



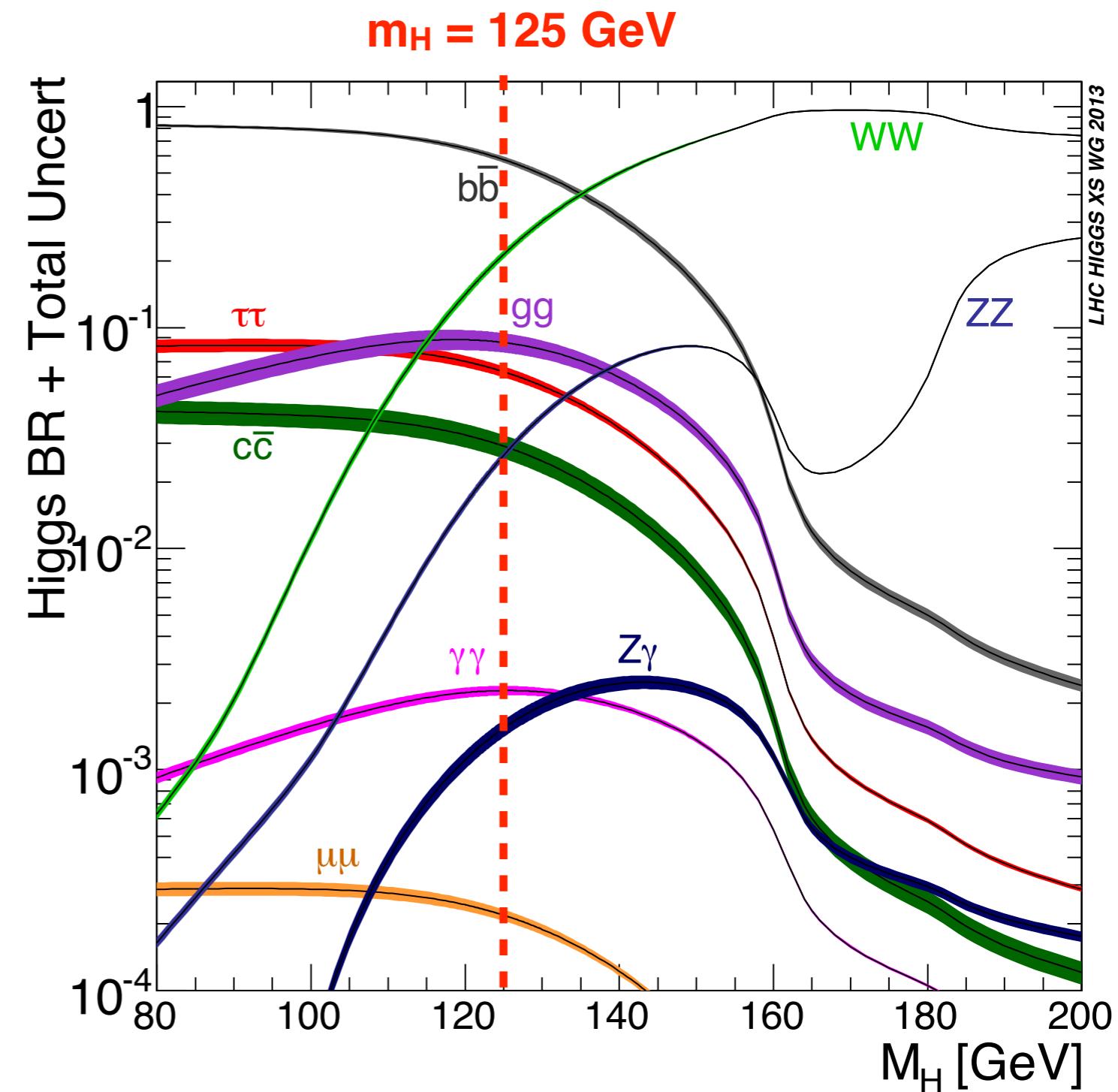
Associated production of heavy vector bosons with Higgs, VH, and HH production

Stephane Cooperstein - University of California San Diego
On behalf of the ATLAS and CMS Collaborations

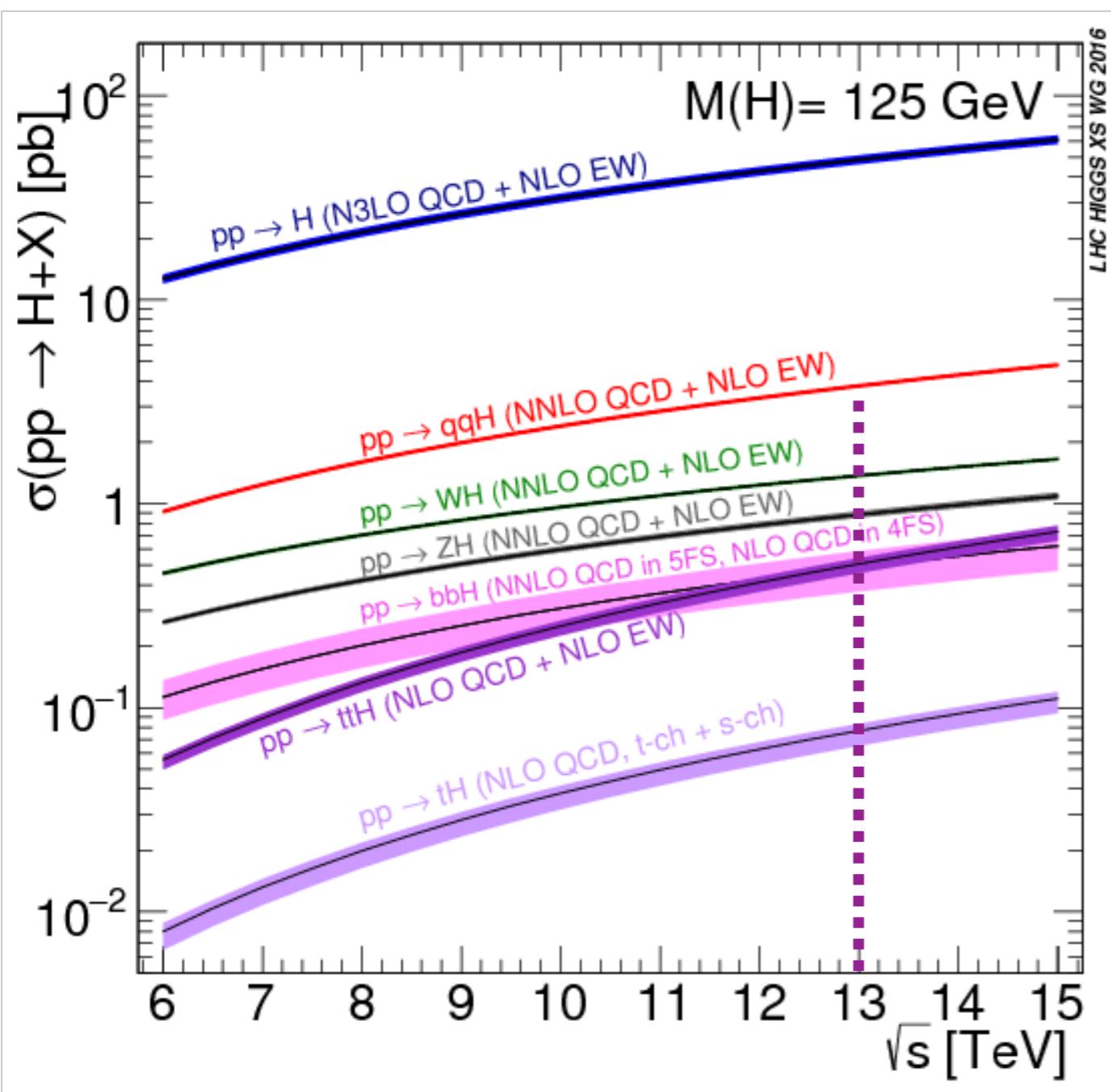


- Observation of VH production via $H \rightarrow b\bar{b}$.
- First EFT constraints from differential VH measurement + prospects.
- Latest results on measurement of Higgs boson pair production + prospects.

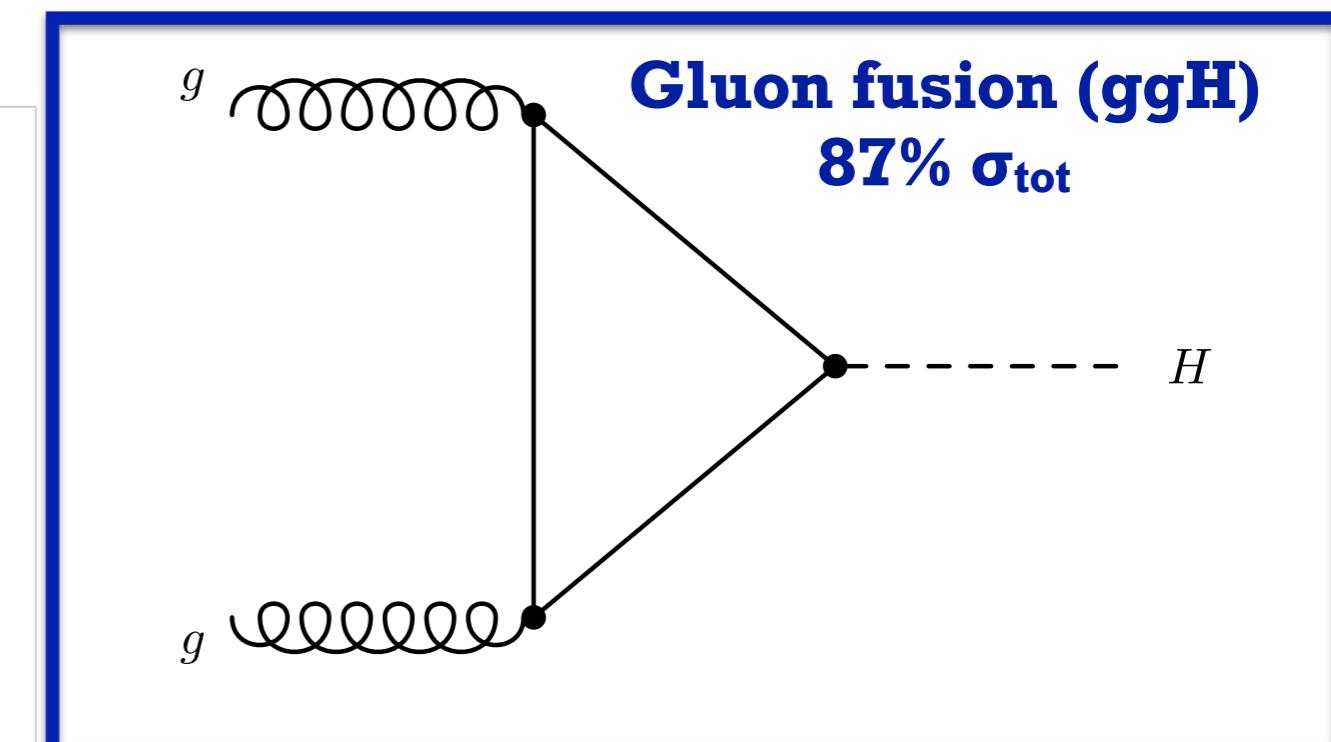
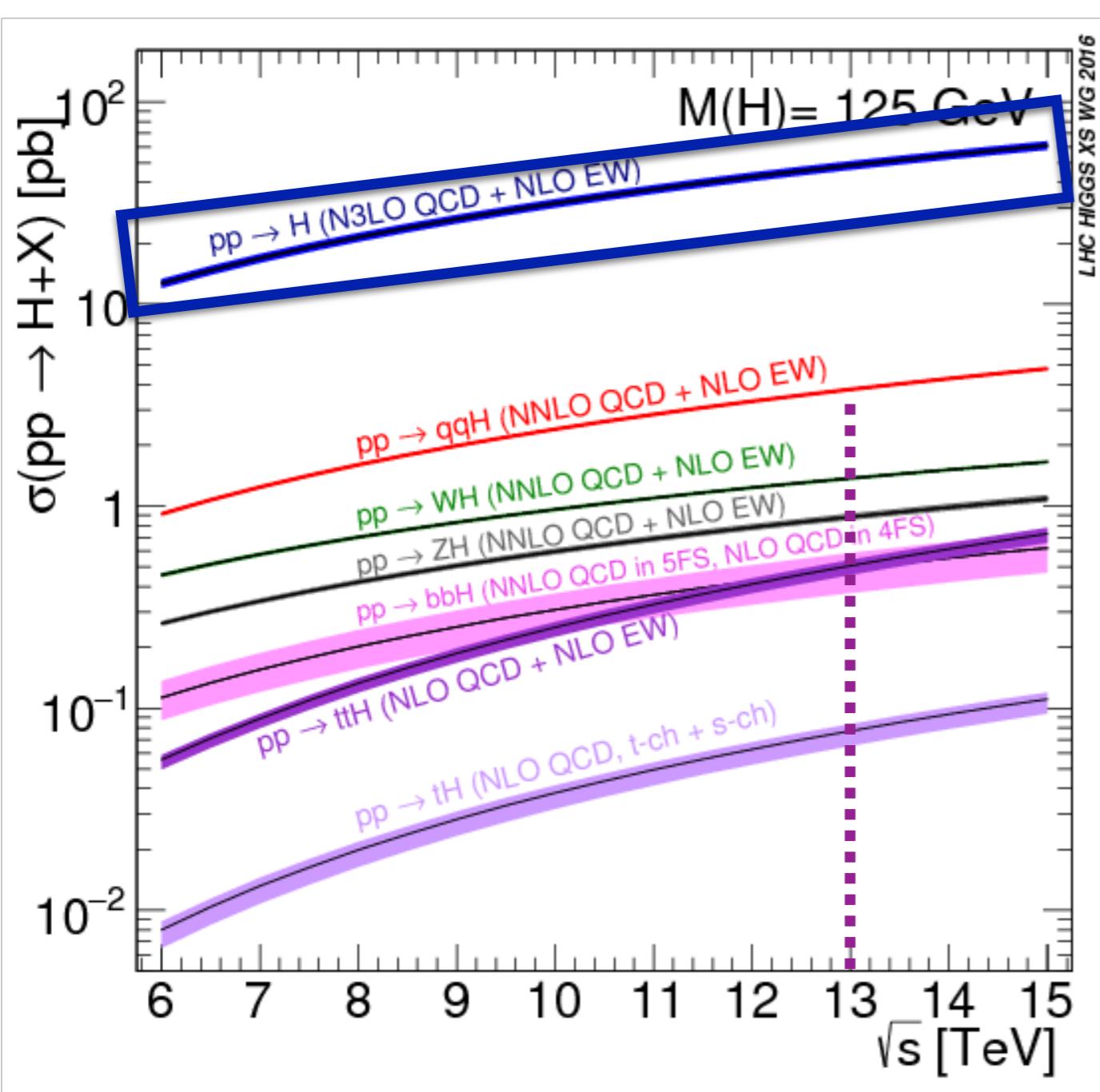
- At $m_H \sim 125$ GeV, many experimentally accessible final states at LHC.
- **$H \rightarrow \gamma\gamma$, $H \rightarrow ZZ$:**
 - Clean signature and good control over background.
- **$H \rightarrow WW$:**
 - Missing energy due to neutrinos from $W \rightarrow l\nu$ decays.
- **$H \rightarrow \tau\tau$:**
 - τ reconstruction more difficult and significant background.
- **$H \rightarrow b\bar{b}$:**
 - Largest branching fraction but very difficult to control background.



