Searches for rare Higgs boson production processes with the CMS detector

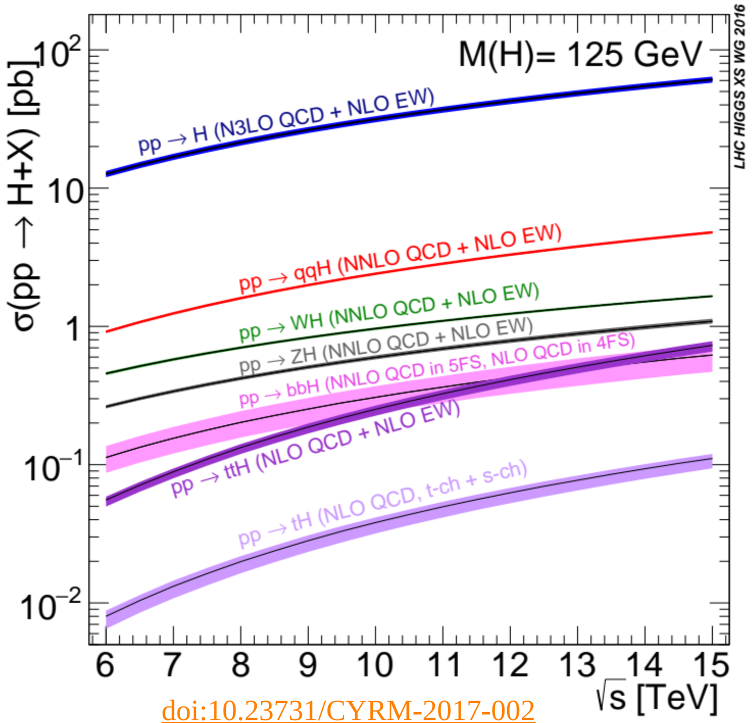
Andrea Cardini* on behalf of the CMS Collaboration

*) Deutsches Elektronen-Synchrotron DESY

Higgs production at the LHC

- The Higgs boson discovery is one of the biggest successes of the LHC

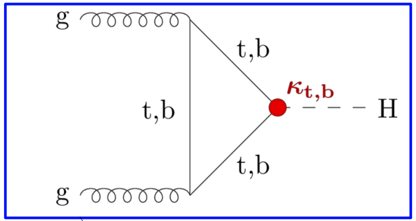
Nature 607, 60-68 (2022)



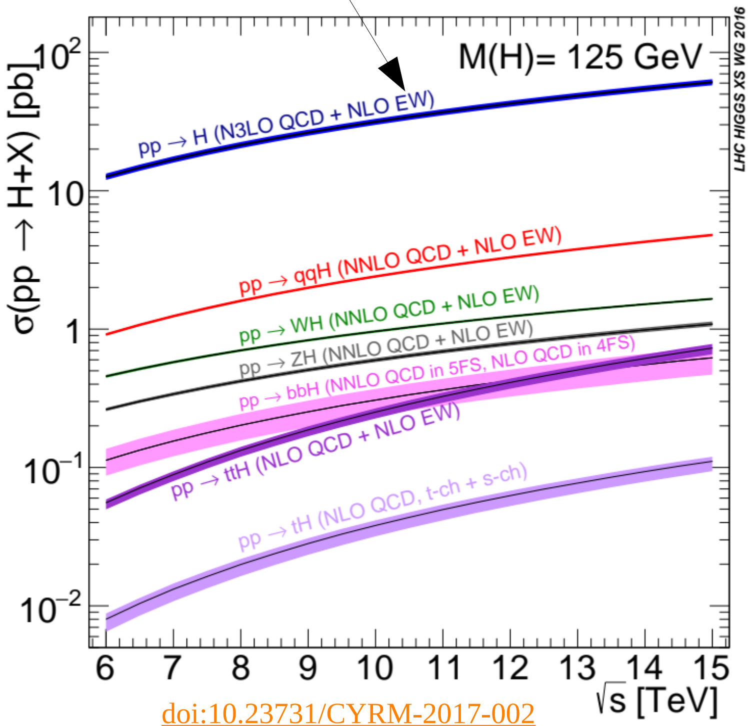
doi:10.23731/CYRM-2017-002

Higgs production at the LHC

- The Higgs boson discovery is one of the biggest successes of the LHC
- Discovered in 2012 via its production via **gluon-gluon fusion**

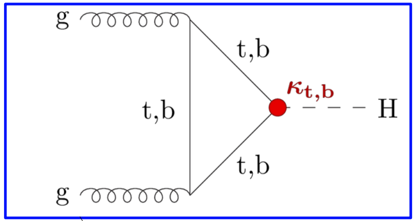


Nature 607, 60-68 (2022)

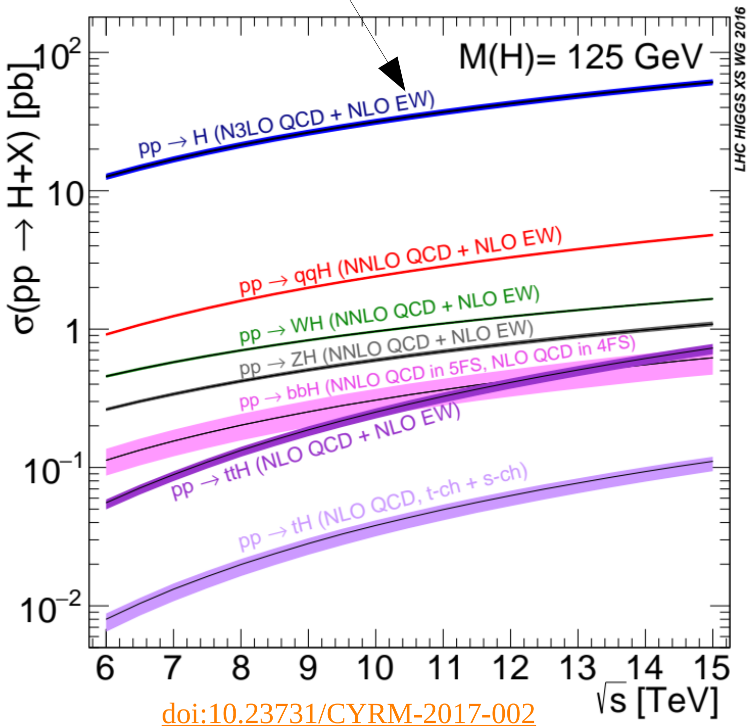


doi:10.23731/CYRM-2017-002

- The Higgs boson discovery is one of the biggest successes of the LHC
- Discovered in 2012 via its production via **gluon-gluon fusion**
- The LHC Run 2 allowed the investigation of the subleading production mechanisms:



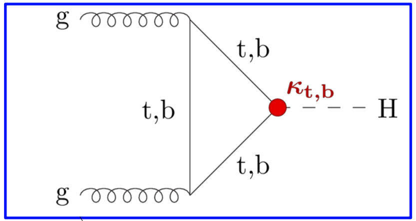
Nature 607, 60-68 (2022)



