Summary of VH production in CMS

You-Ying Li

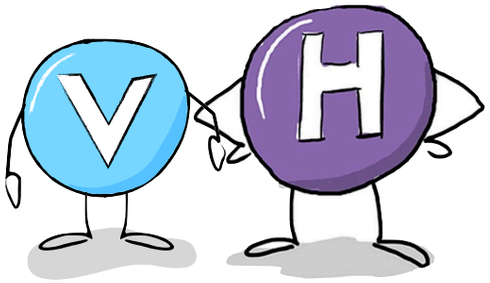
on behalf of the CMS collaborations

Windows on the Universe - 30th Anniversary Rencontres du Vietnam

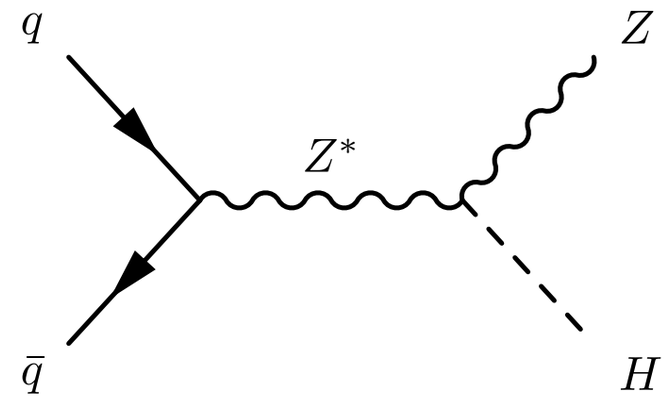
Introduction

- The associated VH production is the third majority of the SM Higgs production in proton-proton collisions.
- The production provides a direct measurement of HWW and HZZ coupling for understanding the electroweak symmetry breaking.
- The measurement also gives the potential BSM physics such as excess from heavy vector bosons or unusual VH kinematics due to anomalous HVV couplings.
- This talk summarizes the measurements of the VH production at bb ,γγ, WW, ZZ, ττ Higgs decay channels under simplified template cross section framework.
- The anomalous HVV coupling inside the VH production is discussed.

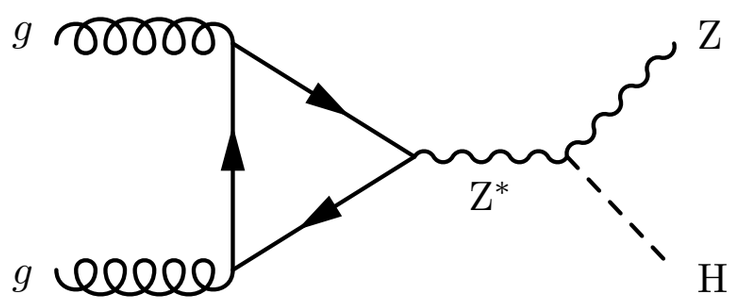
VH production



DY-like process



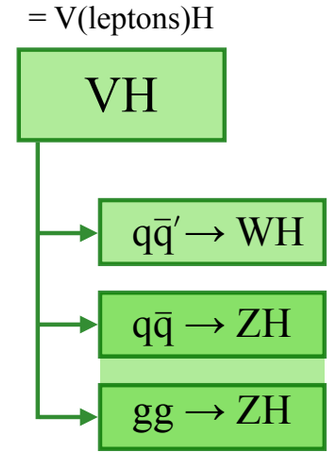
Loop-induced process



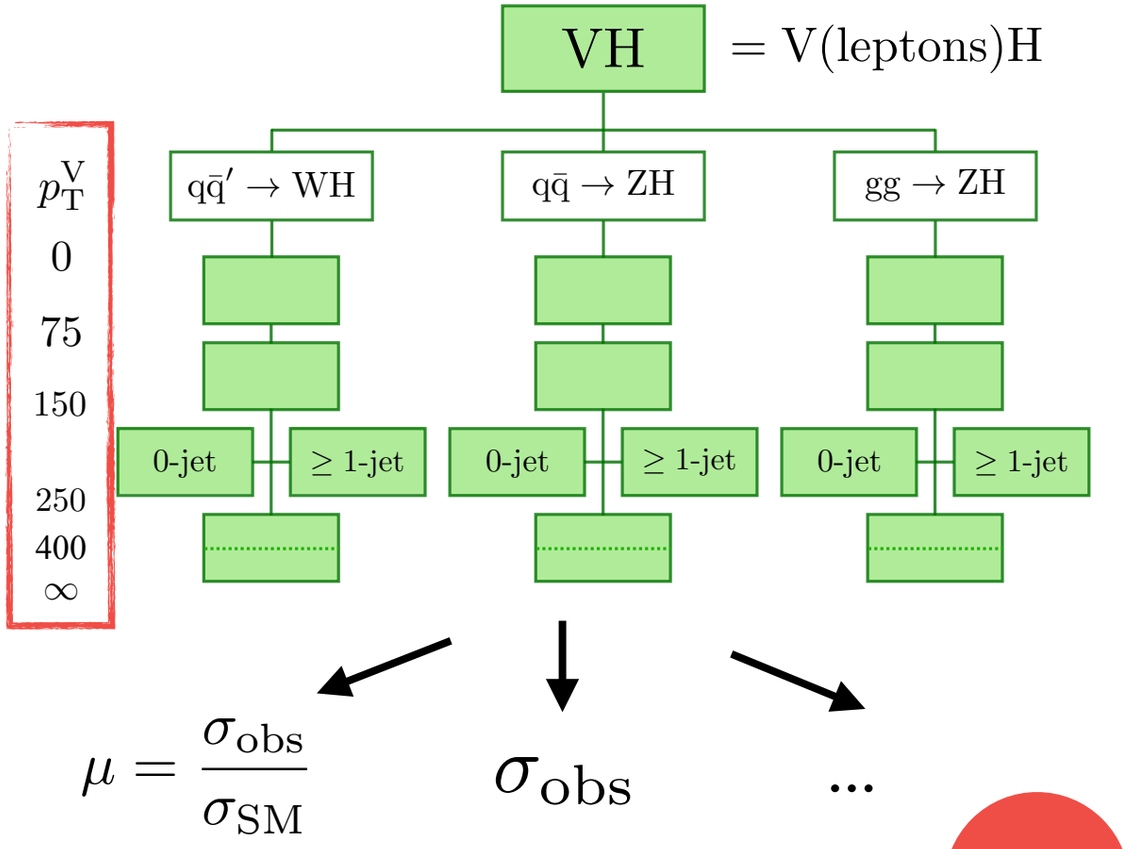
Simplified Template Cross Section (STXS)

- The VH production with the V decaying leptonically, which is VH sensitive mode, is split into exclusive regions of phase space (STXS bins) by particle level.
  - Stage 0 : production mode
  - Stage 1.2 : production mode + $p_T V$ split
- The hadronic VH production is put to qqH STXS bins.
- The granularity of the STXS bins is driven by analysis sensitivity.
- Events are categorized to maximize the sensitivity of the targeted STXS bins.
- BSM effect, i.e. high $p_T V$ region, can be decoupled.
- Higgs decay channel independence framework so that the combination and result reinterpretation become easier.