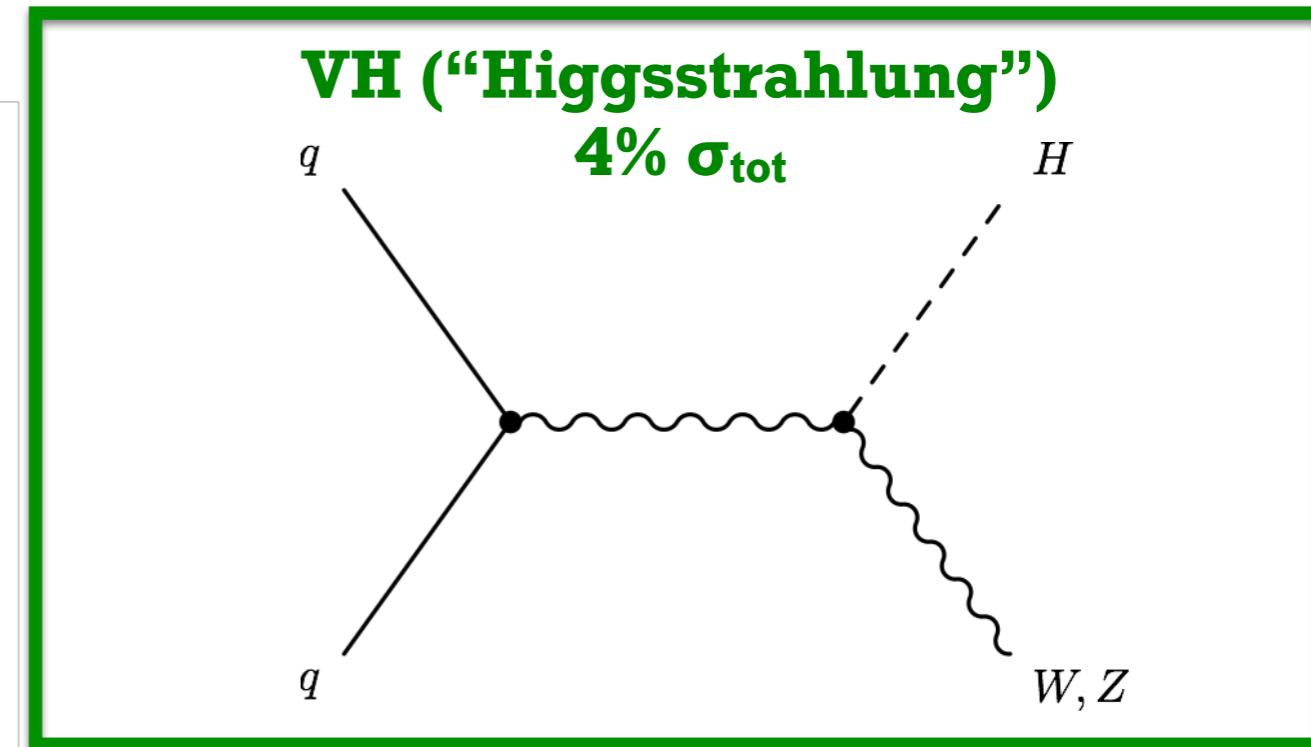
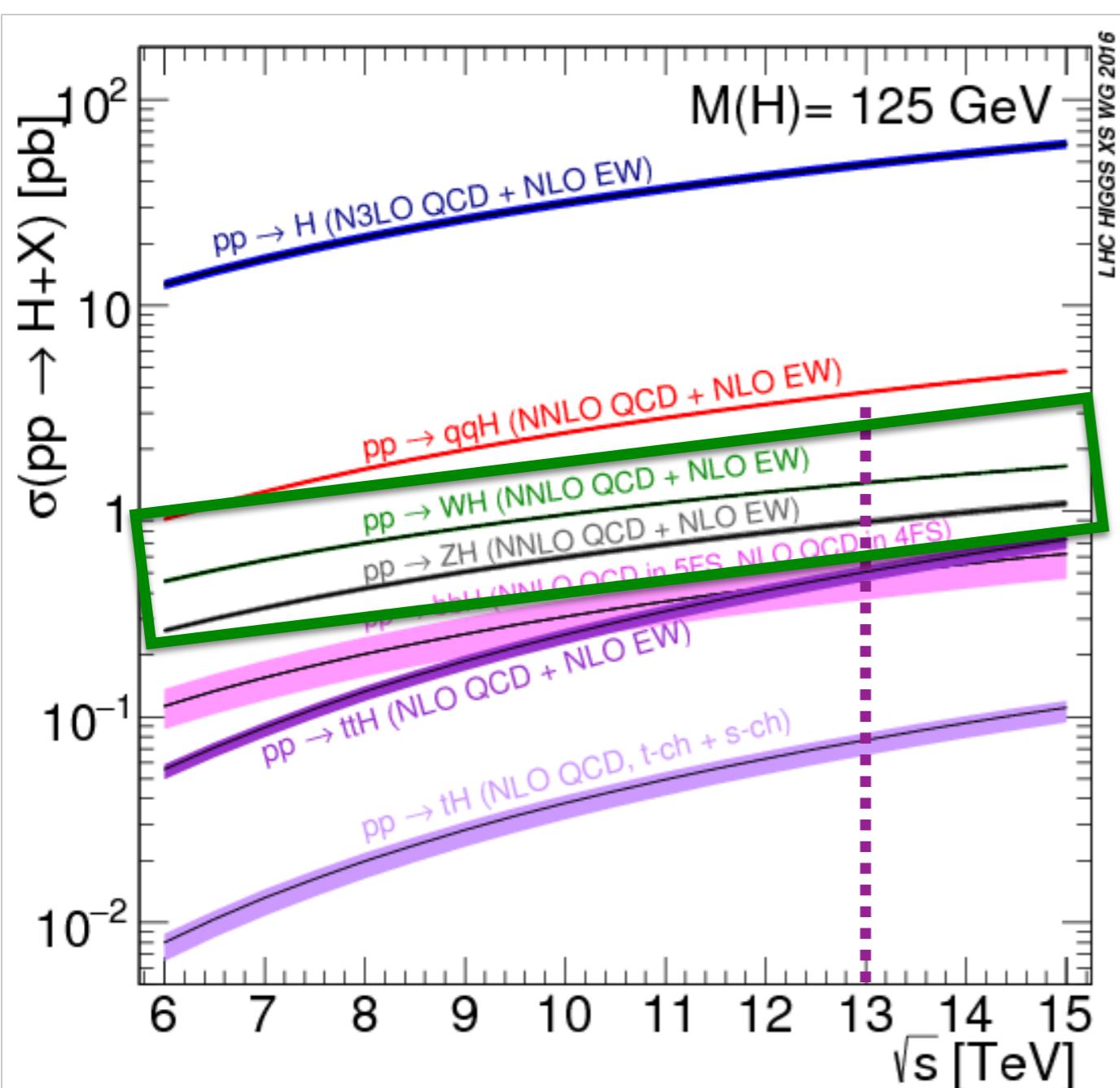
Remaining Higgs decays either completely overwhelmed by background or currently statistics-limited.



- Four Higgs boson production modes measurable with precision at LHC: **ggH**, **VBF**, **VH**, and **ttH**.
- Large variety in experimental challenges depending on production mode as well as decay.



- Dominant signature for Higgs boson discovery.
- Best sensitivity from rare but experimentally very clean $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ \rightarrow 4\ell$ decays.



- Presence of W/Z boson in final state \Rightarrow huge suppression of multijet backgrounds in dominant (58%) $H \rightarrow b\bar{b}$ decay channel.
- VH sensitivity dominated by $H \rightarrow b\bar{b}$.

- Observation of VH , $H \rightarrow b\bar{b}$ was not originally expected until much later in the LHC program.

“The WH channel will be very difficult... even under the most optimistic assumptions.”

— ATLAS-TDR-1999

“the discovery potential for... the WH production mode at the LHC is marginal... For $ZH \rightarrow llb\bar{b}$ a similar signal-to-background ratio is expected as for the WH channel.”

— Int. J. Mod. Phys. A 20:2523-2602 (2005)

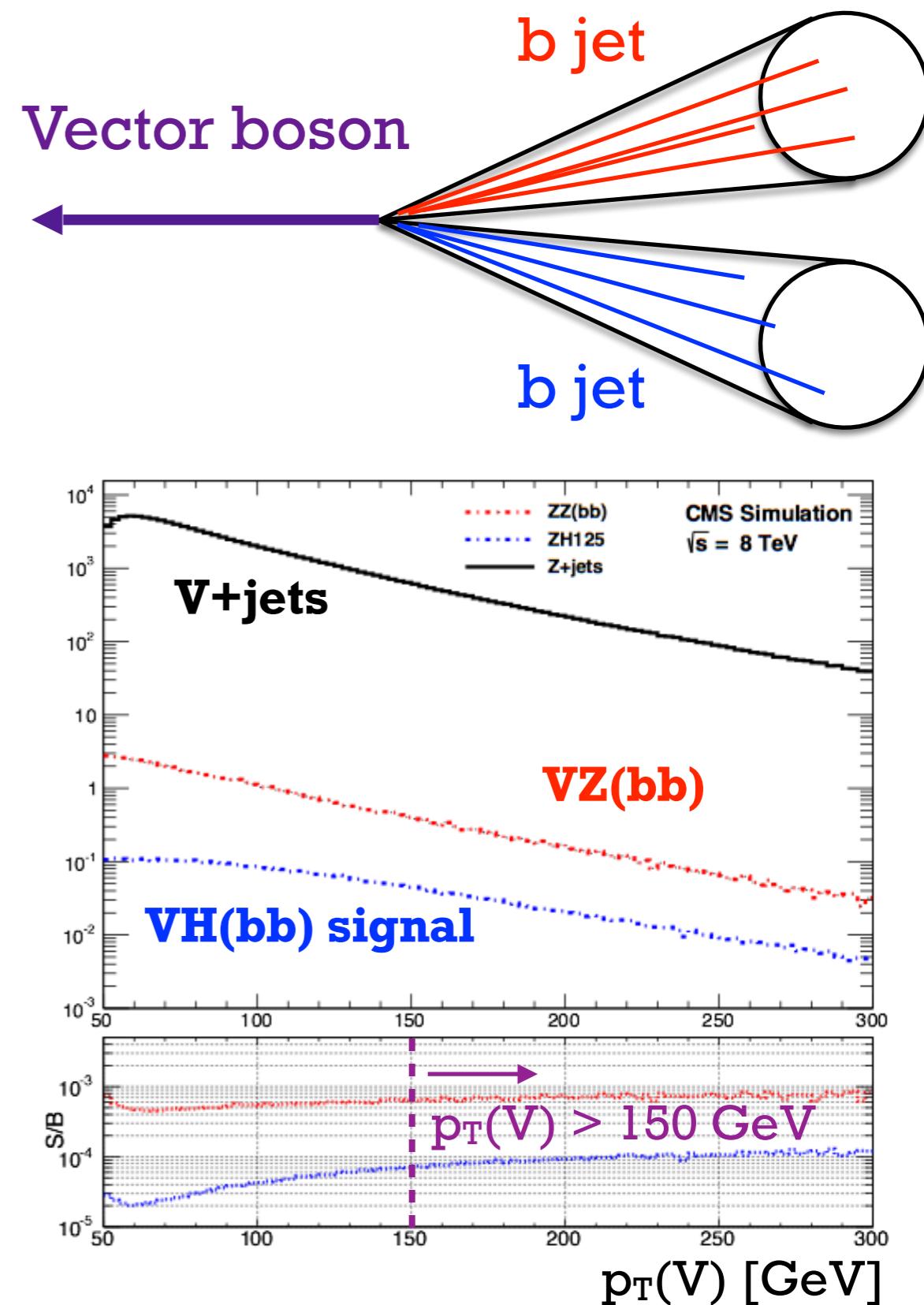
“a Higgs-boson signal could be [observed for $t\bar{t}H(b\bar{b})$]... assuming an integrated luminosity of 300 fb^{-1} ”

— ATLAS-TDR-15

“[$t\bar{t}H$ and WH] are definitely high-luminosity measurements.”

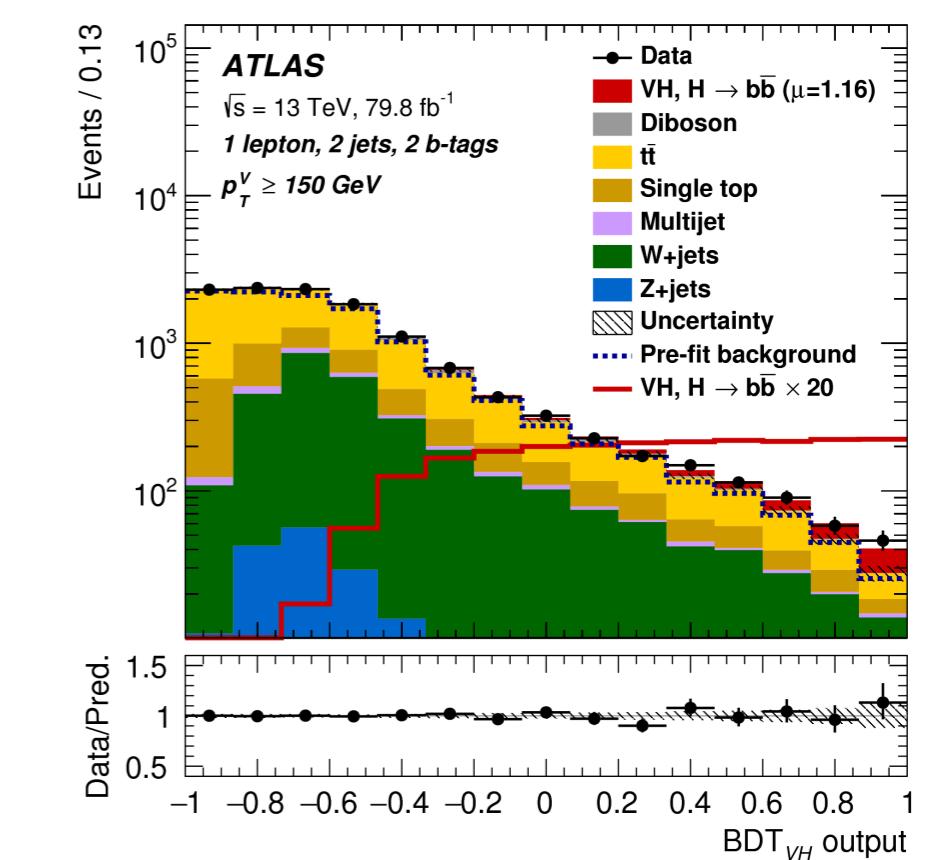
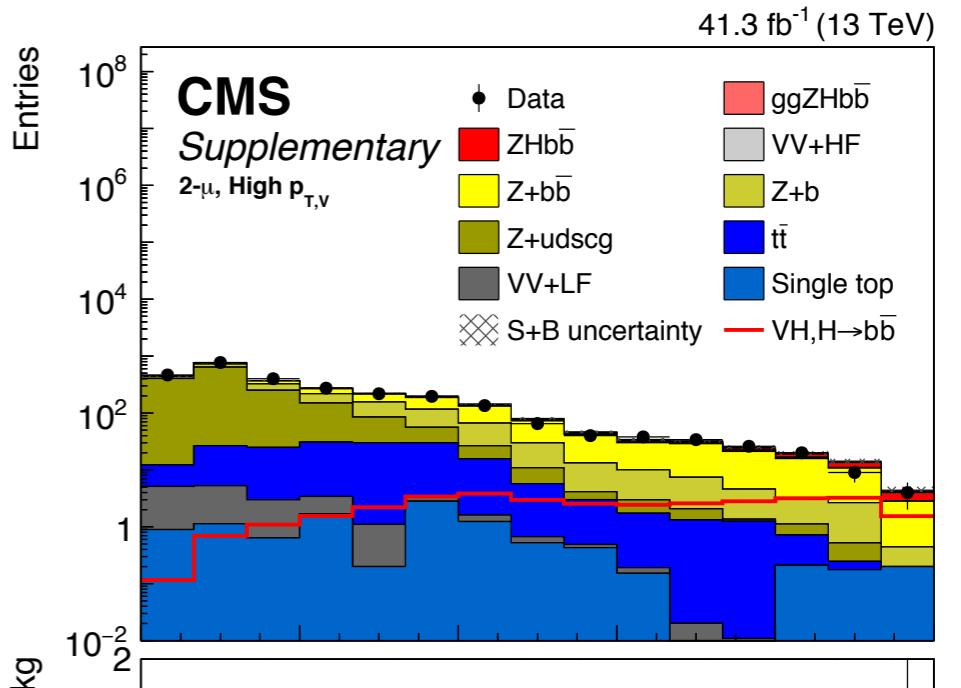
— CERN-PH-TH/2004-103

- S/B greatly enhanced by requiring that **vector boson is boosted and back-to-back to Higgs boson candidate** [1].
- ~5% total VH events with $p_T(V) > 200$ GeV but compensating advantages:
 - **Nearly eliminate QCD multijet**, large reduction in V+jets and top backgrounds.
 - **Improved mass resolution**.
 - Makes $Z \rightarrow vv$ channel accessible (large missing E_T).
- **Key element making VH, $H \rightarrow b\bar{b}$ search possible at the LHC.**



[1] [Phys. Rev. Lett. 100 \(2008\) 242001](#)

- Multivariate classifiers trained to extract S from B separately in each category ($W \rightarrow \ell v$, $Z \rightarrow \ell\ell$, $Z \rightarrow vv$).
- Simultaneous fit of multivariate output in all categories to extract VH, H \rightarrow b \bar{b} signal.