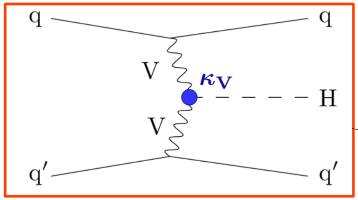
doi:10.23731/CYRM-2017-002

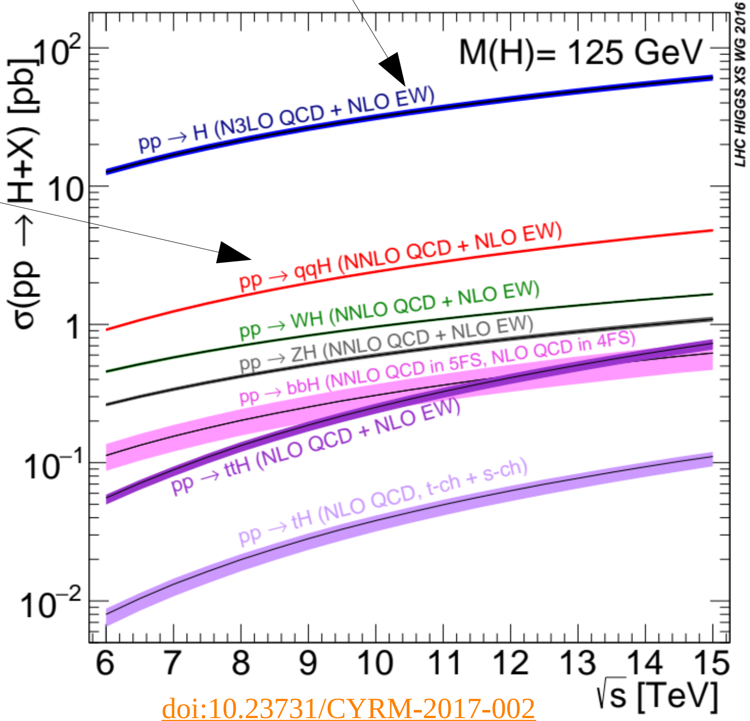
Higgs production at the LHC

- The Higgs boson discovery is one of the biggest successes of the LHC
- Discovered in 2012 via its production via **gluon-gluon fusion**
- The LHC Run 2 allowed the investigation of the subleading production mechanisms:
  - **vector boson fusion**



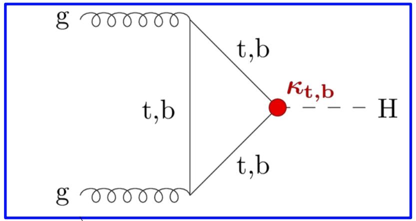
Nature 607, 60-68 (2022)



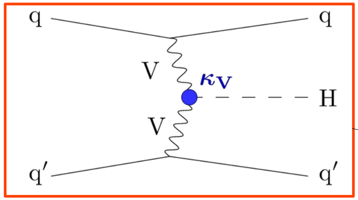


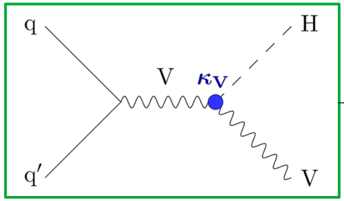
doi:10.23731/CYRM-2017-002

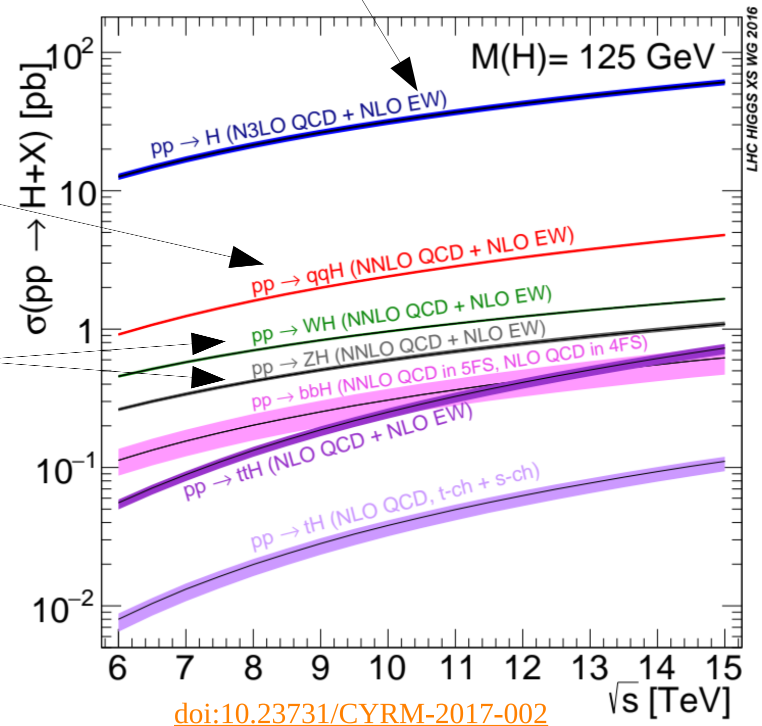
- The Higgs boson discovery is one of the biggest successes of the LHC
- Discovered in 2012 via its production via **gluon-gluon fusion**
- The LHC Run 2 allowed the investigation of the subleading production mechanisms:
  - **vector boson fusion**
  - **Higgs-strahlung** (in association with **W** or **Z** bosons)



Nature 607, 60-68 (2022)



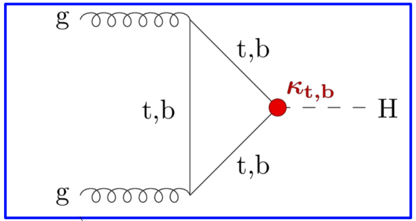




doi:10.23731/CYRM-2017-002

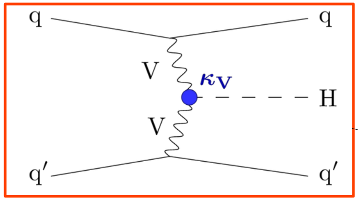
Higgs production at the LHC

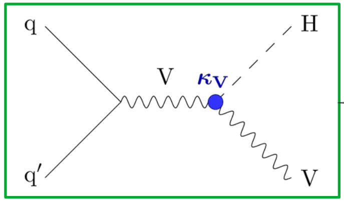
- The Higgs boson discovery is one of the biggest successes of the LHC