STXS Stage 0 bins



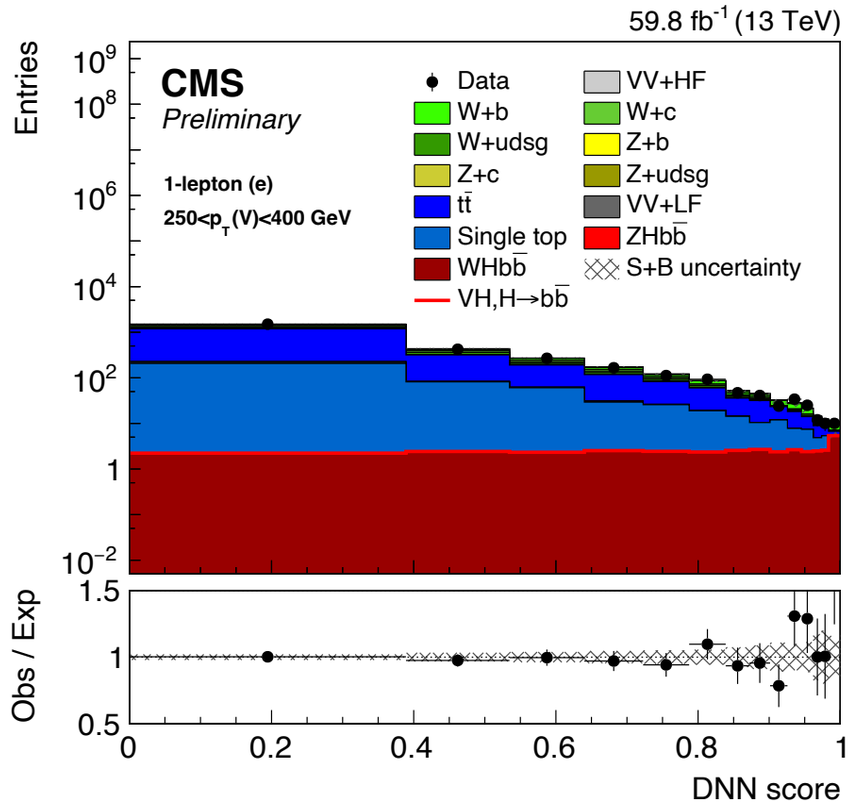
STXS Stage 1.2 bins

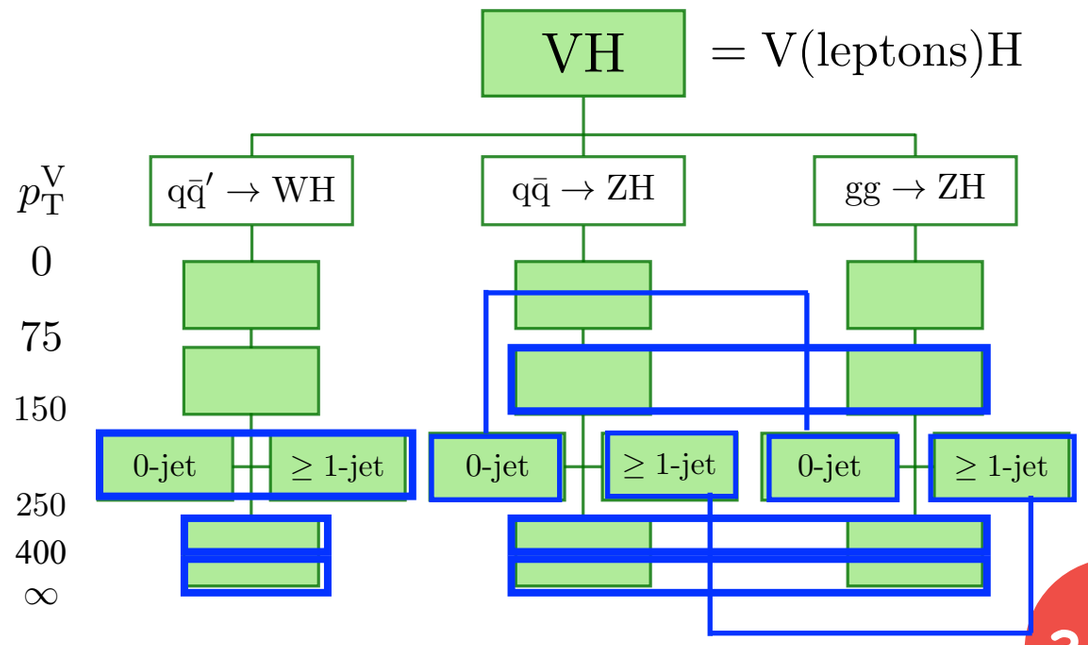


VH @ H→bb

CMS-PAS-HIG-20-001

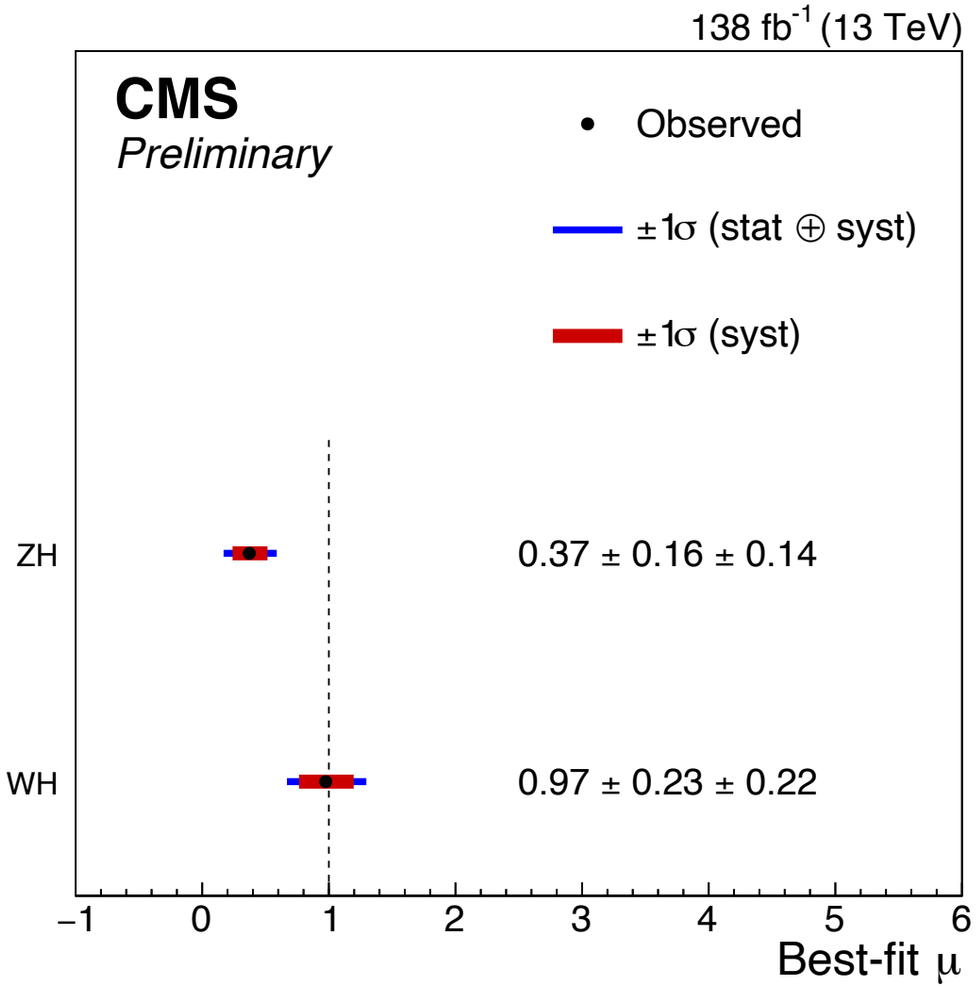
- Three decay channels for the weak boson are considered.
  - → 0-lepton (Z→νν), 1-lepton (W→eν/μν), 2-lepton (Z→ee/μμ)
- Simultaneous analysis for two H→bb topologies :
  - Resolved : Two resolved b-jets
  - Boosted : A single wide-radius jet
    - → if $p_T V > 250$ GeV
- Signal is extracted by the dedicated machine learning output scores.
- STXS bins can achieve up to $p_T V > 400$ GeV which is BSM sensitive.

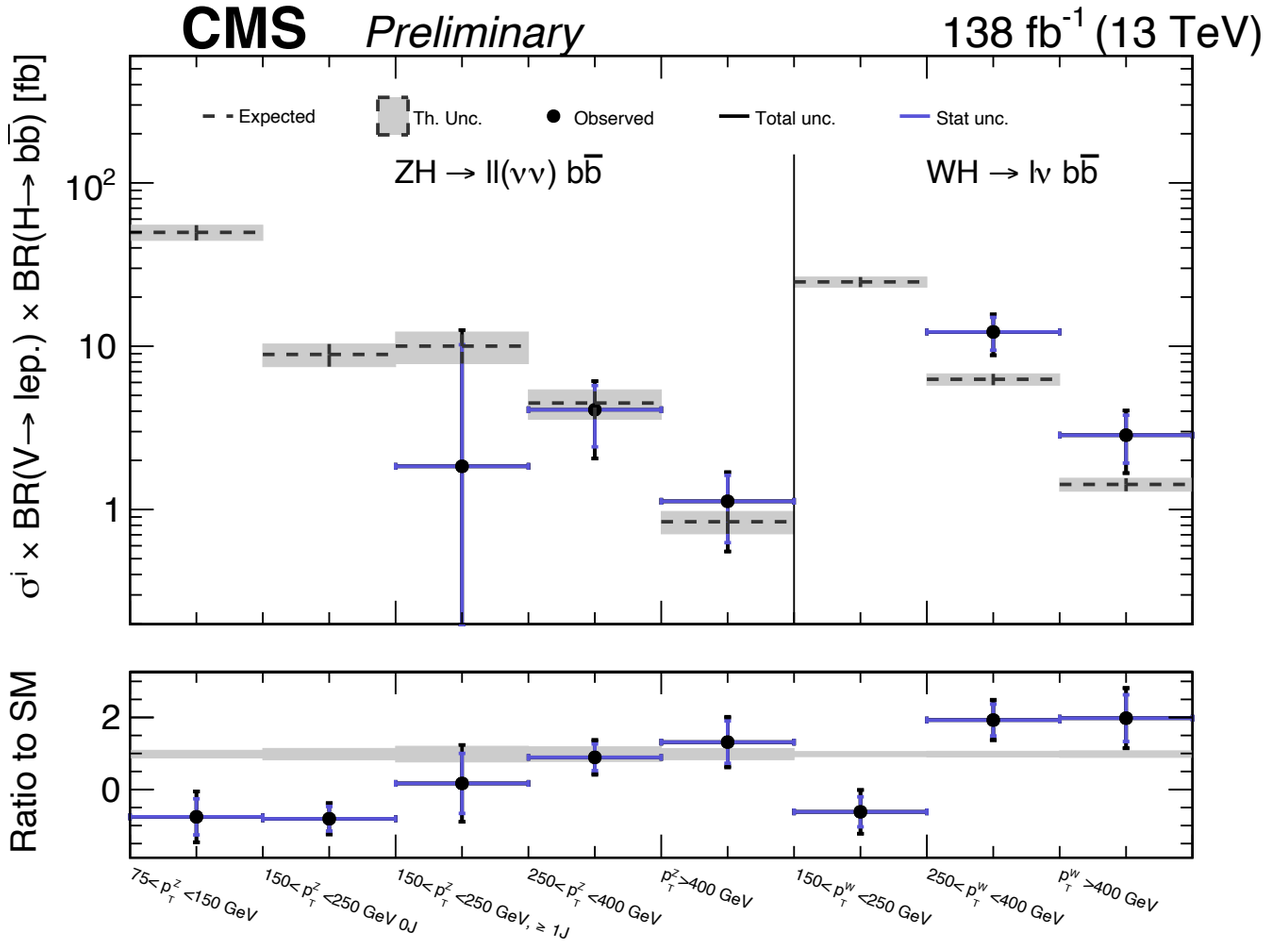




VH @ H→bb

- Resolved and boosted topologies are combined together for $p_T V > 250$ GeV bins.
- The preliminary results of the signal strength reveal that the ZH process less than expected.
- No signal is measured in lower $p_T V$ regions ($p_T V < 250$ GeV).





No significant BSM effect is observed in high pt region.

