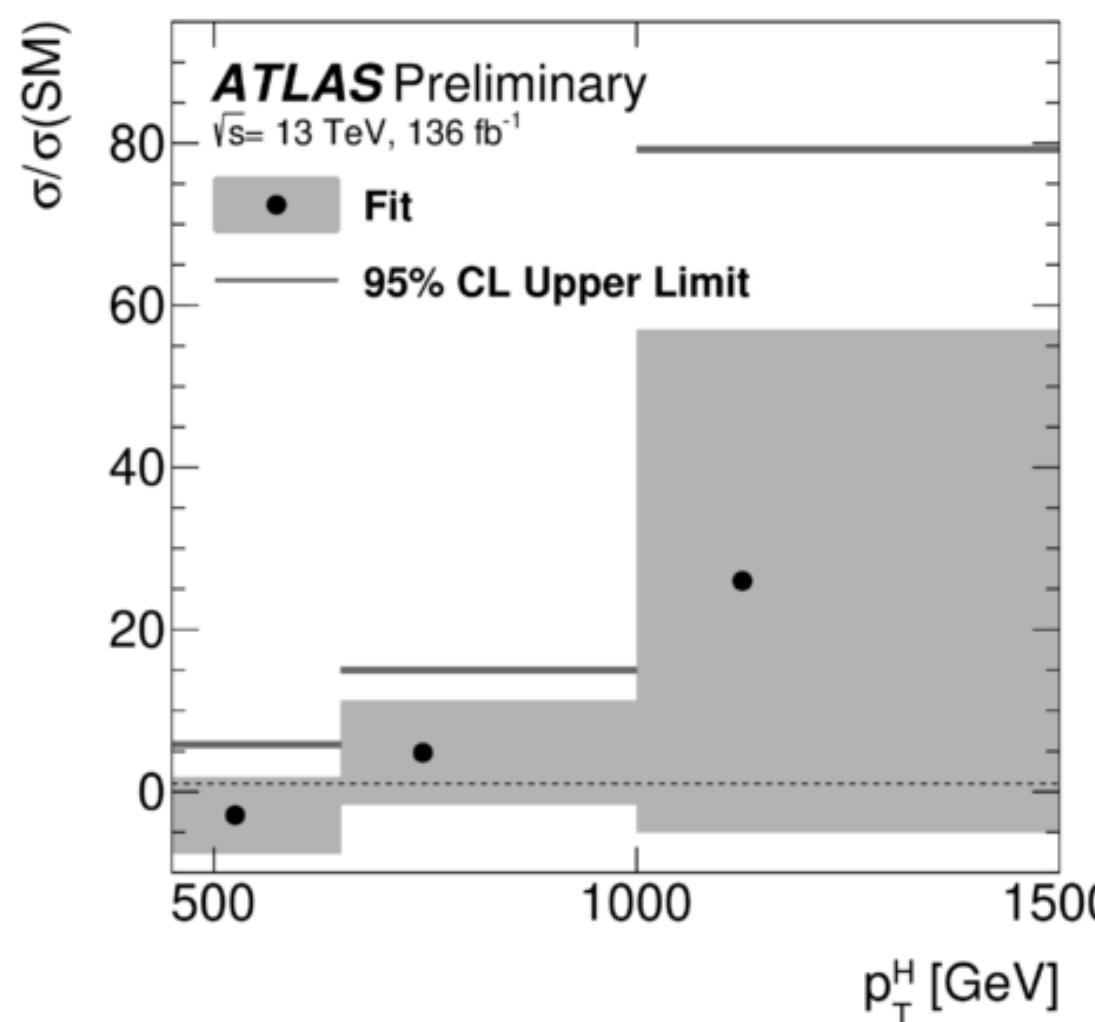
**...getting heavier...**  
**3rd generation**

# $H \rightarrow bb$

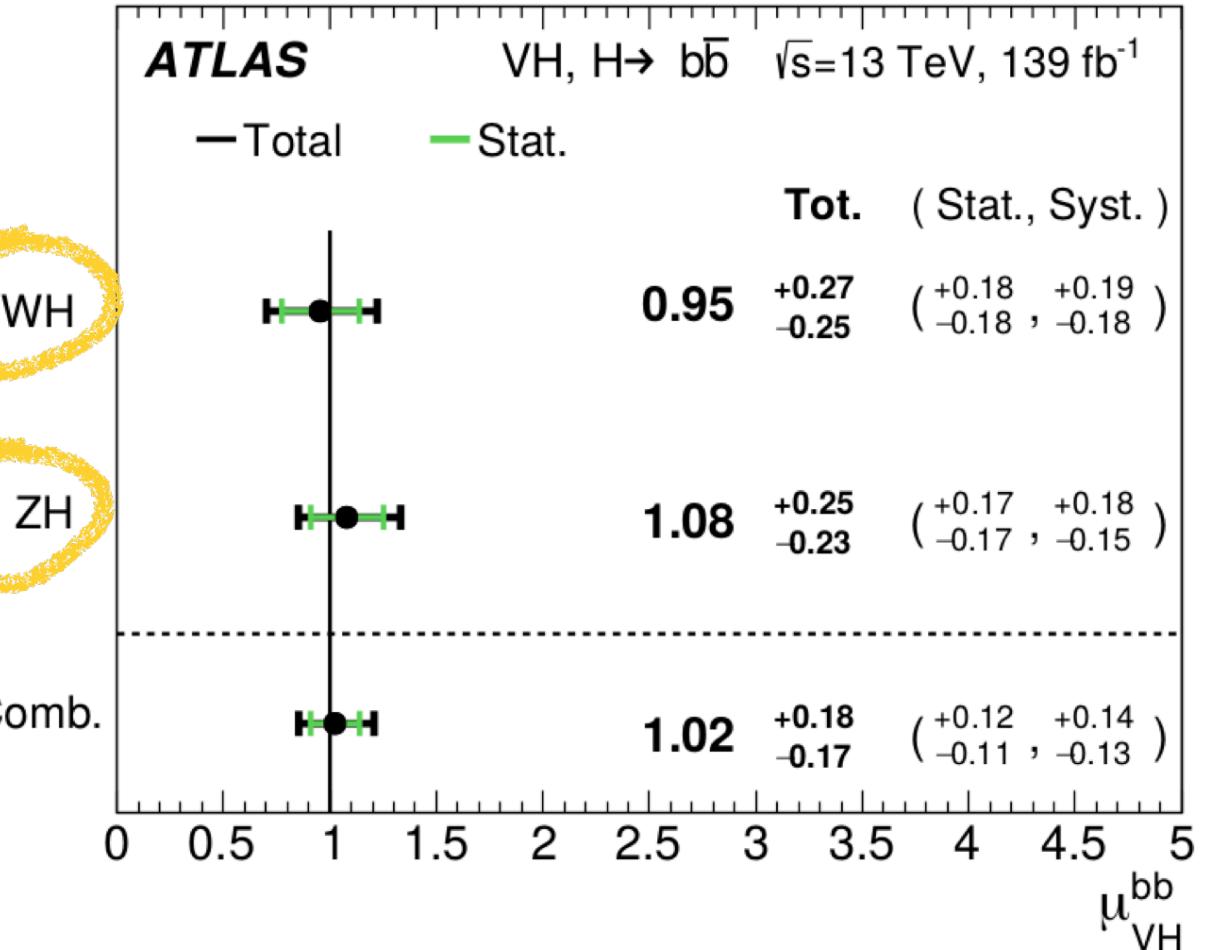
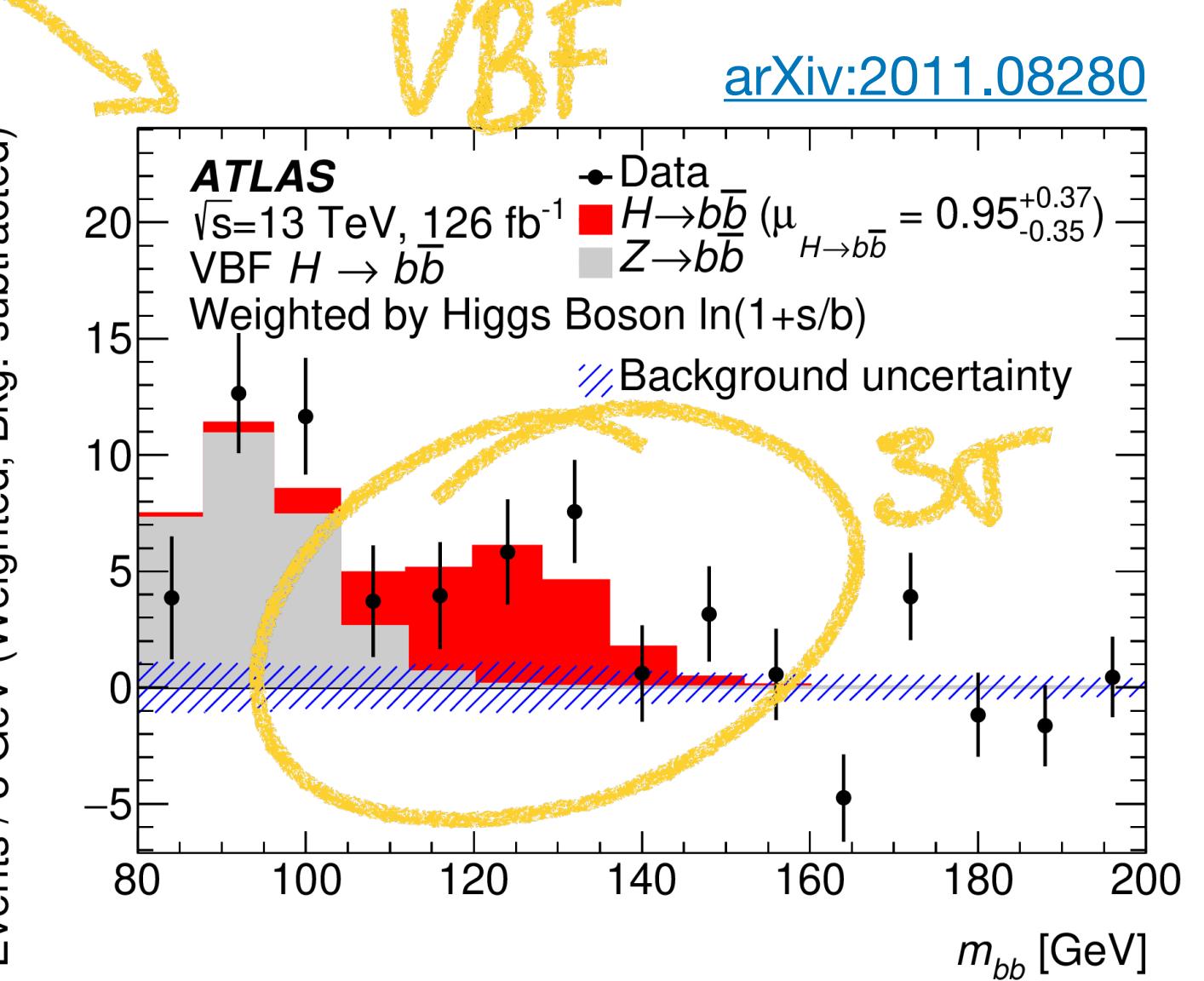
- $H \rightarrow bb$  already observed by both ATLAS and CMS
- VH production (golden channel)
  - WH and ZH Hbb established individually with  $4.0$  ( $4.1$ ) and  $5.3$  ( $5.1$ )  $\sigma$  respectively
  - Has enough signal to start measure cross sections in  $p_T^{V,t}$  bins fiducial volumes (resolved and merged)
  - Results are interpreted in SMEFT framework constraining anomalous couplings
- VBF Hbb combination of photon-tagged and inclusive reaches  $3.0$  ( $3.0$ )  $\sigma$
- ggF Hbb fiducial and differential cross section in  $p_T^H$  bins at high boost

ggH boosted

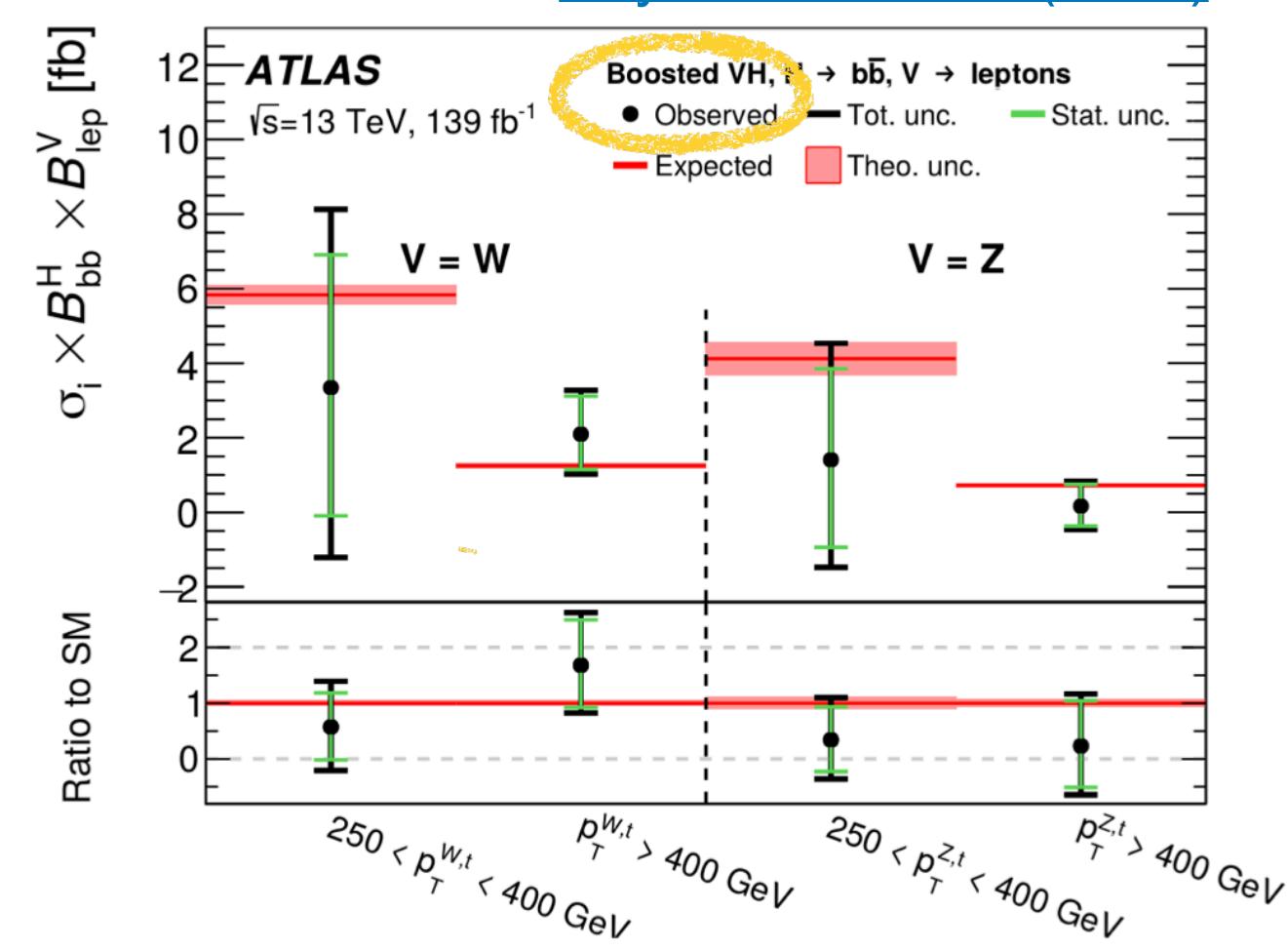
[ATLAS-CONF-2021-010](#)



Events / 8 GeV (Weighted, Bkg.-subtracted)