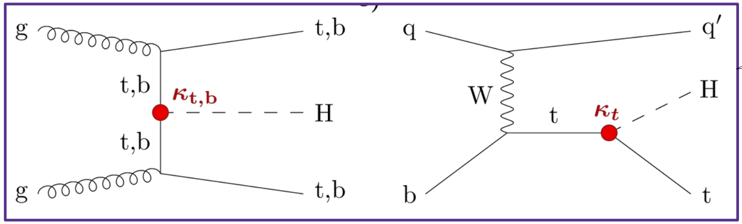


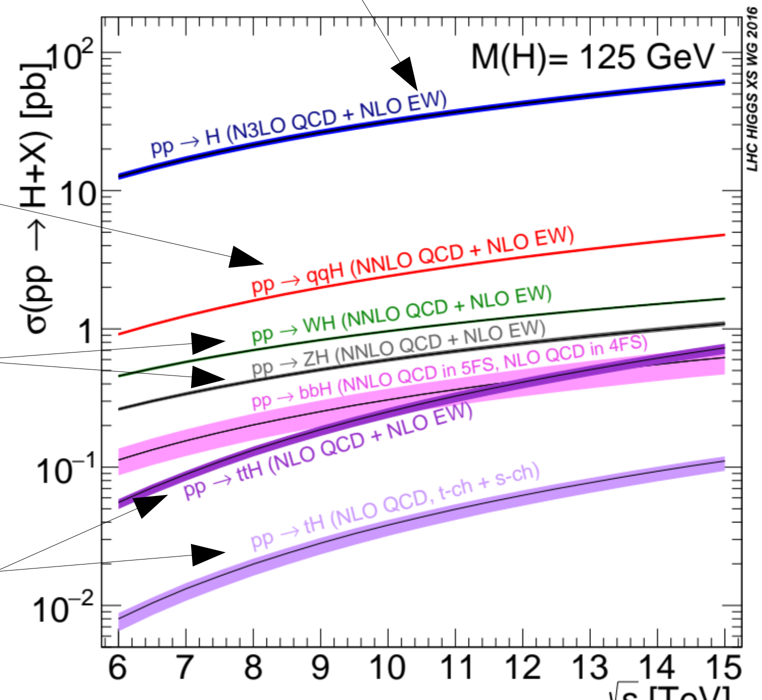
Nature 607, 60-68 (2022)

- Discovered in 2012 via its production via **gluon-gluon fusion**
- The LHC Run 2 allowed the investigation of the subleading production mechanisms:
  - **vector boson fusion**
  - **Higgs-strahlung** (in association with **W** or **Z** bosons)
  - **top-associated production**





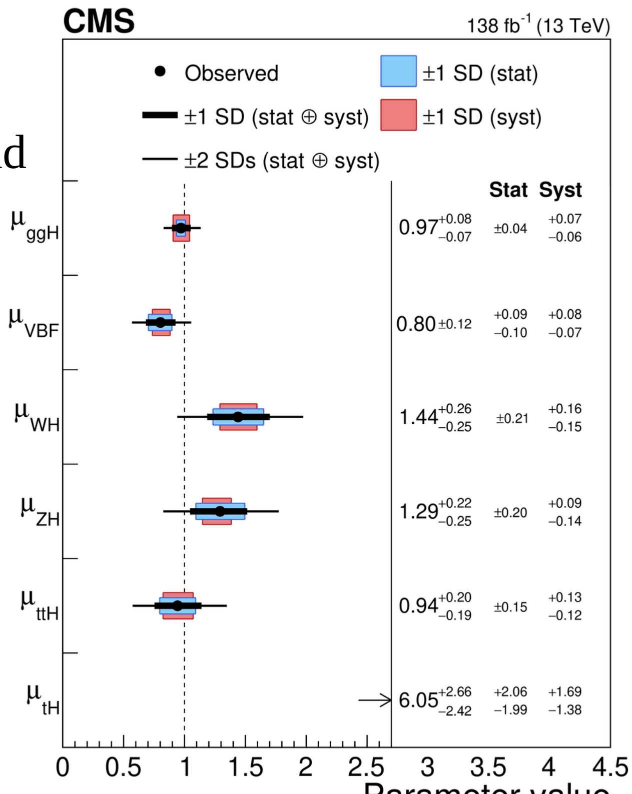




doi:10.23731/CYRM-2017-002

- The Standard Model predicts several Higgs production mechanisms not yet observed at the LHC
- These rare (cross-section < few pb) production mechanisms are excellent tests for the SM predictions
- Tight upper limits on these processes complement Higgs decays in advancing our understanding of the Higgs couplings
- Key feature: other Higgs production mechanisms can act as background
- CMS has investigated several rare production mechanisms:
  - > HH production → talk by Cristina Ana Mantilla Suarez
  - > top-associated production (arXiv:2407.10896 Sub. to JHEP) → talk by Jan Lukas Spaeh
  - > bottom-associated production → this talk
  - > charm-associated production → this talk + poster by Maarten De Coen
  - > WWH production via vector boson scattering → this talk + talk by Jan Lukas Spaeh

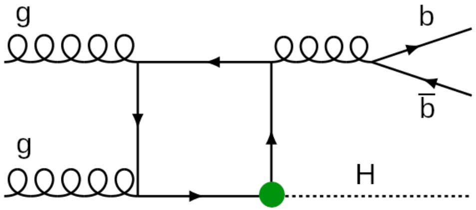
New!

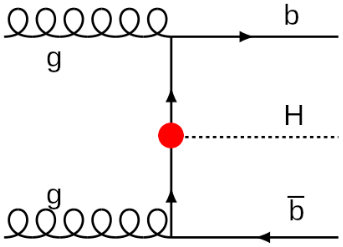


Nature 607, 60-68 (2022)

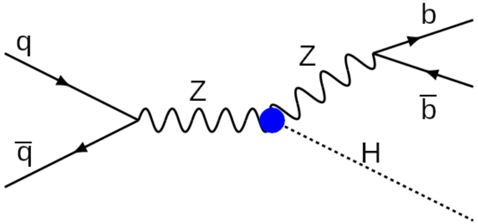
The bottom-associated production – bbH

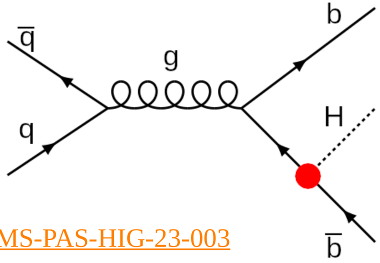
- The bottom-associated production of the Higgs boson (bbH) has cross-section $\sigma(y_b,y_t)$=1.489 pb similar to the top-associated one **but**
  - has higher QCD background and interferes with other Higgs production mechanisms
  - Only the subleading contributions are sensitive to the direct Higgs-bottom Yukawa coupling (**y_b**) at tree level
  - The highest contributions come from the top quark loop (**y_t**)
  - and from the coupling to Vector Bosons (ZH) → treated as background
- In this analysis we constrain the cross-section for the bbH component including Yukawa coupling: $\sigma(y_b,y_t)$





term	σ(pb)
y_t^2	1.040 (+0.468 -0.489)
y_b^2	0.482 (+0.048 -0.070)
y_by_t	– 0.033 (+0.007 -0.008)