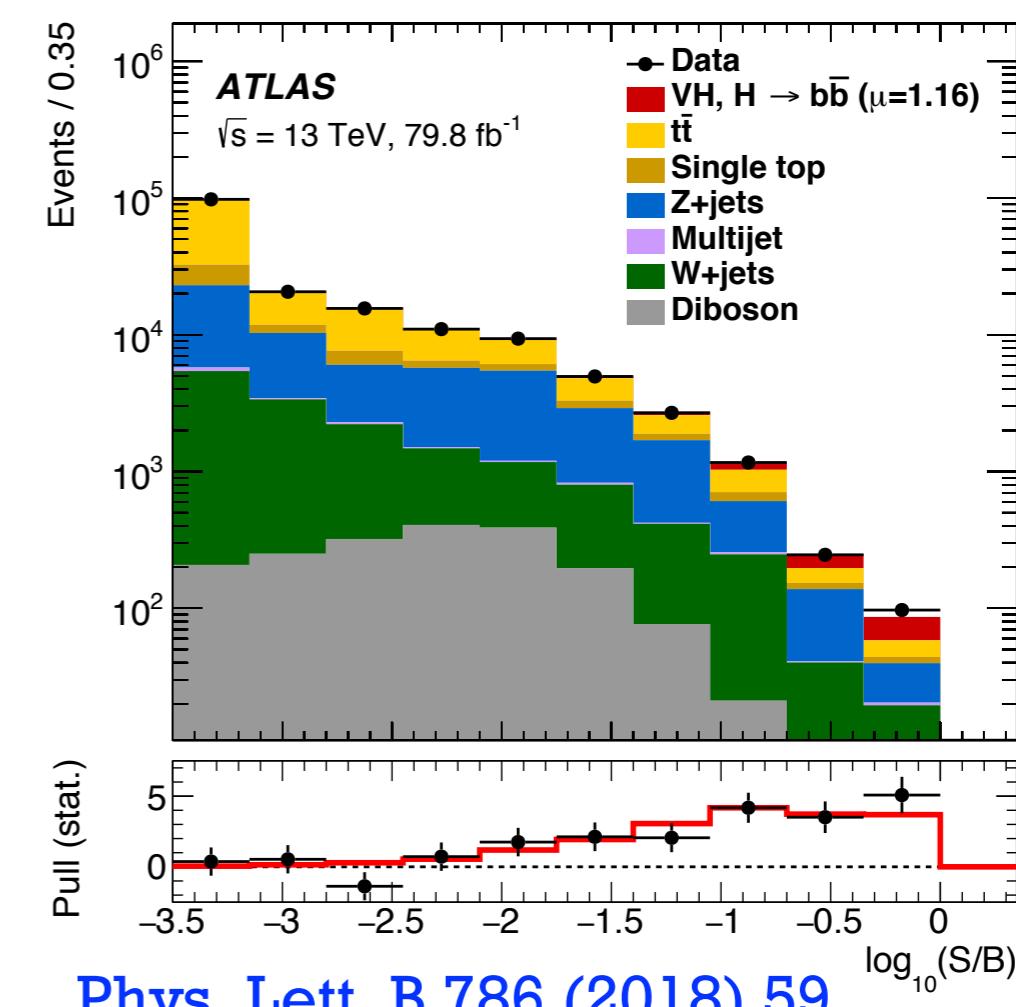
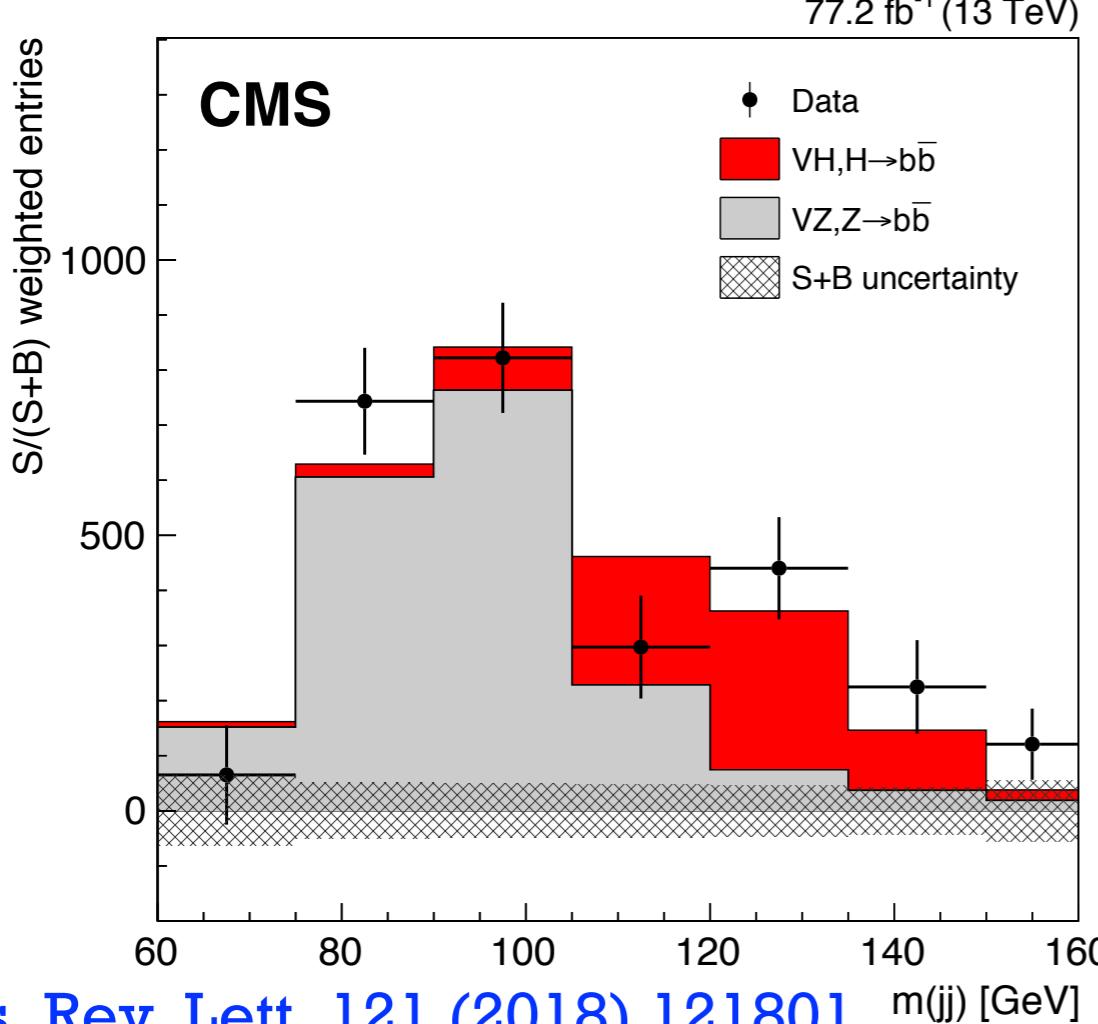
[Phys. Rev. Lett. 121 \(2018\) 121801](#)

[Phys. Lett. B 786 \(2018\) 59](#)

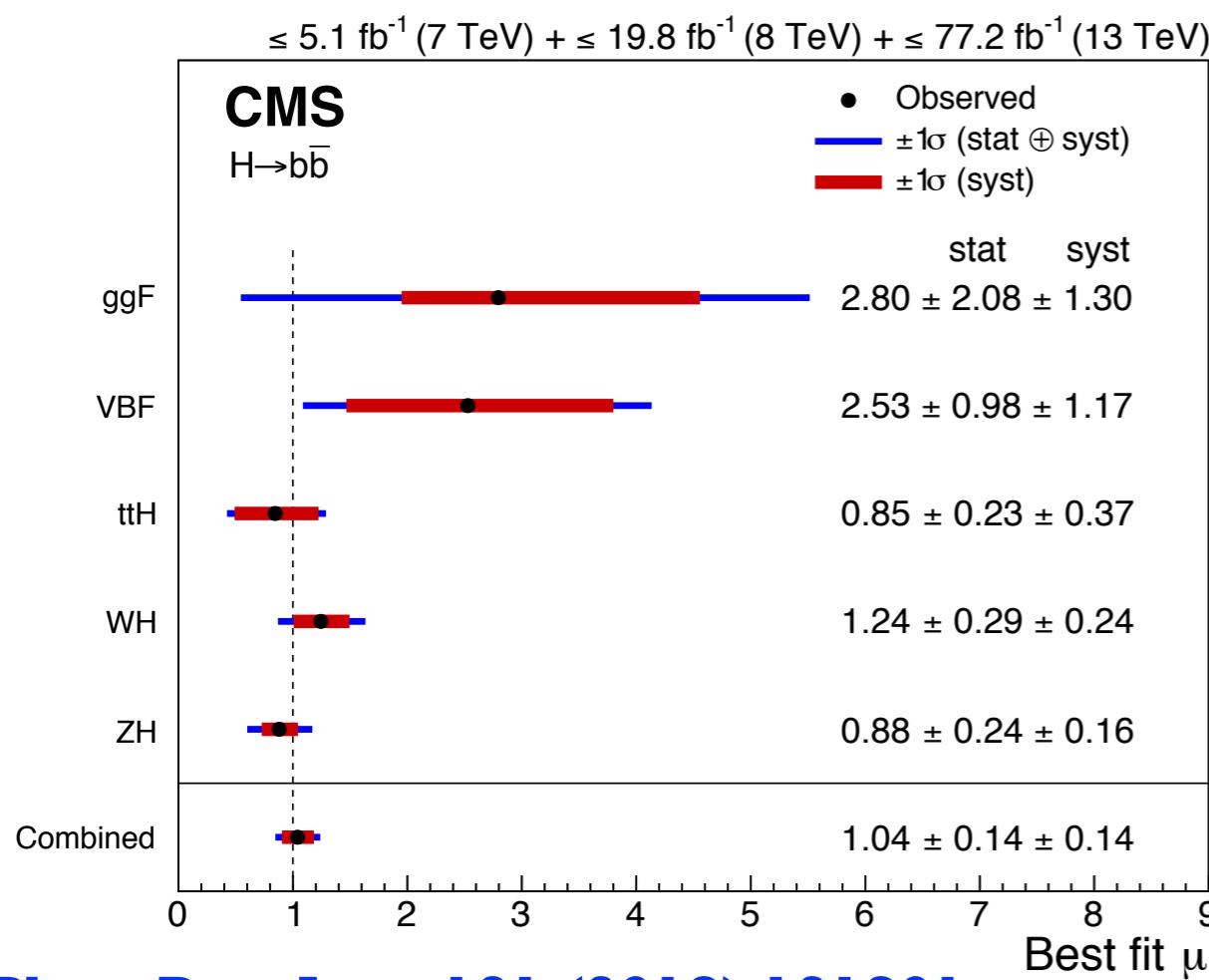
- Just under 5σ for VH, H \rightarrow bb \bar{b} process by both CMS and ATLAS.
- ATLAS: 5.3σ (4.8σ exp.) for VH alone from combining with H \rightarrow ZZ and H \rightarrow $\gamma\gamma$ (13 TeV data only).

$$\mu = \frac{\sigma \cdot BR}{\sigma \cdot BR_{SM}}$$

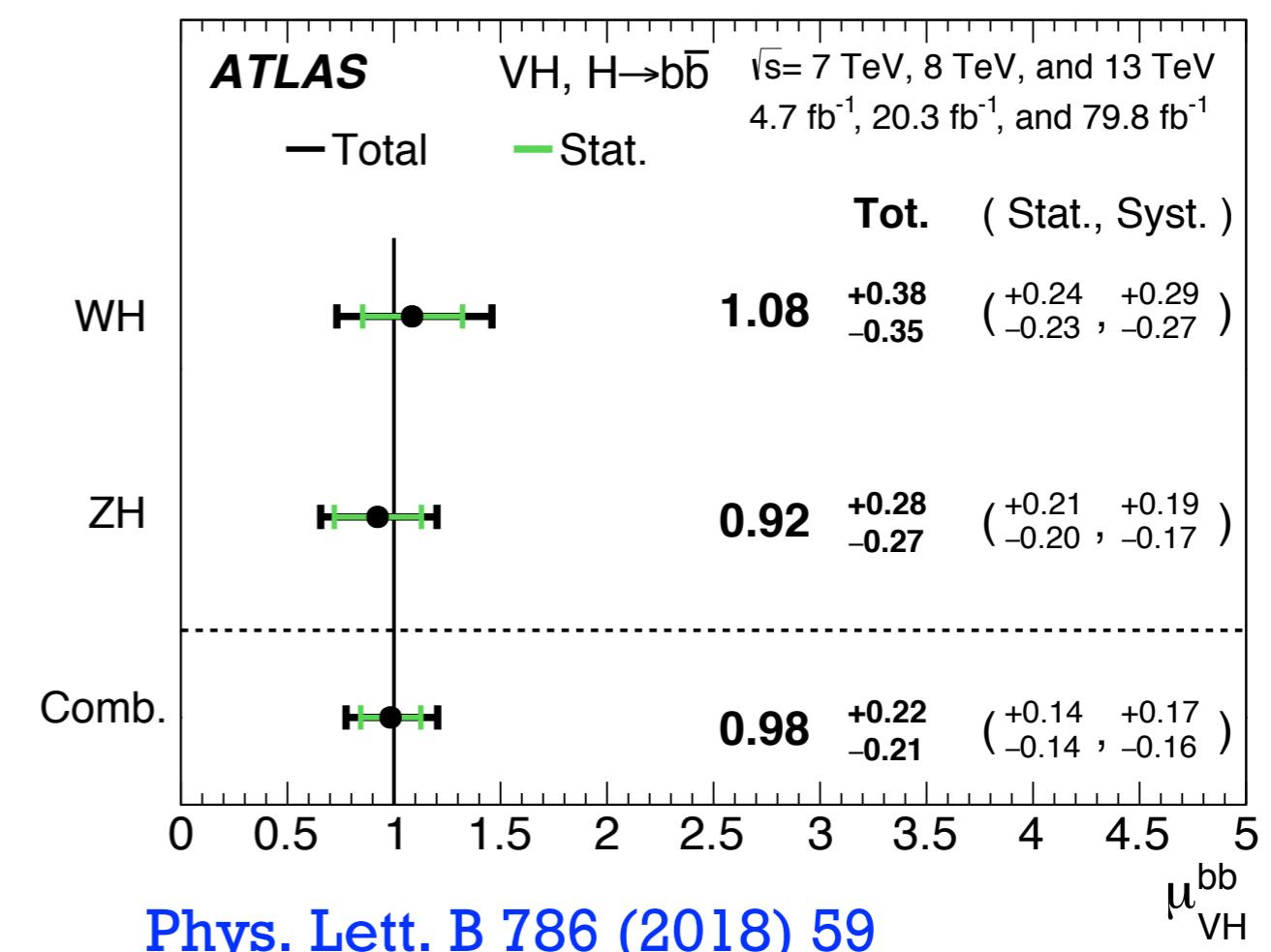
	Significance	Signal strength
CMS (8+13 TeV)	4.8σ (4.9σ exp.)	$\mu_{VH}^{bb} = 1.01 \pm 0.22$
ATLAS (8+13 TeV)	4.9σ (5.1σ exp.)	$\mu_{VH}^{bb} = 0.98^{+0.22}_{-0.21}$



- WH and ZH production measured with similar sensitivity.
 - ZH slightly better (two dedicated channels as opposed to only one)
- Systematic uncertainty comparable to statistical uncertainty, particularly for WH.