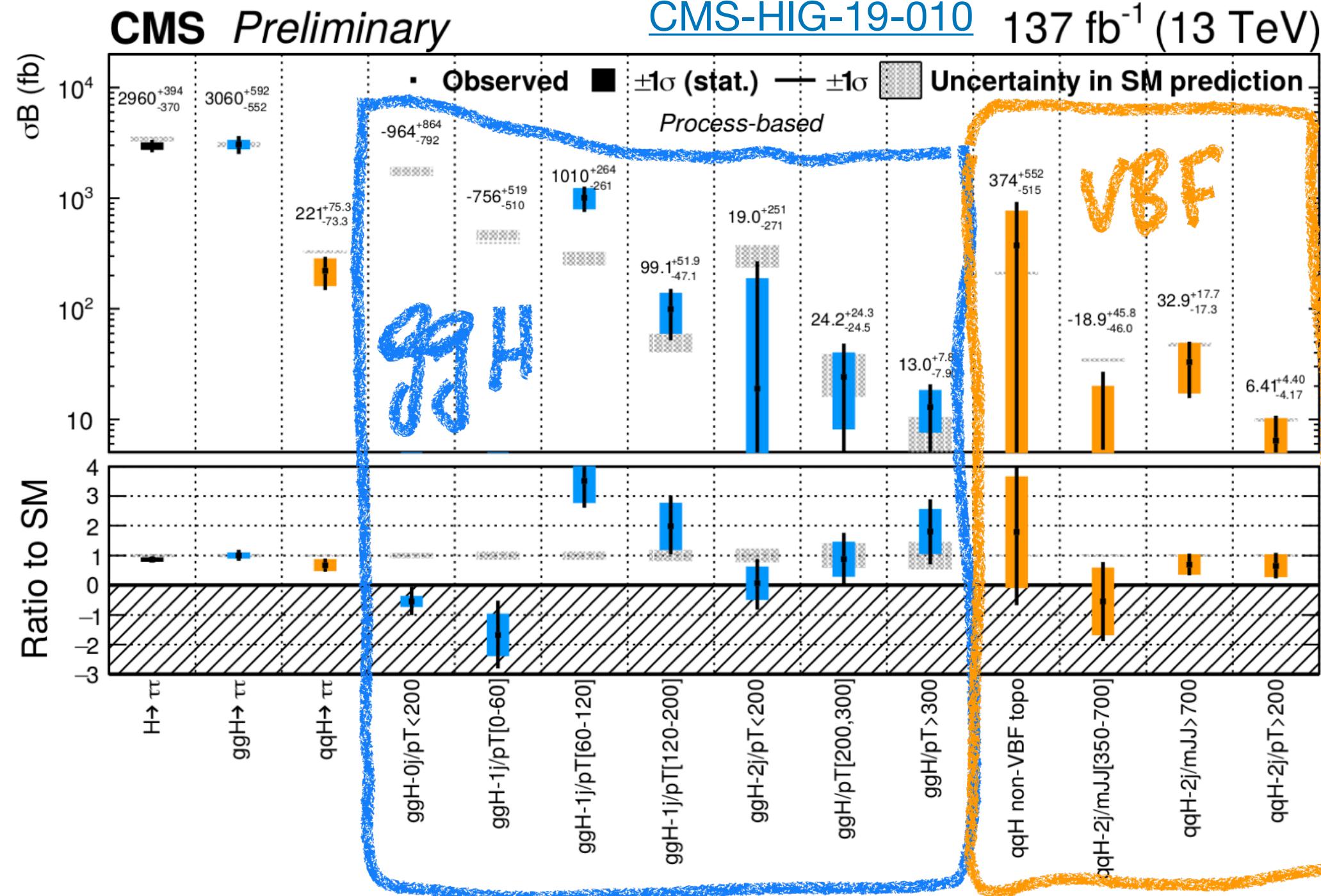
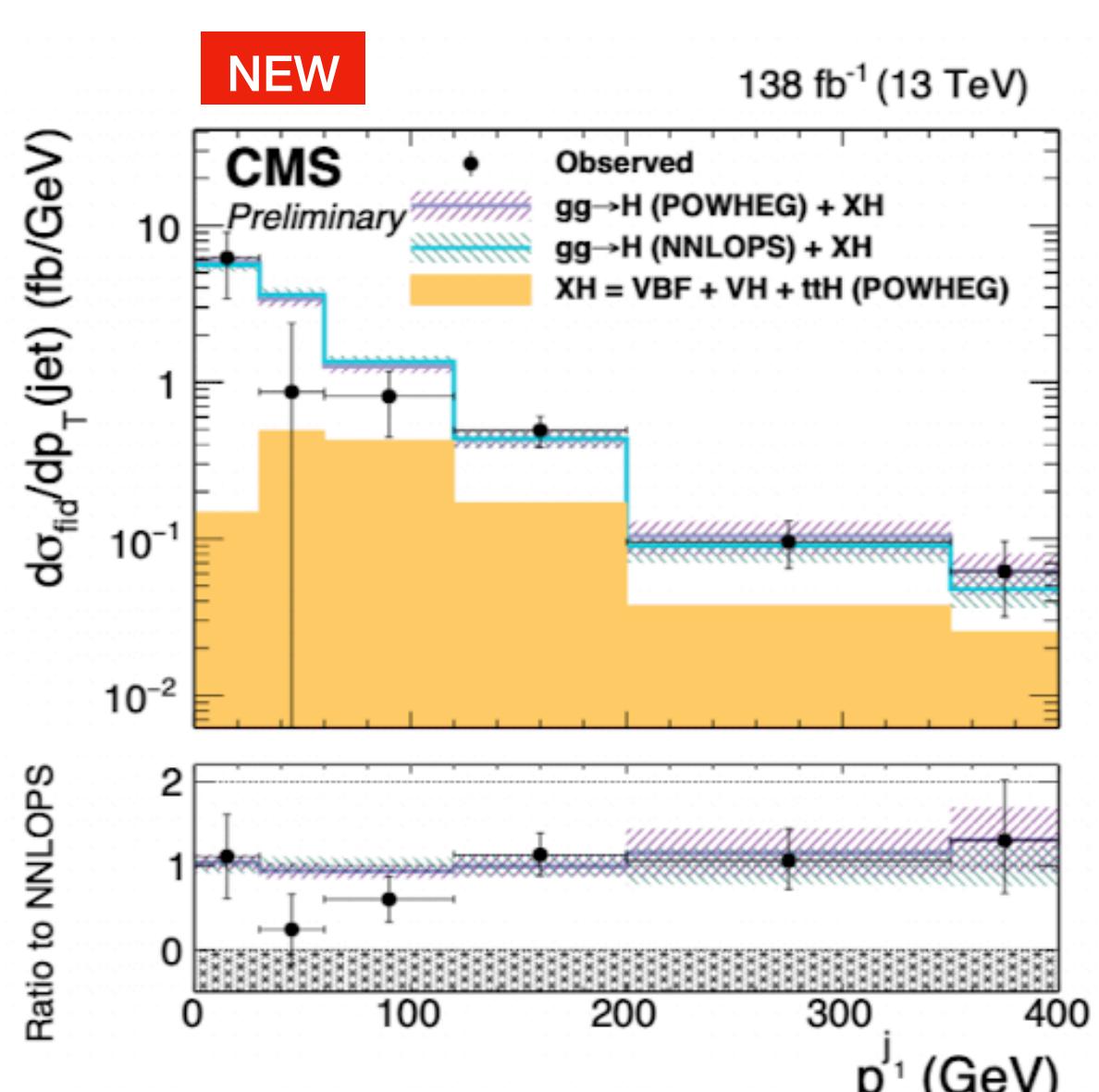
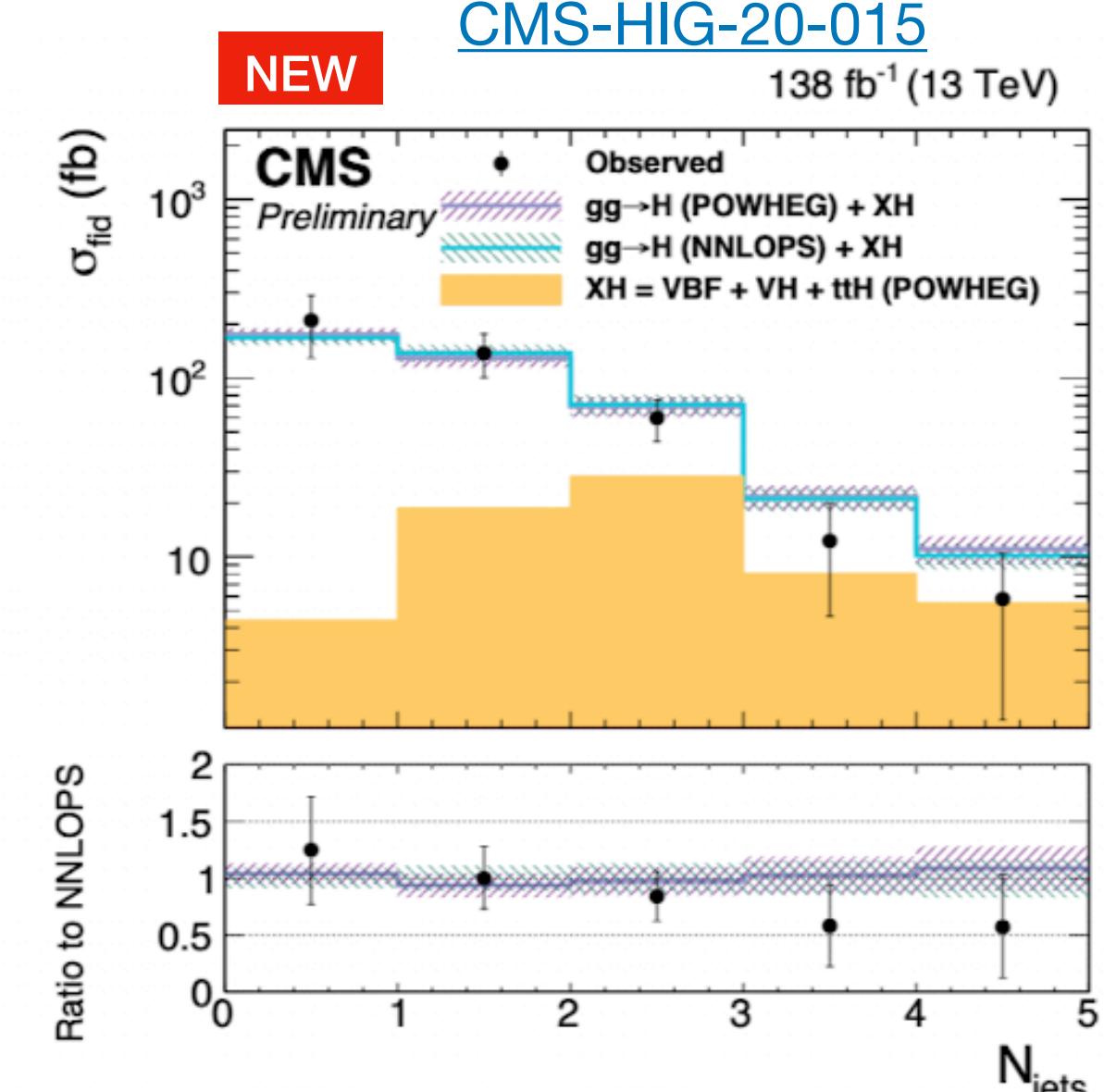
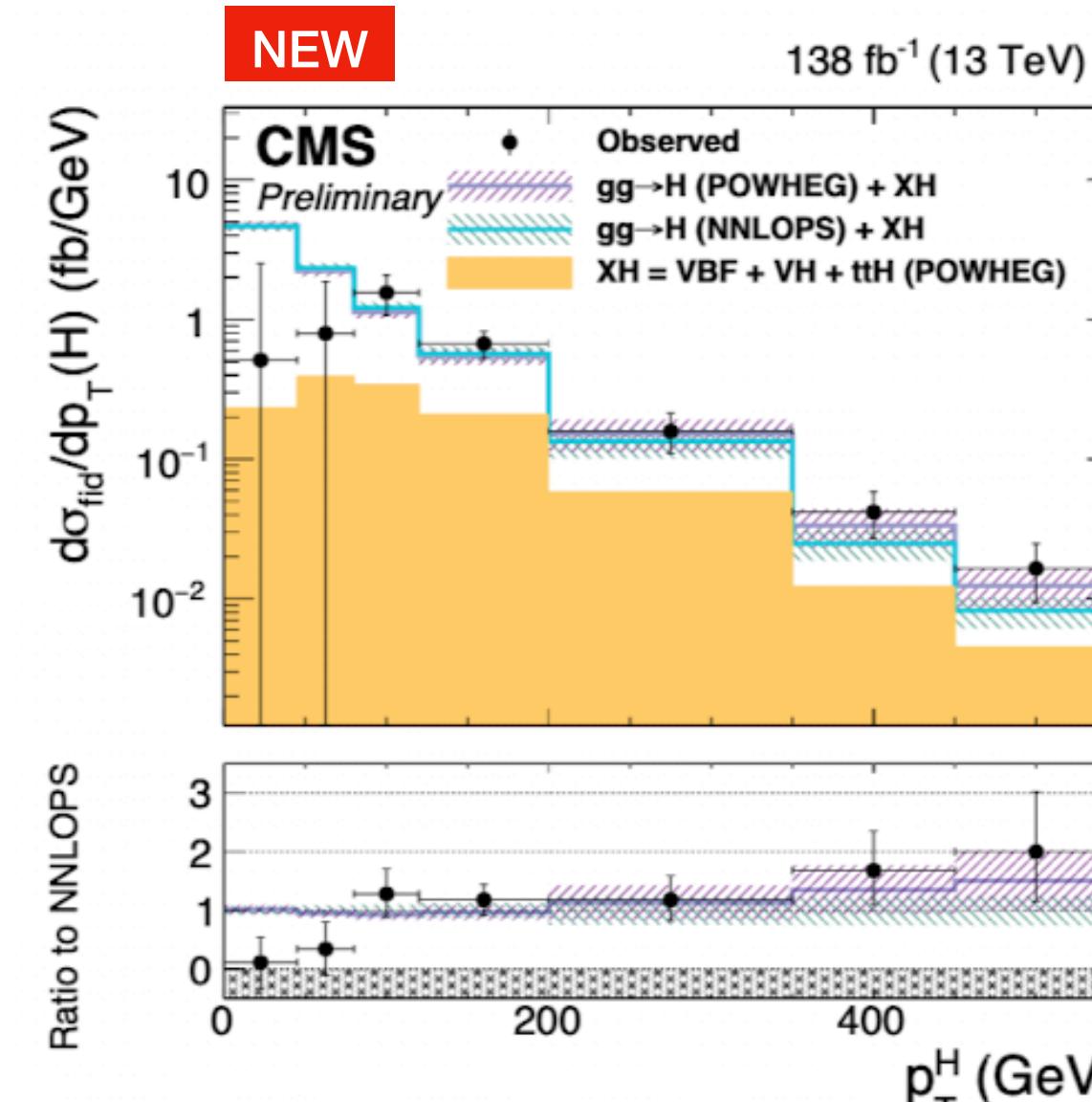
[Phys.Lett. B 816 \(2021\)](#)



## NEW RESULTS FOR THIS CONFERENCE

$$H \rightarrow \tau\tau$$

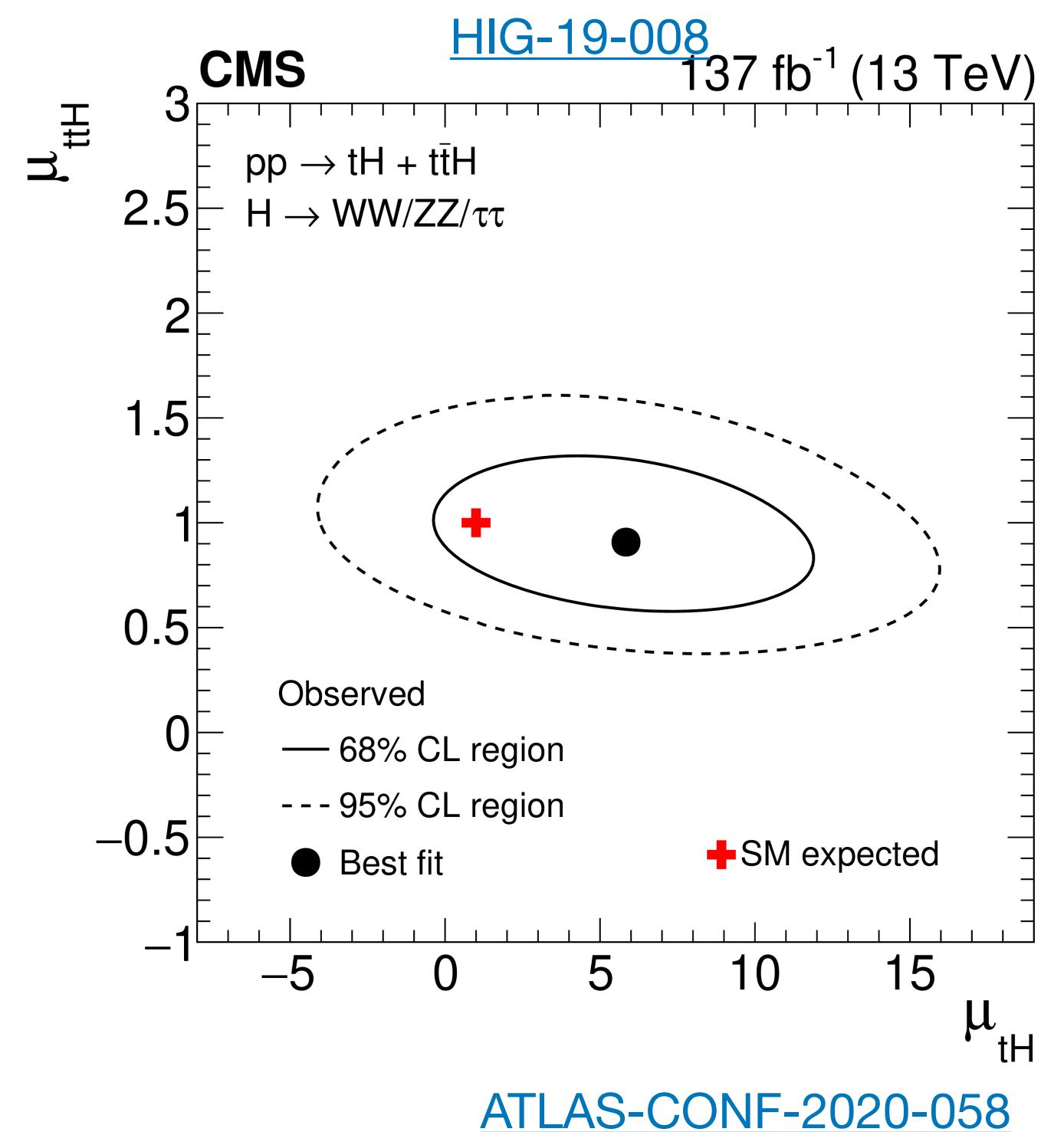
- Already observed by both ATLAS and CMS
- Most sensitive channels are ggF and VBF with precision < 20%
- Cross section measured in STXS\* bins
- New: First fiducial differential with  $\tau$  in  $N_{jets}$ ,  $p_T^j$  and  $p_T^H$



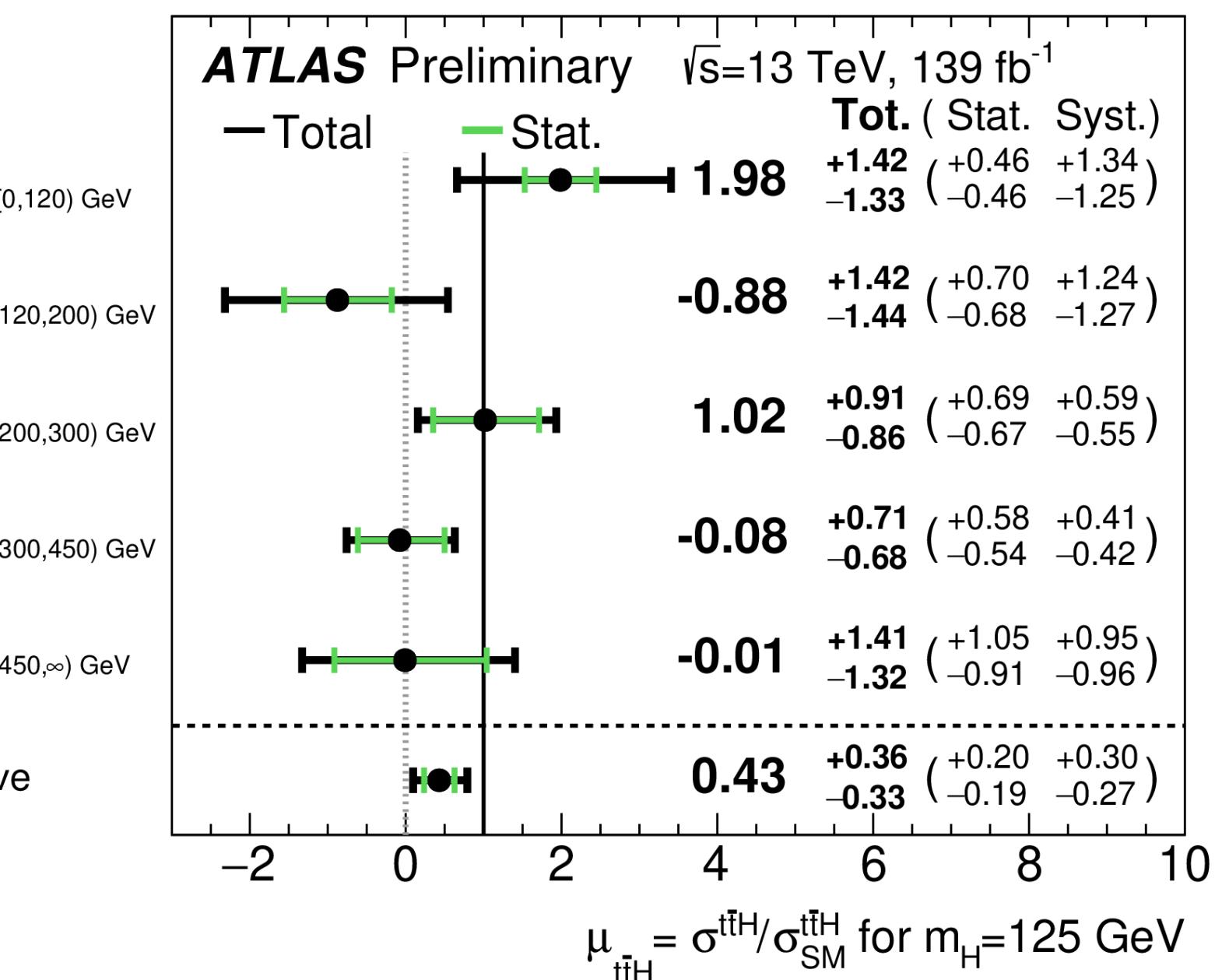
\*STXS: Simplified Template Cross Section framework: agreement on fragmentation of phase space

# ttH and tH

- Direct top coupling accessing vi production mode
  - Targeted with  $\gamma\gamma$ , bb, and multilepton Higgs decays
- CMS recent updated **multilepton** with FullRun2
  - Target both ttH and tH production
  - ML and MEM improve ttH - tH separation
  - **Most sensitive ttH analysis to date**
- ATLAS updated the **H to bb decay** with full run2
  - Significance of 1.3 (3.0)
  - Signal strength  $\mu = 0.43^{+0.36}_{-0.33}$
  - **First ttH signal strength measured in STSx  $p_T^H$  bins**



ATLAS-CONF-2020-058



**...changing spin...**  
**Bosons**

[ATLAS-CONF-2021-014](#)

# $H \rightarrow WW^*$

ATLAS

- Cross section times BR for ggF and VBF are measured simultaneously and are in agreement with the SM

$$\bullet \sigma_{ggF} \cdot BR_{H \rightarrow WW^*} = 12.4 \pm 1.5 \text{ pb}$$

SYSTEMATICALLY LIMITED

$$\bullet \sigma_{VBF} \cdot BR_{H \rightarrow WW^*} = 0.79^{+0.19}_{-0.16} \text{ pb}$$