doi:10.23731/CYRM-2017-002
JHEP 11 (2020) 036
JHEP 07 (2019) 054

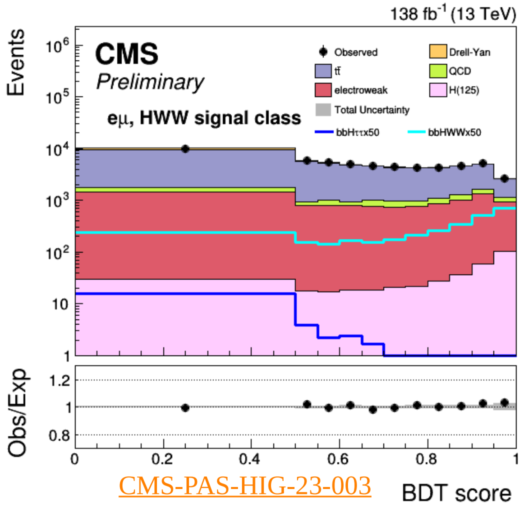
CMS-PAS-HIG-23-003

bbH: Target channels and statistical inference

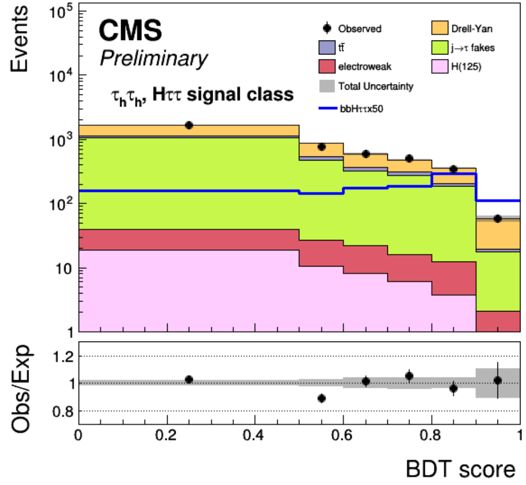
- Target final states with leptons (and τh):
  - > $H \rightarrow \tau\tau \rightarrow \tau_e\tau_h,\ \tau_\mu\tau_h,\ \tau_h\tau_h,\ \tau_e\tau_\mu$
  - > $H \rightarrow WW \rightarrow e\mu$
- Events sorted in background and signal categories via BDT categorization

Channel	$e\mu$	$e\tau_h$	$\mu\tau_h$	$\tau_h\tau_h$
BDT Categories	DY, TT, bbH(→WW), bbH(→ $\tau\tau$)	DY, TT, bbH(→ $\tau\tau$)	DY, TT, bbH(→ $\tau\tau$)	DY+Higgs, TT, j→τ_h fakes, bbH(→ $\tau\tau$)

- Dominant backgrounds: $t\bar{t}$ and DY → require dedicated classes
- For $\tau_h\tau_h$ channel the background composition is more balanced, $j \rightarrow \tau_h$ misid. require a dedicated category
- For eμ channel the driving sensitivity comes from $H \rightarrow WW$

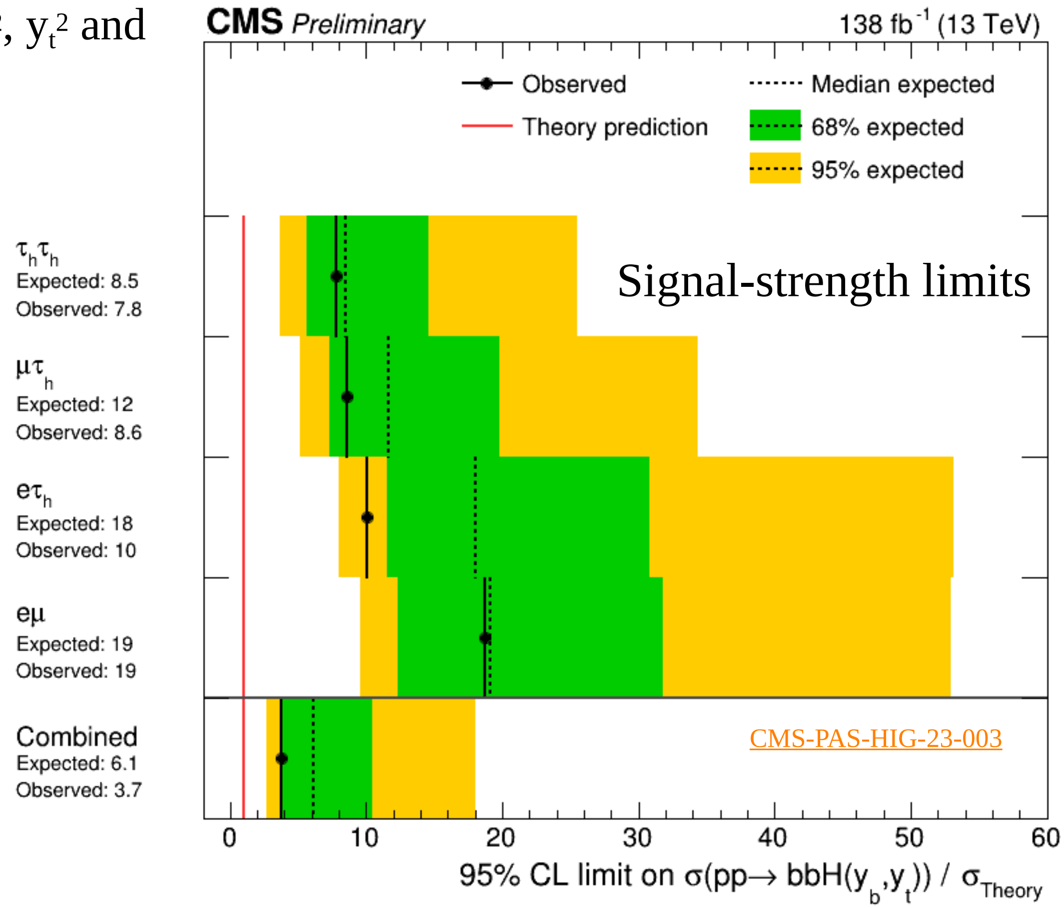


CMS-PAS-HIG-23-003



bbH: Limits and interpretation

- Inclusive measurement*: the different contributions to the signal are scaled by varying proportionally the y_b^2, y_t^2 and $y_b y_t$ terms
- **Observed upper limits at few times the SM expectation**



*bbH(y_b,y_t): terms depending on Yukawa couplings, ZH is treated as background

- Inclusive measurement*: the different contributions to the signal are scaled by varying proportionally the y_b^2, y_t^2 and $y_b y_t$ terms