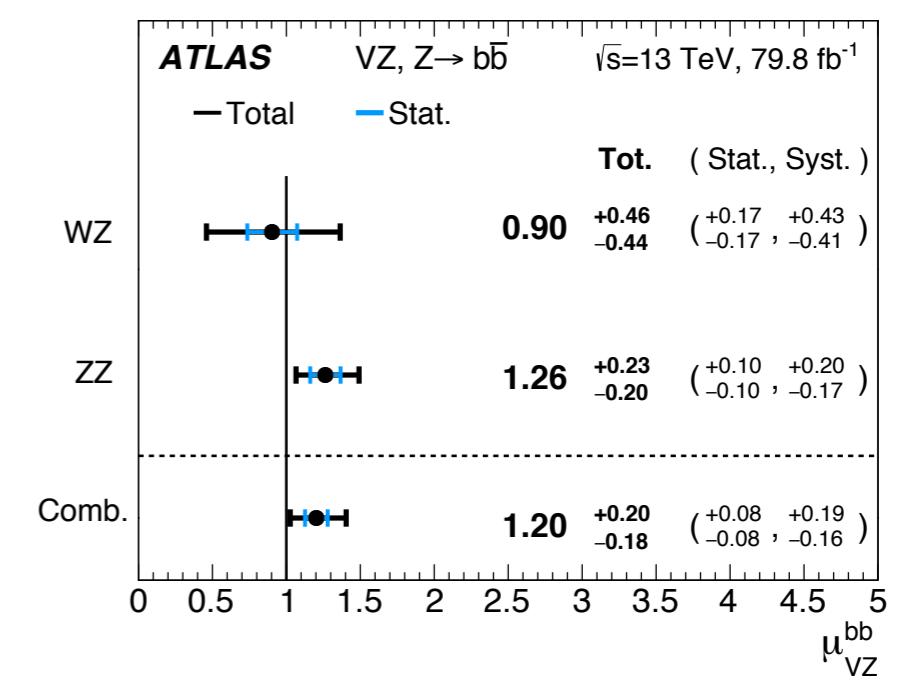
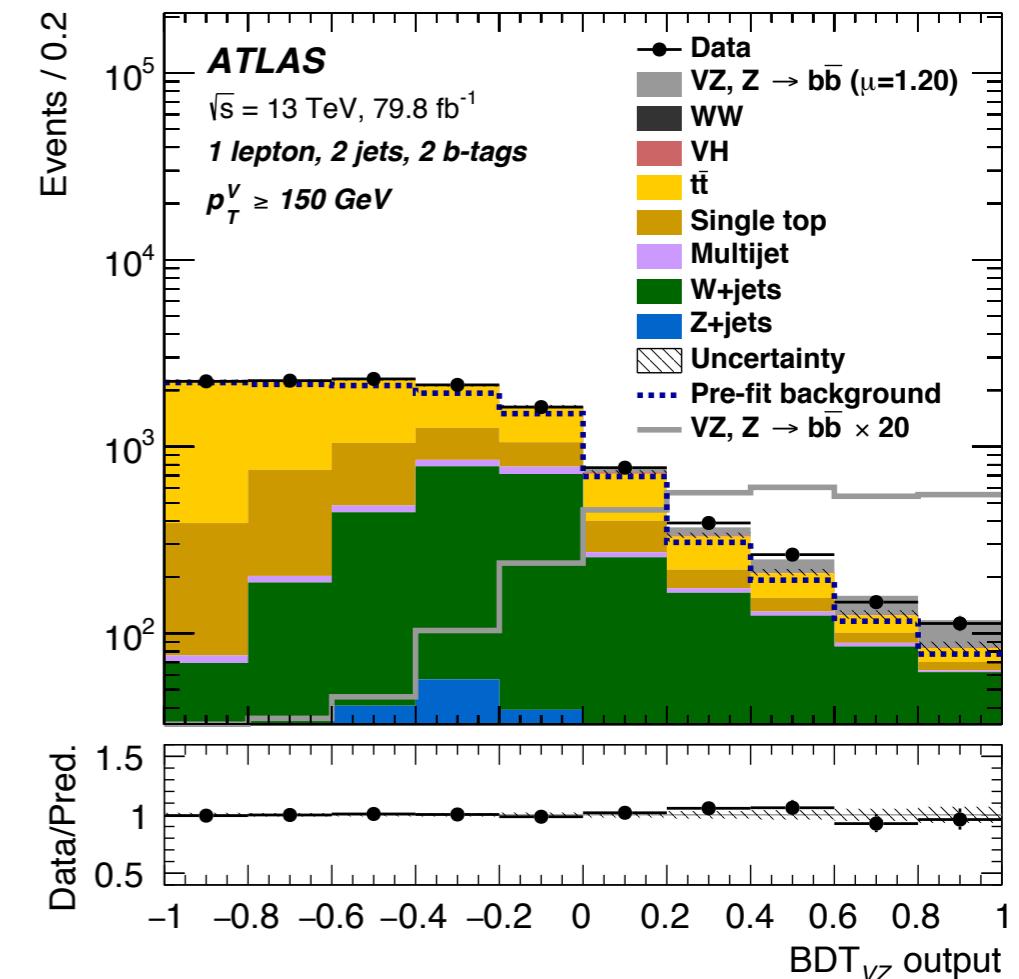


[Phys. Rev. Lett. 121 \(2018\) 121801](#)

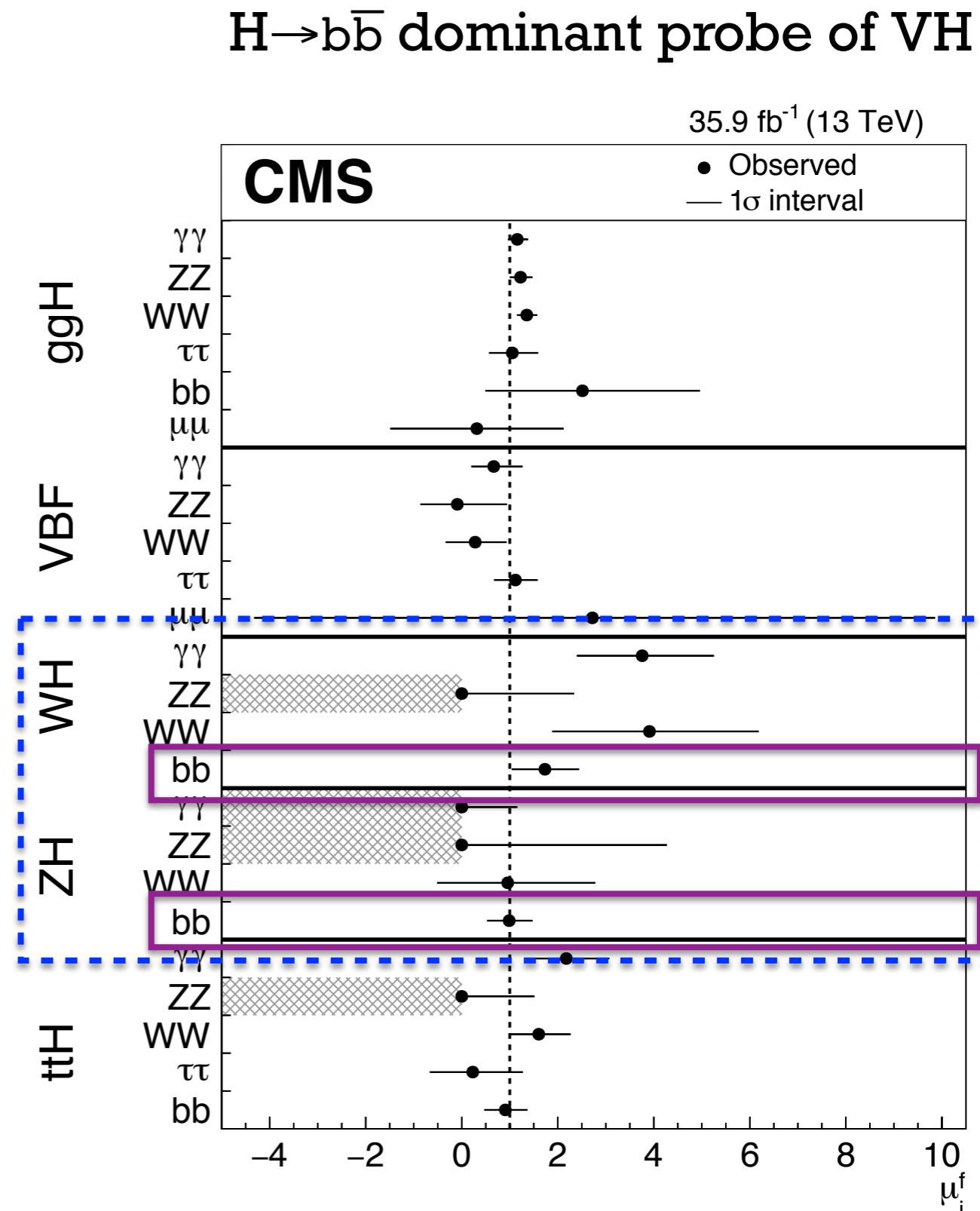


[Phys. Lett. B 786 \(2018\) 59](#)

- VZ, Z \rightarrow b \bar{b} : same final state and similar kinematics as VH, H \rightarrow b \bar{b} signal.
- Validate analysis strategy by extracting VZ, Z \rightarrow b \bar{b} signal with minimal changes:
 - **shift M(b \bar{b}) selection to include Z(b \bar{b})** (CMS analysis only).
 - **retrain multivariate classifier** to discriminate VZ, Z \rightarrow b \bar{b} “signal”.
 - Otherwise everything is the same as the VH, H \rightarrow b \bar{b} analysis:
 - **same MVA inputs, same fit strategy.**



- **Complementary probe for new physics effects with respect to direct searches.**
- Deviations from SM due to BSM Higgs couplings tend to be more pronounced in high-energy tails of kinematic distributions.
- $H \rightarrow b\bar{b}$ analysis at LHC already requires the Higgs candidate to have high momentum to suppress backgrounds.
 - **$H \rightarrow b\bar{b}$ analysis is well suited to make interesting differential VH measurements soon after observation.**



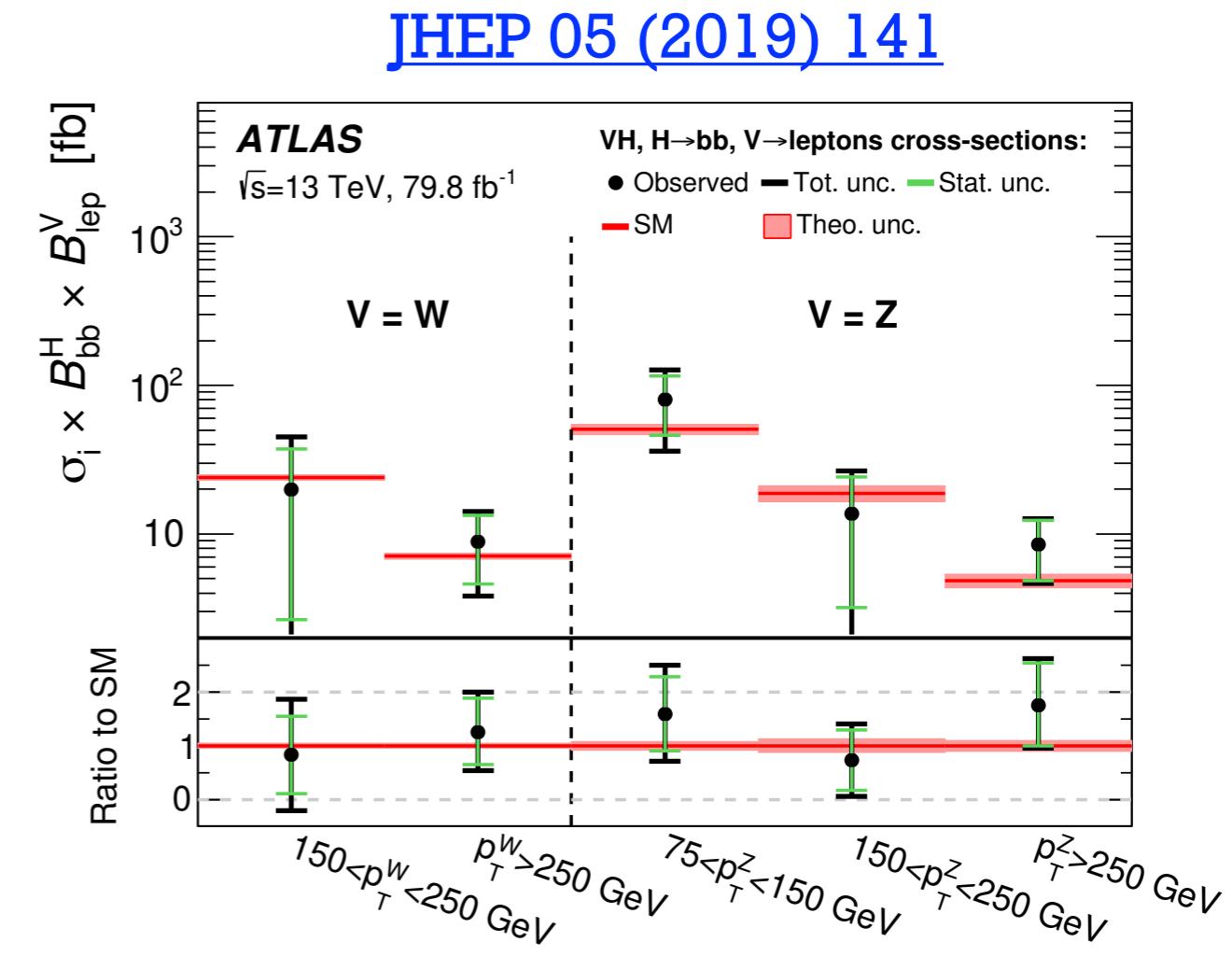
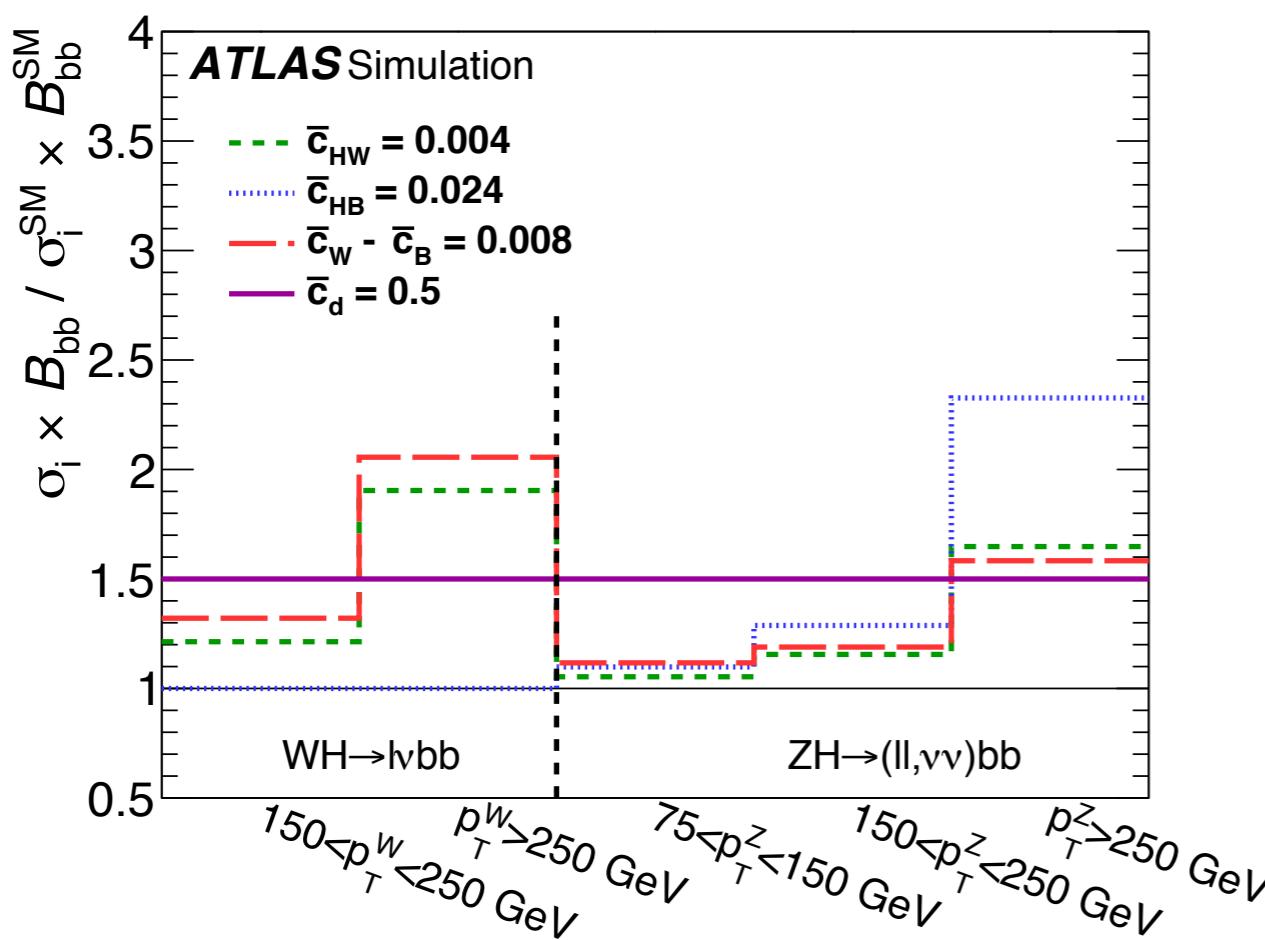
[Eur. Phys. J. C 79 \(2019\) 421](#)

- Effective Lagrangian with dimension-six operators added to SM.
- Consider operators which modify H-W and/or H-Z interactions.
- Access to VH production via $H \rightarrow b\bar{b}$ allows direct constraints on these operators.