VH @ H→WW

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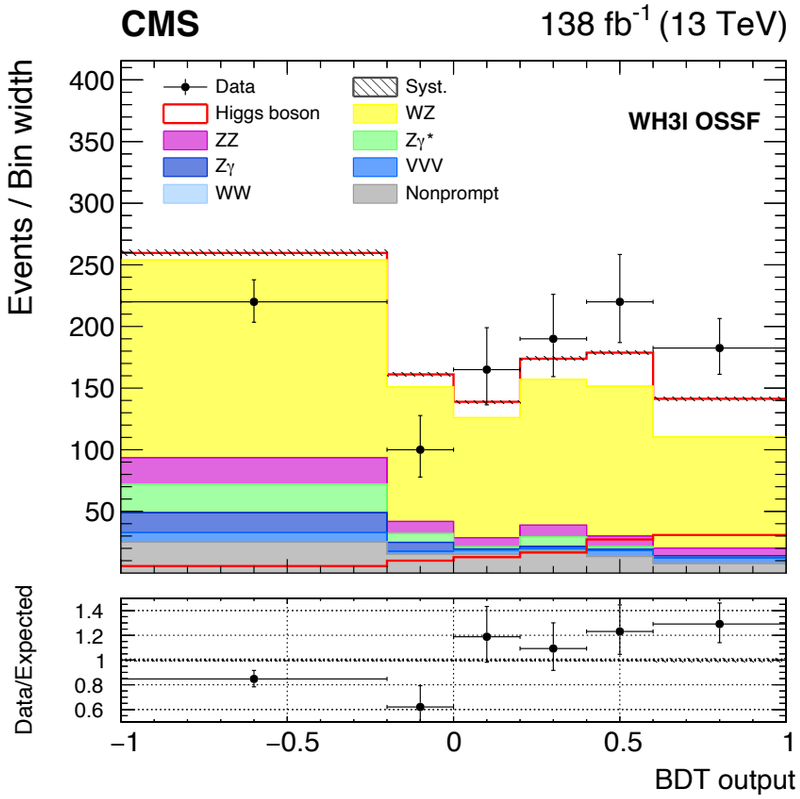
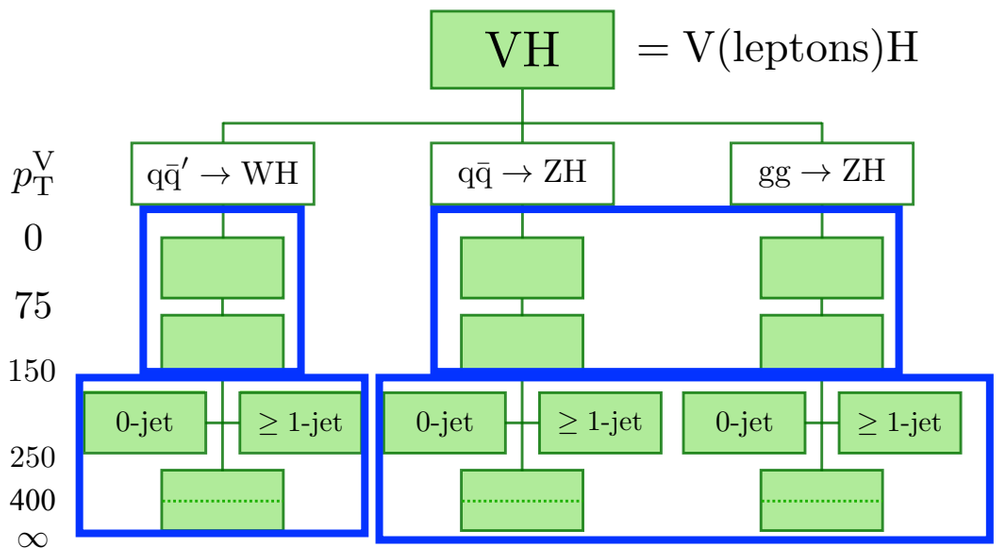
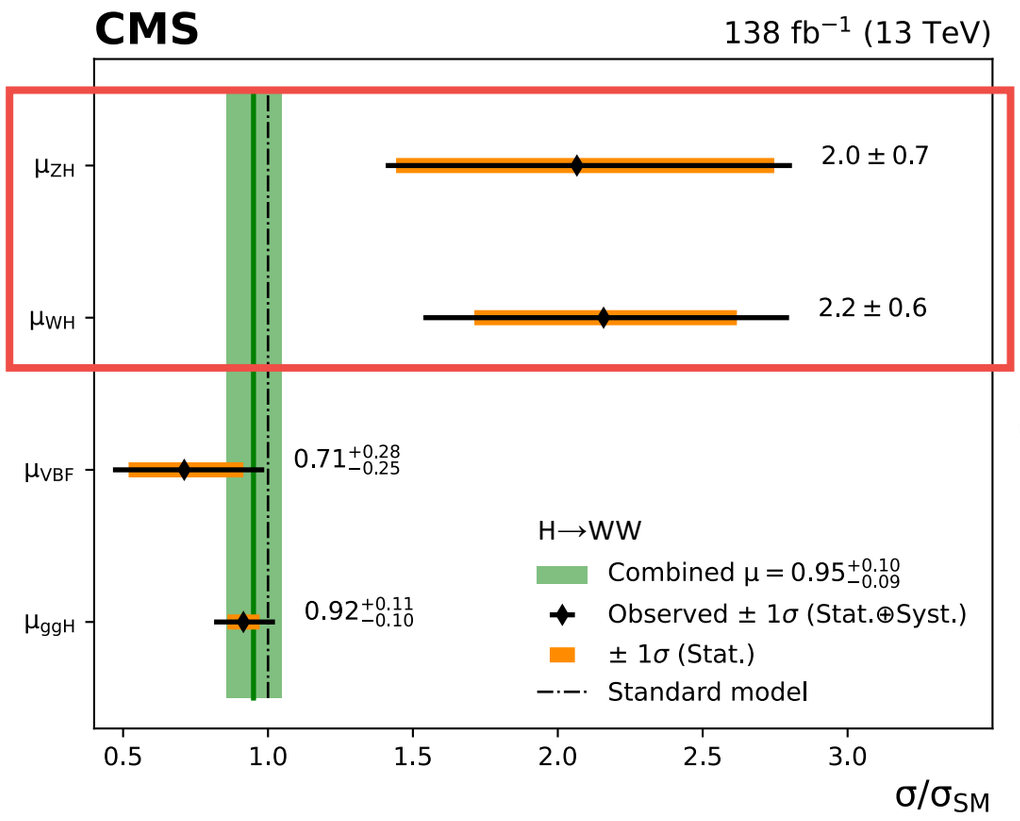
- Analysis targets :
  - VH leptonic : Z→ll/W→lν and H→2l2ν/H→lνqq
  - VH hadronic : V→qq (two resolved jets) and H→2l2ν
- Main backgrounds :
  - WZ, ZZ, Zγ/Zγ* (VH leptonic)
  - WW, Top, ττ (VH hadronic)
- Dedicated leptons/dijet selections for event categorization and background reduction.
- BDT output score or m_H proxies are considered for signal extraction.
- The STXS stage1.2 bins are reduced to 4 bins for the leptonic VH with a boundary of $p_T V$ = 150 GeV.

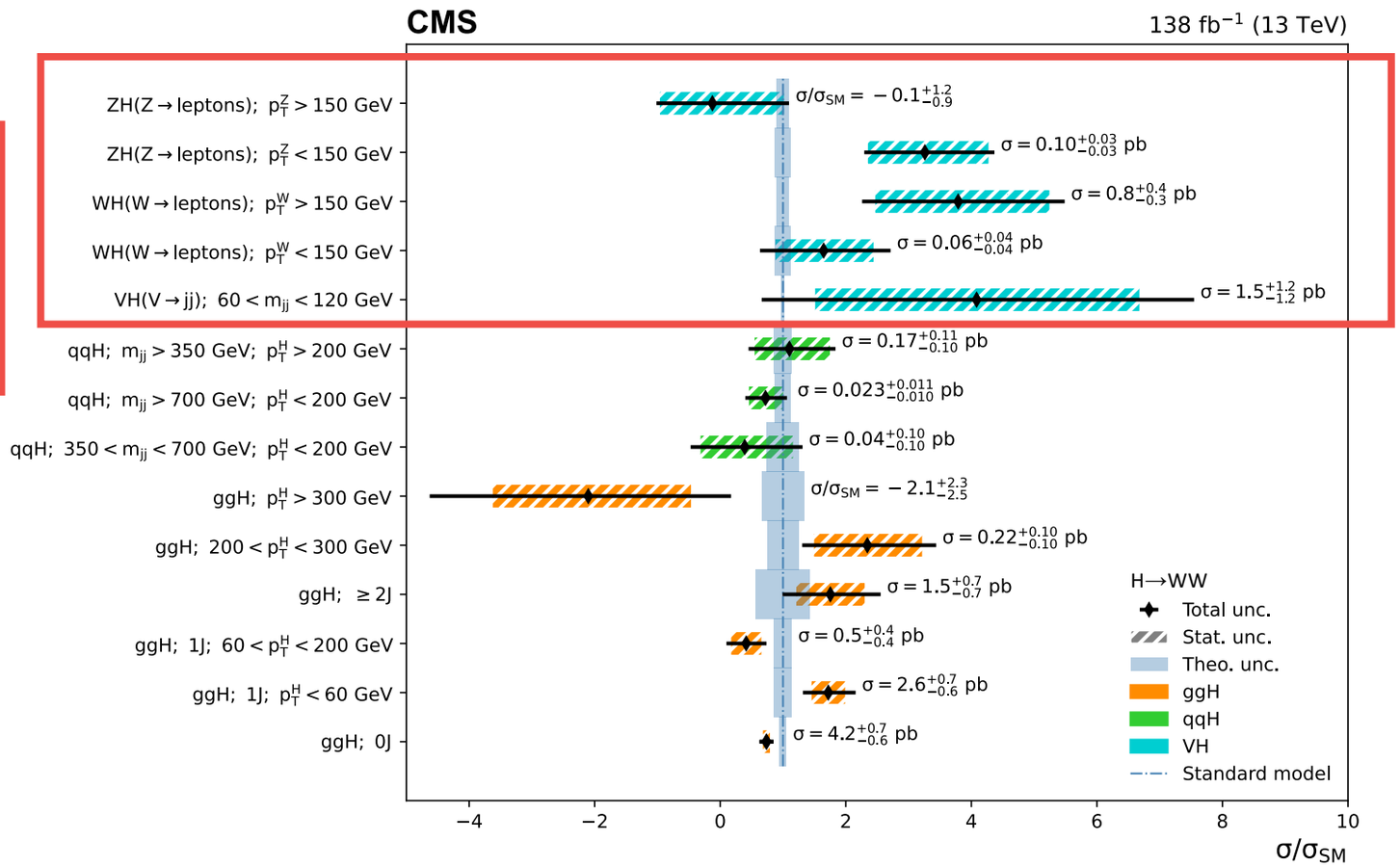




VH @ H→WW

- The WH and ZH processes at H→WW are made as the evidence from the signal strength modifier results.
- The results are dominated by stat. uncertainties, but overall compatible to the SM predictions.