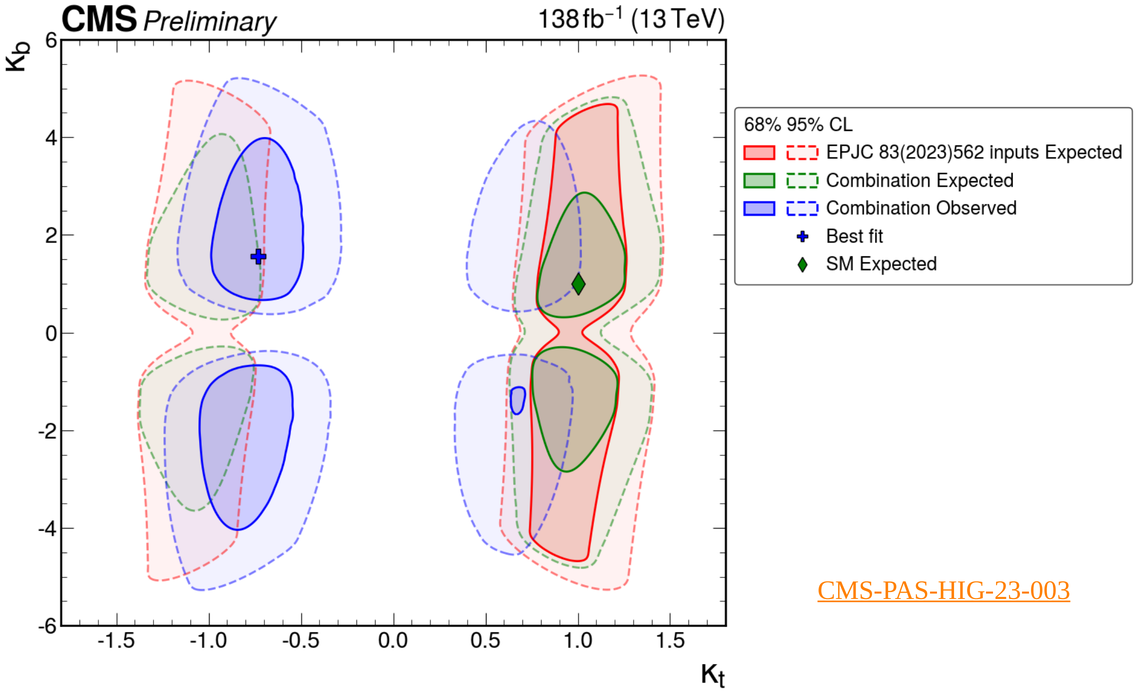
- **Observed upper limits at few times the SM expectation**

- Scan performed on coupling modifiers κ_t and κ_b, with κ_τ freely floating

- Combined with the results from EPJC 83(2023)562 (STXS $H \to \tau\tau$ cross-section measurement – performed with veto on b-jets) to better constrain κ_t

- The best fit point is $(\kappa_t,\kappa_b) = (-0.73,1.58)$

- Limits on the couplings are compatible with the SM at 95% CL



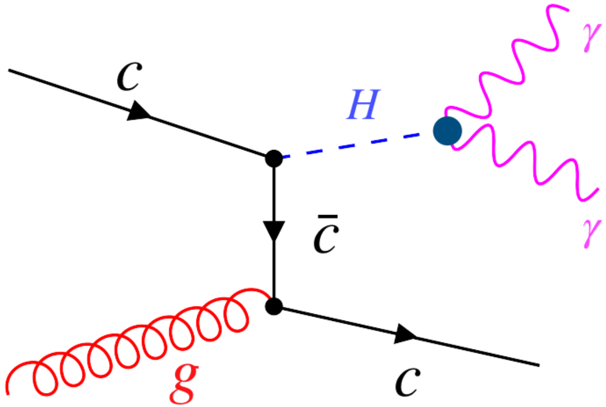
CMS-PAS-HIG-23-003

*bbH(y_b,y_t): terms depending on Yukawa couplings, ZH is treated as background

The charm-associated production – cH

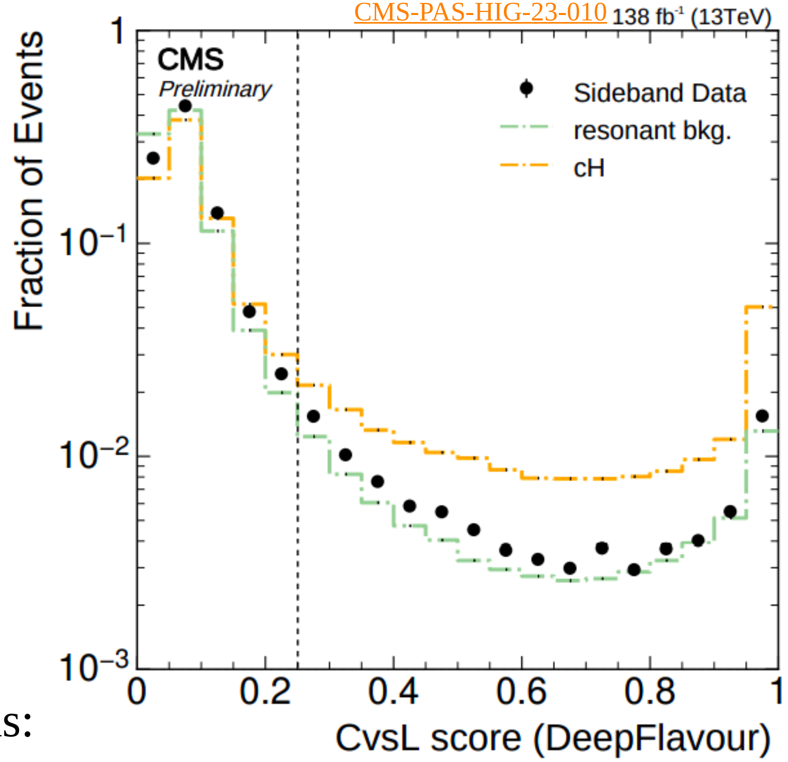
New!

- Going to even rarer production mechanism is the charm-associated production
  - 2nd generation fermion → weaker coupling strength
  - $\sigma(cH)$~90.13±0.47 fb × BR($H\rightarrow\gamma\gamma$)~0.2% → $\sigma\times$BR ~ 0.2 fb
  - Key difficulty: identifying c-jets from **u/d/s/g-** and b-jets
  - Target channel: cH($\rightarrow\gamma\gamma$) to limit number of c-jets to 1 and take advantage of clean γγ final state



credits to T. Bevilacqua for the diagram

CMS-PAS-HIG-23-010

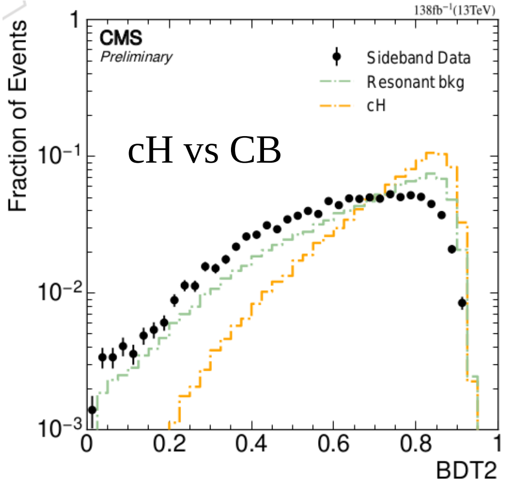


- Higgs backgrounds:
  - the **gluon-gluon fusion** + gluon-jet faking a c-jet
  - bH production with b→c-jet fake