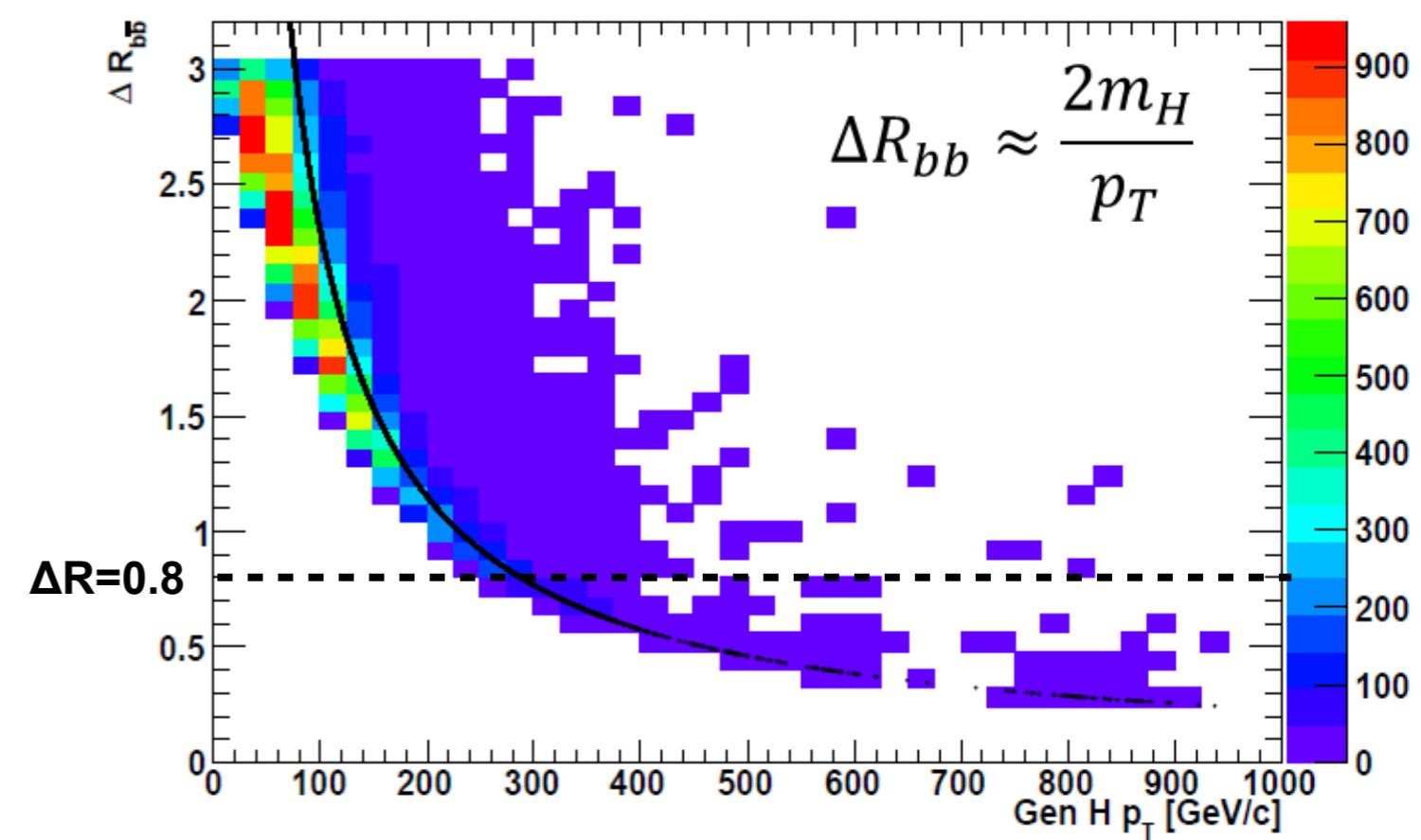
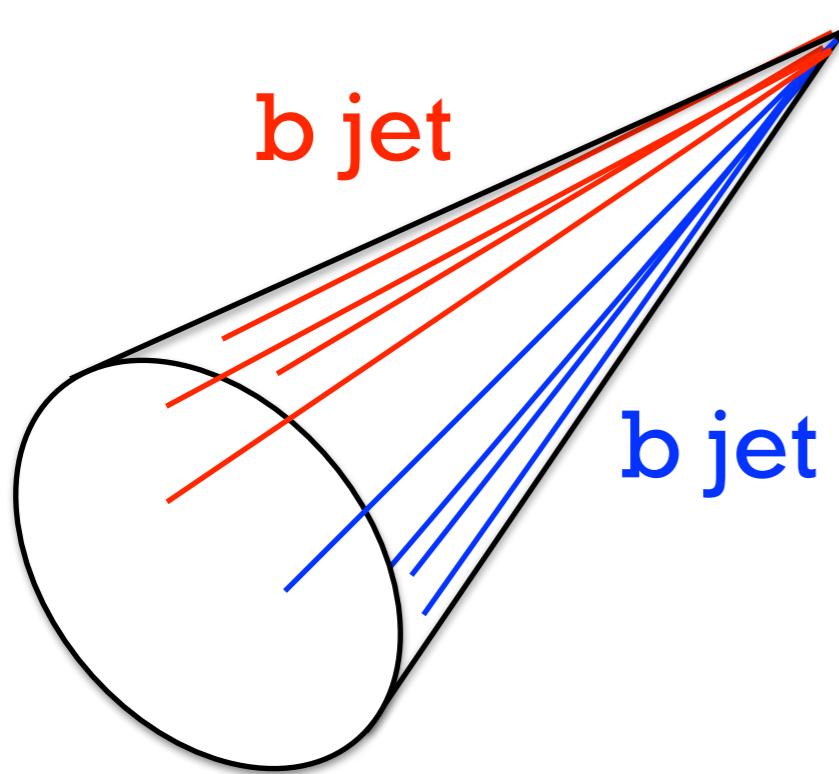
- $O_{HW} = i(D^\mu H)^\dagger \sigma^a (D^\nu H) W_{\mu\nu}^a,$
- $O_{HB} = i(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu},$
- $O_W = \frac{i}{2} \left(H^\dagger \sigma^a \overset{\leftrightarrow}{D}{}^\mu H \right) D^\nu W_{\mu\nu}^a,$
- $O_B = \frac{i}{2} \left(H^\dagger \overset{\leftrightarrow}{D}{}^\mu H \right) \partial^\nu B_{\mu\nu}.$

$$\bar{c}_{HW} = \frac{m_W^2}{g} \frac{c_{HW}}{\Lambda^2}, \quad \bar{c}_{HB} = \frac{m_W^2}{g'} \frac{c_{HB}}{\Lambda^2}, \quad \bar{c}_W = \frac{m_W^2}{g} \frac{c_W}{\Lambda^2}, \quad \bar{c}_B = \frac{m_W^2}{g'} \frac{c_B}{\Lambda^2}, \quad \bar{c}_d = v^2 \frac{c_d}{\Lambda^2},$$

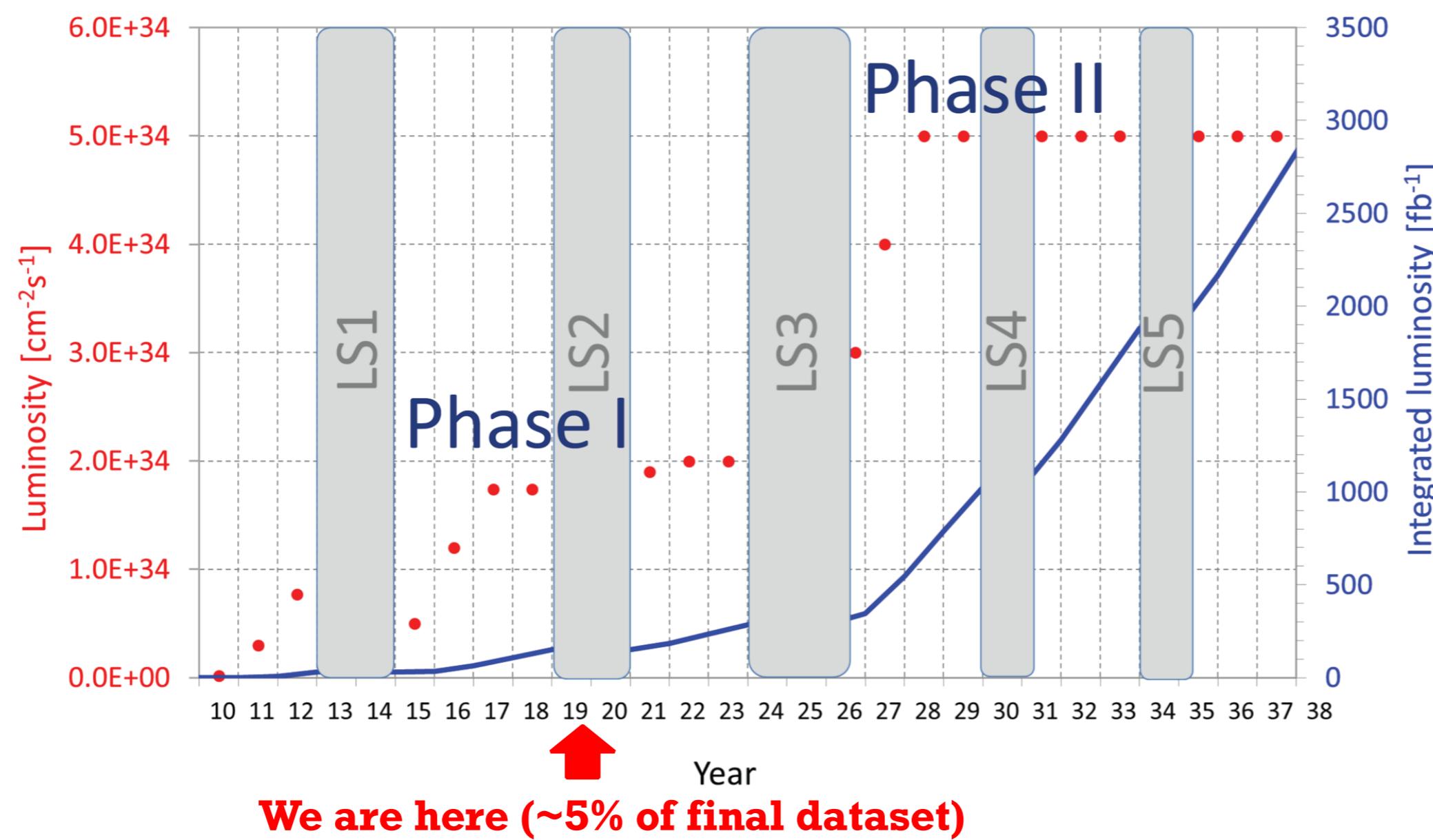
- Reinterpretation of same data used for ATLAS $H \rightarrow b\bar{b}$ observation.
- First sensitive differential measurement of VH.
 - Split WH vs. ZH and into several $p_T(V)$ bins.
- Constraints on EFT parameters largely driven by $p_T(V) > 250$ GeV.



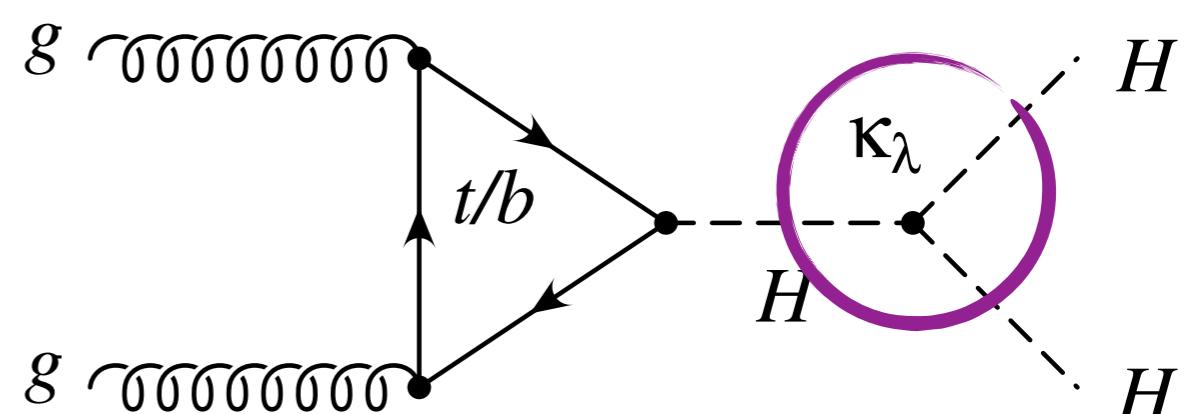
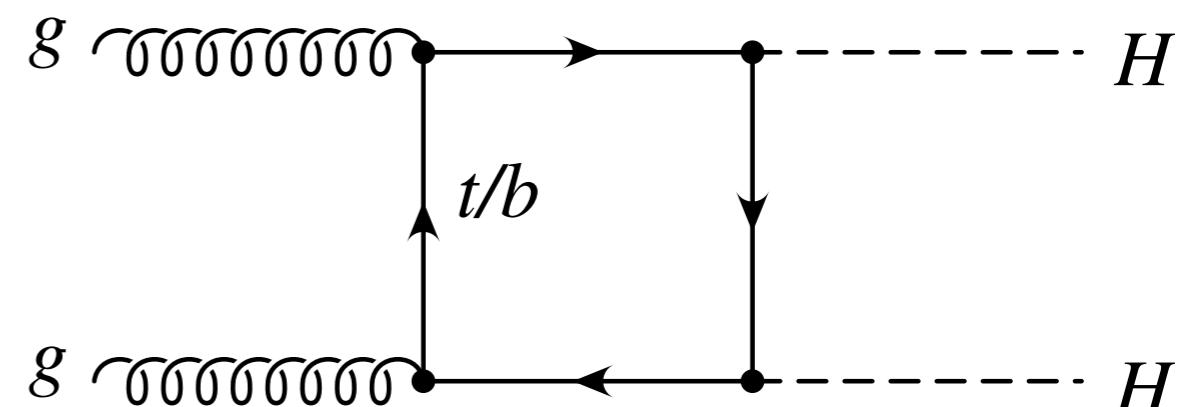
- Angular separation between b jets decreases with increasing Higgs boson momentum.
- Reconstruct H \rightarrow bb candidate as a single large-radius jet and use jet substructure techniques.
- Could significantly improve measurement precision in most crucial high-p_T(V) bins.



- Current EFT constraints from VH are dominated by statistical uncertainties at high $p_T(V)$.
- Can expect significant improvement from inclusion of full Run-2 and Run-3 datasets.
- At HL-LHC, experimentally cleaner decay modes ($H \rightarrow ZZ$, $H \rightarrow \gamma\gamma$) will also contribute significantly.



- Direct access to Higgs self-coupling λ .
- Probe shape of EWSB potential.
- Destructive interference \Rightarrow small rate:
 - $\sigma_{\text{SM}}(\text{HH}) = 33 \text{ fb} @ 13 \text{ TeV.}$
- BSM effects could significantly enhance $\sigma(\text{HH})$.



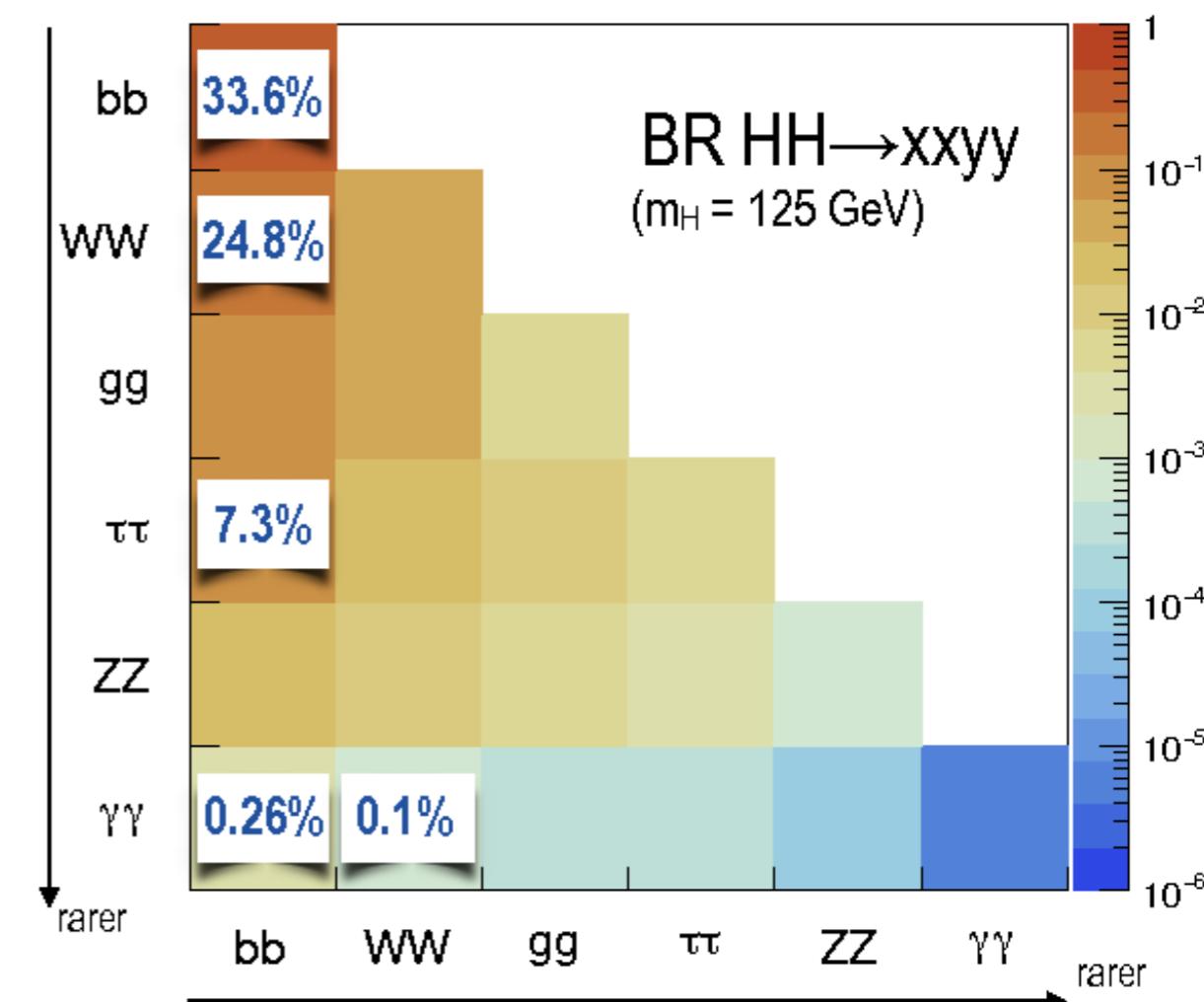
- A variety of complementary final states to measure HH at the LHC:

- $H \rightarrow b\bar{b}$: highest BR but more experimentally challenging.