Obs. significance for WH (ZH) = 3.61 (3.73) σ

VH @ H→ττ

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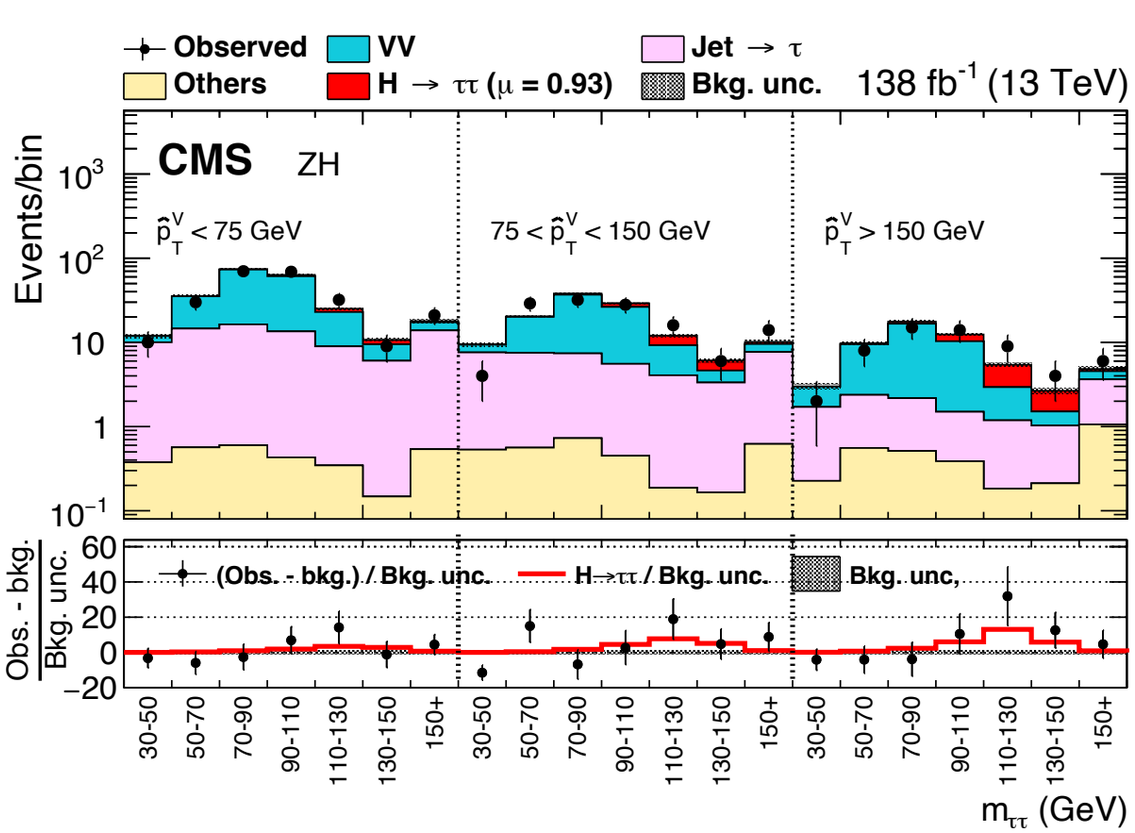
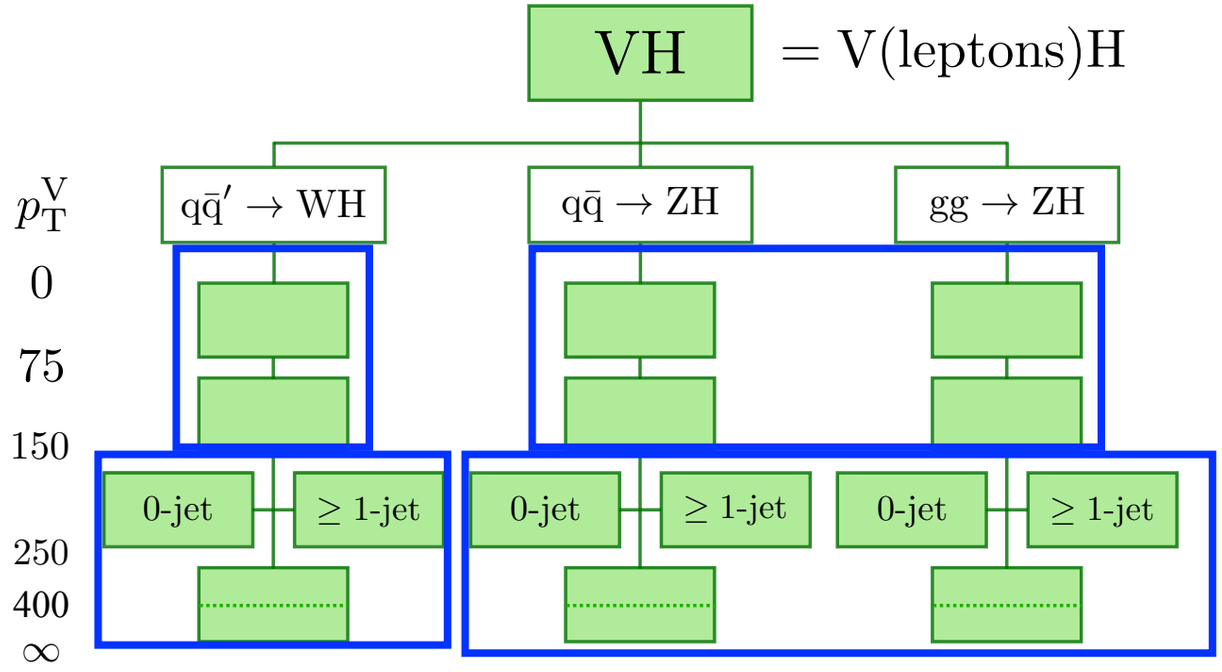
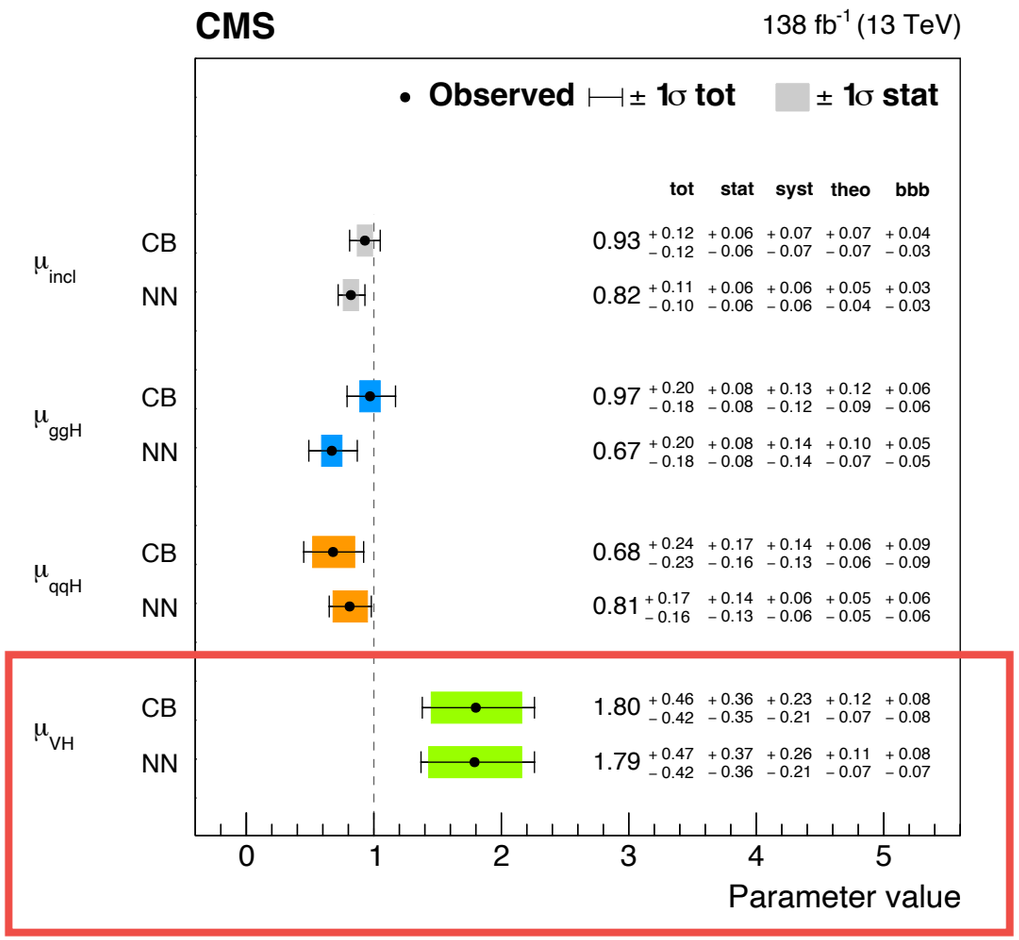
- Consider the $\tau_h\tau_h$, $e\tau_h$, $\mu\tau_h$ final states of the H→ττ decay and W/Z decaying to e/μ.
- Main backgrounds are composed of W(lν)Z(ττ) and ZZ→4l and jet misidentified to τ_h.
- H→WW is treated as an irreducible background.
- Observable : $m_{\tau\tau}$, $p_T V$
- Reduced STXS stage 1.2 is chosen due to limited sensitivity.