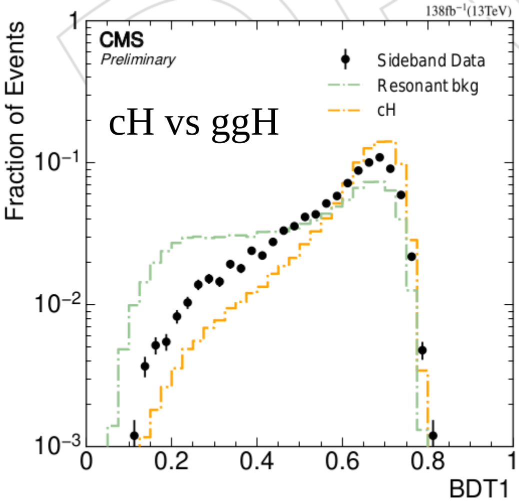
cH: Event categorization and statistical inference

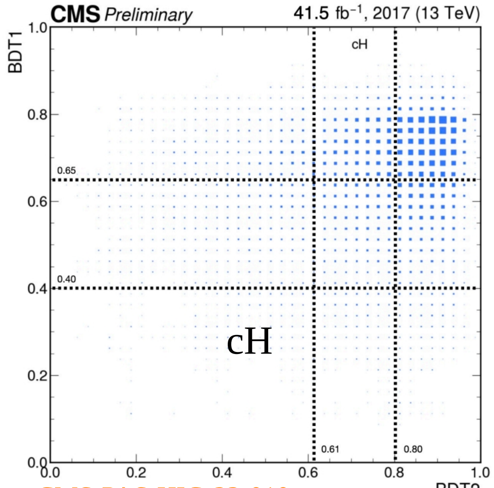
- Dedicated BDT models trained to separate cH signal from:
  - Main Higgs background: ggH
  - Continuous Background (CB): γγ / γ+jet production

New!



- Performance on data studied by looking at sideband region: invariant mass outside the Higgs mass window: $m_{\gamma\gamma} \in (115,135)$ GeV
- Define 9 categories for the measurement based on the BDT scores
- Limits on signal strength obtained from parametric fit on data using the $m_{\gamma\gamma}$ distribution in each analysis category
- Leading systematics: flavor scheme and QCD scale uncertainties for cH production, and theoretical unc. for ggH+cc production





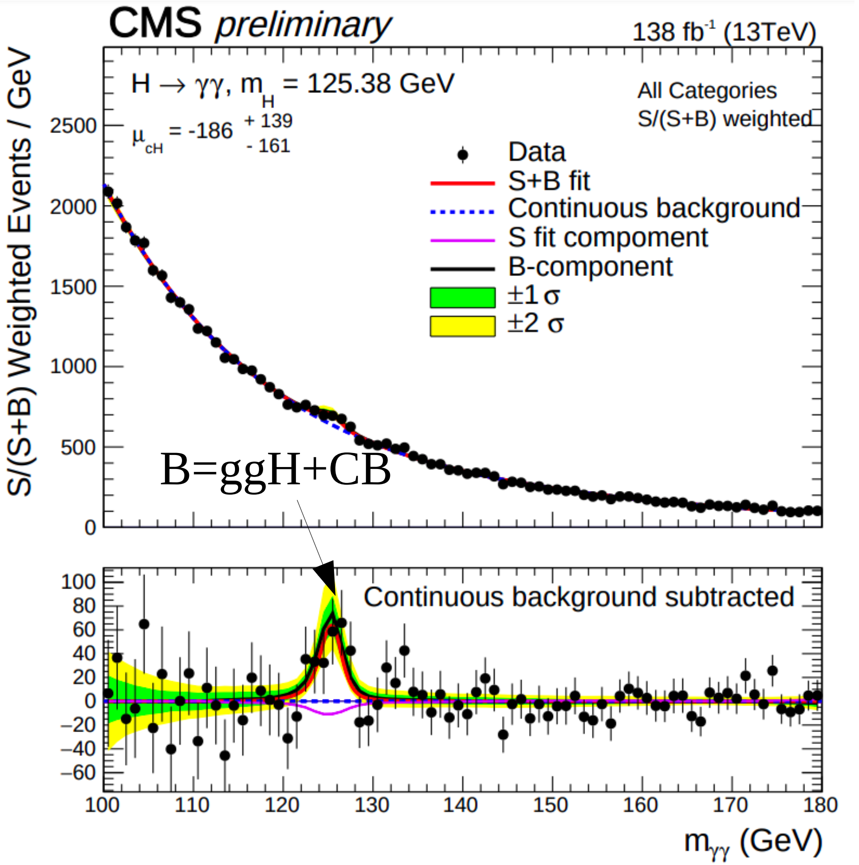
CMS-PAS-HIG-23-010

cH: Limits and interpretation

- No signal observed → place upper limits on the signal strength
- Upward fluctuation of the background around the Higgs mass
  - > Set upper limits on the cH cross-section
  - > Found an observed (expected) upper limit at 95% CL on the signal strength of
    - $\mu_{cH} < 243$ (355)
- These limits can be interpreted as observed (expected) upper limits at 95%CL on the Higgs Yukawa coupling to charm quarks:
  - > $|\kappa_c| < 38.1$ ($|\kappa_c| < 72.5$)
  - > Limits are derived following the "flat direction" approach (Phys. Rev. D 100 (2019), 073013) keeping signal strengths for other Higgs production mechanisms to 1 and ignoring κ_c contribution to ggH

New!

CMS-PAS-HIG-23-010

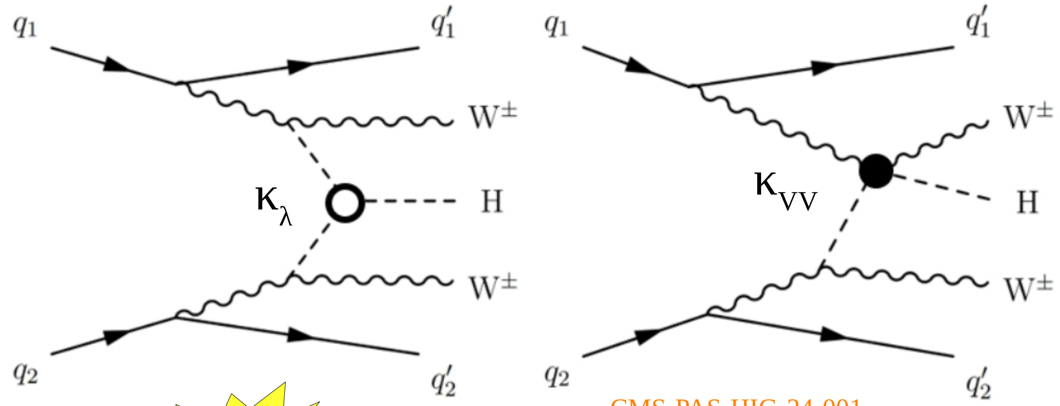


H+ same-sign WW production via VBS

- The Vector Boson Scattering (VBS) cross-section measurement was historically used as a hint towards the existence of the Higgs boson now CMS wants to use it as a probe for the Higgs self-coupling (κ_λ) and the VVHH coupling (κ_{VV})