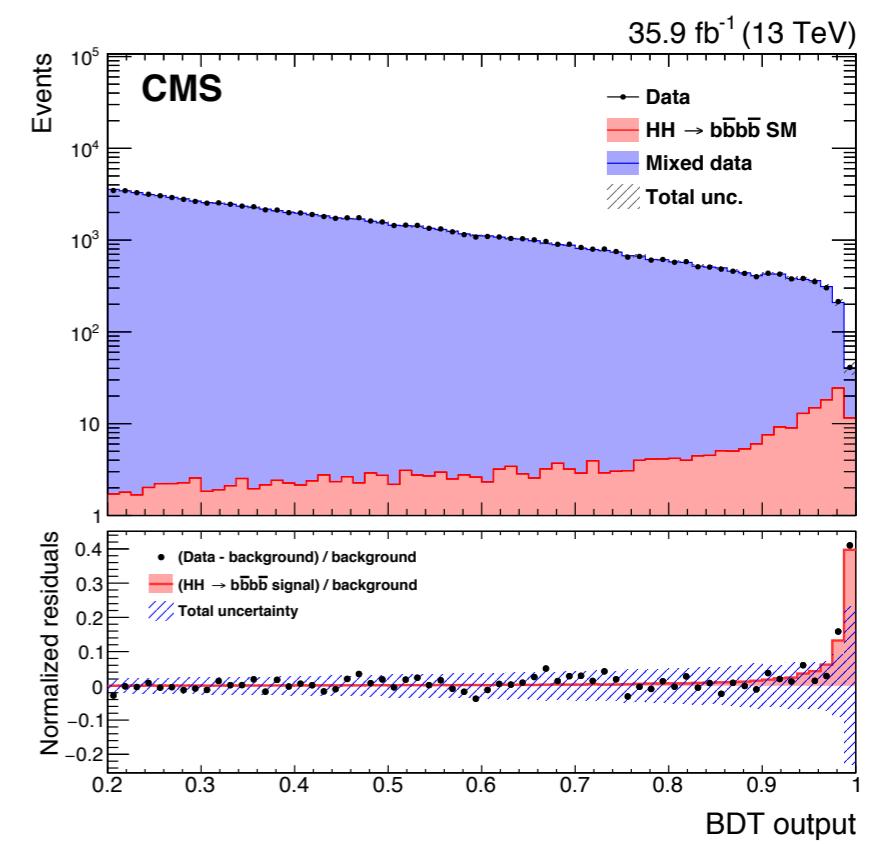
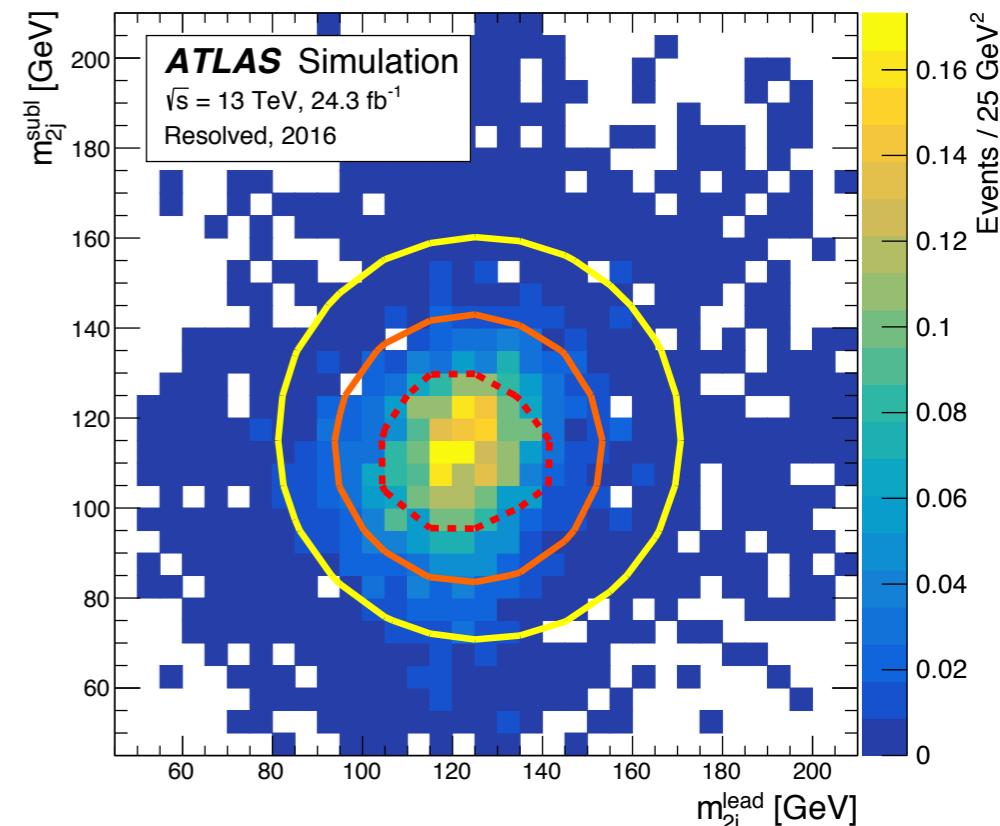
- $H \rightarrow \gamma\gamma$: small BR but excellent mass resolution.

$$\sigma_{\text{SM}}(\text{HH}) \sim 33 \text{ fb.}$$



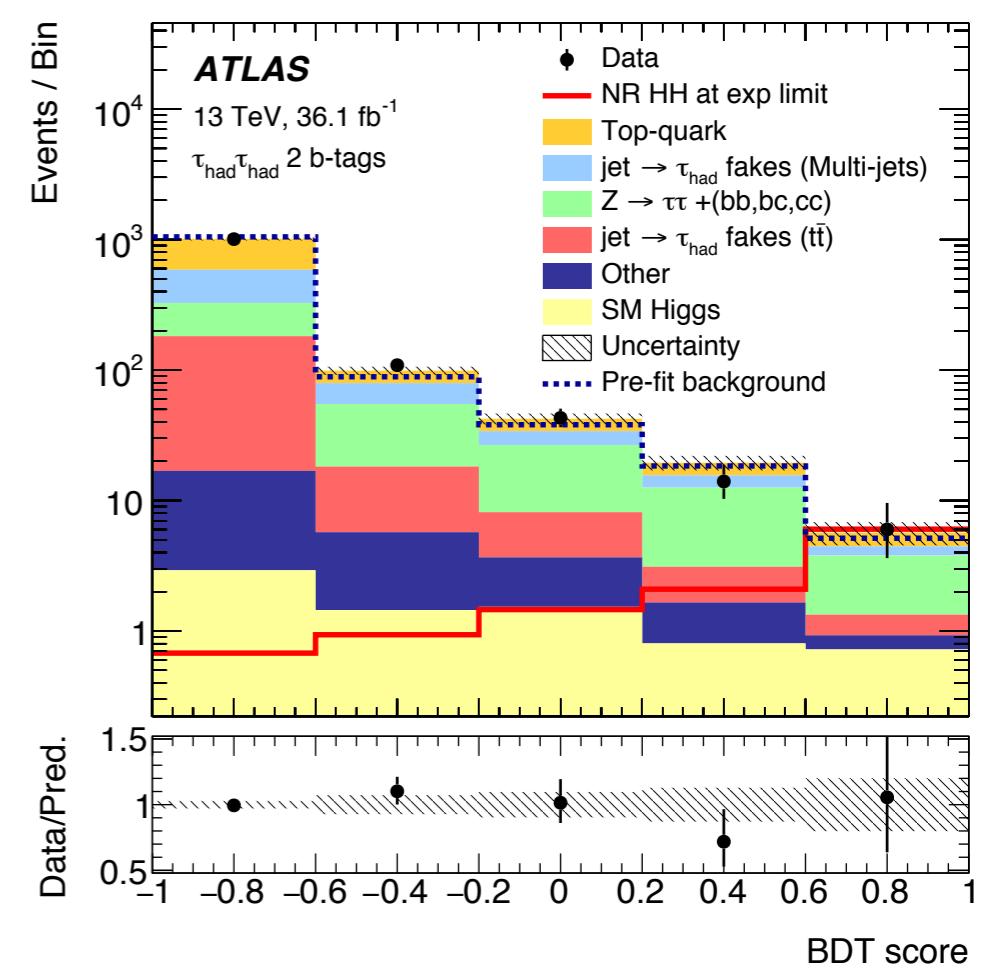
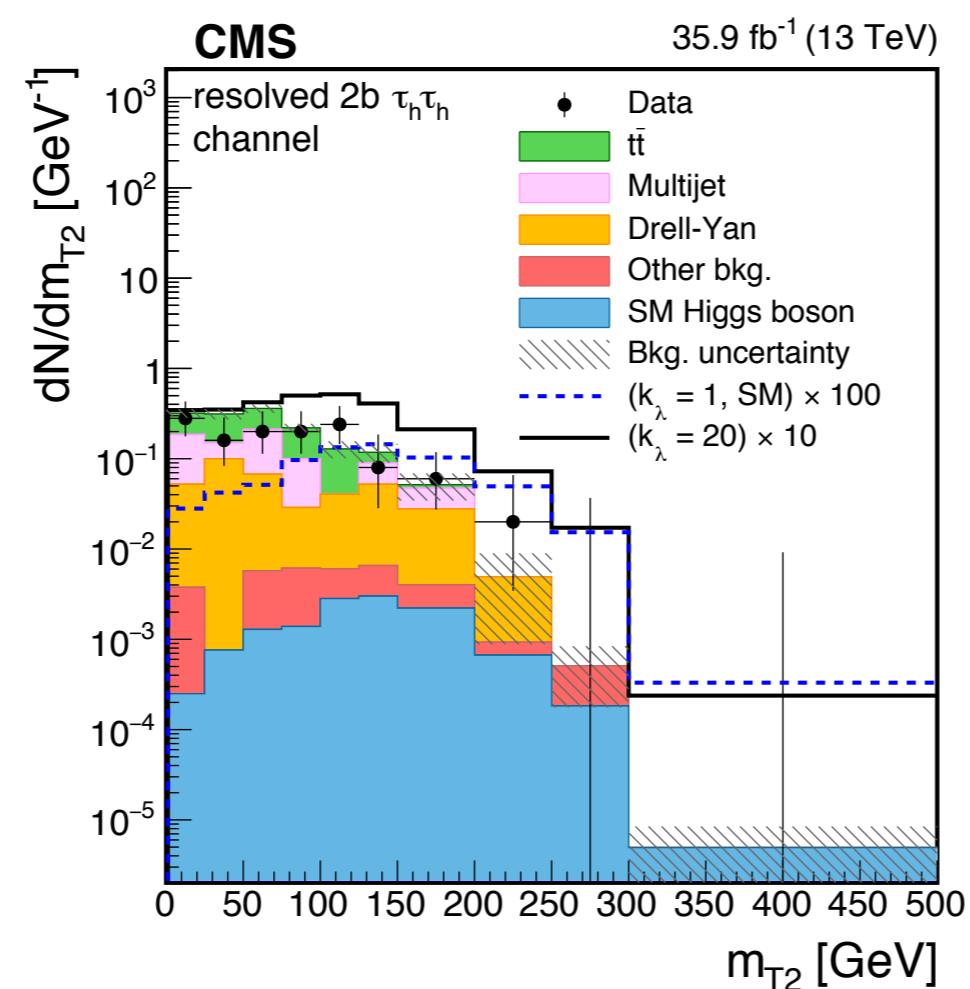
- 33.6% of total σ_{HH} but challenging large multijet background.
- Data-driven techniques to model multijet contribution \Rightarrow large systematic uncertainties.

$\sigma/\sigma_{\text{SM}} @ 95\% \text{ CL}$	
CMS JHEP 04 (2019) 112	< 75 (37 exp.)
ATLAS JHEP 01 (2019) 030	< 12.9 (20.7 exp.)

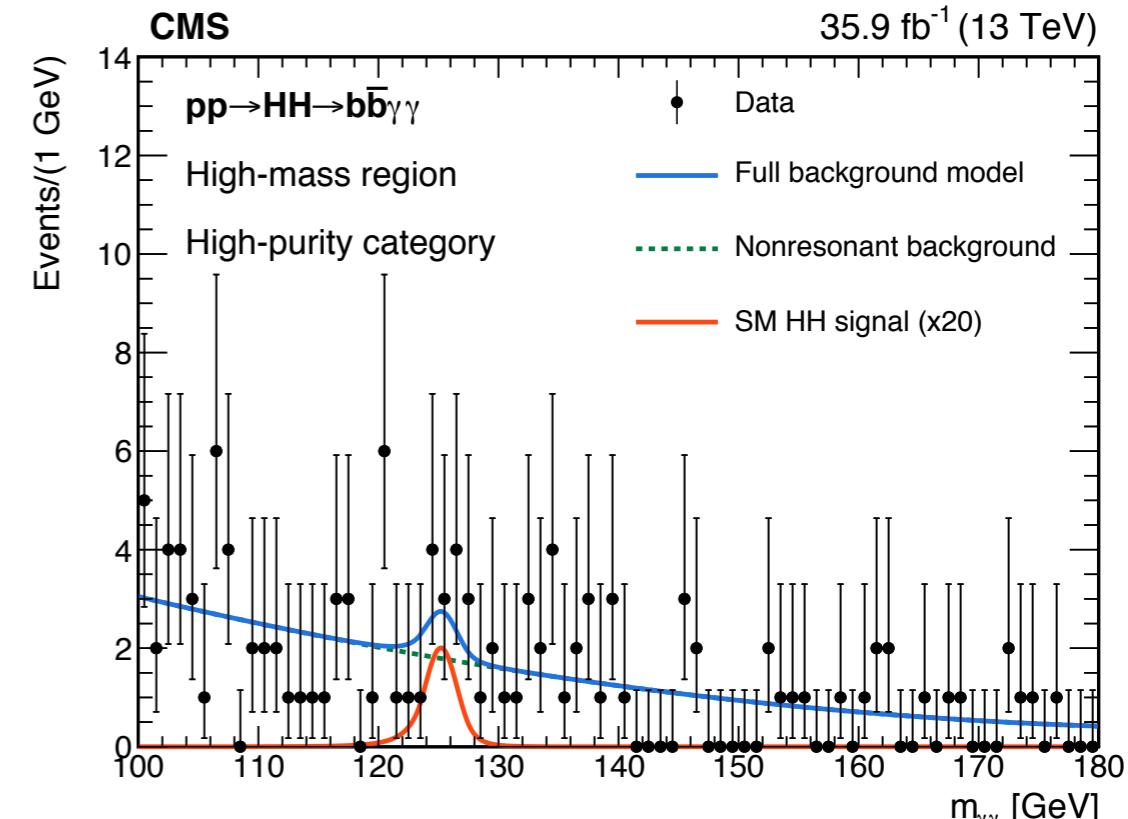


- SM $\sigma^* \text{BR} \sim 2.44 \text{ fb}$.
- CMS: fit m_{T2} in cut-based categories of $m(\tau\tau)$ vs. $m(bb)$.
- ATLAS: fit directly output of multivariate classifier.