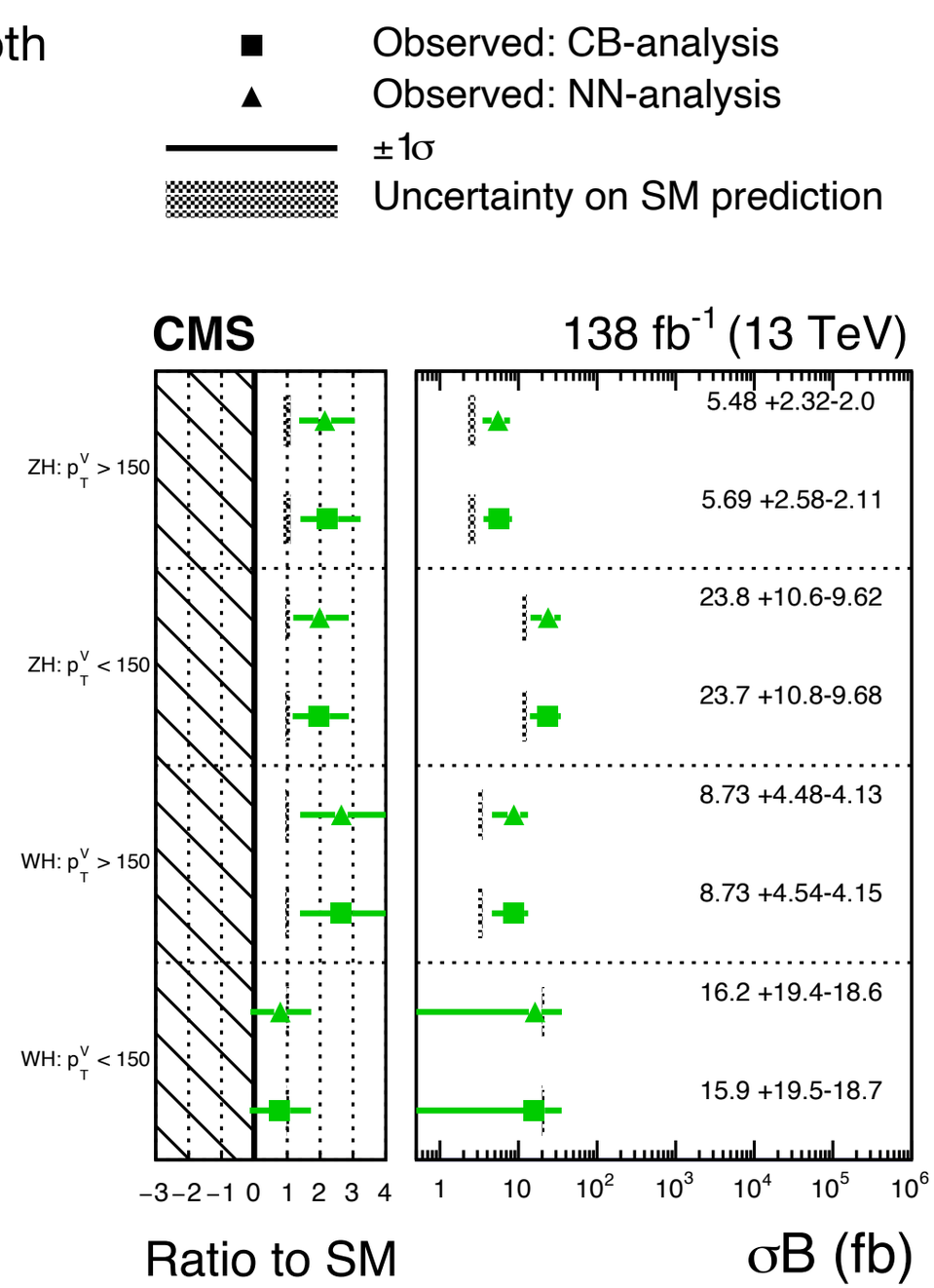




VH @ H→ττ

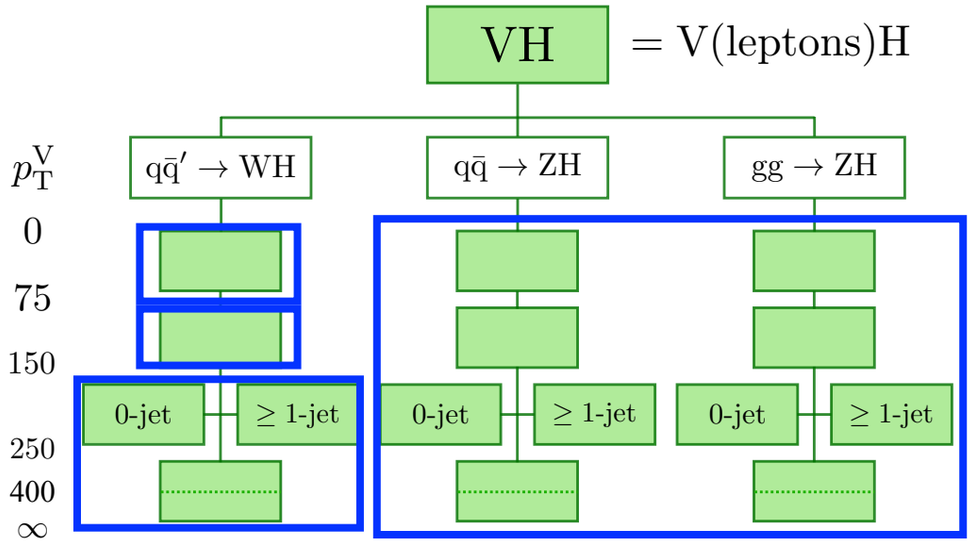
- Two methods (CB and NN) are applied to the ggH/qqH analysis but do not affect to the VH analysis since both productions has less correlation.
- Agree with the SM prediction.





VH @ H→γγ

- Two isolated photons in H→γγ provide clear signature with fully reconstructed final states and narrow peak in diphoton mass spectrum.
- Events are mainly categorized according to the decay modes of the W/Z boson (→ ll, lν, νν, qq) and p_T^V.
- ZH process is not split at STXS stage 1.2 from stage 0.



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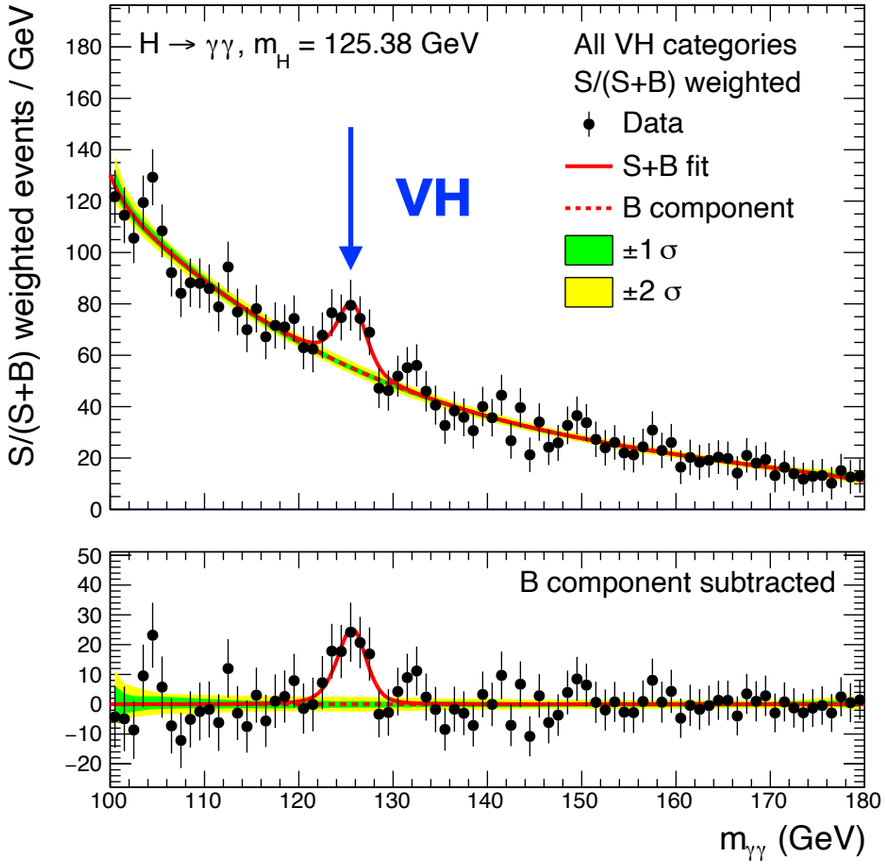
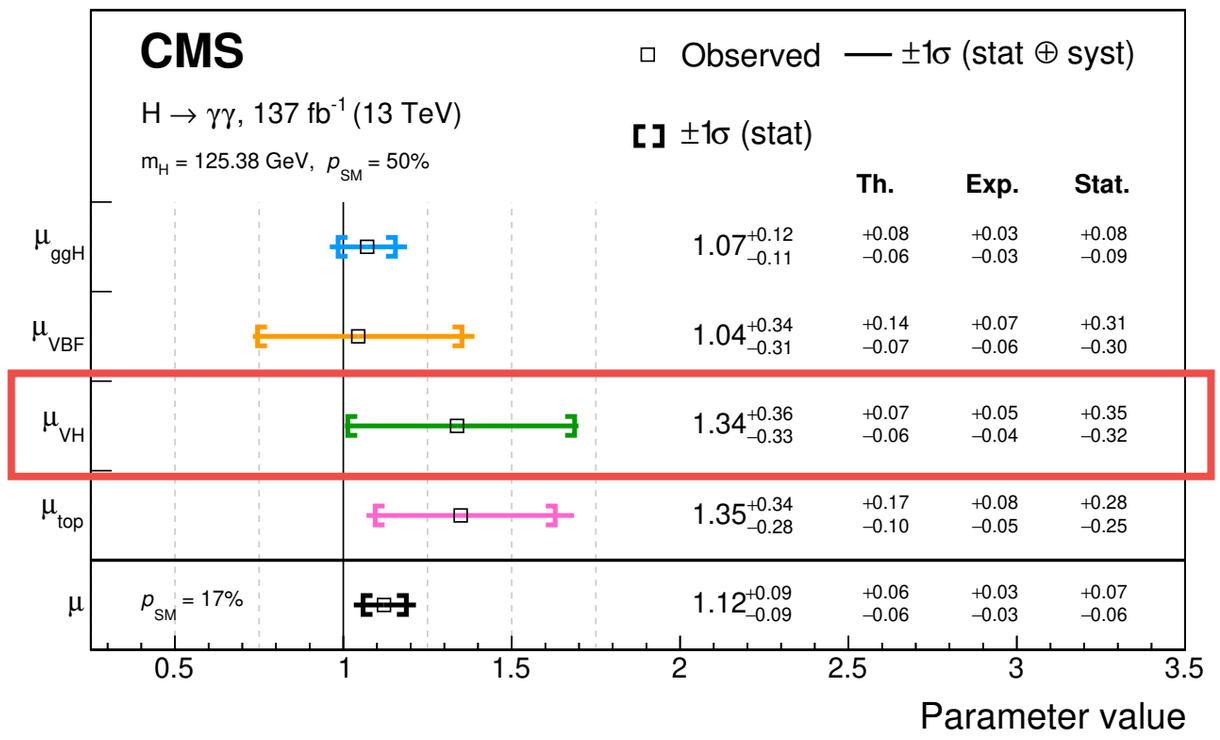