- ggF EXP and THEORY ARE SIMILAR
- VBF THEORY UNCERTAINTY DOMINATES

- Production cross section of ggF and VBF measured in 11 STXS categories

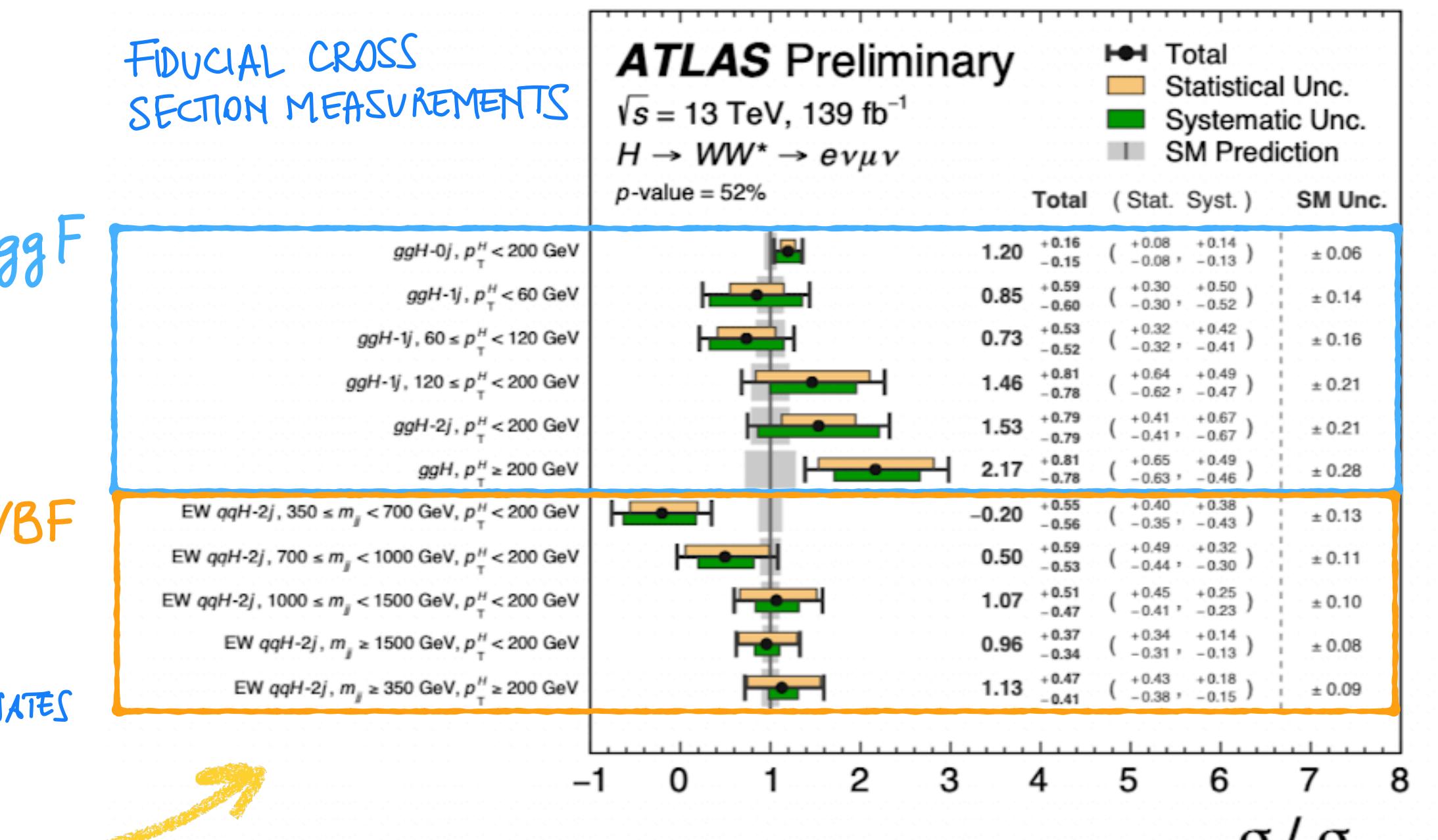
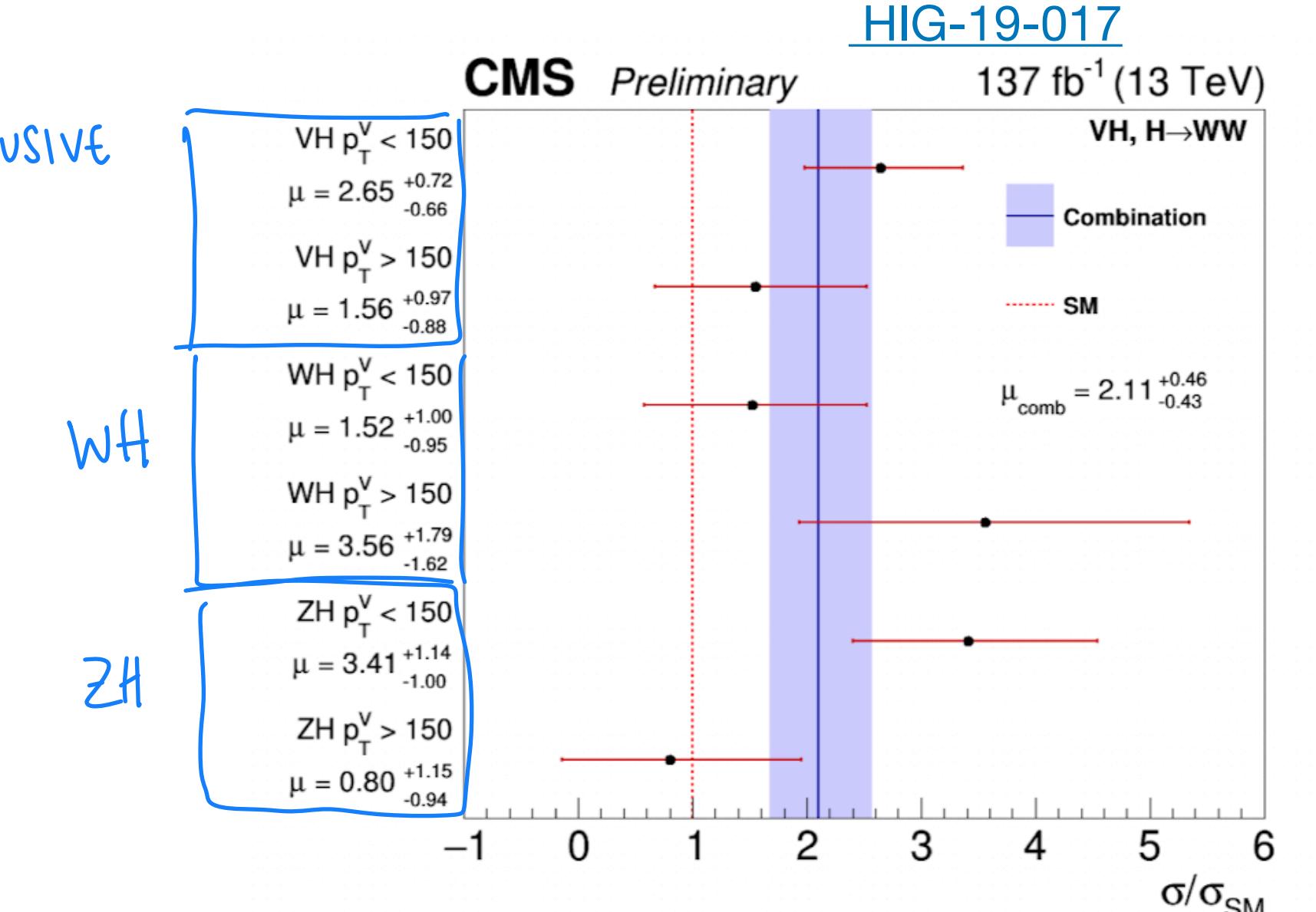
CMS

- VH direct probe to H-VV coupling
- Measure inclusive production cross sections of WH and ZH

- Two different categorisation

- Maximise sensitivity of VH observation :  $4.7$  ( $2.8$ )  $\sigma$

- Measure signal strength in STXS  $p_T^V$  bins

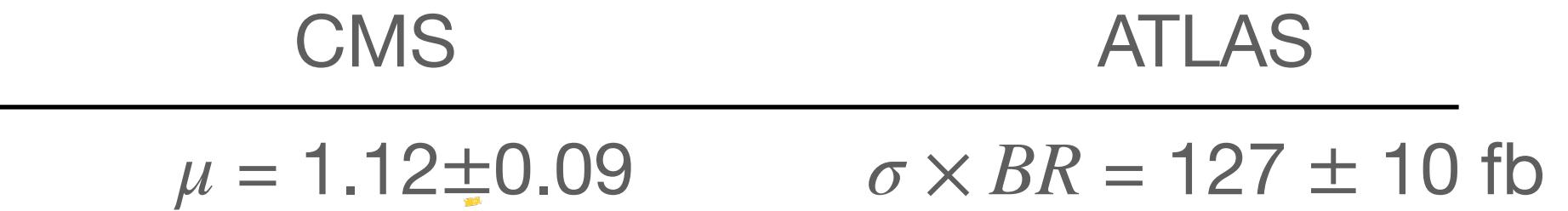
FIDUCIAL CROSS SECTION MEASUREMENTSggFVBFWfZH

$$H \rightarrow \gamma\gamma$$

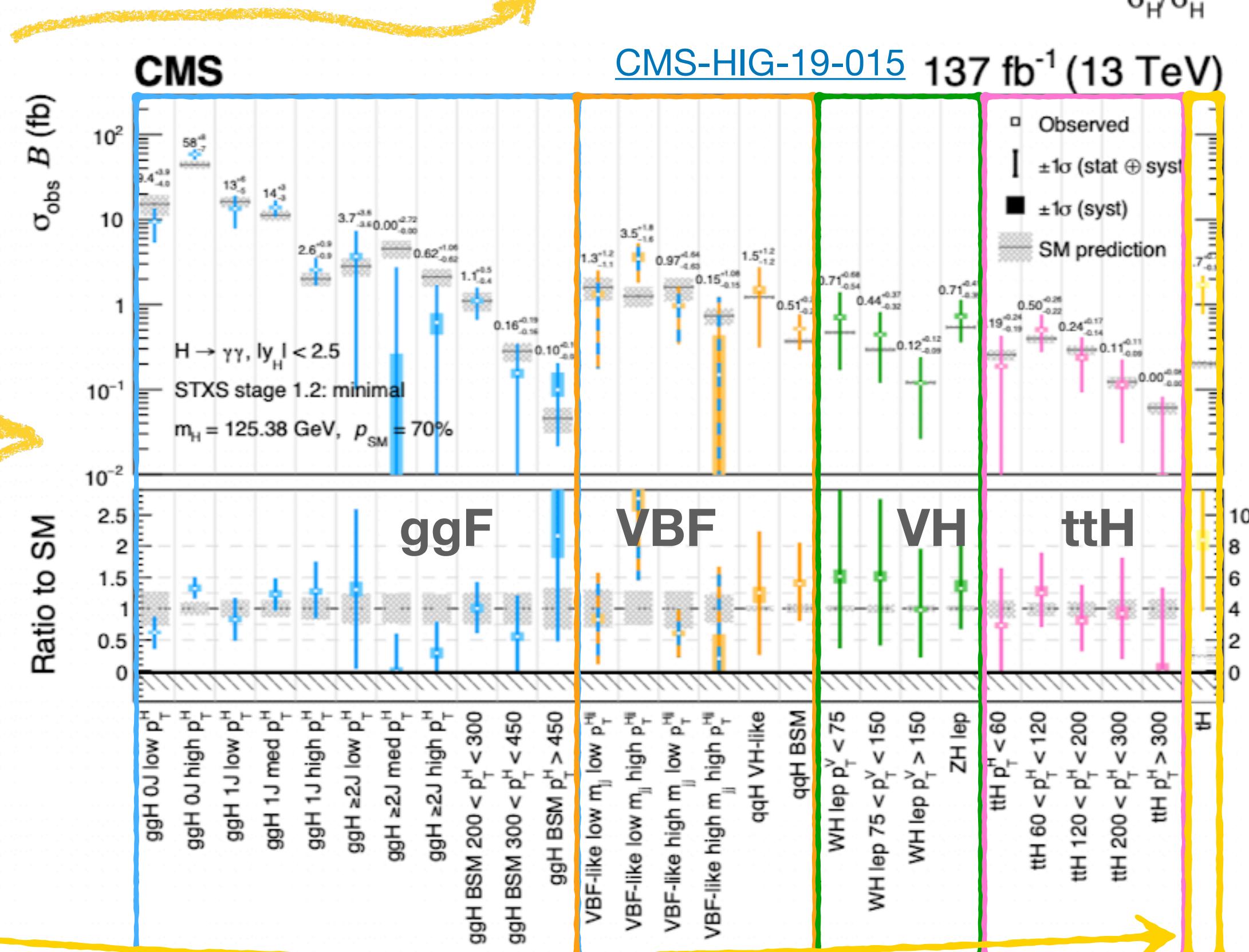
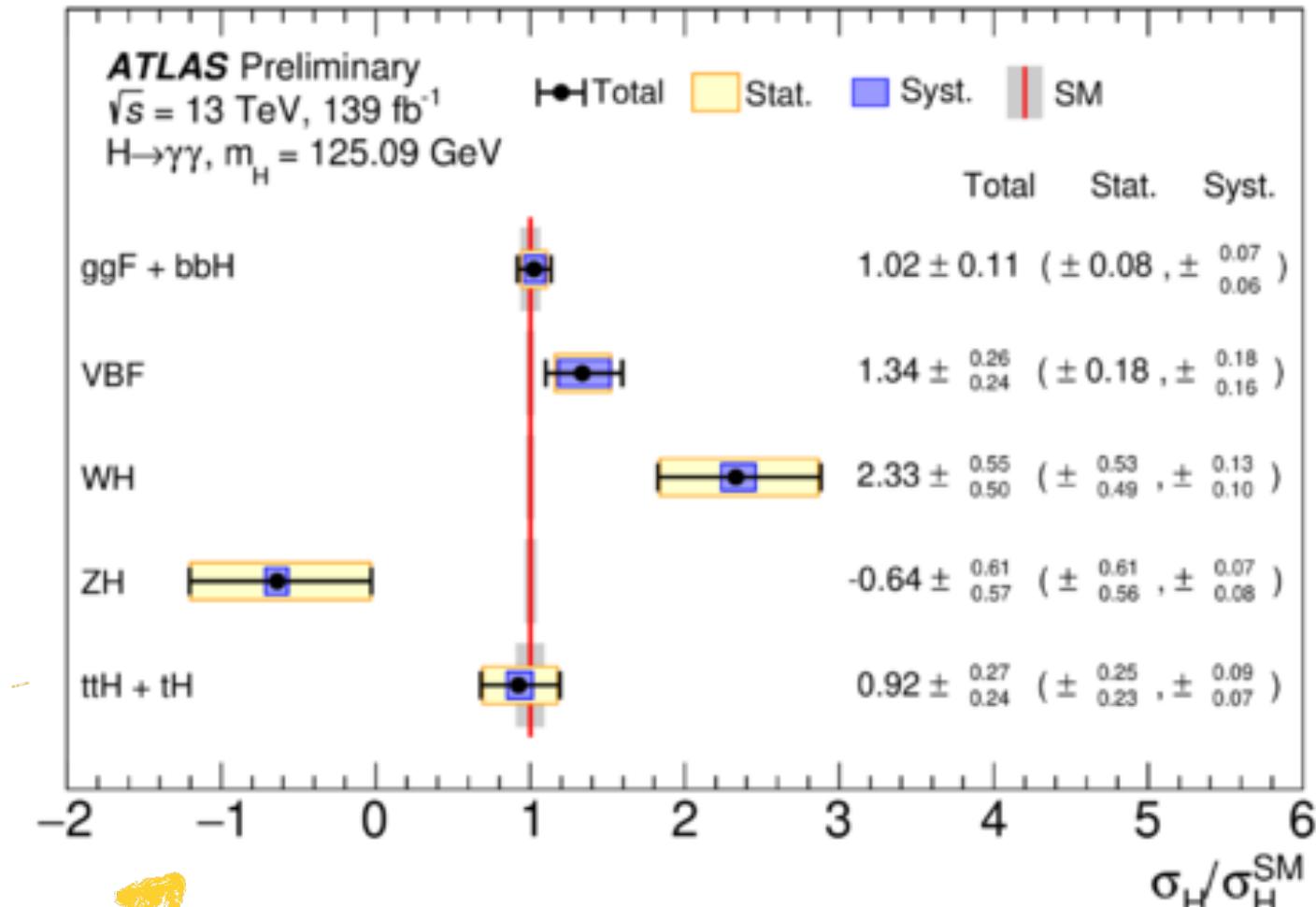
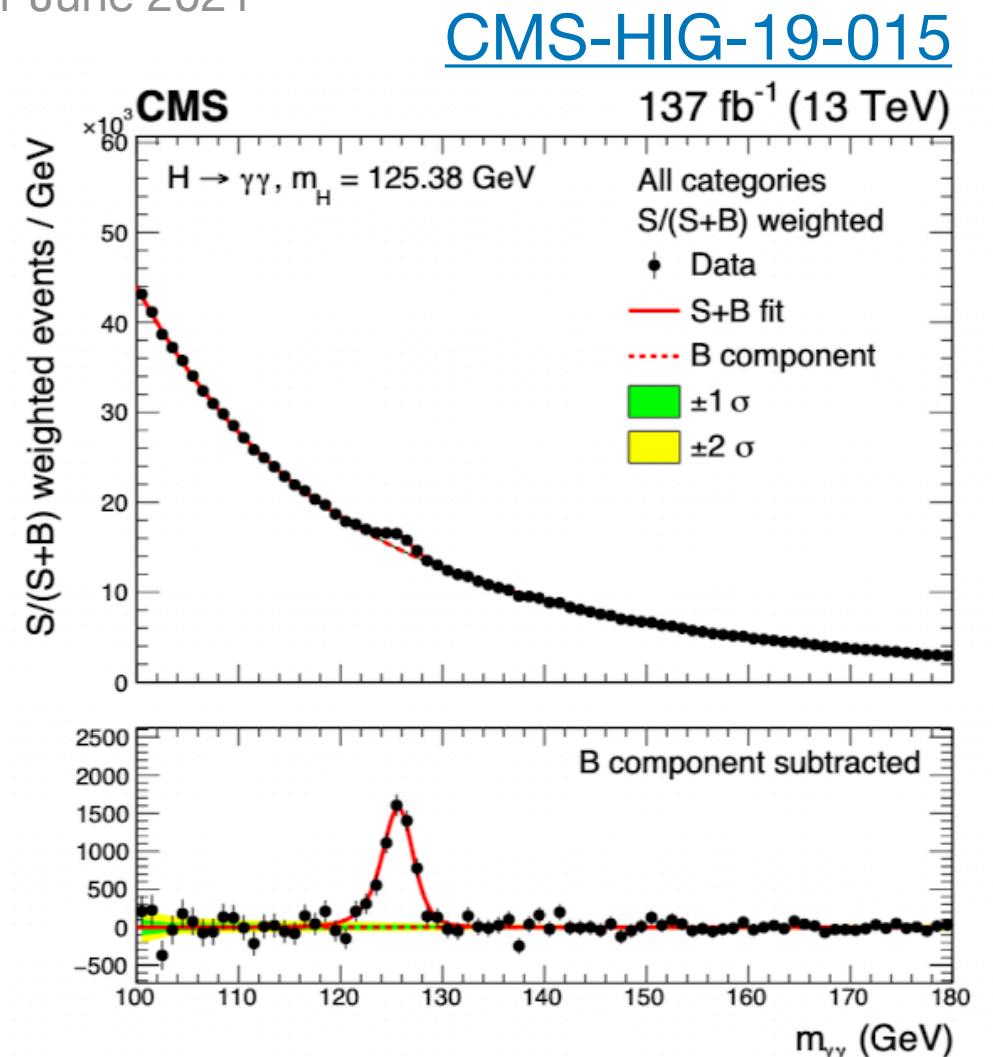
- Fully into the precision phase
- CMS and ATLAS released full Run2 updates

- All main production included (ggH+bbH, VBF, VH, ttH, tH)

- Inclusive signal measured with  $< 10\%$  unc.



- Cross sections measured in several (17 or 27) STXS kinematic regions for all production modes



# $H \rightarrow ZZ^*$

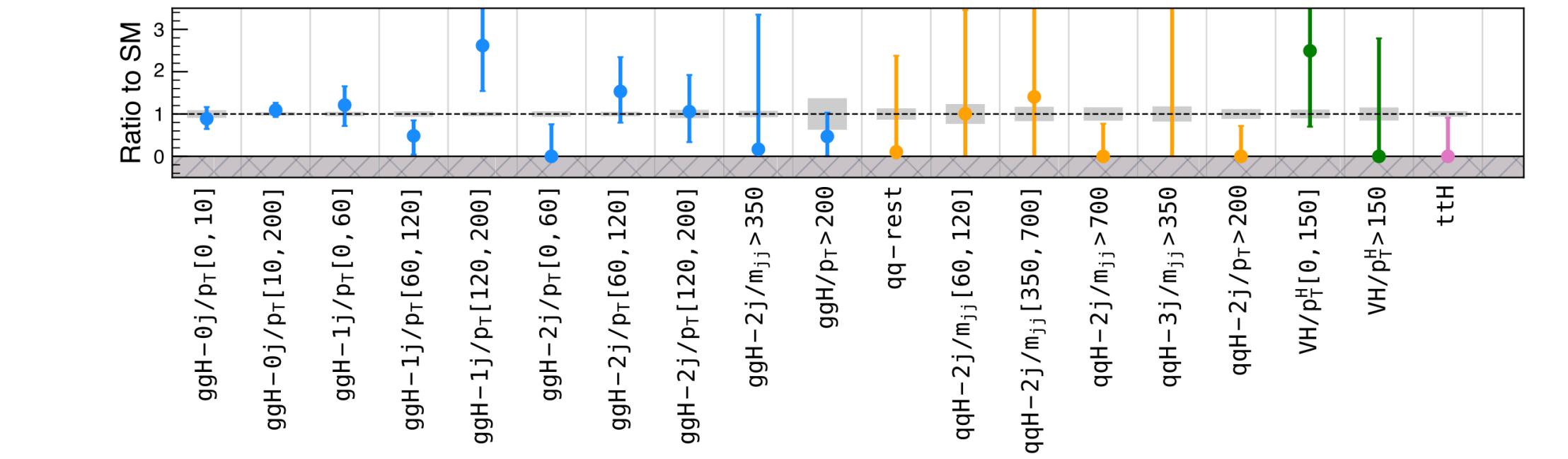
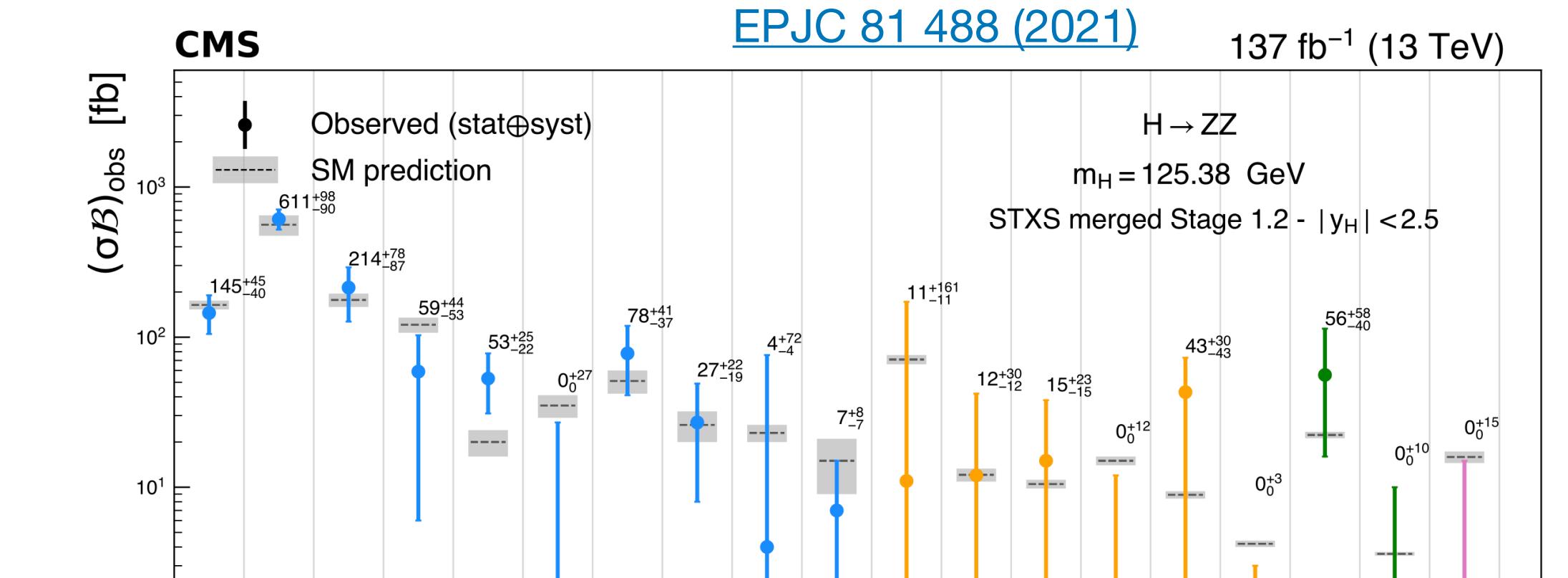
- Fully into the precision phase
- CMS and ATLAS released full Run2 updates before LHCP2020
- Inclusive signal measured with  $\sim 10\%$  uncertainty