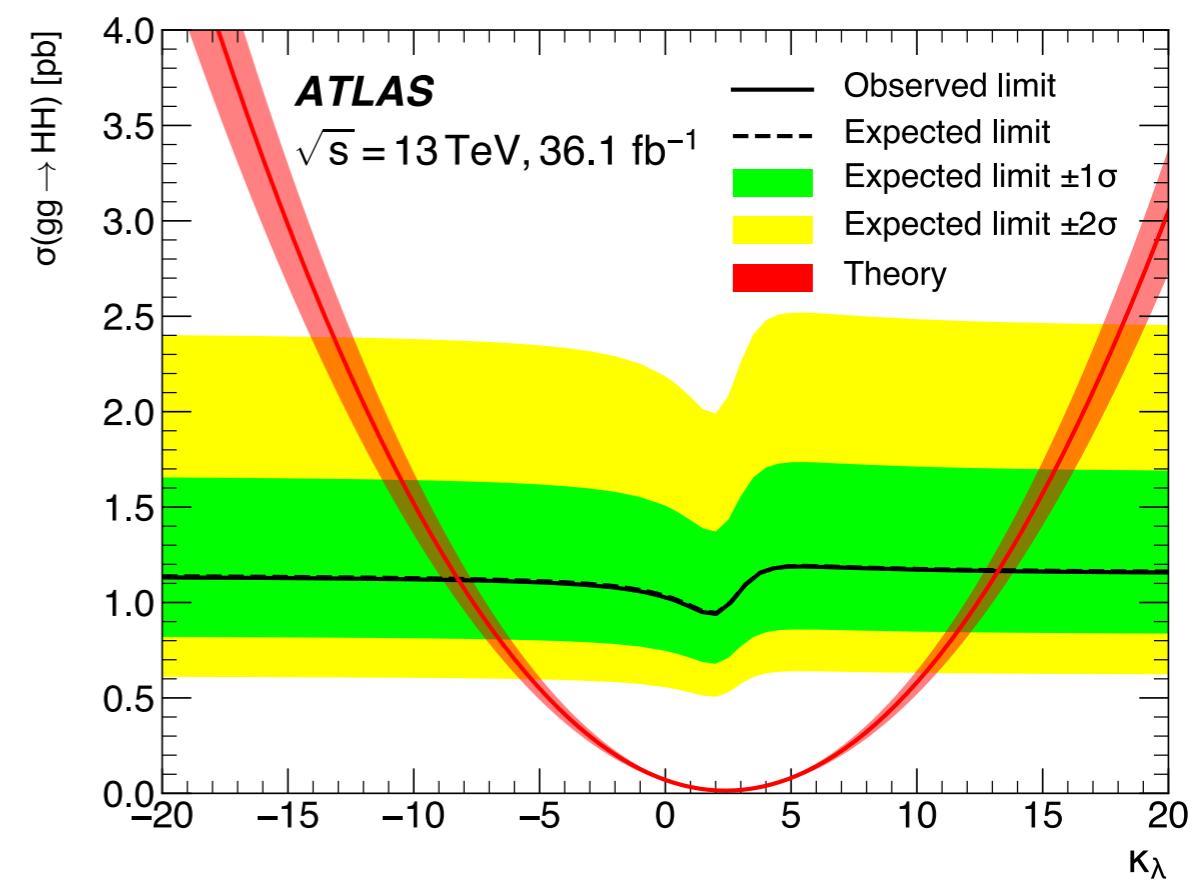
$\sigma/\sigma_{\text{SM}}$ @ 95% CL
CMS Phys. Lett. B 778 (2018) 101 < 30 (25 exp.)
ATLAS Phys. Rev. Lett. 121 (2018) 191801 < 12.7 (14.8 exp.)



- SM $\sigma^* \text{BR} \sim 0.09 \text{ fb}$.
- Categorize events with multivariate classifier and fit $m(\gamma\gamma)$.
- Benefits from excellent experimental resolution on $m(\gamma\gamma)$.



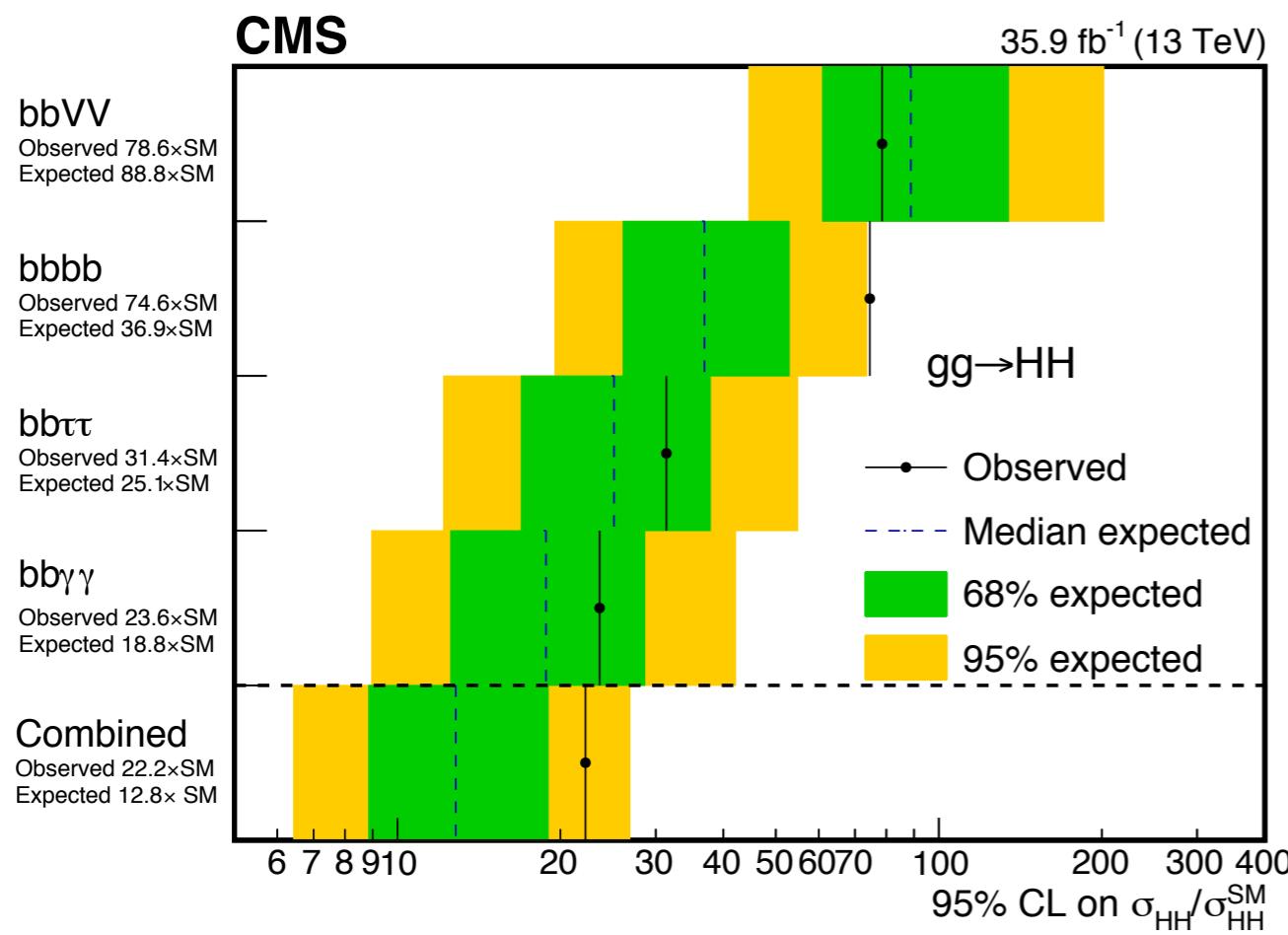
	$\sigma/\sigma_{\text{SM}} @ 95\% \text{ CL}$	$\kappa_\lambda @ 95\% \text{ CL}$
CMS Phys. Lett. B 788 (2018) 7	< 19.2 (16.5 exp.)	[-11, 17]
ATLAS JHEP 11 (2018) 040	< 22 (28 exp.)	[-8.2, 13.2]



- Sensitivity of individual channels differs, but combined HH sensitivity similar between the two experiments.
- $\sim 10 * \sigma_{\text{SM}}(\text{HH})$

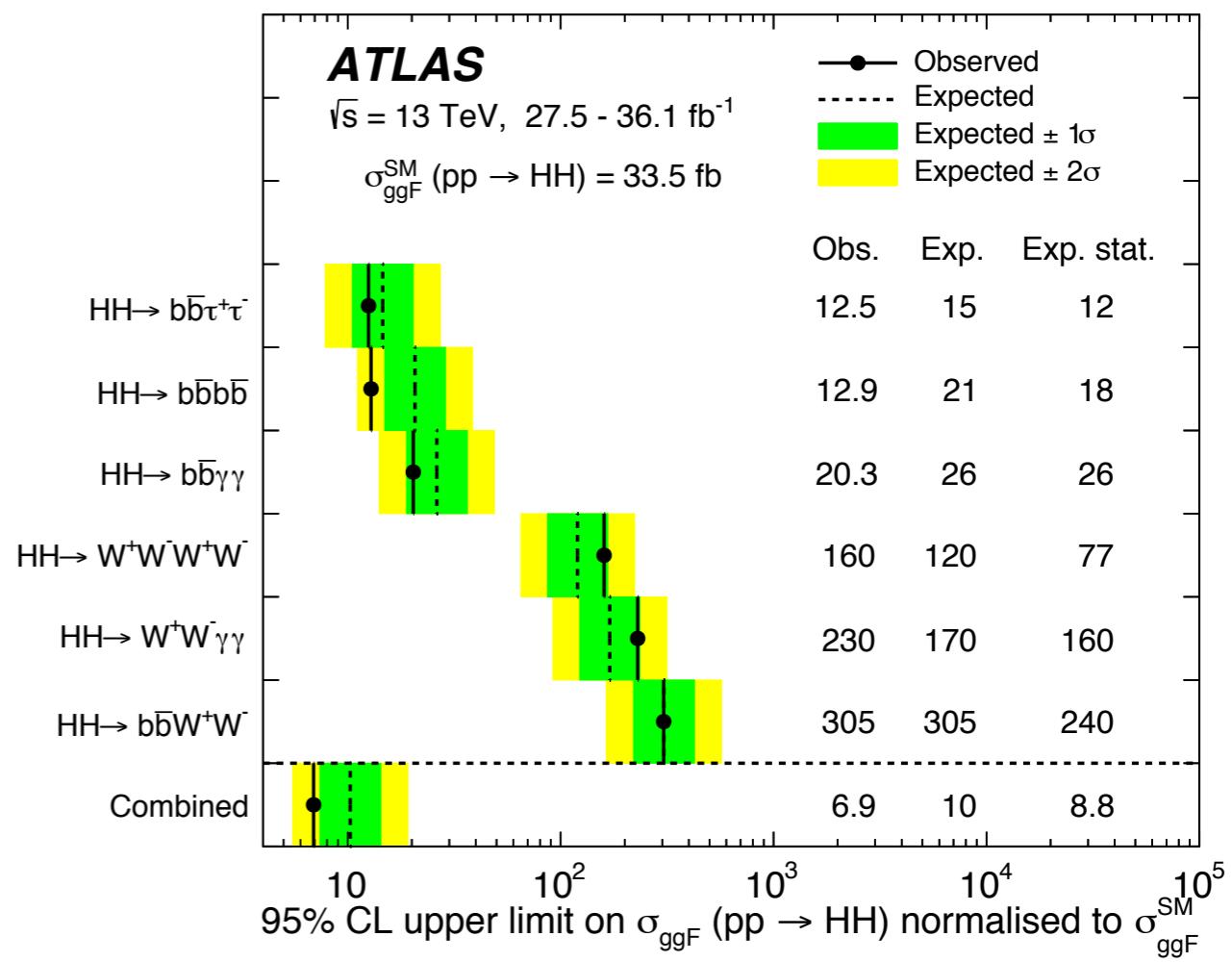
[Phys. Rev. Lett. 122 \(2019\) 121803](#)

$-11.8 < \kappa_\lambda < 18.8$ @ 95% CL



[arXiv:1906.02025, submitted to PLB](#)