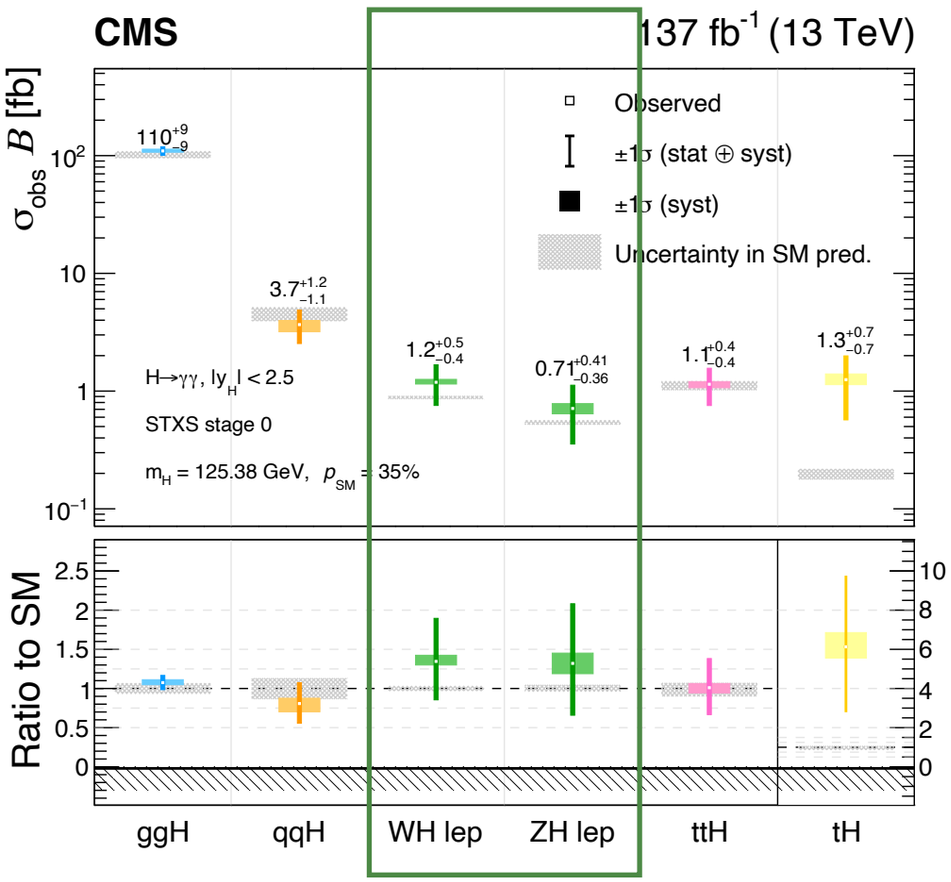


Obs. significance = 4.7 σ →Close to discovery

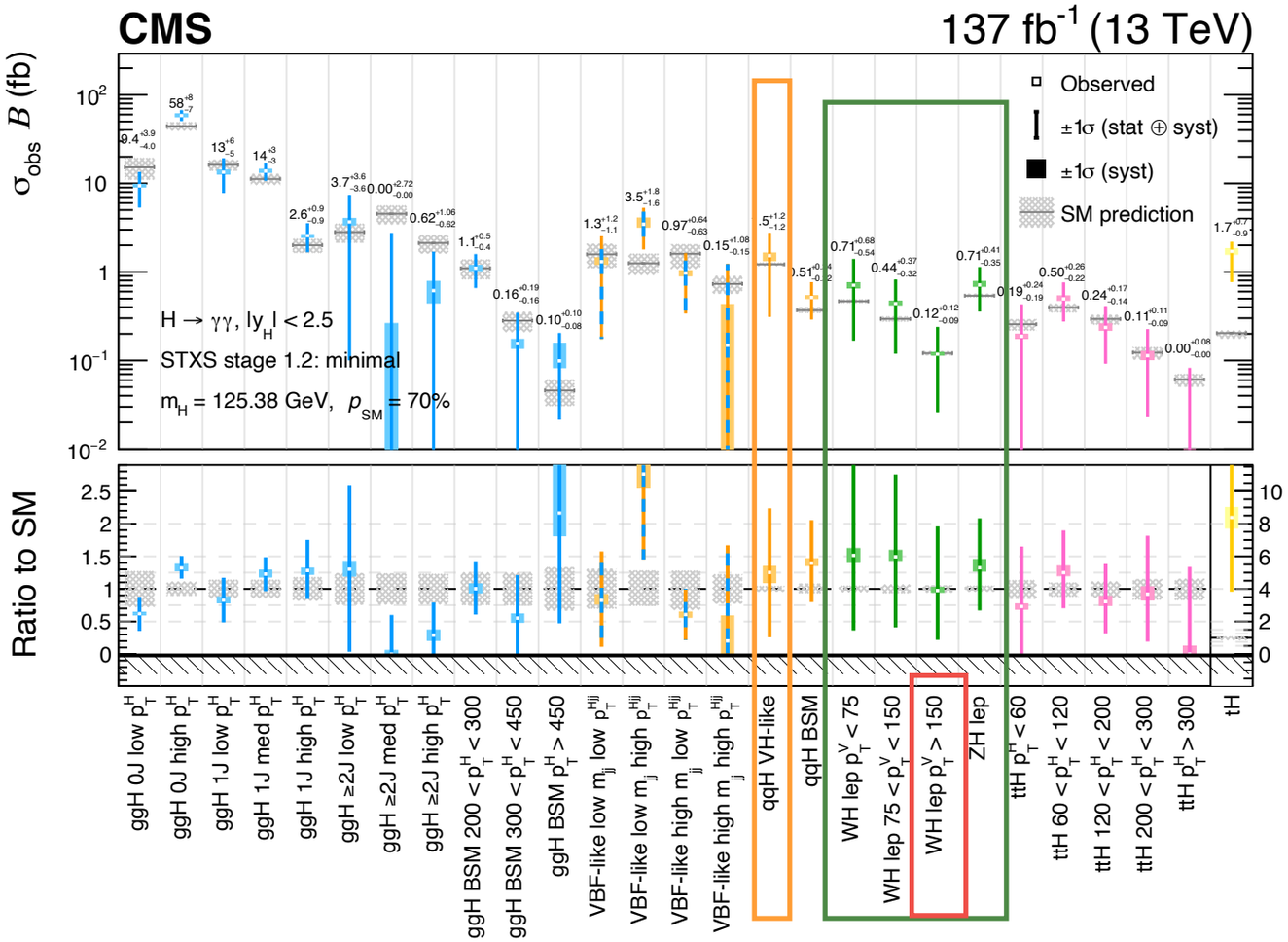
VH @ H→γγ

- Two STXS stages, stage 0 and reduced stage 1.2 (fine bins), are measured.
- Dominated by stat. uncertainty and no significant deviation with respect to the SM predictions.

Stage 0



Reduced Stage 1.2

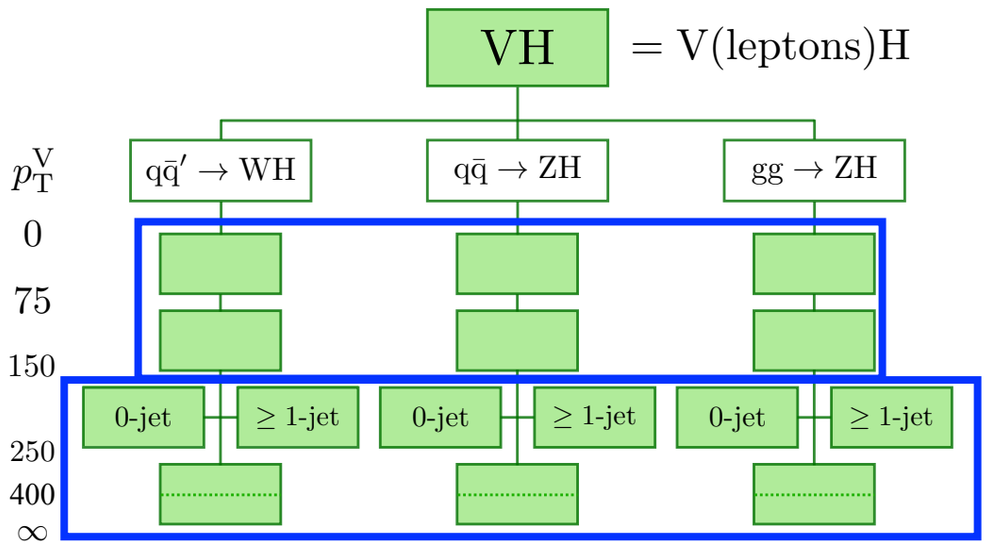


Observed significance for WH lep (ZH lep)= 3.2 (2.2) σ

High energy scale has no significant excess

VH @ H→ZZ→4ℓ

- Leptonic and hadronic decays of the weak boson are considered.
- The sensitivity is strongly suppressed due to limited statistics.
- STXS stage 1.2 bins are merged down to only two bins.



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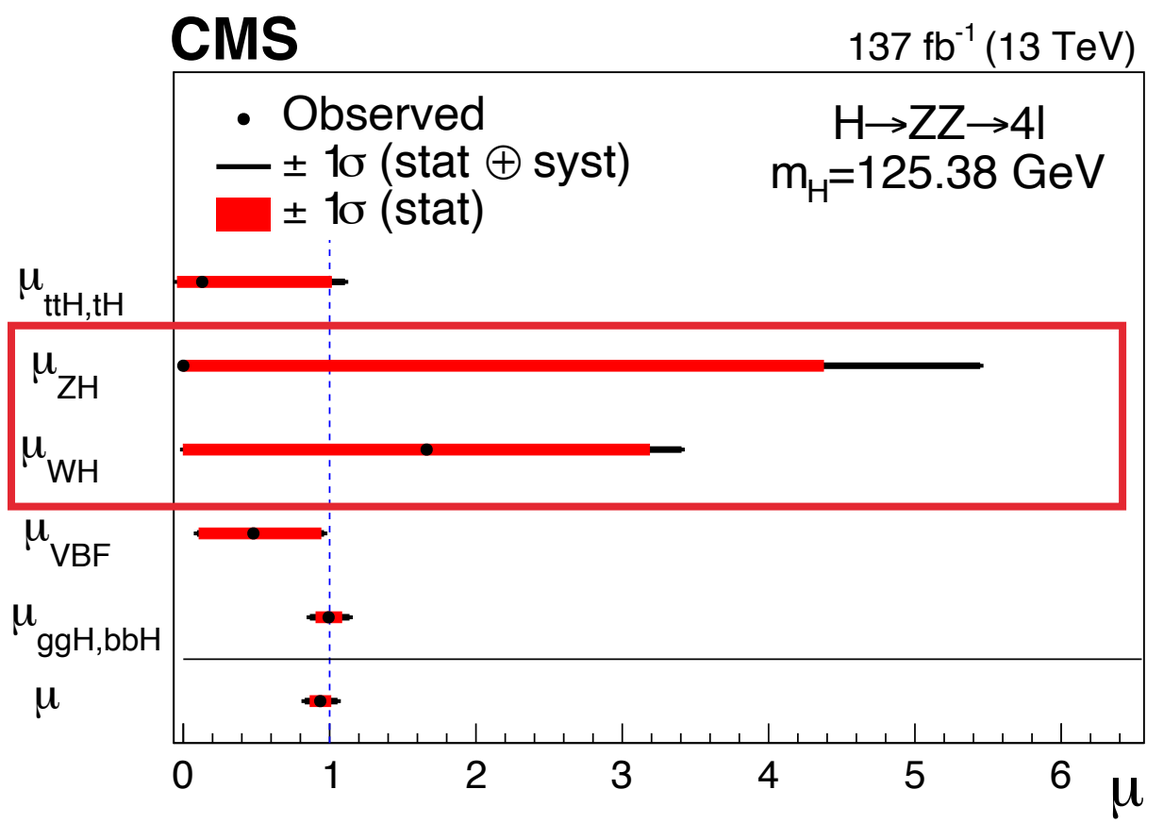
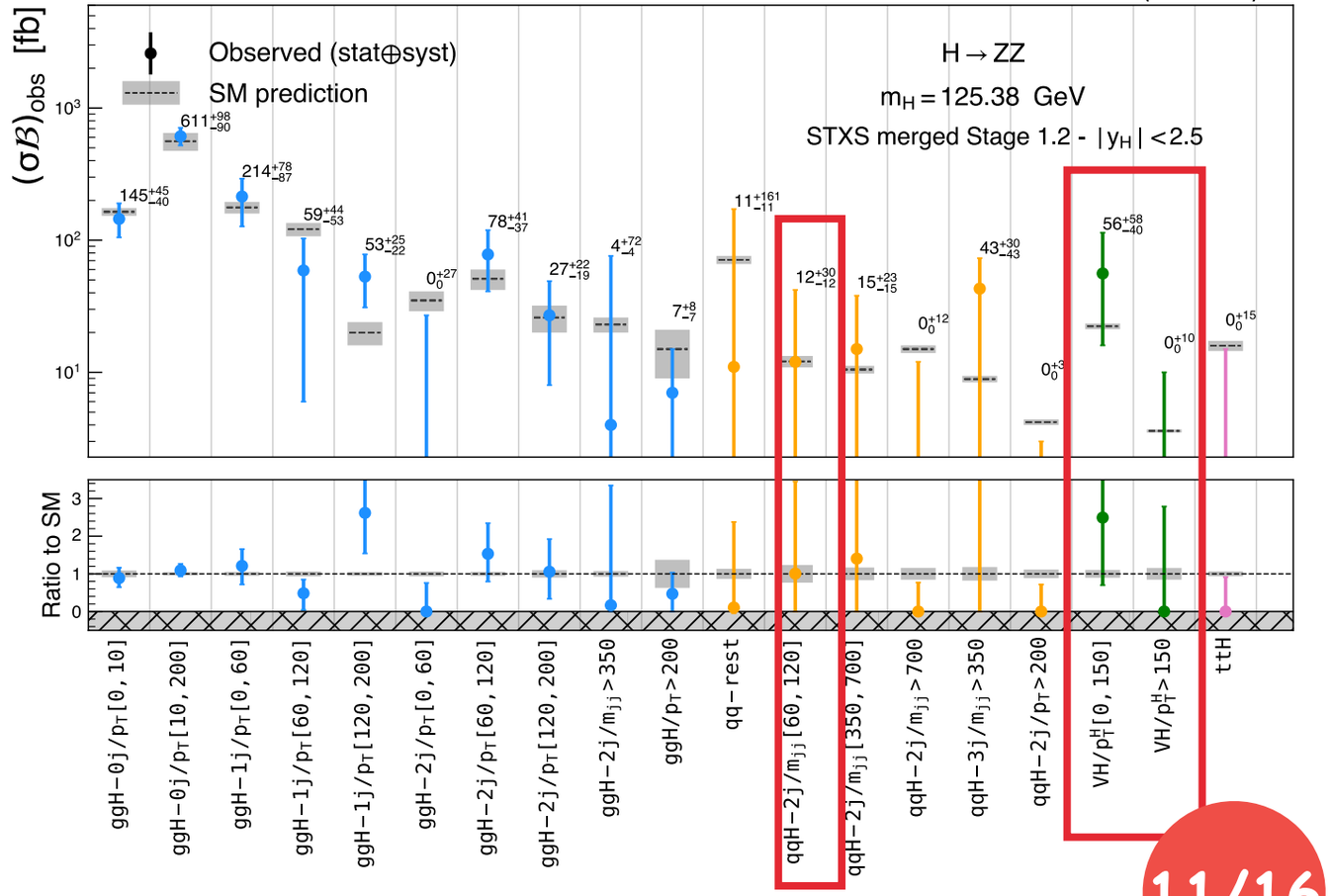