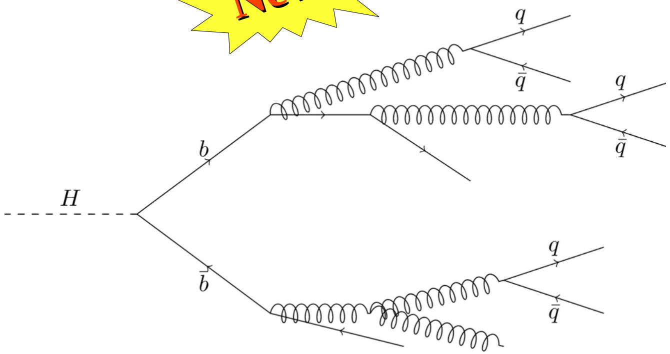
- The production of two same-sign W bosons accompanying the Higgs boson appears in the detector as:
  - pair of electrons/muons/taus with same electric charge
  - two forward jets with high $\Delta\eta_{jj}$
  - Higgs decay to a $b\bar{b}$ pair

- The complex final states helps separating this process from the main backgrounds:
  - $t\bar{t}$ and multi-boson production



CMS-PAS-HIG-24-001

New!

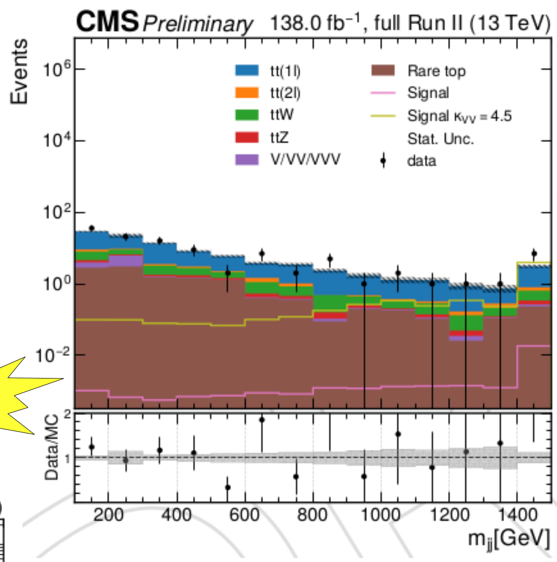


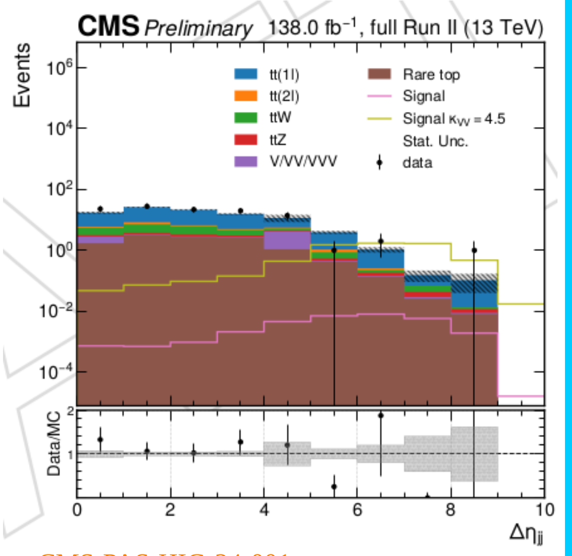
Target topology with merged b-jets

qq → HW±W±: Event selection and categorization

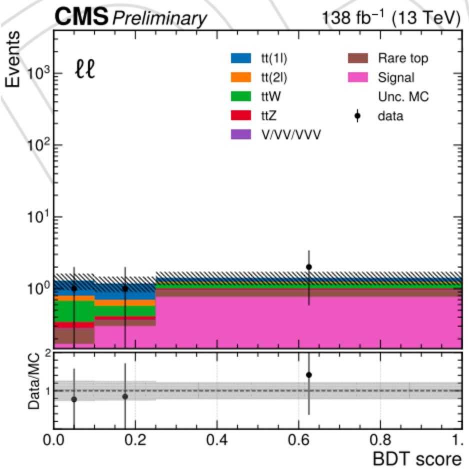
- Events are categorized based on the number of hadronically decaying tau leptons in the event (0 or 1)
- The VBS topology is targeted by requiring high di-jet invariant mass and pseudorapidity separation
  - m_{jj}> 100 GeV and $\Delta\eta_{jj}$>3

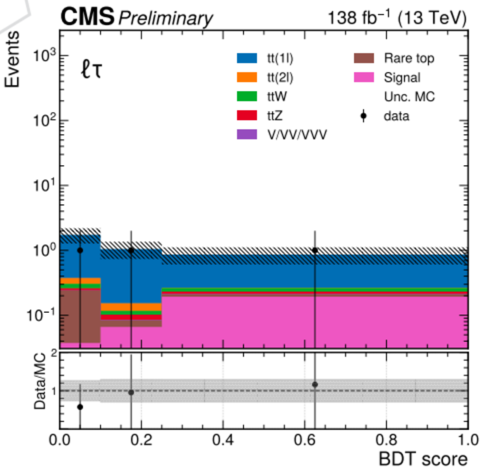
New!