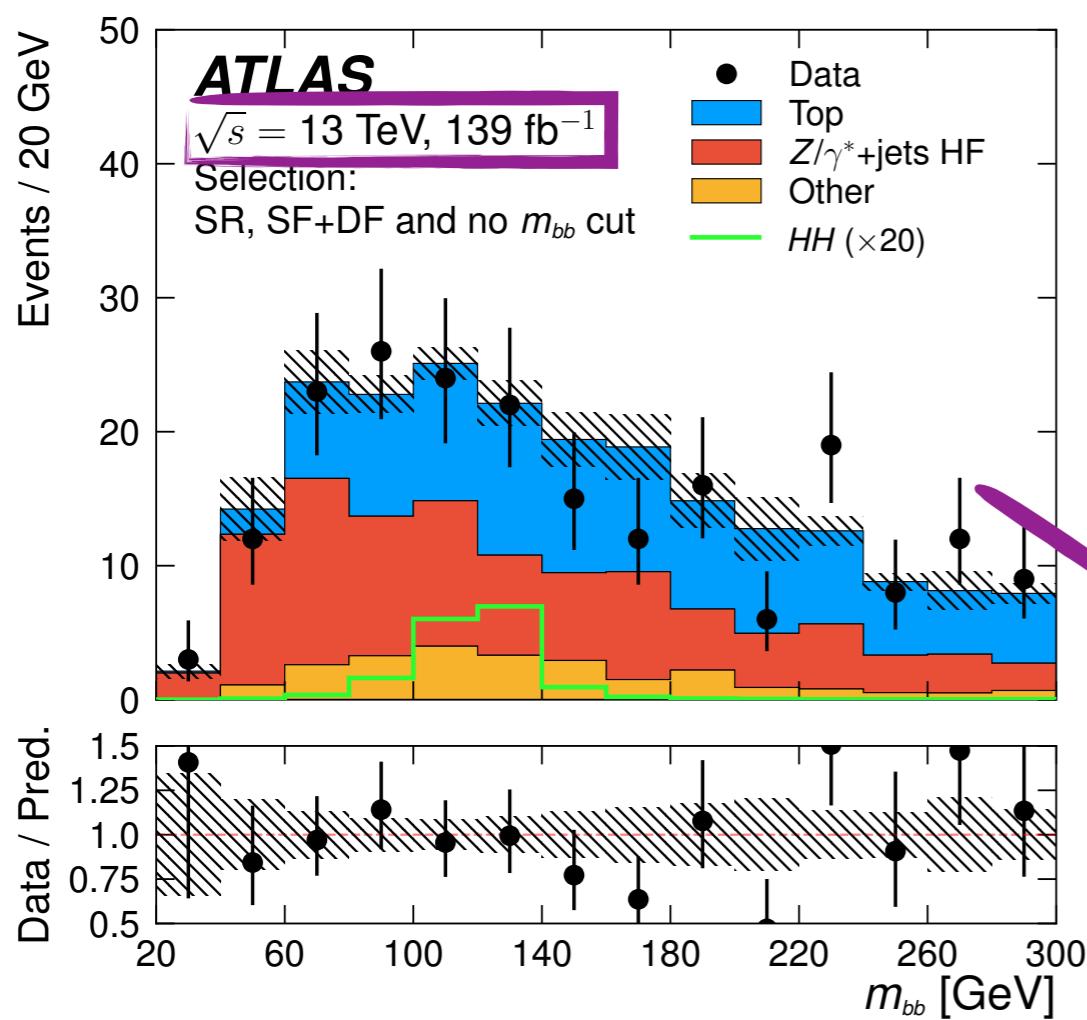
$-5.0 < \kappa_\lambda < 12.0$ @ 95% CL



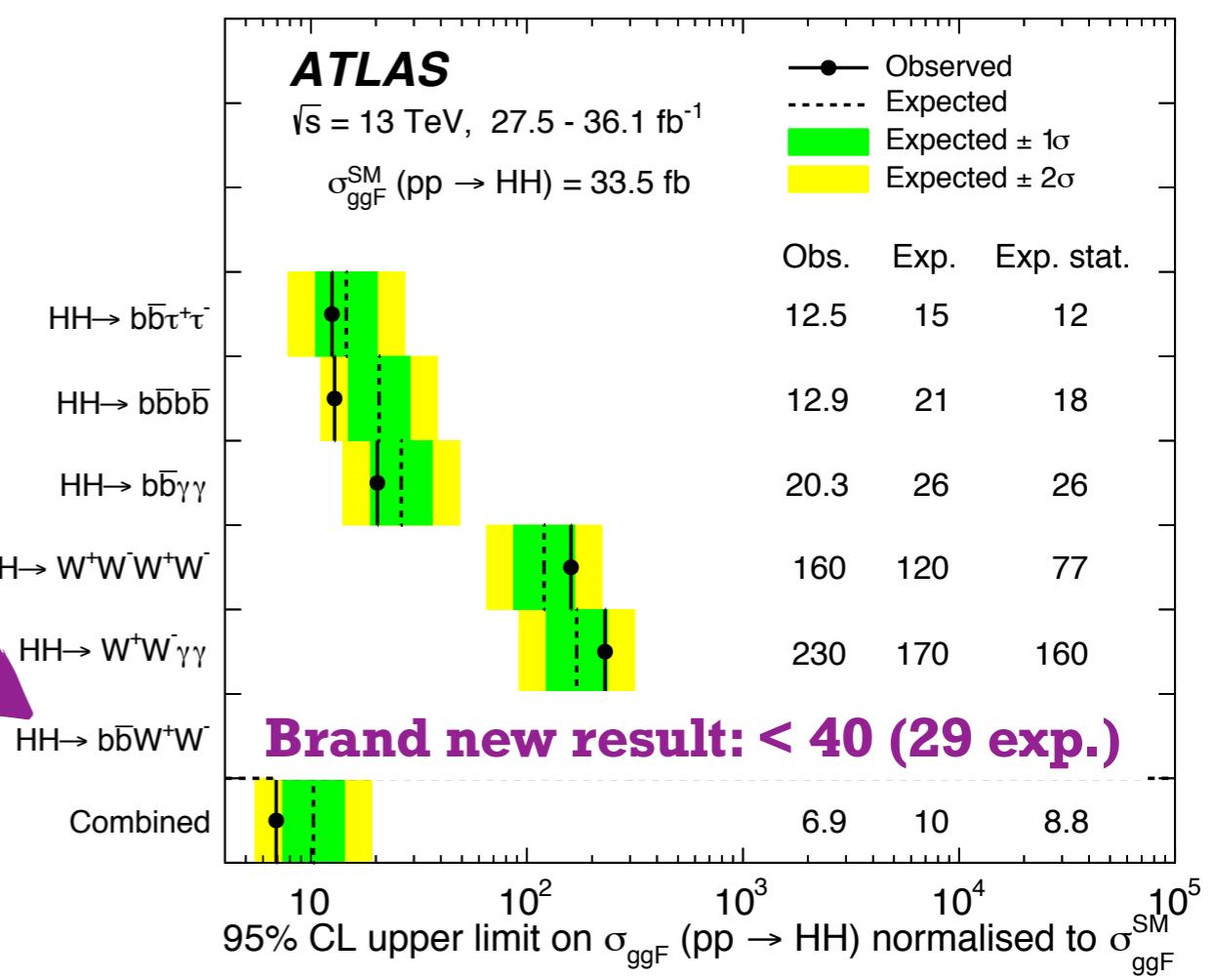
- Sensitivity of individual channels differs, but combined HH sensitivity similar between the two experiments.
- $\sim 10 * \sigma_{\text{SM}}(\text{HH})$

[arXiv:1906.02025, submitted to PLB](https://arxiv.org/abs/1906.02025)

[arXiv:1908.06765](https://arxiv.org/abs/1908.06765)



$-5.0 < \kappa_\lambda < 12.0 @ 95\% \text{ CL}$

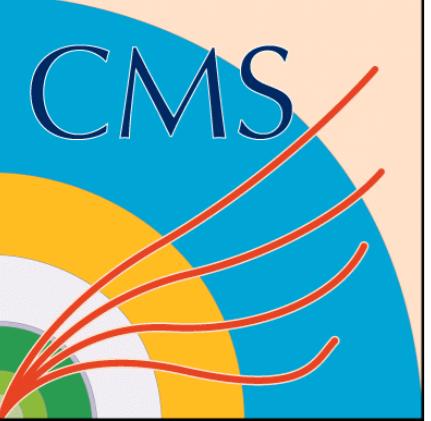


- Extrapolations from current Run-2 analyses on 13 TeV data to HL-LHC (3000 fb^{-1}).
- $\sim 4\sigma$ sensitivity (ATLAS + CMS combination) projected for end of HL-LHC using current analyses as baseline.
 - $\sim 50\%$ precision on κ_λ .

[arXiv:1902.00134](https://arxiv.org/abs/1902.00134)

	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \rightarrow b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \rightarrow b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \rightarrow b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \rightarrow b\bar{b}VV(l\nu\nu)$	-	0.59	-	0.56
$HH \rightarrow b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6
	Combined		Combined	
	4.5		4.0	

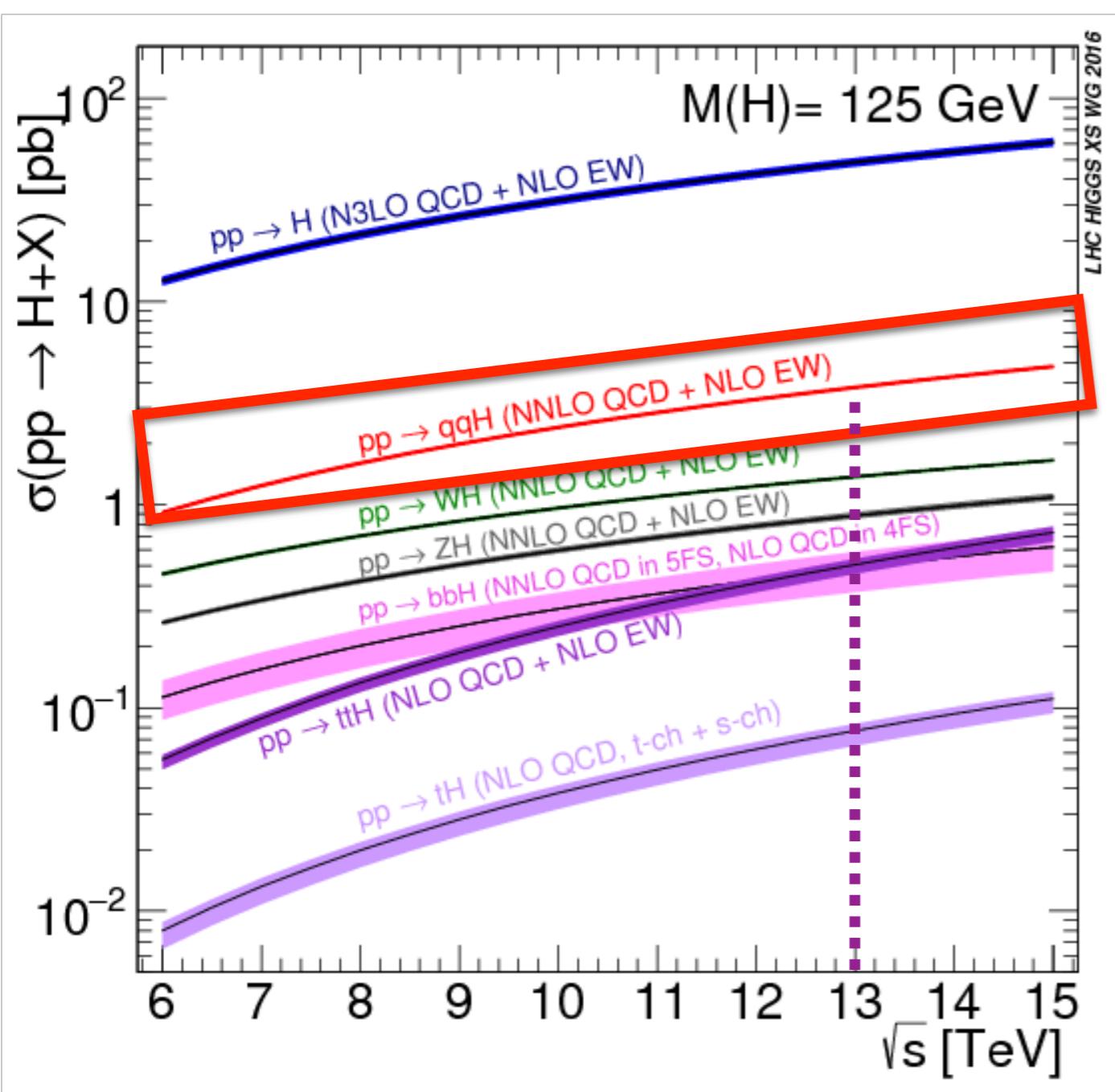
- Observation of VH production achieved with Run-2 data, driven by $H \rightarrow b\bar{b}$ channel.
- Beginning of era of EFT constraints from differential measurements of VH production observables.
- Sensitivity to $\sim 10 * \sigma_{\text{SM}}(HH)$ achieved using 1/4 of available 13 TeV dataset.
 - Only 1-2% of final HL-LHC dataset.



Thank you!

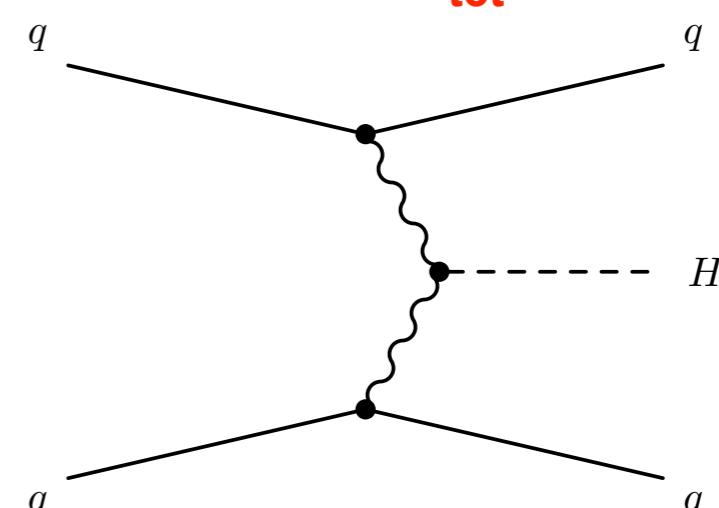


Additional Material

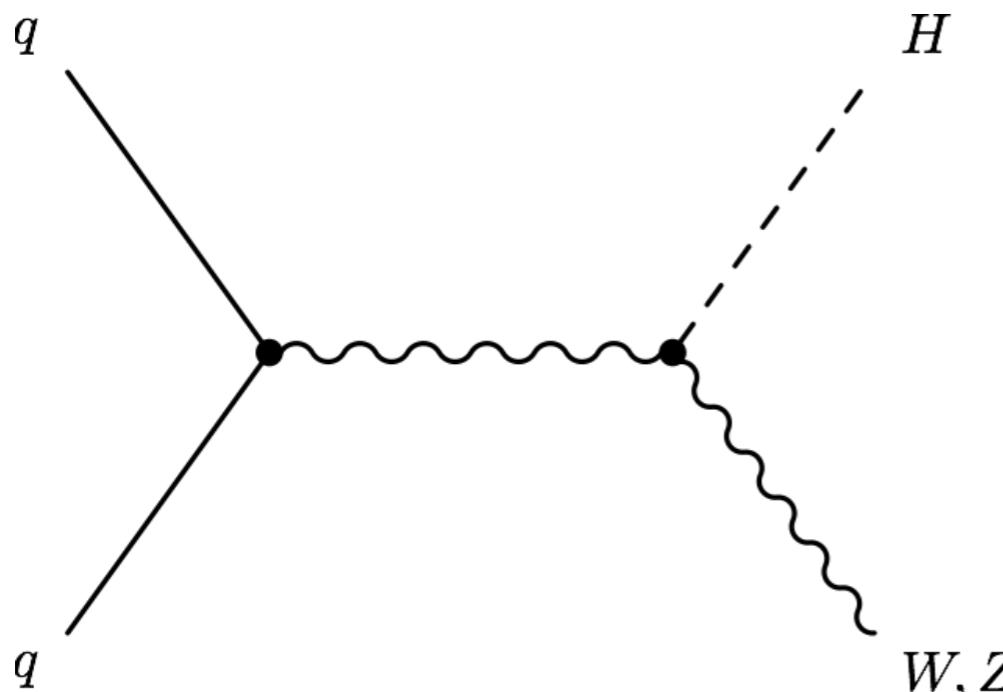


Vector boson fusion (qqH)

7% σ_{tot}



- Order of magnitude smaller σ than ggH but experimentally distinct signature.
- Two quark jets with large $\Delta\eta(qq)$ and large $m(qq)$.

**1-lepton: W \rightarrow lv:**

- Exactly one electron or muon + missing E_T .
- $p_T(\ell v) > 150$ GeV.

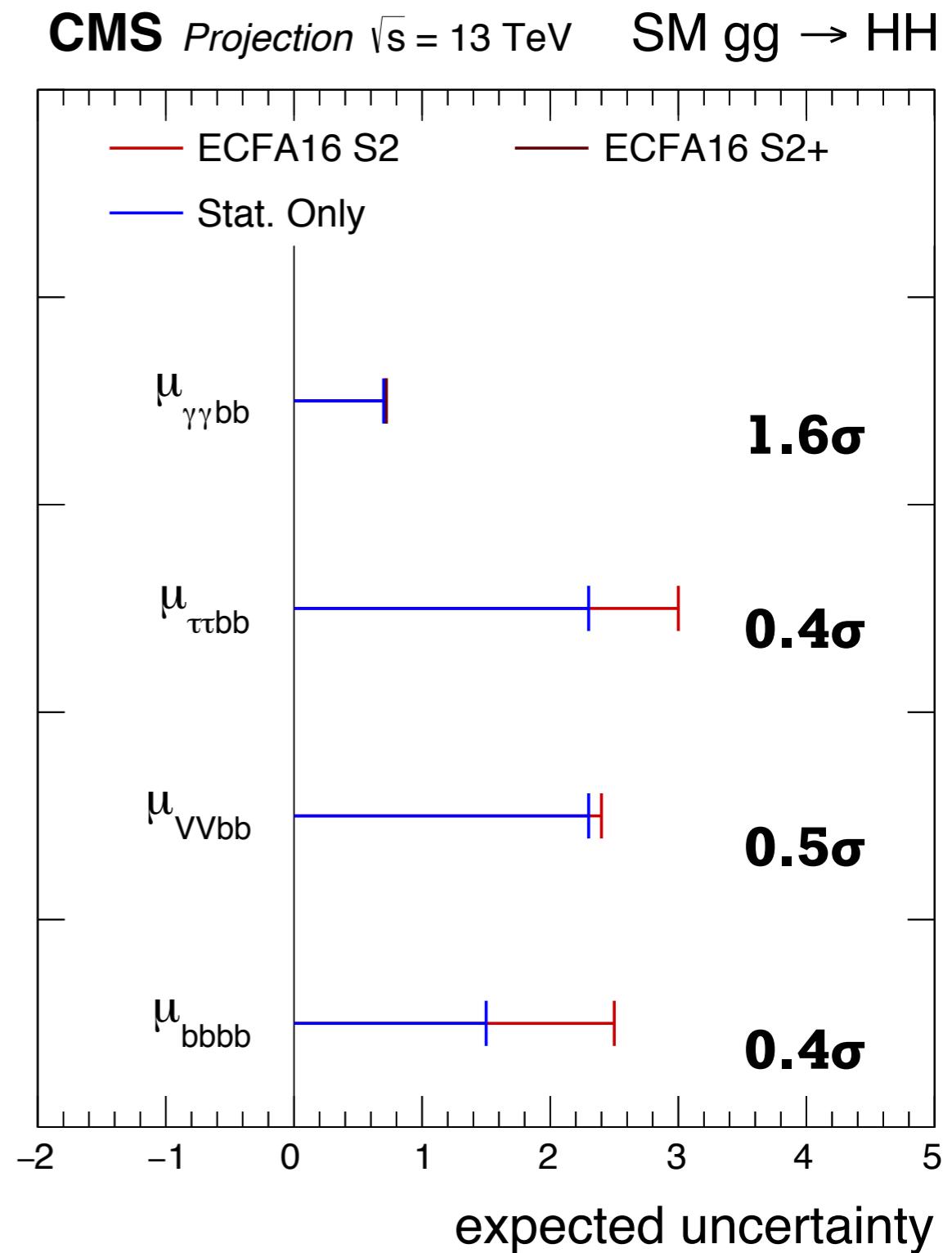
0-lepton: Z \rightarrow vv:

- Require large missing E_T (~ 150 GeV) back-to-back with respect to $H\rightarrow b\bar{b}$ candidate.

2-lepton: Z \rightarrow l+l-:

- Two opposite-sign electrons or muons.
- $|M_{ll} - M_{Z,PDG}| < 15$ GeV
- $p_T(ll)$ [50, 150] or > 150 GeV.

- Extrapolations from analyses on 2.3 fb^{-1} 13 TeV data collected in 2015 to HL-LHC (3000 fb^{-1}).
- Different scenarios:
 - No systematic uncertainties.
 - ECFA16 S2: reduced theory and experimental uncertainties.
 - ECFA16 S2+: including future detector performance.
- $\sim 2\sigma$ sensitivity projected for end of HL-LHC using 2015 analyses as baseline.



[CMS-PAS-FTR-16-002](#)