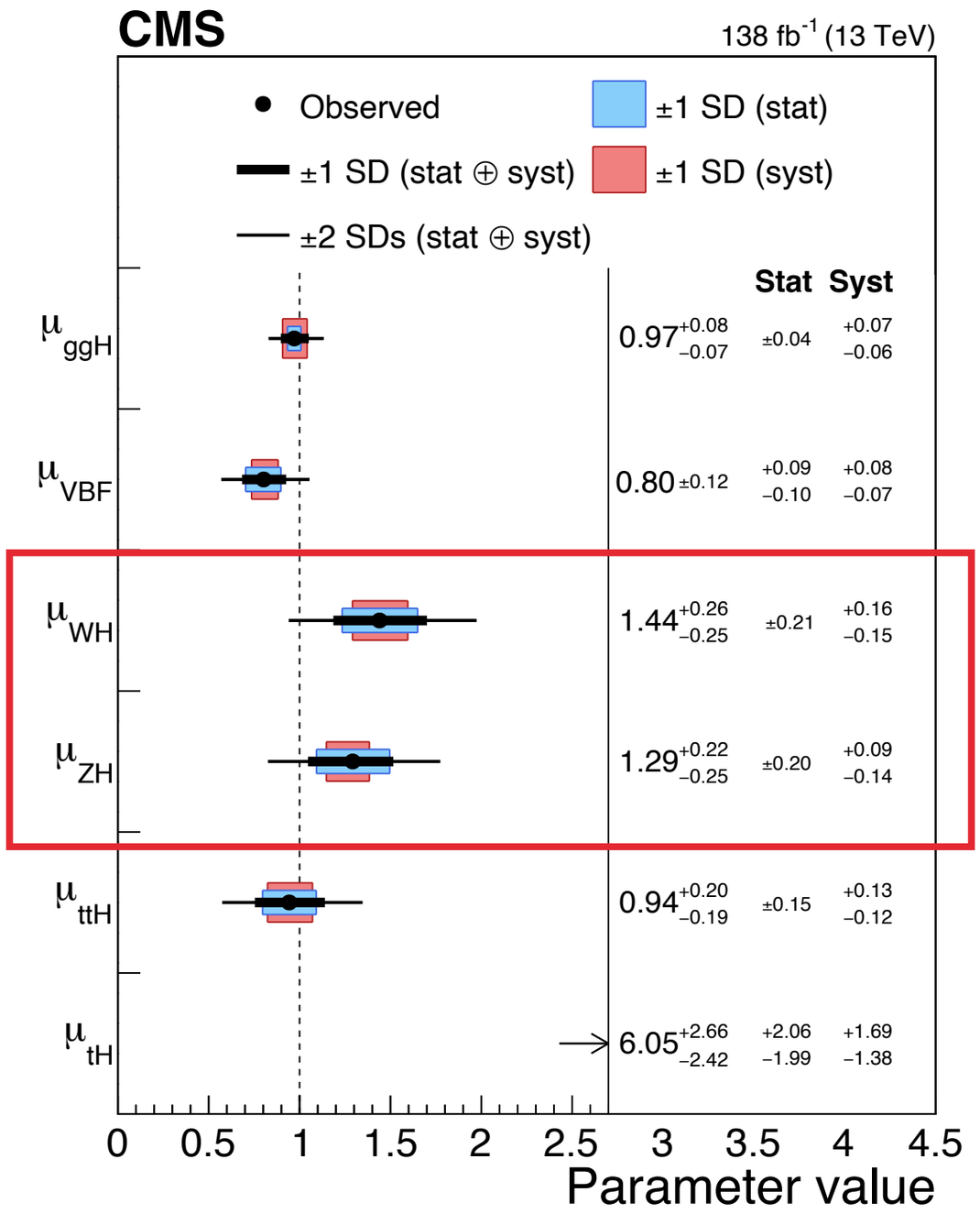


VH combination @ CMS

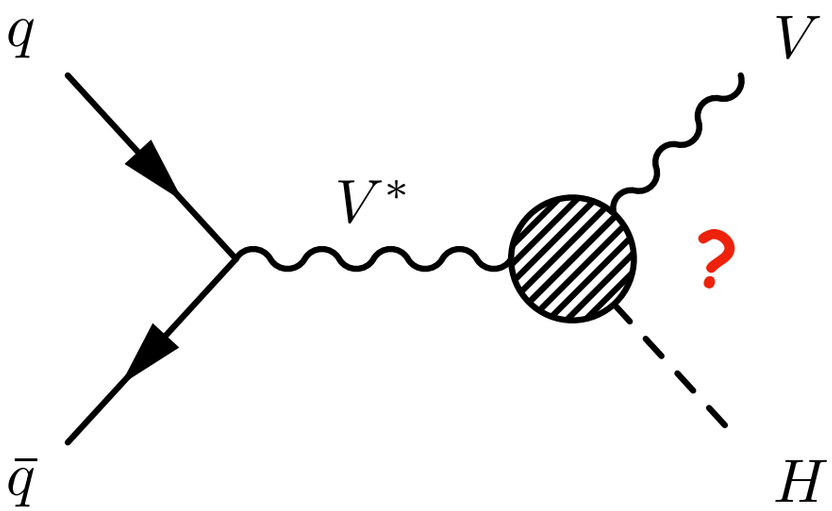
Nature 607 (2022) 60-68

- The combination includes sensitive Higgs decay channels, bb ,γγ, WW, ZZ, ττ (Included H→bb results are employed from the previous results Phys. Lett. B 780 (2018) 501).
- Dominated by statistical uncertainties.
- The agreement with the SM predictions for the VH production.

This is not the end story of the VH associated production.



Anomalous HVV coupling under VH production



VH production

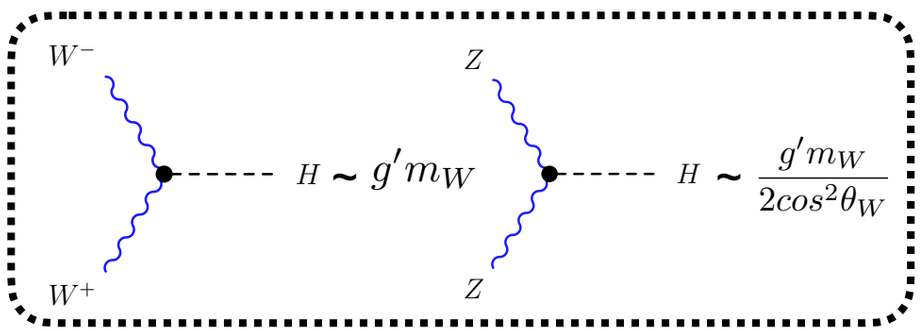
Phys. Rev. D 102, 056022 (2020)

A generic Lorentz-invariant amplitude for HVV coupling can be donated as

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

Form factor with BSM scale — **CP-Even** — **CP-Odd**

AC



SM CP-Even

There are three kinds of HVV anomalous coupling involving in form factors, loop level CP-Even and CP-Odd with three independent parameters Λ_1, a2, a3.