CMS

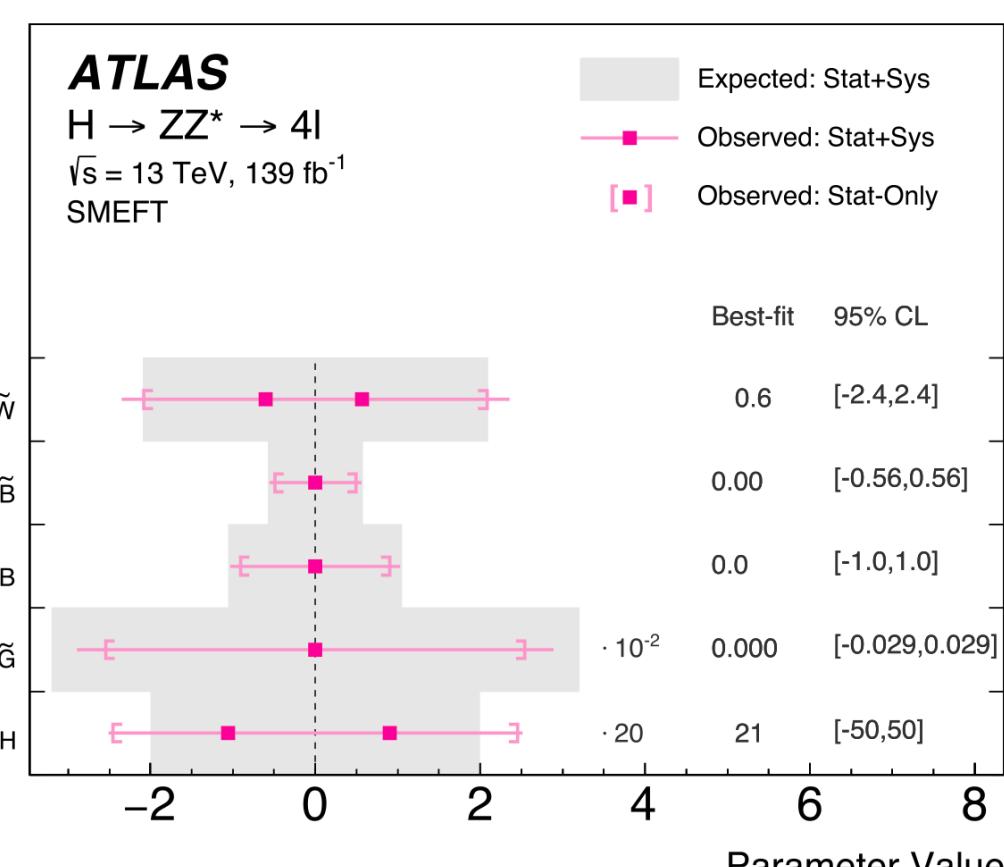
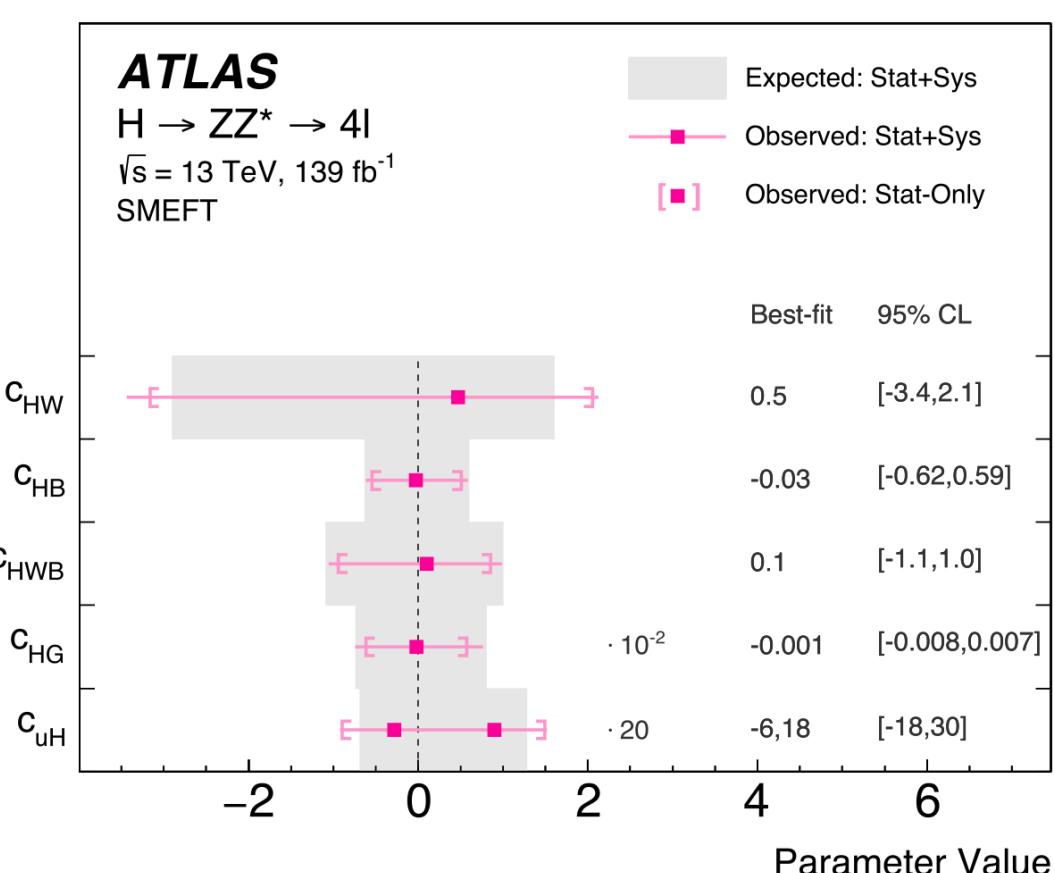
$$\mu = 1.01 \pm 0.11$$

ATLAS

$$\mu = 0.94^{+0.12}_{-0.11}$$



- Fiducial differential cross section measurements
- Cross section measure in exclusive STXS regions
- Interpretation in SM EFT with Wilson coefficients



# Combination

$$(\sigma \times B)_{if} = (\sigma \times B)_{i,ZZ} \cdot \left( \frac{B_f}{B_{ZZ}} \right)$$

- Combination of analyses with Run2 data allows great precision in inclusive signal strength measurements

	<a href="#">ATLAS-CONF-20-027</a>	<a href="#">CMS-HIG-19-005</a>
Total signal strength	$\mu = 1.06 \pm 0.07$	$\mu = 1.02^{+0.07}_{-0.06}$

- ATLAS recently released a measurement of cross sections in STXS bins using the combination of

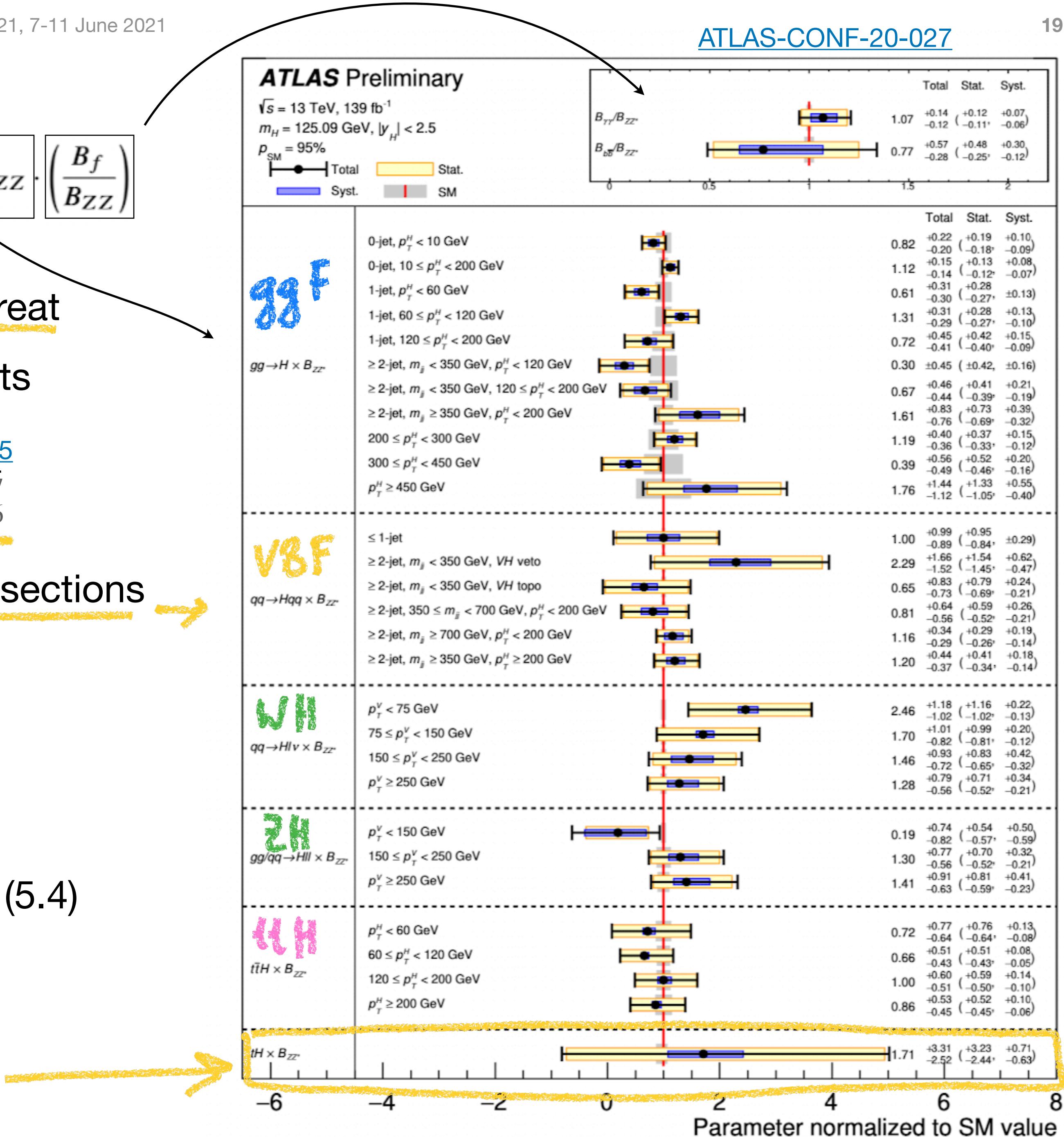
$VHbb, H \rightarrow \gamma\gamma, H \rightarrow 4l$

- Includes ggF, VBF, ZH, WH, ttH, tH production

- WH and ZH observed with 6.3 (5.2) and 5.0 (5.4)

- First observation of WH !

- Upper limit on  $\mu(tH) < 8.4$  (8.2) @95 CL



# **CP & Spin**

# CP & SPIN STRUCTURE

- CMS and ATLAS set stringent constraints on the  $J^{CP}$  structure using  $H\text{-}VV$  coupling in Run1 data
  - Pure pseudoscalar Higgs state excluded
  - Small non-SM anomalous couplings or mixed state of scalar and pseudoscalar are not excluded yet
  - $H\text{-}VV$  couplings : CP-odd contributions suppressed by  $1/\Lambda^2$  factor

$$A(HV_1V_2) = \frac{1}{v} \left[ a_1^{VV} + \frac{\kappa_1^{VV} q_{V1}^2 + \kappa_2^{VV} q_{V2}^2}{(\Lambda_1^{VV})^2} + \frac{\kappa_3^{VV} (q_{V1} + q_{V2})^2}{(\Lambda_Q^{VV})^2} \right] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^* + \frac{1}{v} a_2^{VV} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + \frac{1}{v} a_3^{VV} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu},$$

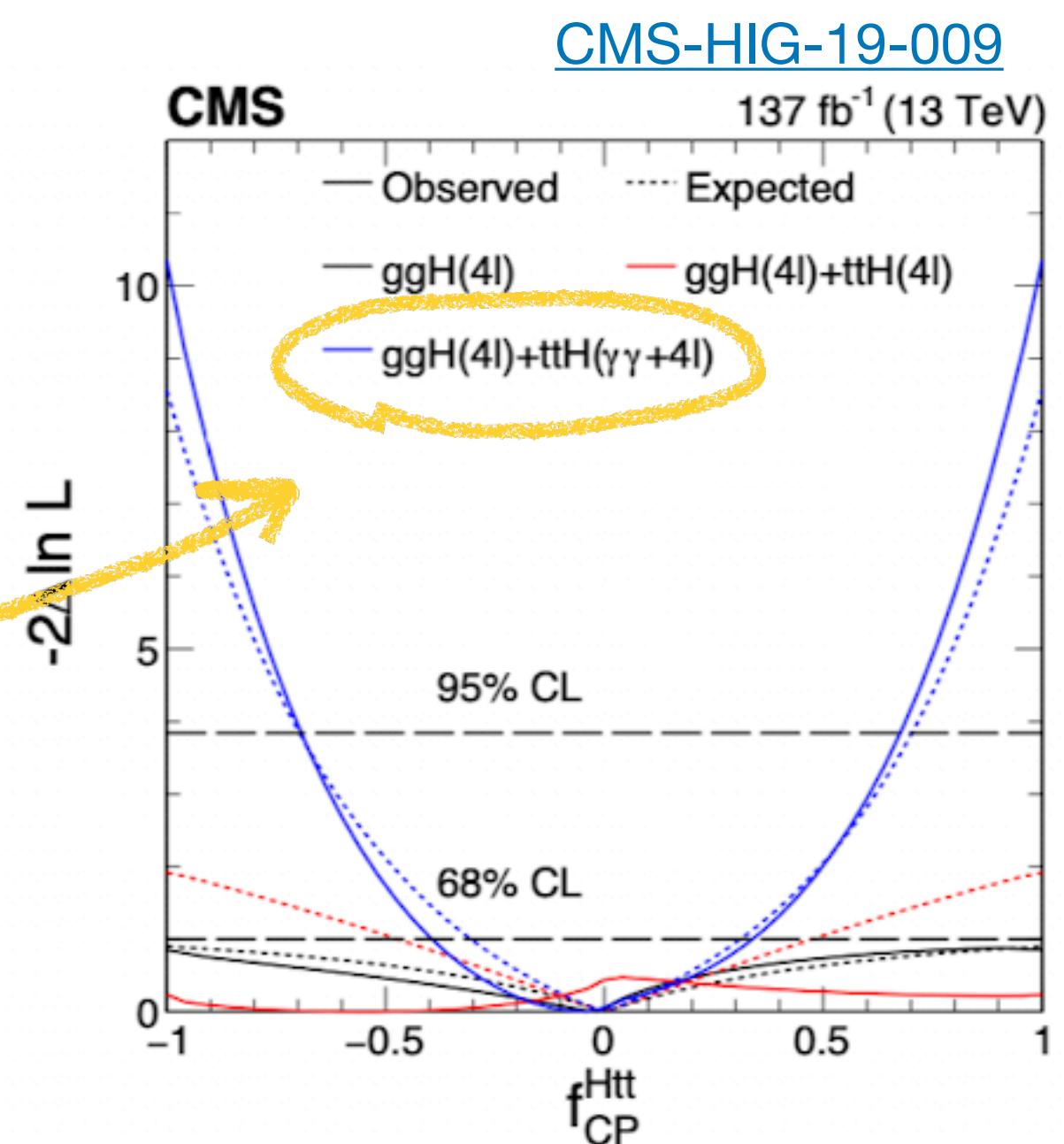
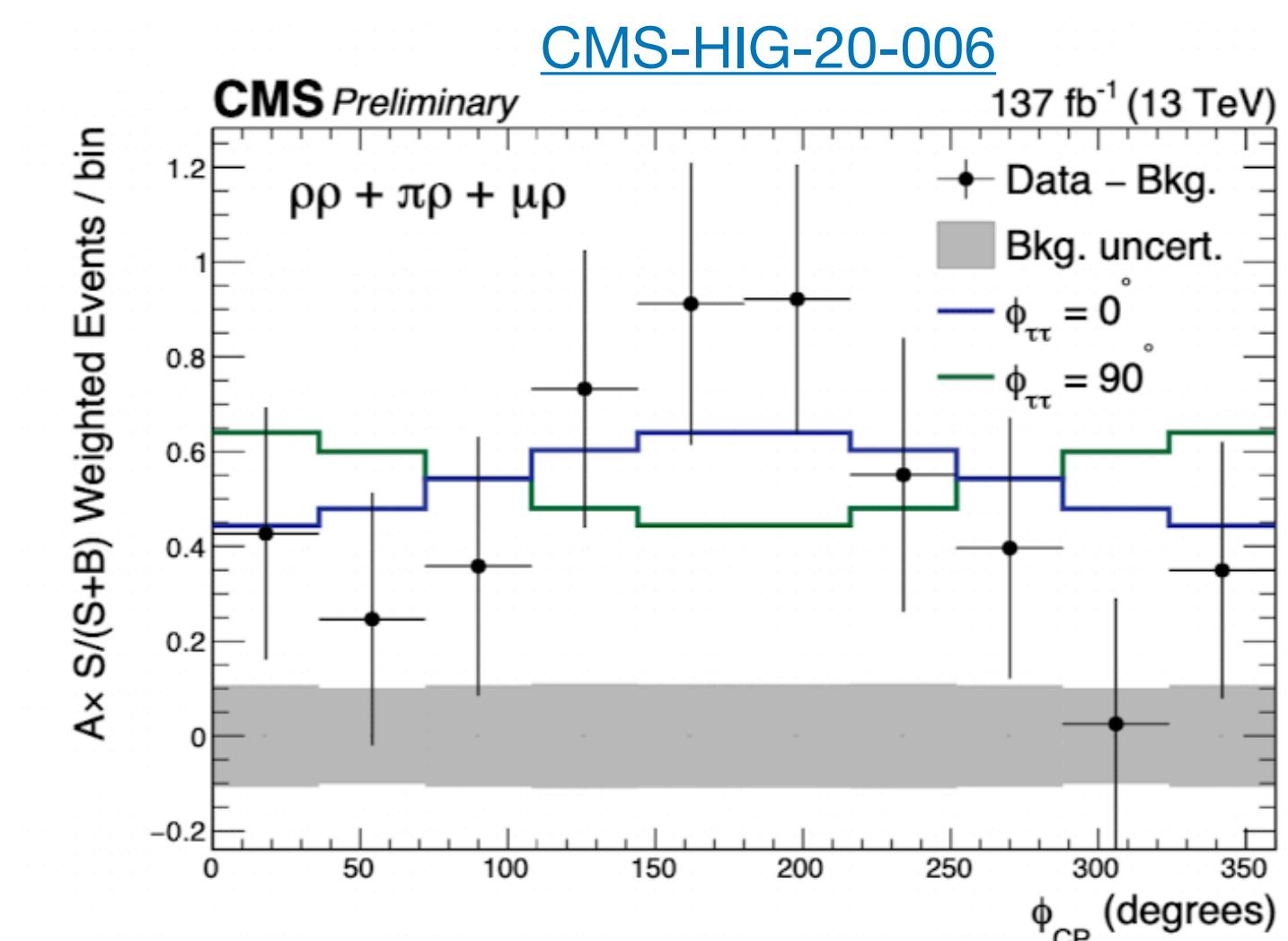
- $H\text{-}ff$  couplings : CP-even and CP-odd could be of the same order

$$A(Hff) = -\frac{m_f}{v} \bar{\psi}_f (\kappa_f + \boxed{i\tilde{\kappa}_f \gamma_5}) \psi_f,$$