CMS-PAS-HIG-24-001

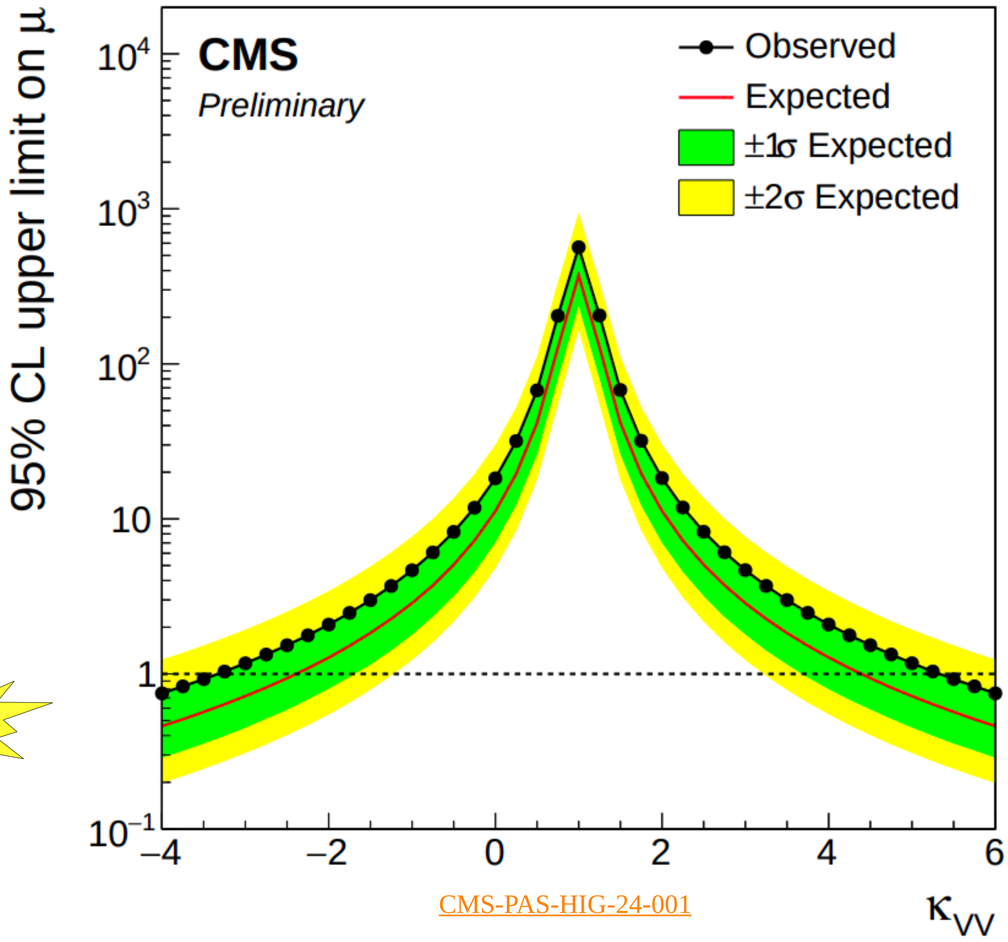




- Backgrounds are constrained in a control region defined by inverting the requirement on the b-tagging (a loose requirement is still in place)
- BDT models are trained to separate the signal from all backgrounds (binary classification)

- A binned likelihood fit simultaneously in all categories is used to measure the signal strength for a defined value of κ_{WW}
- Performing fits for different values of κ_{WW} allows to set observed (expected) limits on the coupling at 95% CL
  - $\kappa_{WW} \in$ [-3.33, 5.33] ([-2.39, 4.39])

New!

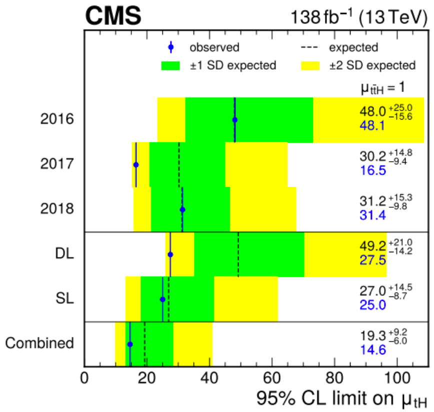


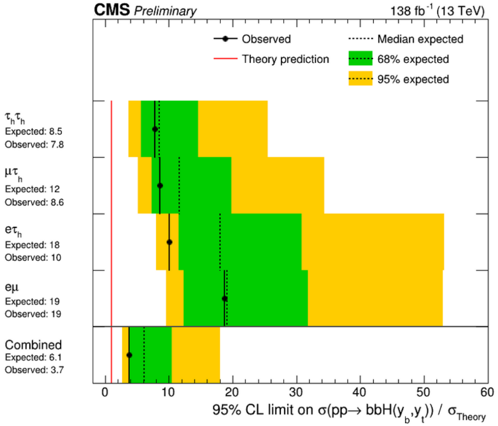
CMS-PAS-HIG-24-001

Conclusions and prospects

- CMS set upper limits on several rare Higgs production mechanisms using the full Run 2 statistics

	Limits at 95% CL	
parameter	Observed	Expected
μ_{tH}	14.6	19.3
μ_{bbH}	3.7	6.1
μ_{cH}	243	355



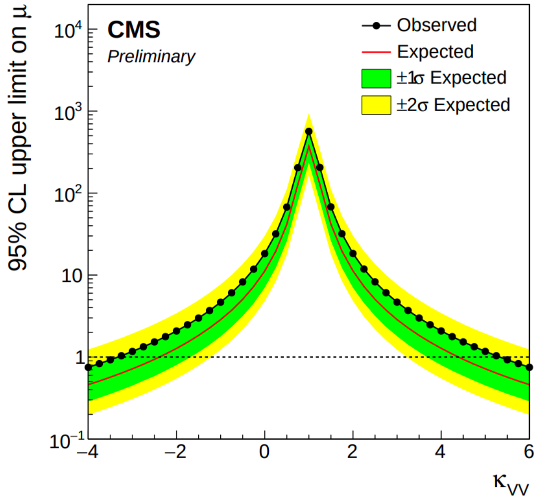


- All searches allowed to add more stringent limits on the Higgs couplings to fermions or vector bosons

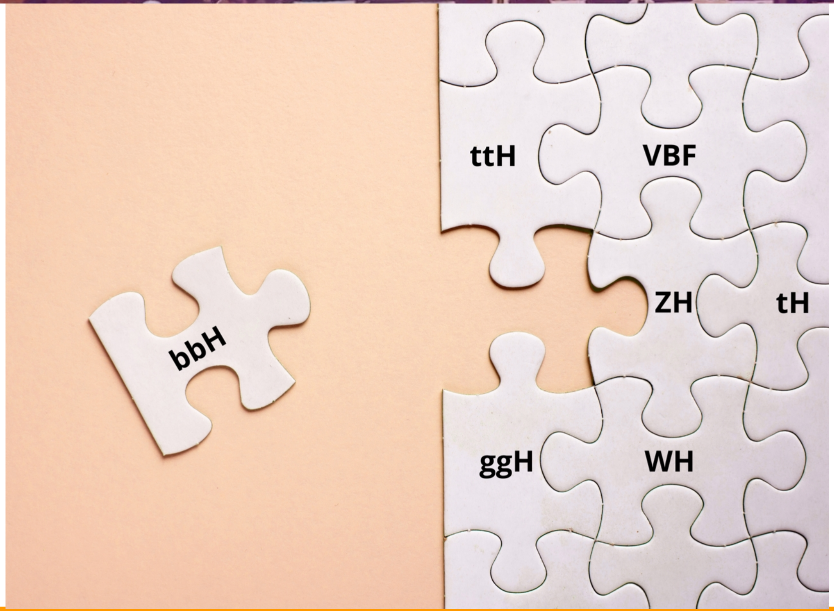
- We look forward to more amazing results with the addition of Run 3 data

To be continued

in **Run 3**



Let's continue adding pieces to the Higgs production puzzle.



Andrea Cardini* on behalf of the CMS Collaboration

*) Deutsches Elektronen-Synchrotron DESY