CP structure inside HVV

$$A(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q^2_{\mathrm{V1}} + \kappa_2^{\mathrm{VV}} q^2_{\mathrm{V2}}}{\left(\Lambda_1^{\mathrm{VV}}\right)^2}\right] m^2_{\mathrm{V1}} \epsilon^*_{\mathrm{V1}} \epsilon^*_{\mathrm{V2}} + a_2^{\mathrm{VV}} f^{*(1)}_{\mu\nu} f^{*(2),\mu\nu} + a_3^{\mathrm{VV}} f^{*(1)}_{\mu\nu} \tilde{f}^{*(2),\mu\nu}$$

SM CP-Even — **CP-Odd**

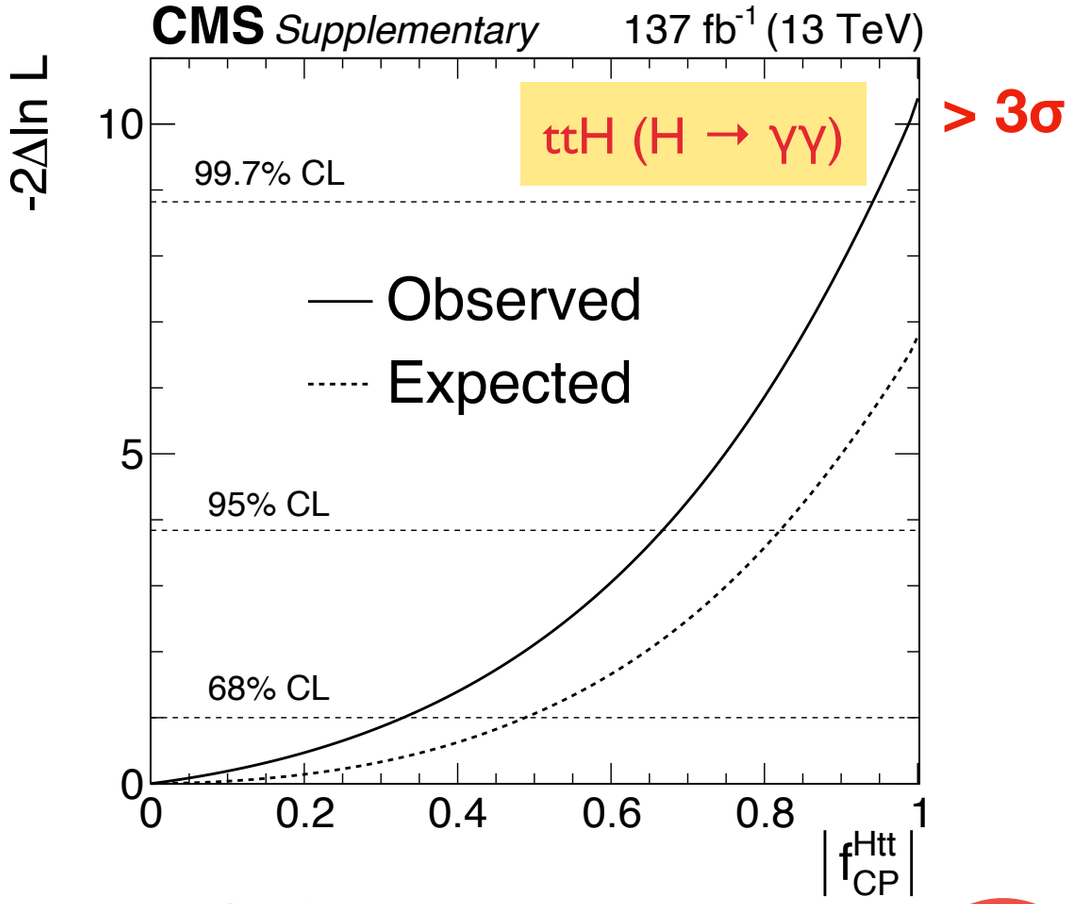
Admixture

- Higgs boson owns quantum numbers of $J^{cp} = 0^{++}$
- Leave room for a small CP-Odd admixture which gives CP violation
- **Measure "effective cross-section fraction"**

$$f_{a_3} = \frac{|a_3|^2}{|a_1|^2 + |a_3|^2} sgn\left(\frac{a_3}{a_1}\right)$$

  - Cancel the systematic uncertainties
  - Independent of the coupling convention under different theoretical framework

Phys.Rev.Lett. 125 (2020) 6, 061801

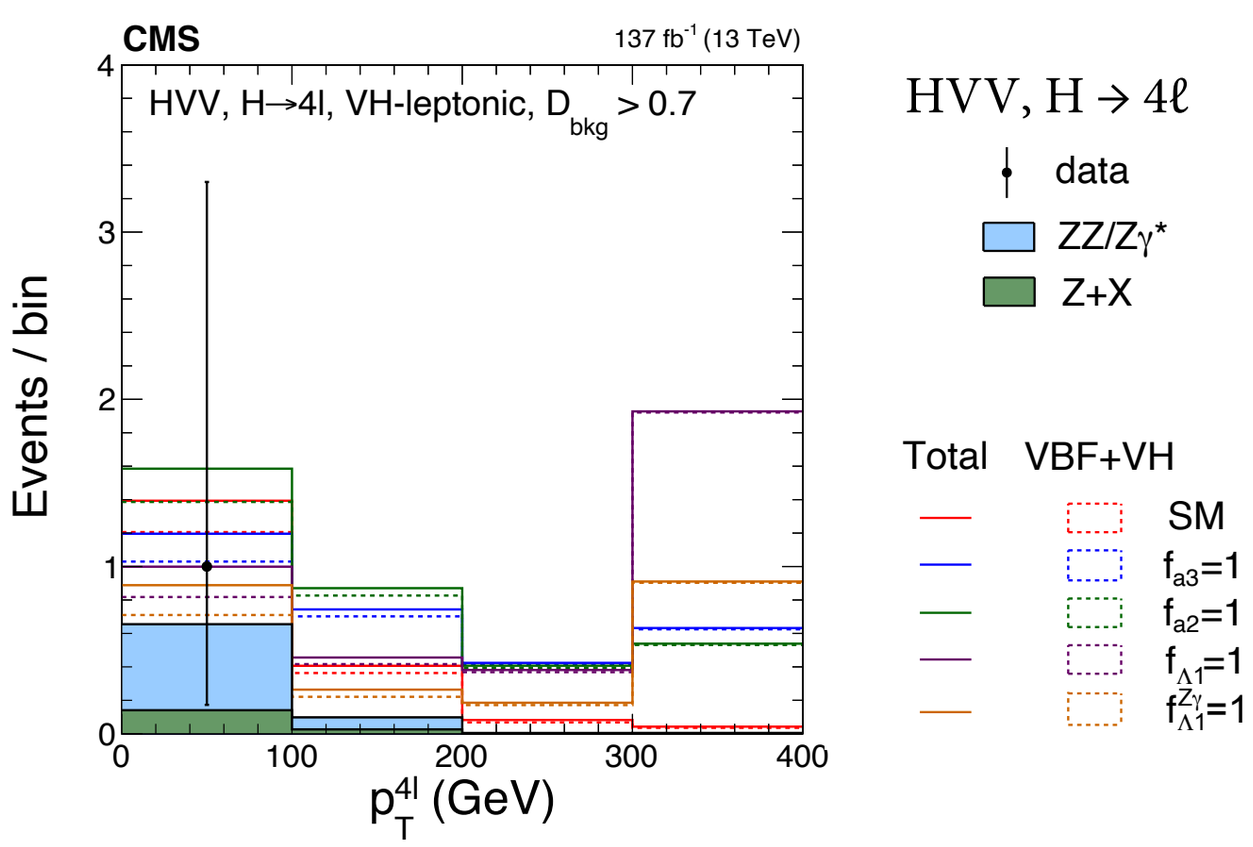


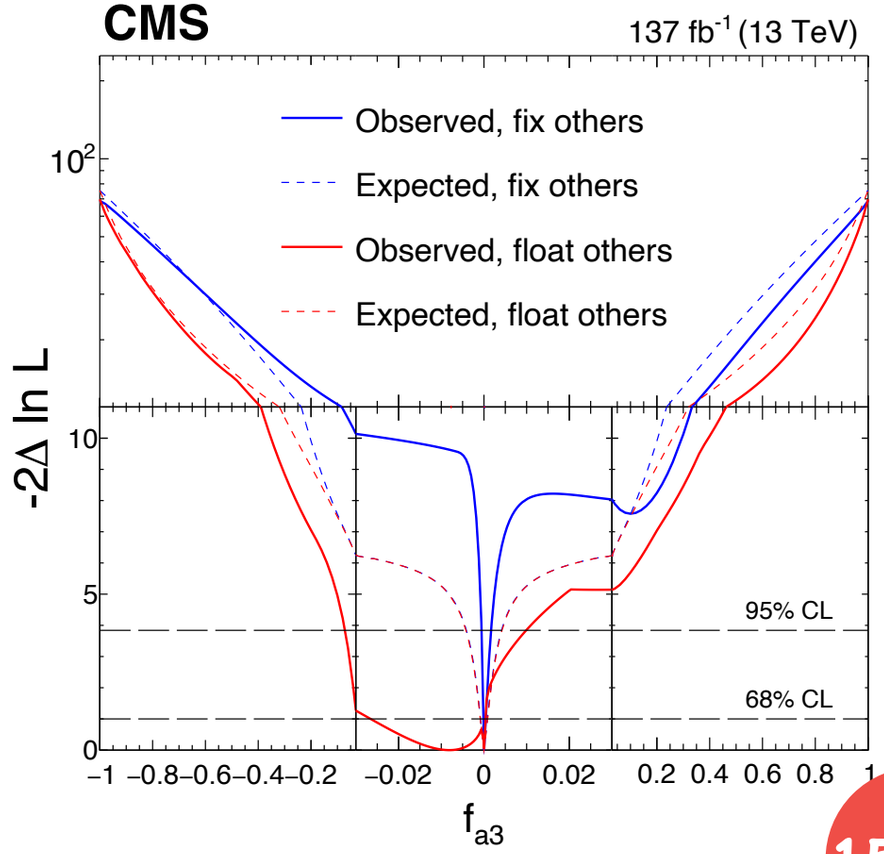
Currently at CMS, only H→ZZ analysis is involved in the AC of the VH production.

Anomalous coupling inside VH @ H→ZZ

- Based on the strategy of the VH (H→ZZ) analysis, extra discriminants built by kinematics or matrix elements are applied to separate events like SM and CP-Odd.
- The CP effect (f_{a3}) are measured by simultaneously scaling the HVV coupling in the H→ZZ decay, VBF and VH production.
- The results are compatible to the SM prediction although they aren't purely from the VH production.

Phys. Rev. D 104 (2021) 052004





Summary

- The signal strength and cross section measurements of the VH associated production at the CMS experiment in LHC Run II period is presented.
- The analyses are based on the simplified template cross section framework (STXS).
- The results are still dominated by statistical uncertainty but compatible to the standard model prediction.
- Leave room for the BSM effect hidden in VH production as the anomalous HVV coupling discussed in this talk.