*CP-ODD*

# CP in Hff and HV

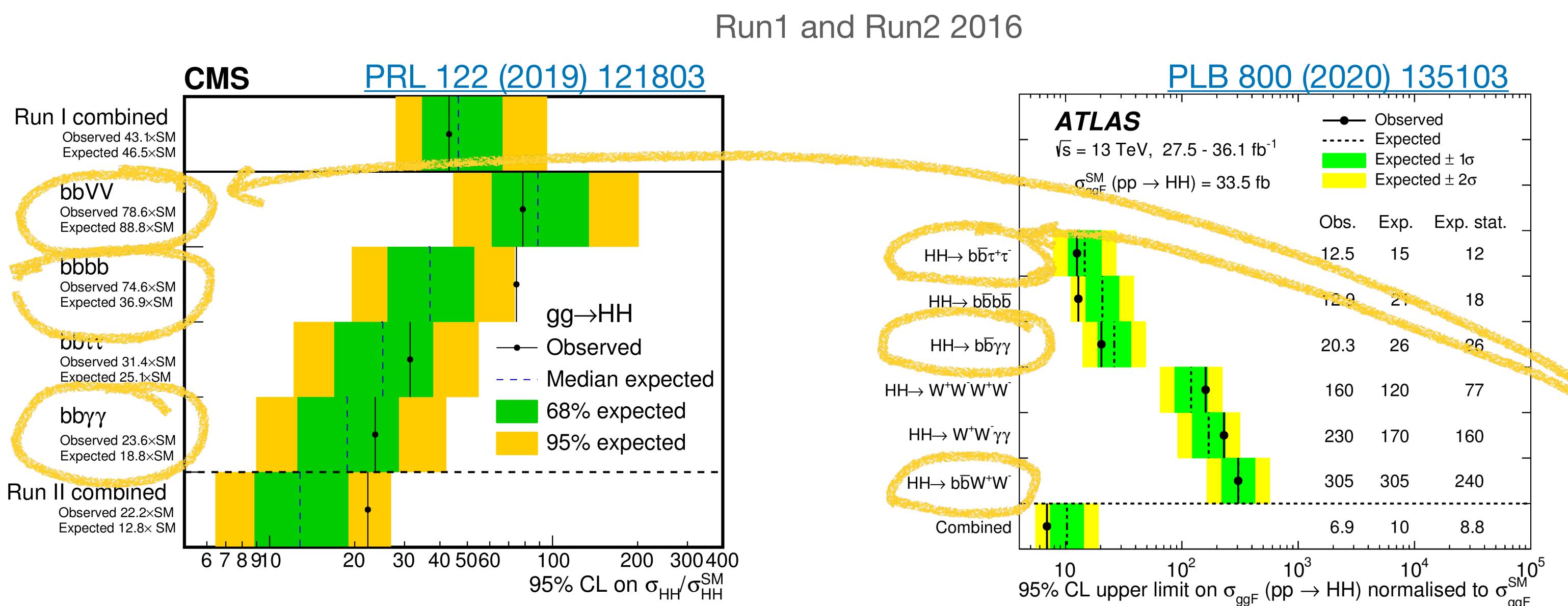
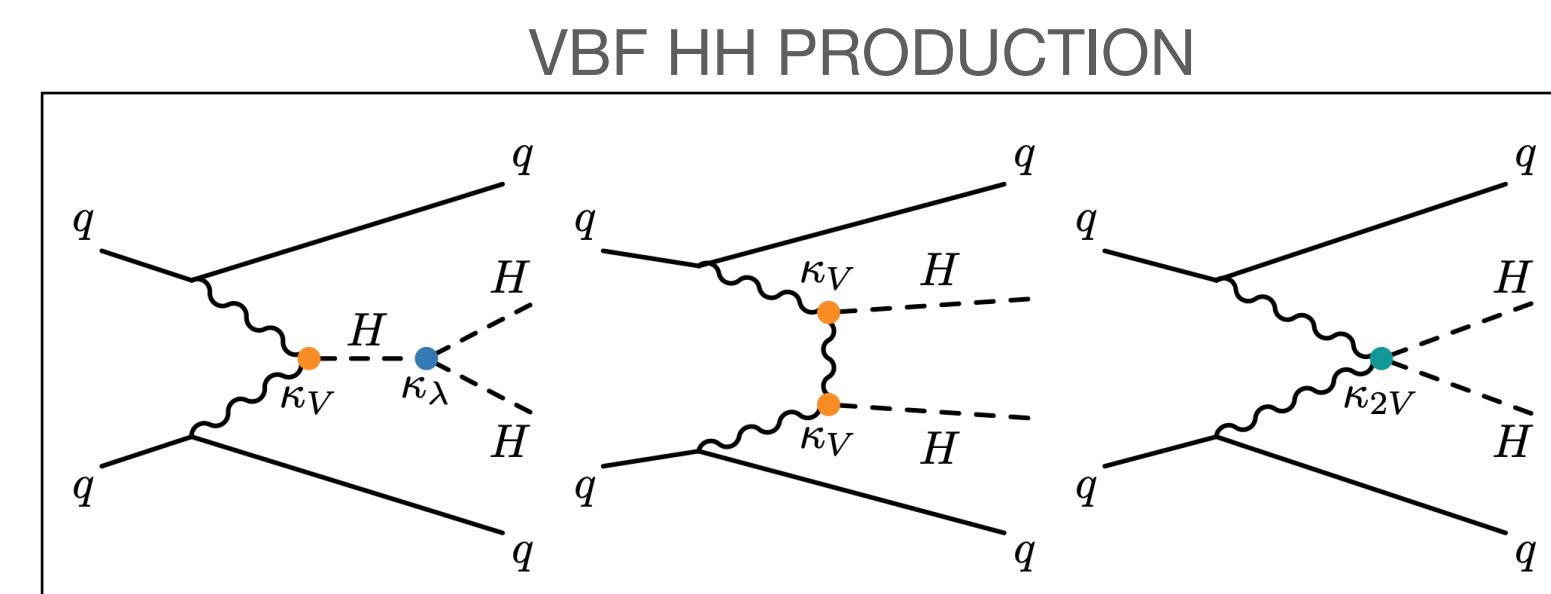
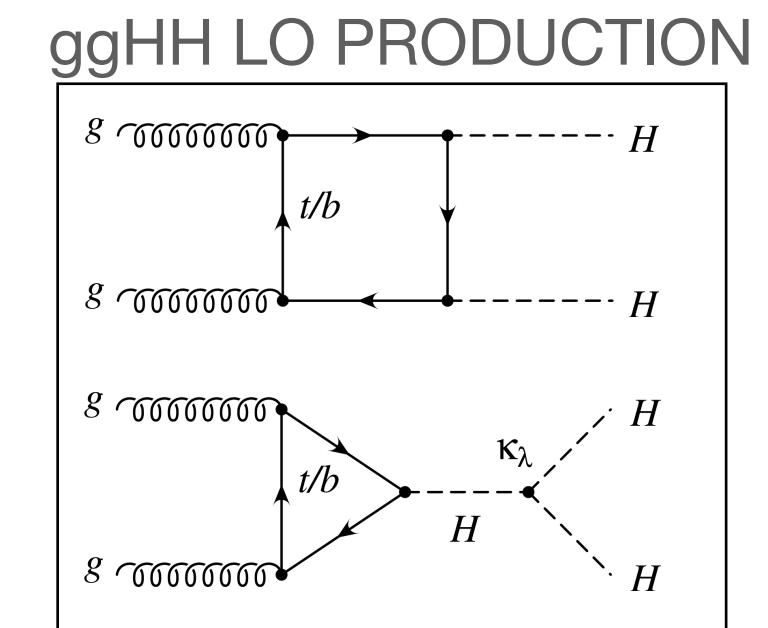
- Run2 data allow direct measurement of the CP structure of Hff with top and  $\tau$
- $t\bar{t}H+tH, H \rightarrow \gamma\gamma$  excluded at  $3\sigma$  pure CP-odd [PRL125,061802\(2020\)](#) [PRL125,061801\(2020\)](#)
- $H \rightarrow \tau\tau$  first measurement of the CP structure of the  $\tau$  Yukawa
  - Based on angular distributions of three hadronic decays of the tau
  - Data favour CP-even hypothesis and excludes with  $3.2$  ( $2.3$ )  $\sigma$  a pure CP-odd @ 68% CL
- $H \rightarrow 4l$  also tests for H-VV anomalous couplings
  - Study of the tensor structure of H-VV, H-gg, and H-tt
    - First study of CP property of H-gg and H-tt couplings
    - Improved sensitivity thanks to combined fit of all 5 anomalous couplings
    - Results are translated to EFT coefficient
    - No deviations from SM expectation



HH

# HH production

- Extremely low cross section
- Main production mechanisms are ggHH and VBF HH
- ggHH sensitive to  $\lambda$ 
  - Self-coupling can also be accessed with single-H production
  - VBF has unique sensitivity to  $k_{2V}$  (new from Run2)

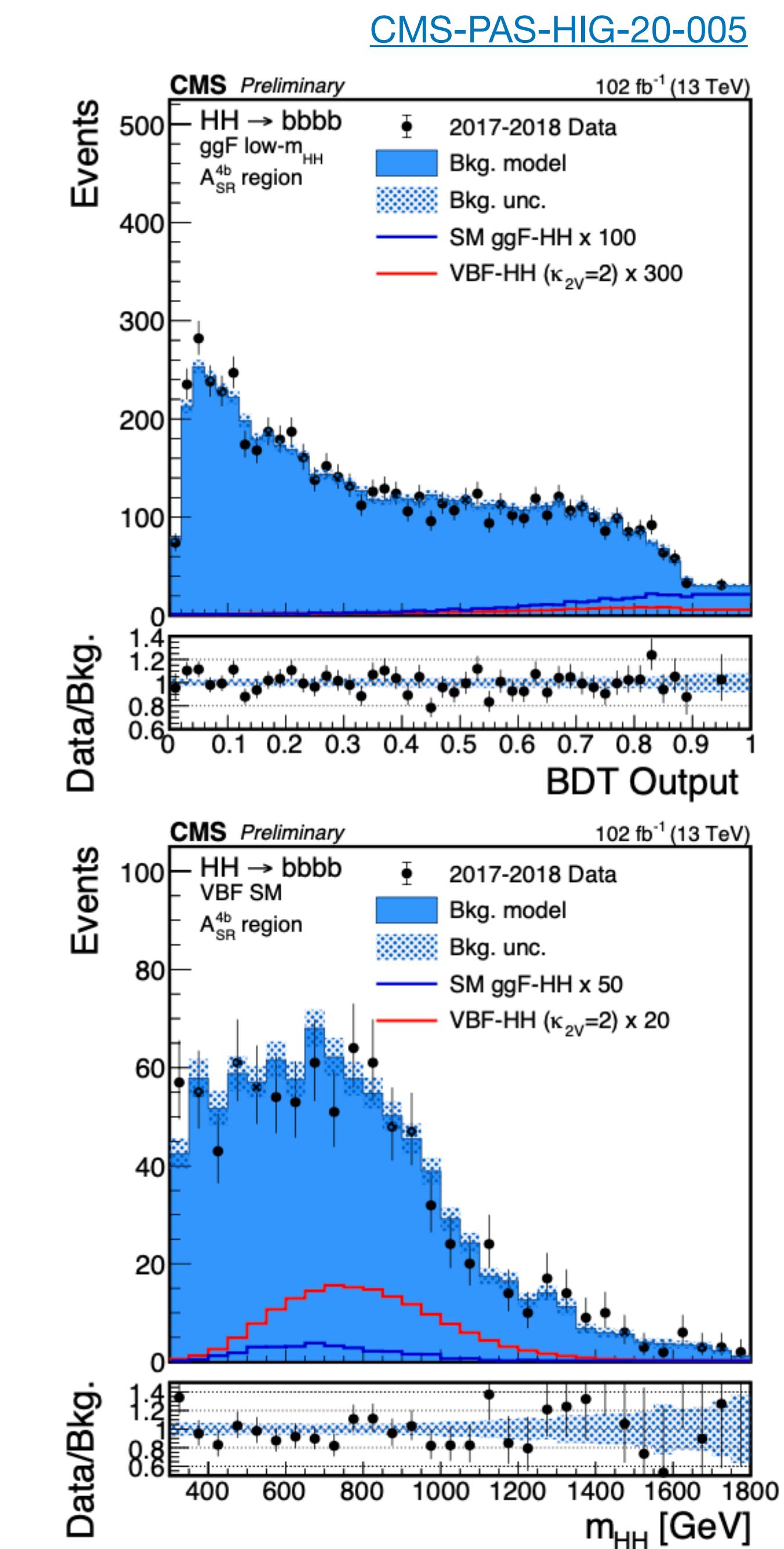
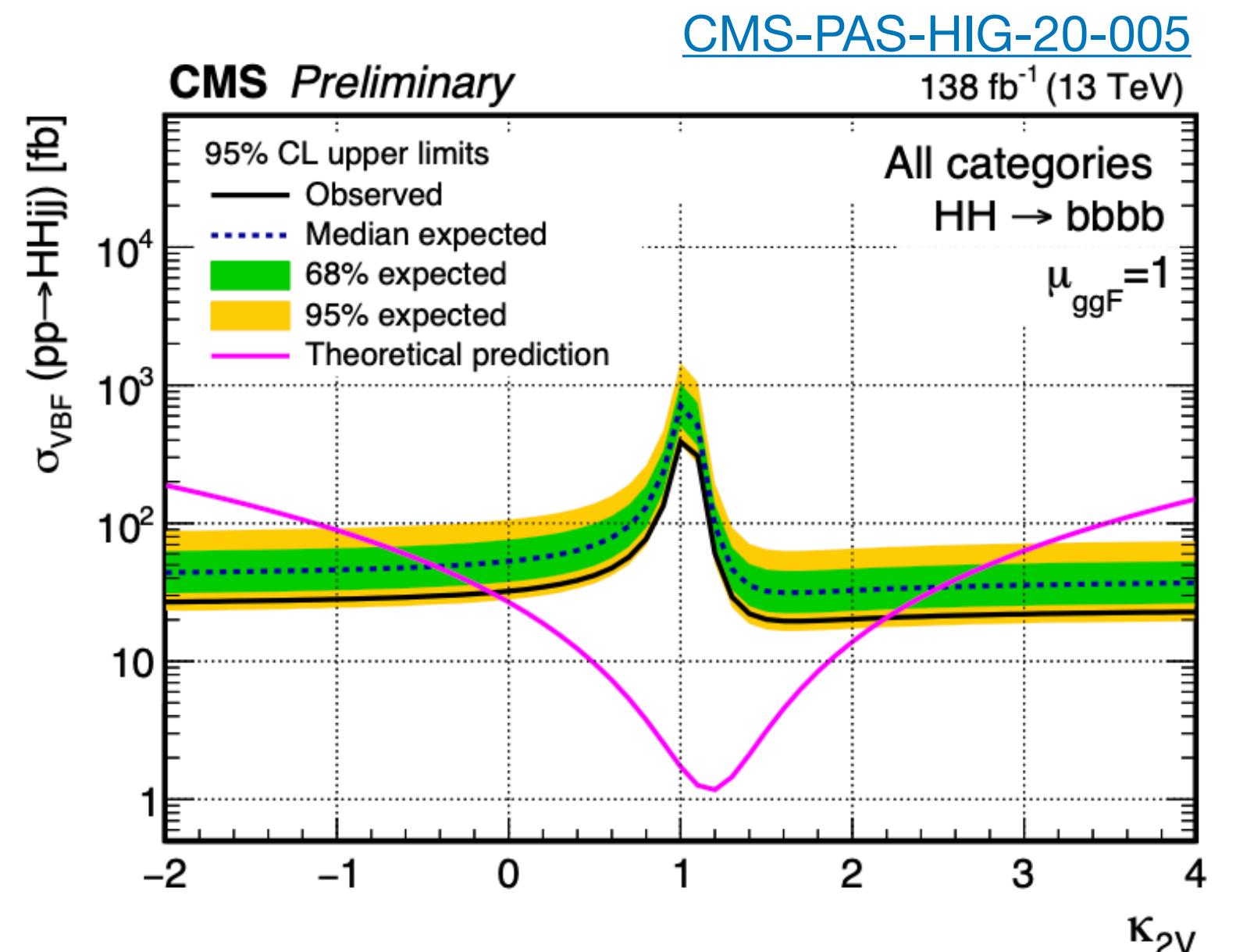
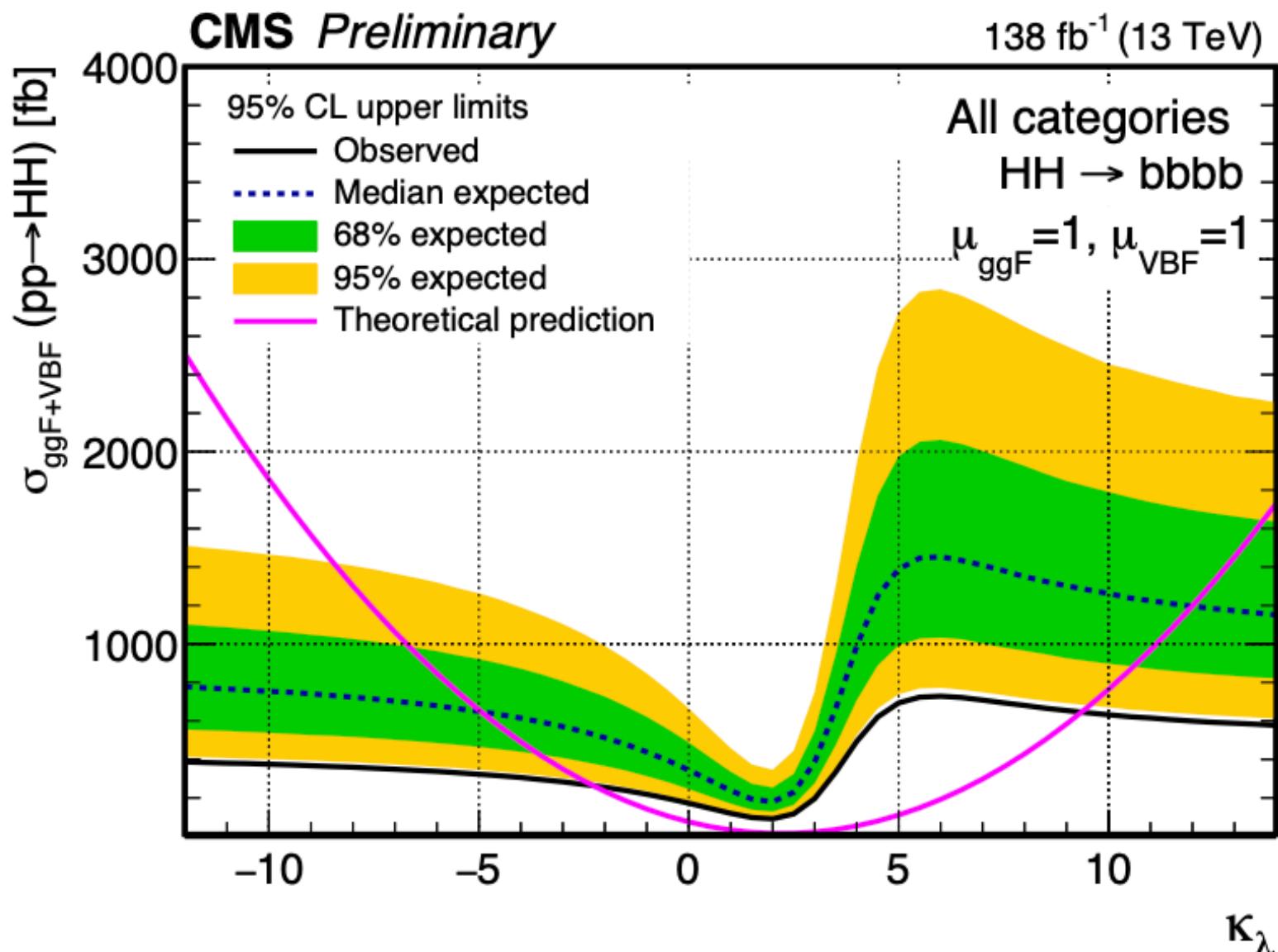


- Golden channels are  $bb\gamma\gamma$ ,  $bbbb$ , and  $bb\tau\tau$
- Full Run2 HH results are appearing from both ATLAS and CMS
- Updated with Run2 dataset

## NEW RESULTS FOR THIS CONFERENCE

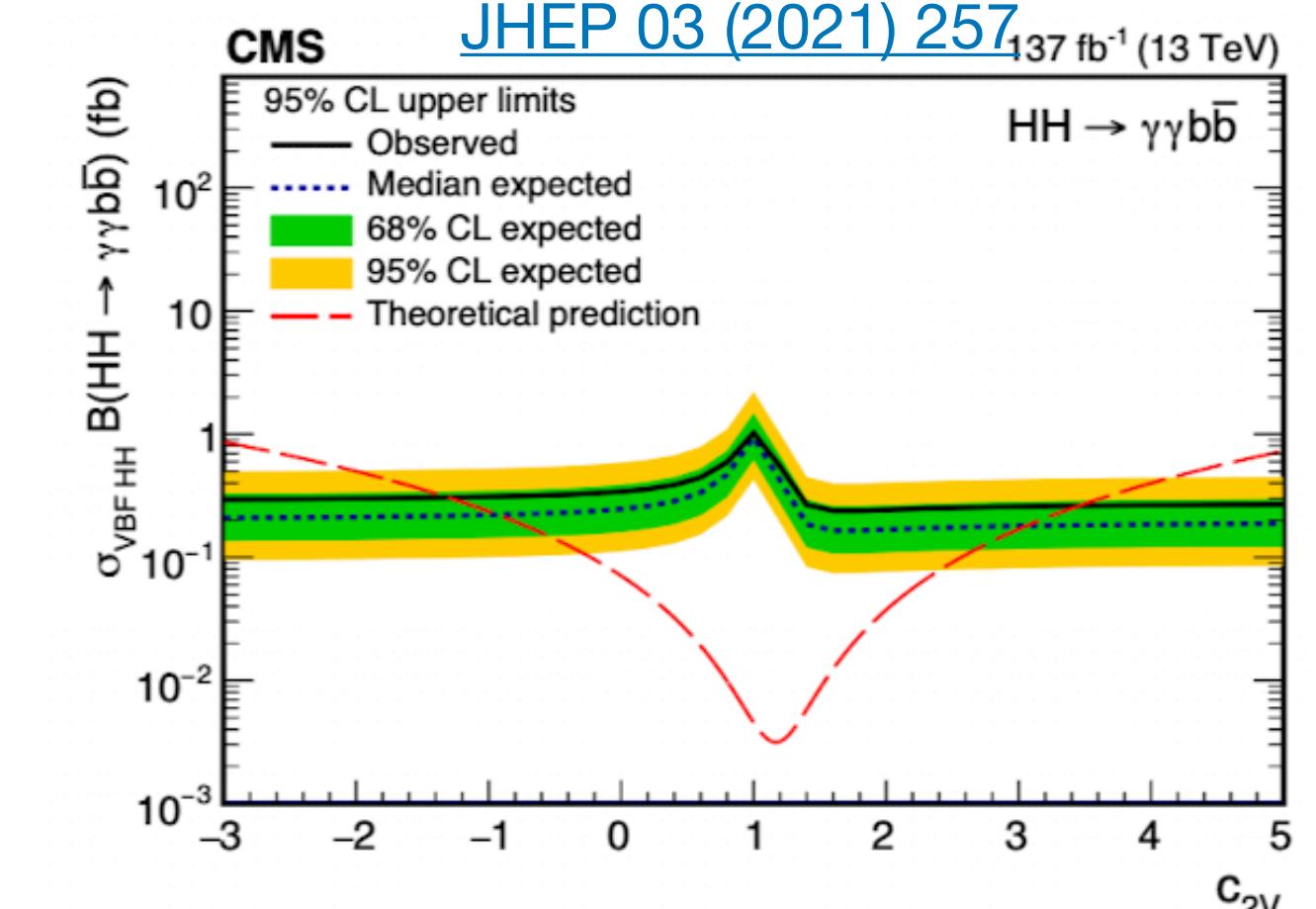
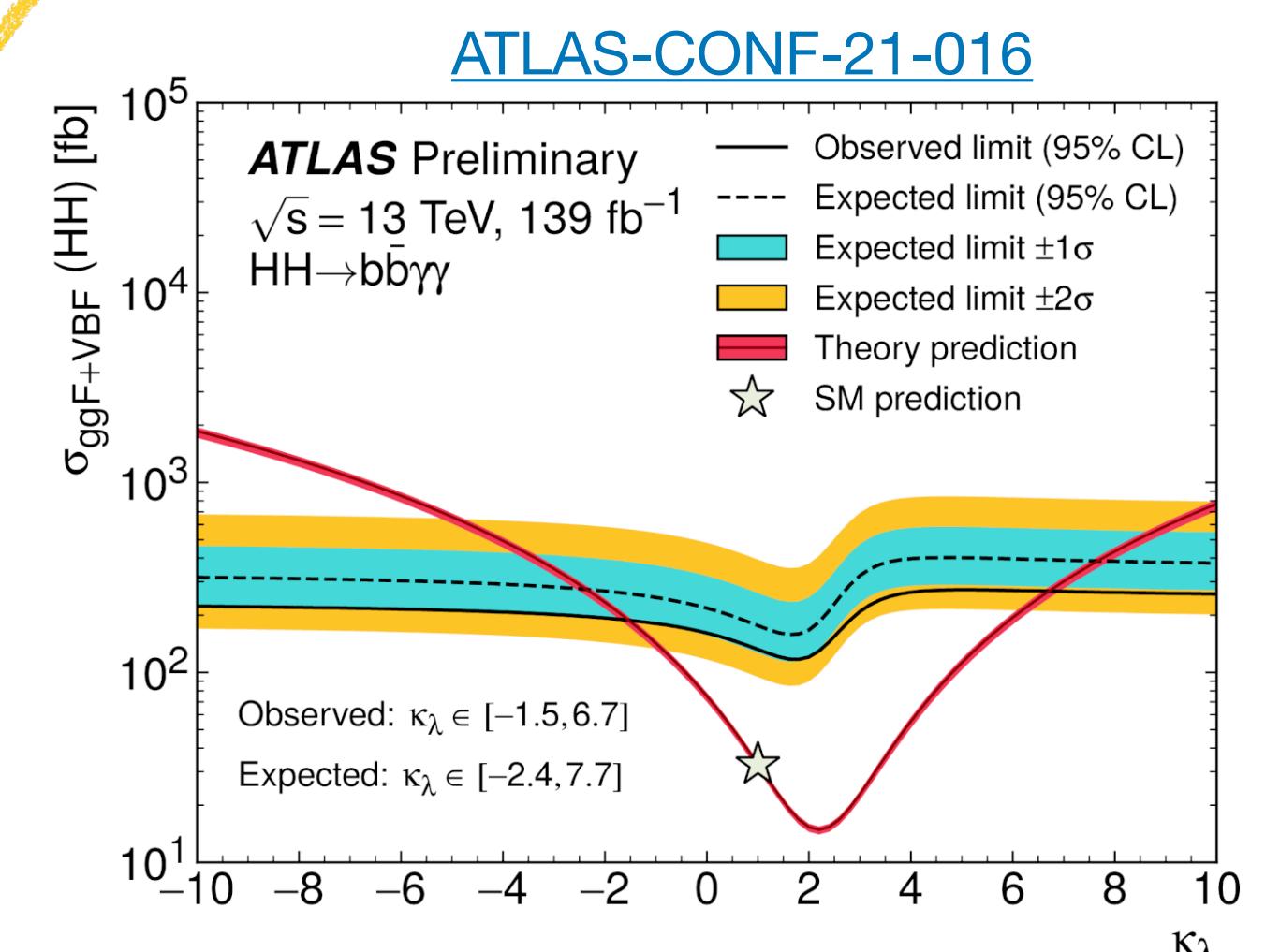
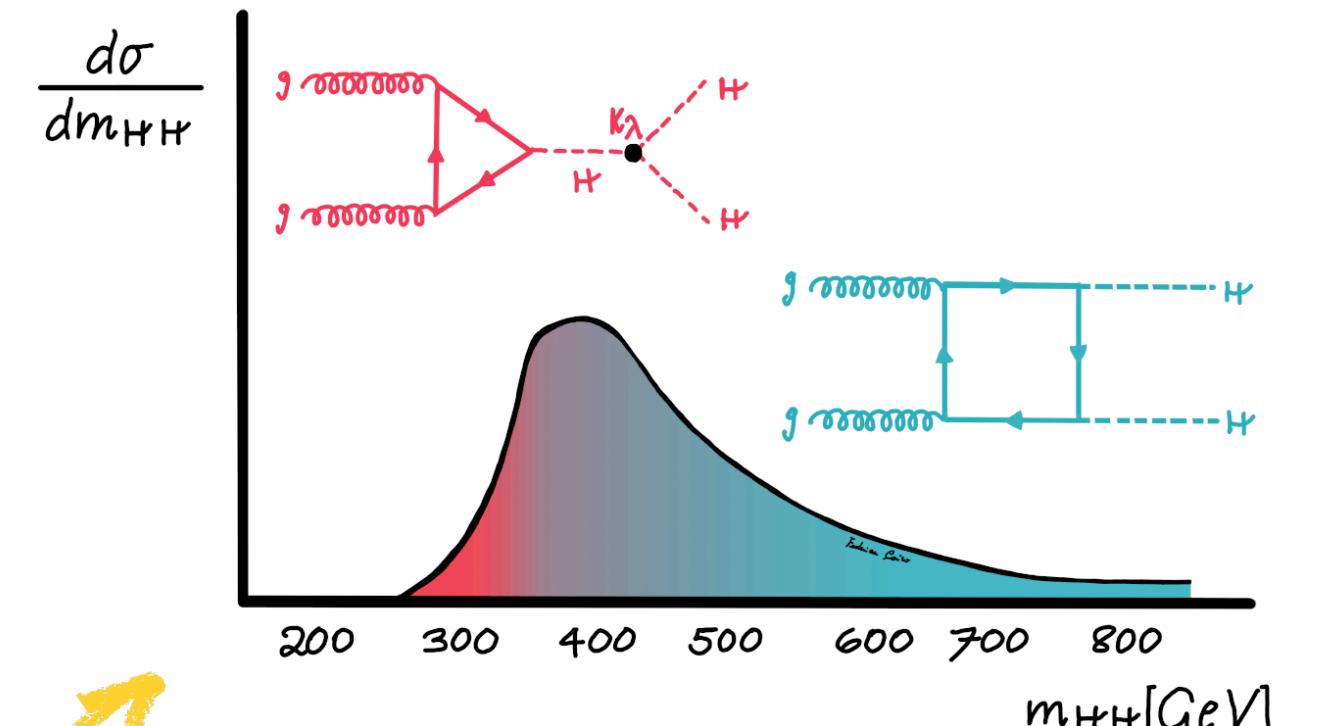
$$HH \rightarrow b\bar{b}b\bar{b}$$

- CMS H to 4b increased by a factor 3 sensitivity
- Targets ggF and VBF
- Most stringent limit on HH production to date
  - Excluding 3.6 (7.3) times the SM
- Constraining  $\kappa_\lambda$  within [-2.3, 9.4] and  $\kappa_{2V}$  within [-0.1, 2.2] @ 95%CL



# $HH \rightarrow b\bar{b}\gamma\gamma$

- Clean but rare final state
- ATLAS recent release of full Run2 result targeting ggH and VBF production
  - Divided in low mass and high mass regions to target different  $k_\lambda$  ranges
    - High mass ( $m_{b\bar{b}\gamma\gamma}^* > 350$  GeV) region targets SM signals ( $k_\lambda = 1$ )
    - Low mass ( $m_{b\bar{b}\gamma\gamma}^* < 350$  GeV) region sensitive to BSM signals ( $k_\lambda = 10$ )
  - Excludes 4.1 (5.5) times the SM and  $k_\lambda$  in [-1.5,6.7] ([-2.4,7.7]) @95%CL
- CMS equivalent analysis with Full Run2
  - Excluding 7.7 (5.2) times the SM and  $k_\lambda$  in [-3.3,8.5] ([-2.5,8.2]) @95%CL
  - Setting also limits on  $c_{2V}$  coupling between H pair and V pair



# OUTLOOK

- New techniques and ideas makes measurements more precise and new channels possible to reach
- Run3 projections show increasing precision
- History is showing that projections are usually more pessimistic than final results
  - See VHbb, H $\mu\mu$ , HH for example
- Every year there are an impressive number of new results
  - It is a thriving research area

Thank you!

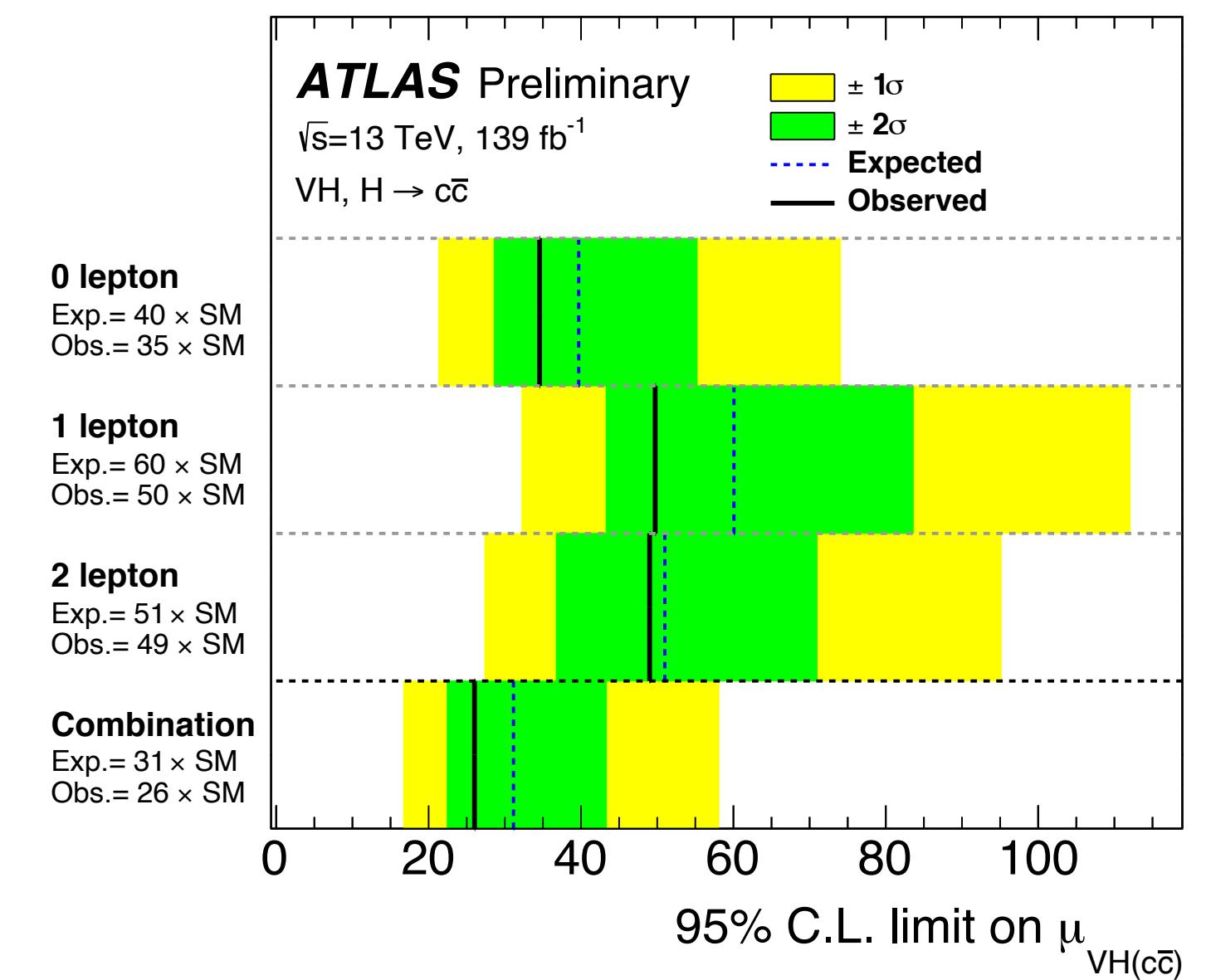
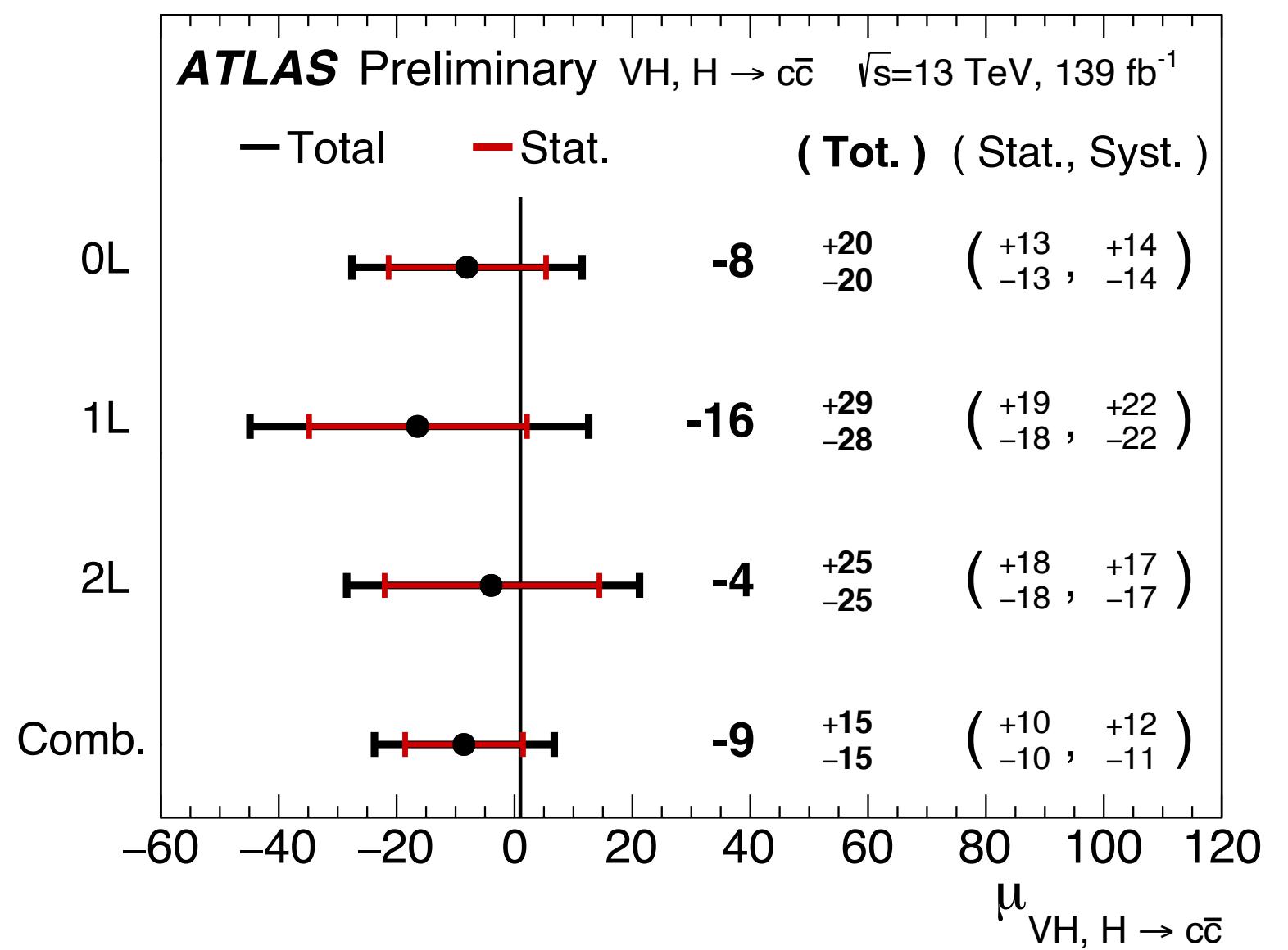
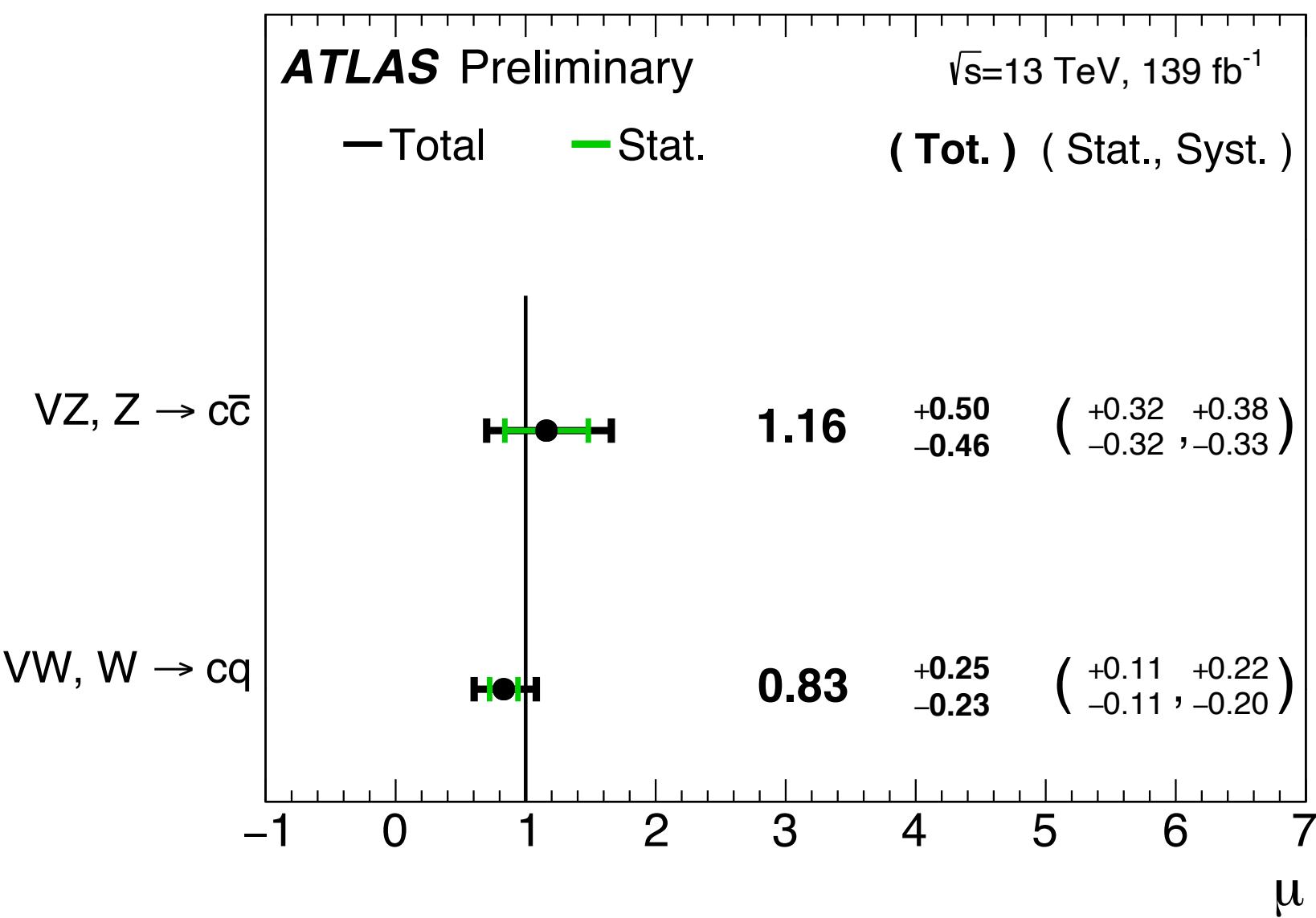


# BACKUP

# NEW RESULTS FOR THIS CONFERENCE

[ATLAS-CONF-2021-027](https://atlas.cern/conference/ATLAS-CONF-2021-027)

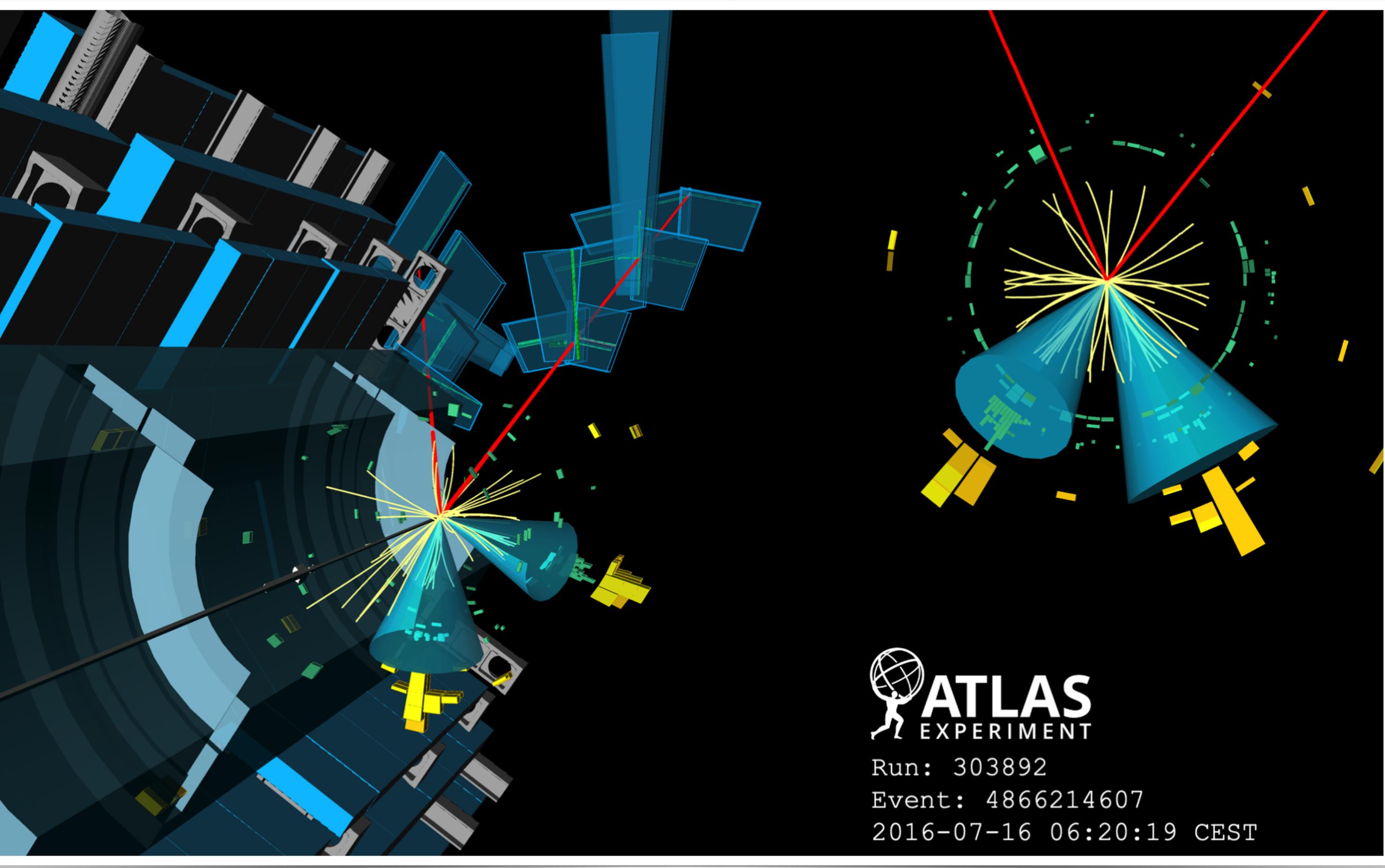
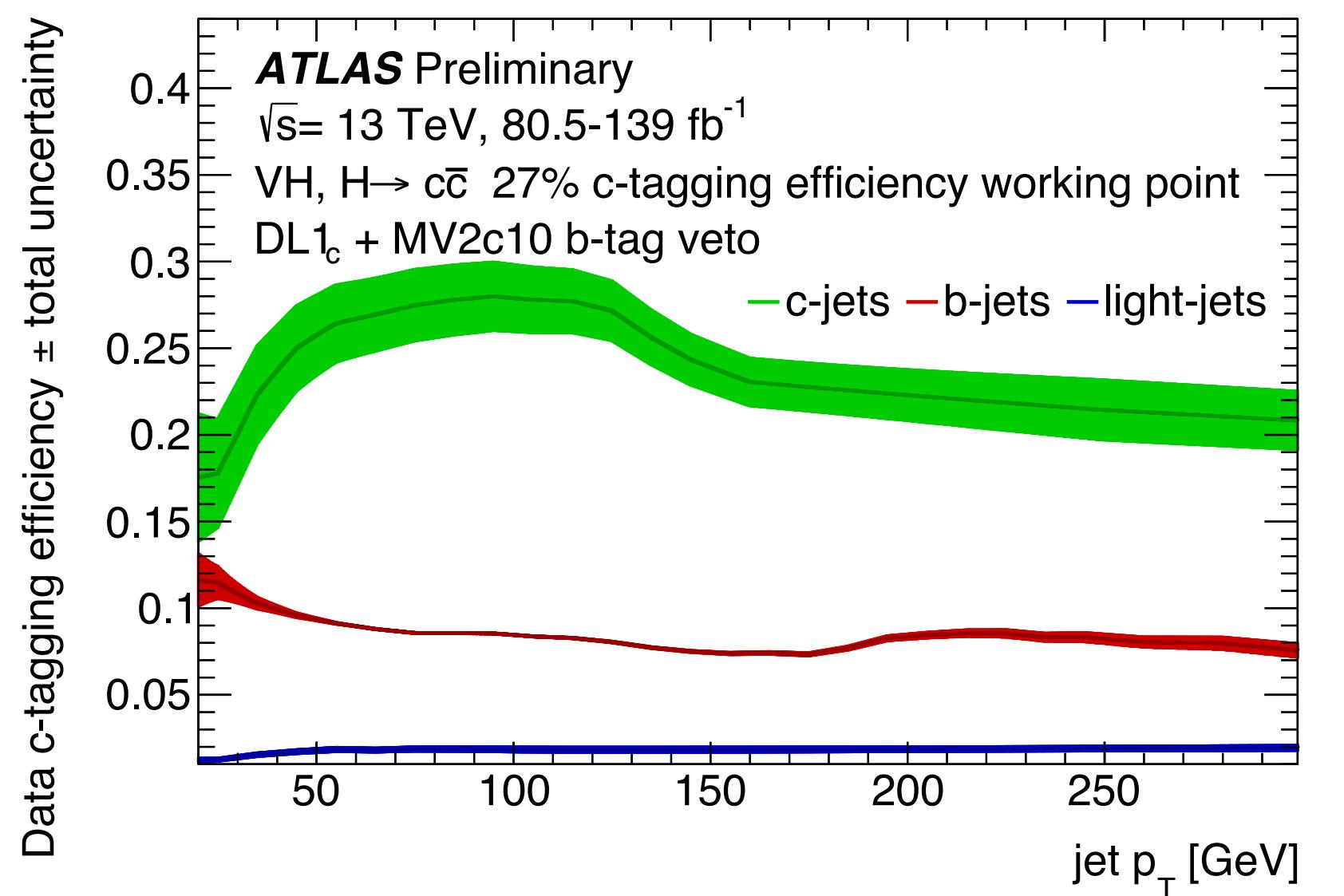
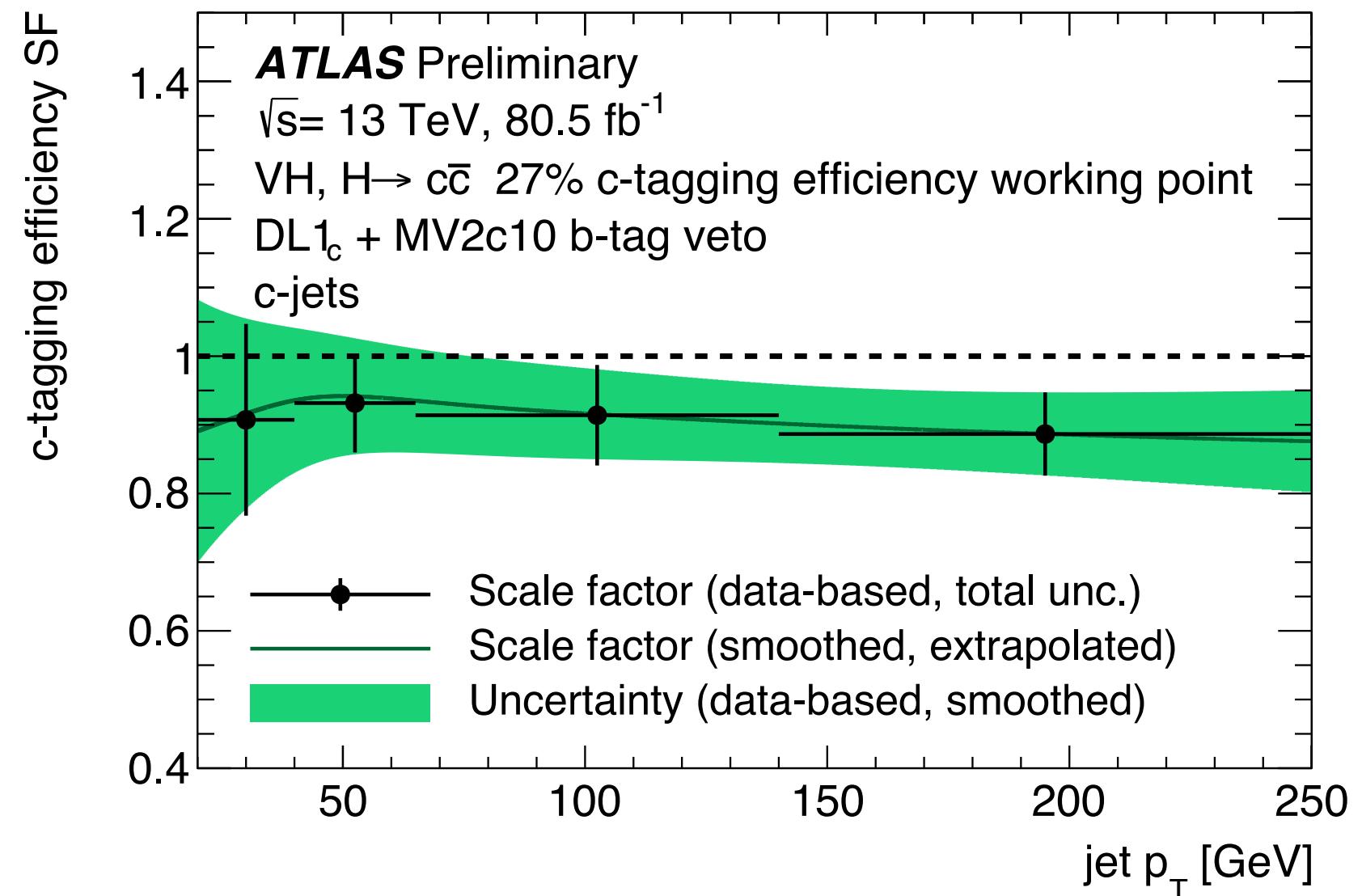
$H \rightarrow cc$

[ATLAS-CONF-2021-027](https://atlas.cern/conference/ATLAS-CONF-2021-027)


# NEW RESULTS FOR THIS CONFERENCE

[ATLAS-CONF-2021-027](#)

$$H \rightarrow cc$$

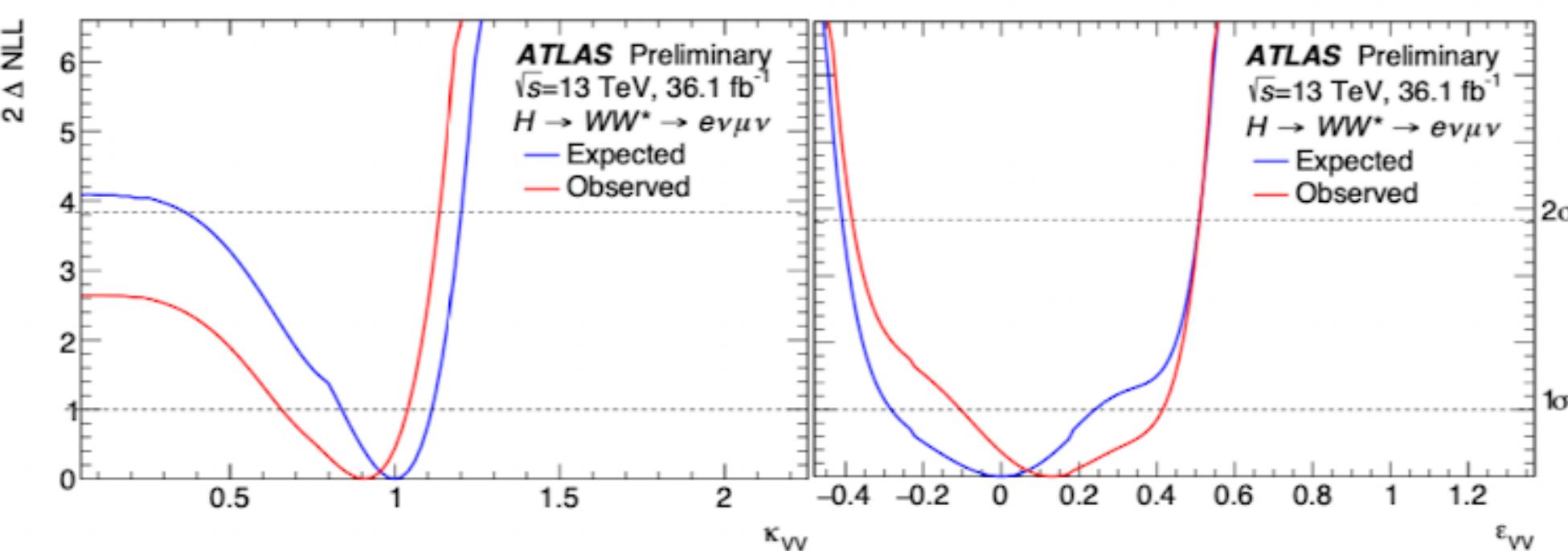
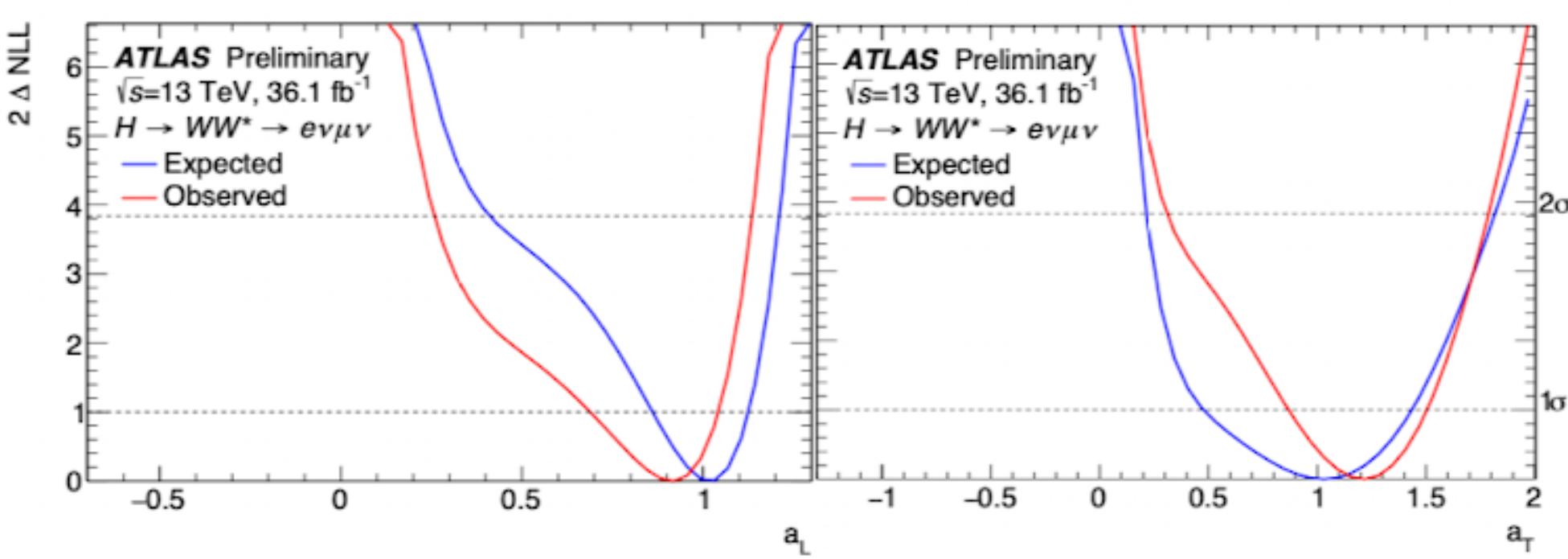
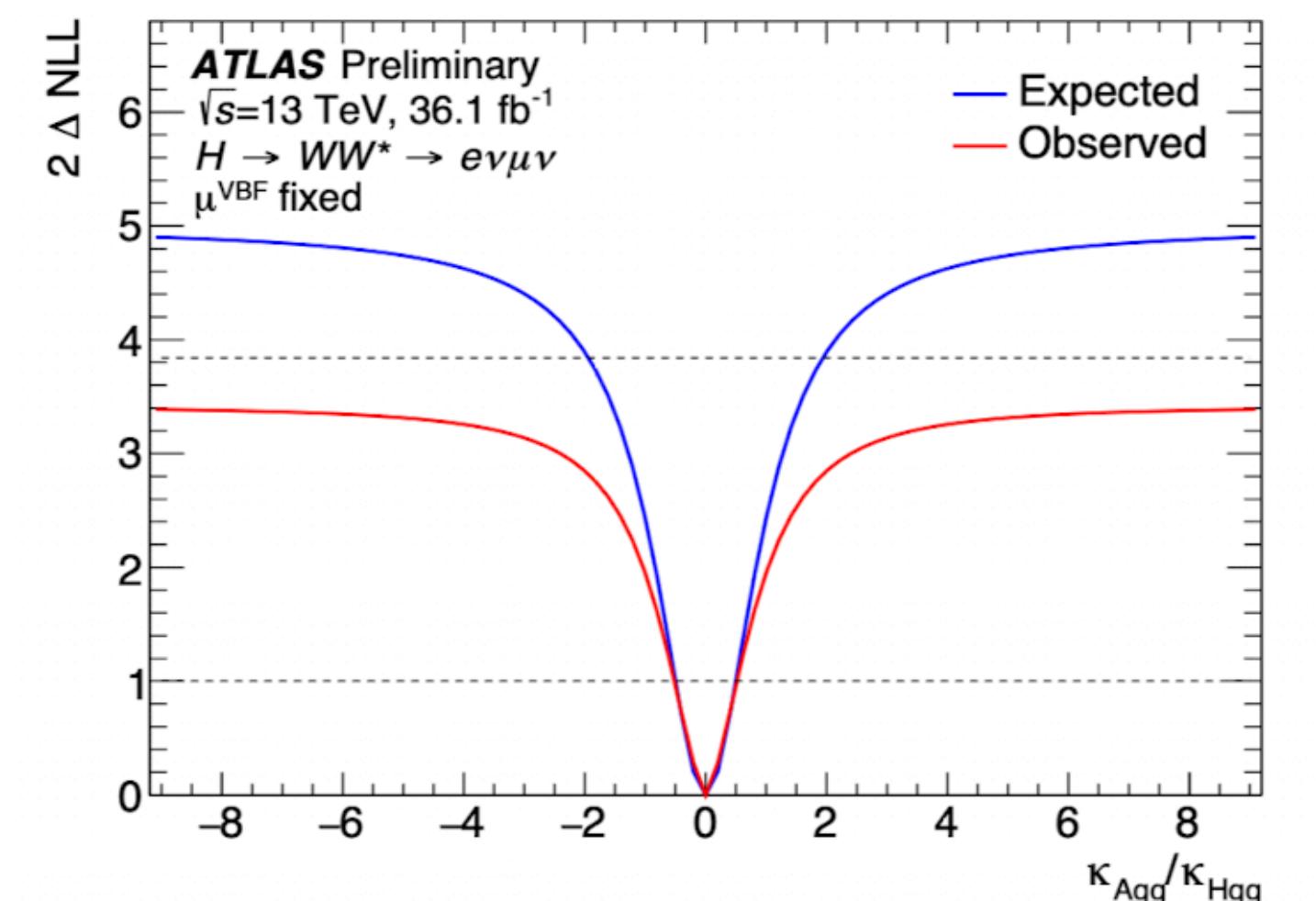


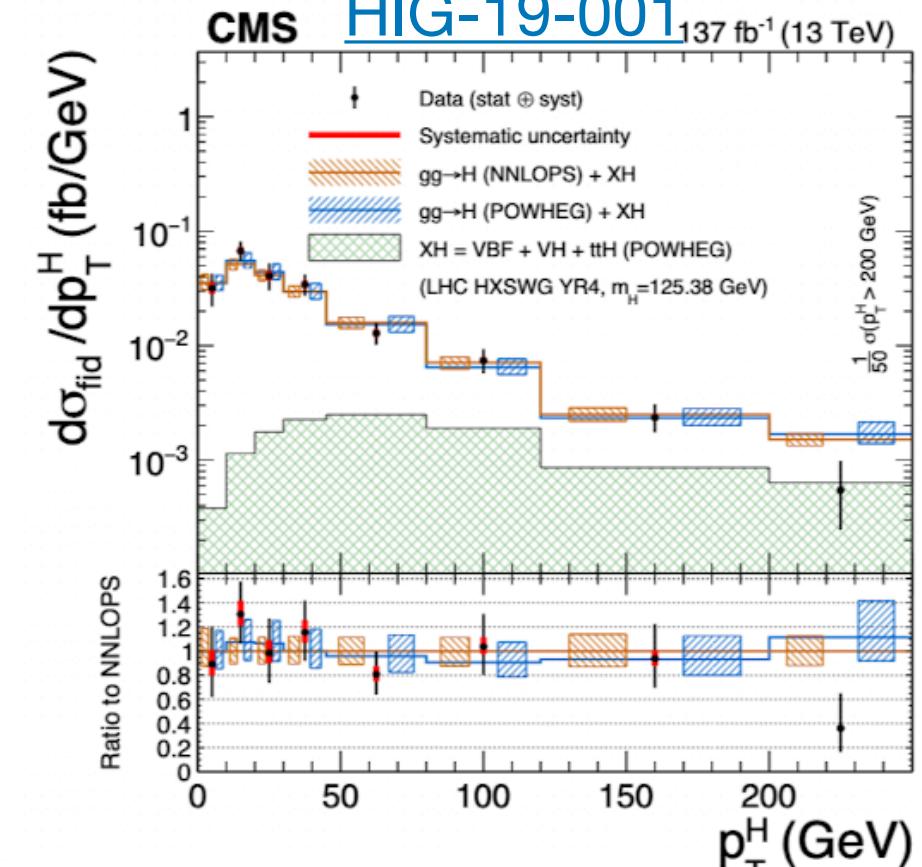
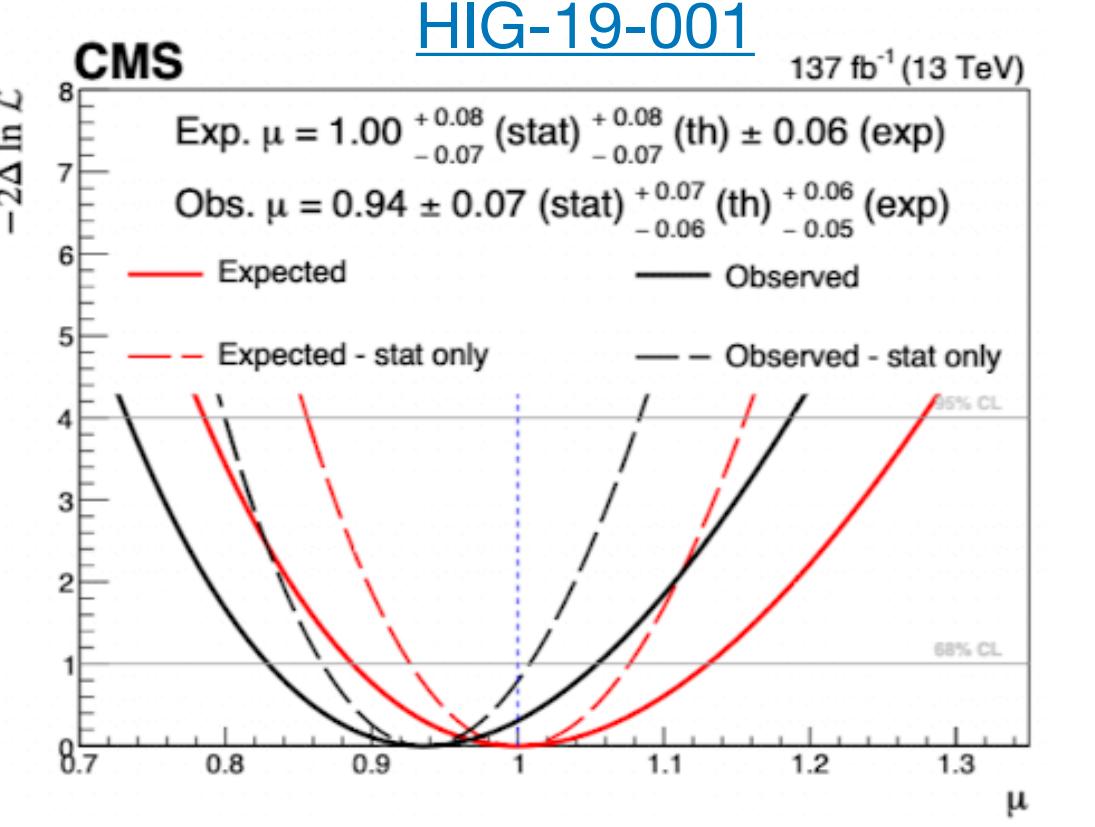
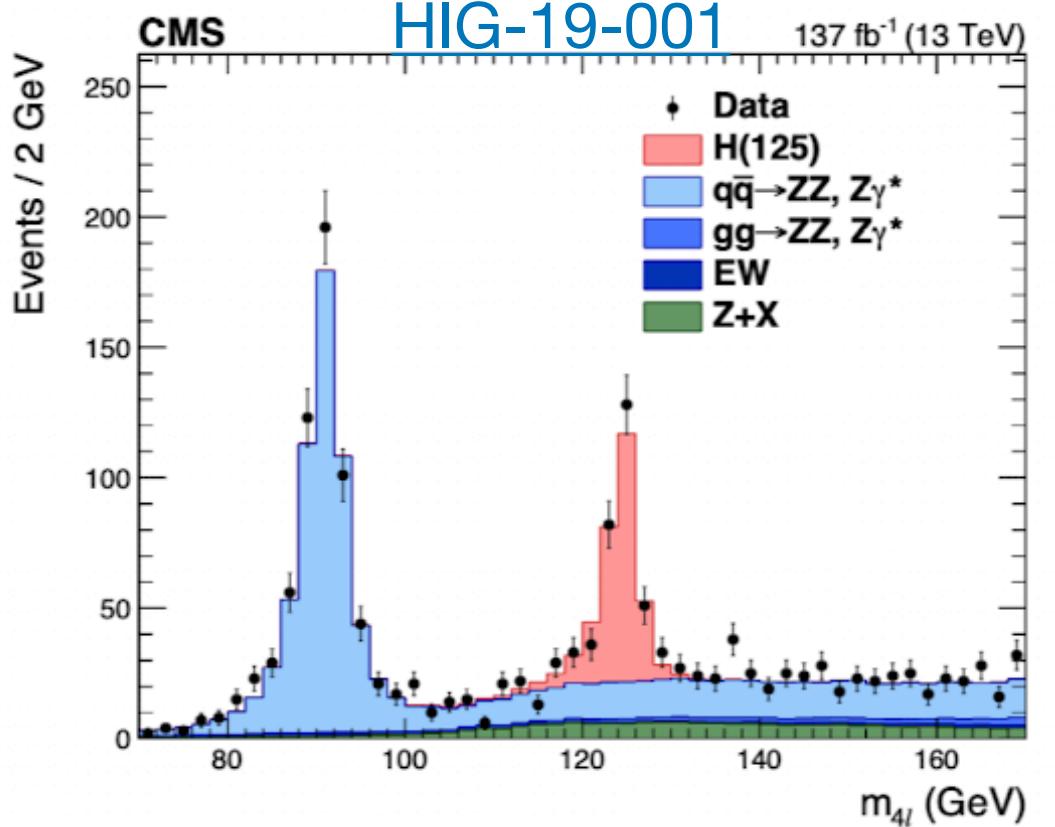
From a charming place

To ATLAS

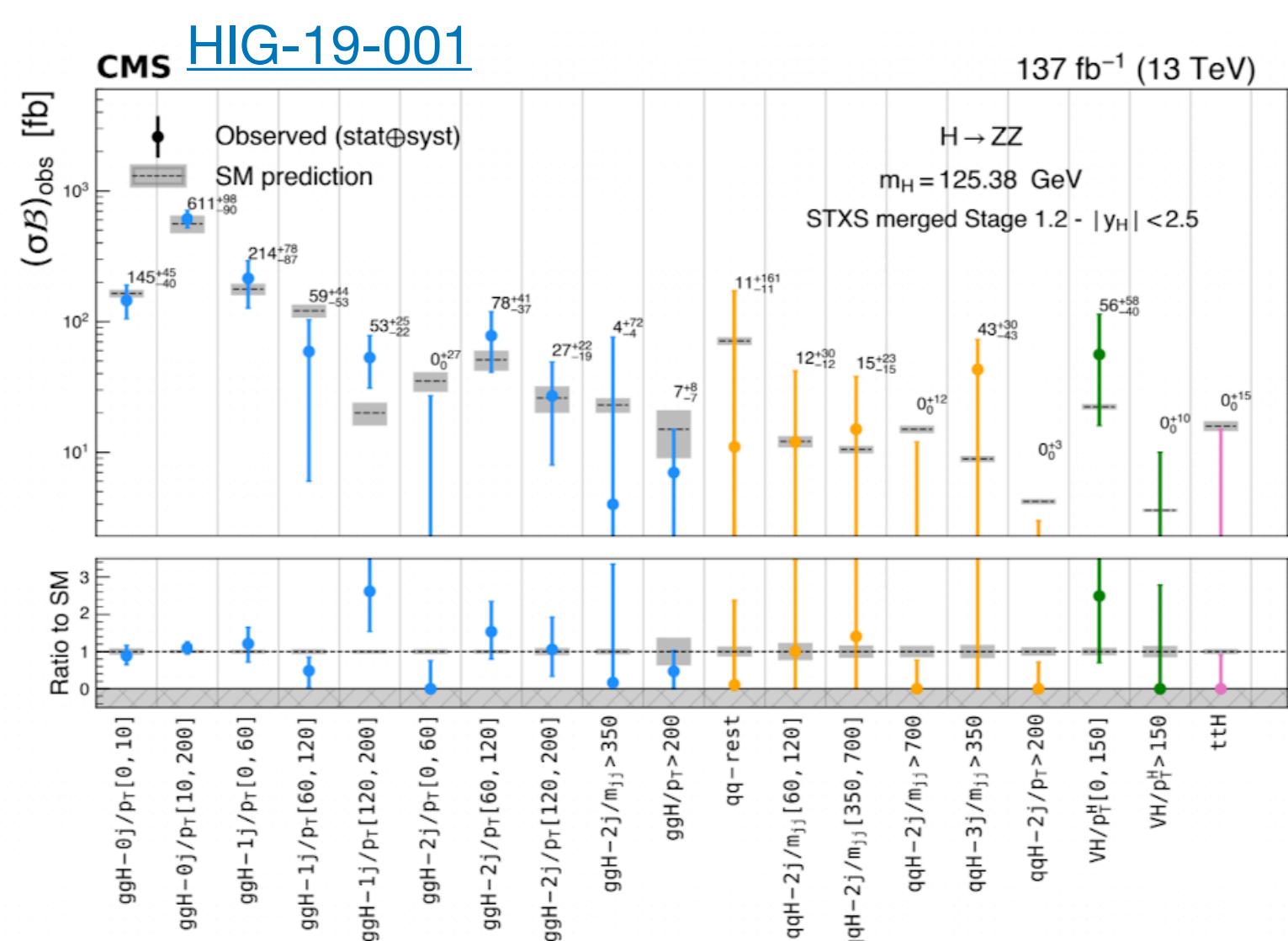
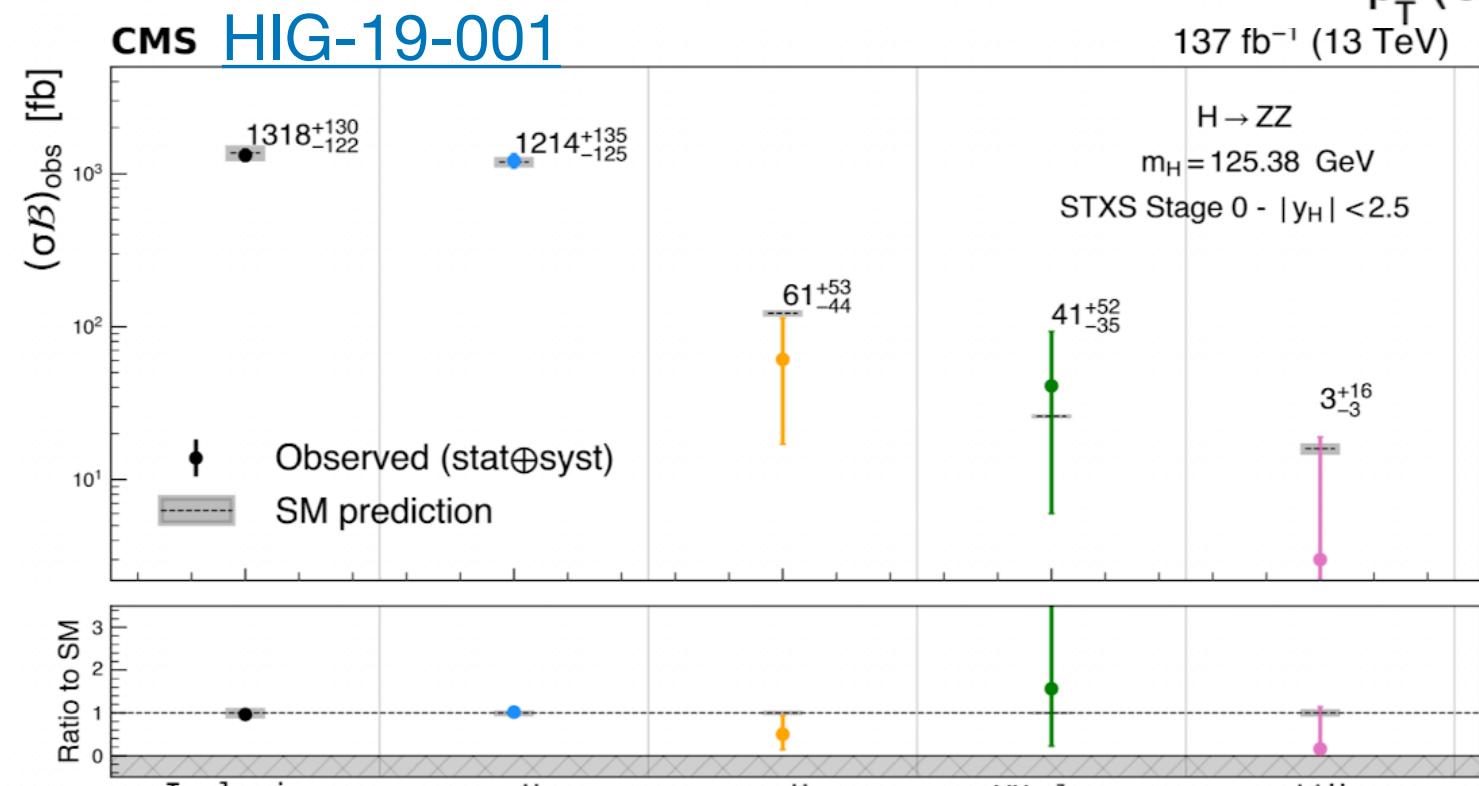
# H to WW\* to $e\nu\mu\nu$

- Constrain on the anomalous coupling on CP structure of the ggH production
  - Uses both total yield of events and kinematic information
  - Exploits an EFT of Higgs Characterisation (HC) and provides results as ration between CP-odd and CP-even coupling strength scale factors of the effective Higgs-gluon vertex
- VBF production mode used to access individually longitudinal and transverse polarisation of the W and Z boson in both production and decay; first limit on this
  - Polarisation coupling strength scale factors ( $a_L$  and  $a_T$ ) are compatible with the SM
  - Polarisation scale factors transformed in pseudo-observable



$$H \rightarrow ZZ \rightarrow 4l$$


- CMS recent release with Full Run2 dataset (accepted by EPJC)
- Several interesting measurements of the H boson
- Signal strength at  $m_H = 125.38$  GeV:  $\mu = 0.94 \pm 0.07$  (stat)  $^{+0.09}_{-0.08}$  (syst)
- Fiducial cross section measured  $\sigma_{\text{fid}} = 2.84^{+0.34}_{-0.31} = 2.84^{+0.23}_{-0.22}$  (stat)  $^{+0.26}_{-0.21}$  (syst) fb
  - Compatible with the SM expectation  $2.84 \pm 0.15$  fb
- Differential cross section measure as a function of  $|y^H|$ ,  $p_T^H$ ,  $N^j$ ,  $p_T^j$
- Cross section in 19 mutually exclusive categories following STXS 1.2 framework
  - Some of the bins had to be merged because of lack of statistics
  - All results are in agreement with the SM predictions



# Longer list of SM Higgs results from last LHCP

- **CMS - LATEST FIRST**

- 19-009 - H to 4l Anomalous couplings (04/21) [PRD]
- 19-015 - H to  $\gamma\gamma$  Production  $\sigma$  and properties (03/21) [JHEP]
- 19-001 - H to 4l Production  $\sigma$  (03/21) [EPJC]
- - 19-017 - VH H to WW
- 19-018 - HH to  $bb\gamma\gamma$  non resonant (11/20) [JHEP]
- 19-008 - ttH to  $e, \mu, \tau$  (11/20)
- 19-006 - H to  $\mu\mu$  evidence (09/20) [JHEP]
- 19-012 - H to  $Z\rho, Z\phi$  (07/20)
- - 19-004 - HH 4l2b non resonant
- - 19-010 - H to  $\tau\tau$  couplings
- - 20-006 - H to  $\tau\tau$  CP of Yukawa
- 19-001 - H to WW Inclusive and differential
- 19-003 - H to bb High boost

- **ATLAS - LATEST FIRST**

- 21-027 VHcc
- 21-016  $HH \rightarrow bb\gamma\gamma$  (03/21)
- 21-014 H to WW STXS and couplings (03/21)
- $H \rightarrow ll\gamma$  evidence (03/21)
- VBF H to bb inclusive (11/20) [EPJC]
- VBF H to bb photon tagger (10/20) [JHEP]
- 20-058 ttH to bb  $\geq 1$  lep (10/20)
- 20-055 H to WW CP and polarisation (10/20)
- 20-052 H to invisible combination (10/20)
- 20-053 EFT interpretation of STXS (10/20)
- VH to bb boosted (08/20) [PLB]
- 20-026 H to  $\gamma\gamma$  STXS and couplings (08/20)
- VH to bb all hadronic (07/20) [PRD]
- VHbb STXS (07/20) [EPJC]
- H to  $\mu\mu$  (07/20) [PLB]
- 20-045 VBF H WW (07/20)
- 20-027 H combination (07/20)
- H to  $Z\gamma$  (05/20) [PLB]
- $HH \rightarrow bb\tau\tau$  (07/20)