# Higgs rare productions and decays at CMS

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*“Particle physics is never as exciting as today.*

*This is largely because of the discovered Higgs boson.”*

*-Tai Tsun Wu*

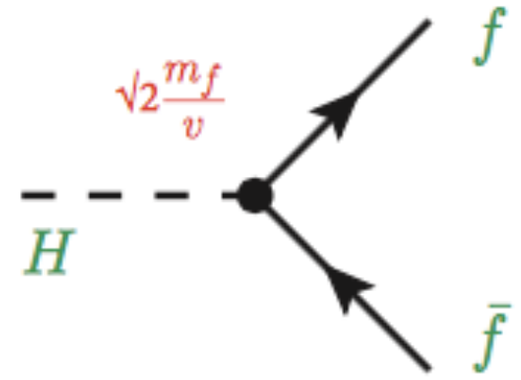
# Contents of this talk

- **Rare productions and decays of Higgs boson are important portals to new physics**
- **CMS experiment has a large program to study these processes and keep improving sensitivities**
  - Focus on full Run-2 results recently released
- Results of Higgs rare decays
  - H→ff, H→llγ
- Results of Higgs rare productions
  - HH, cH

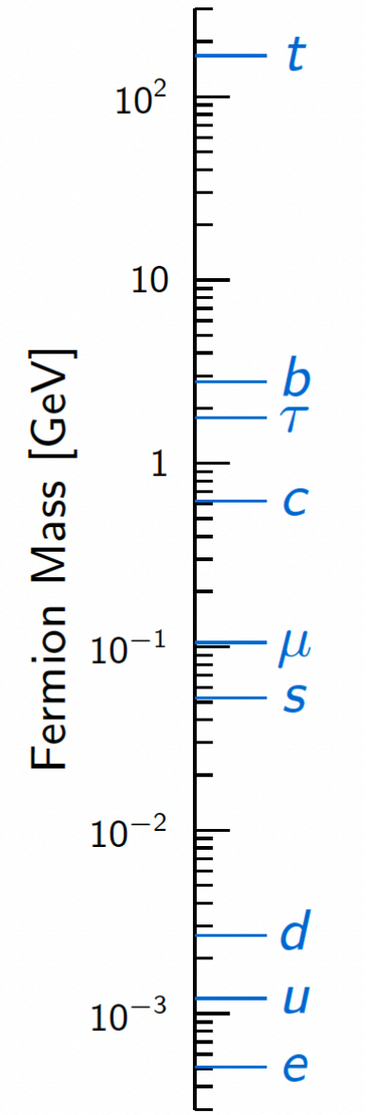
# $H \to ff$

# Yukawa couplings

- In Standard Model, Higgs boson couples to fermions (quarks and leptons) through Yukawa interactions
  - **giving masses to quarks and leptons**

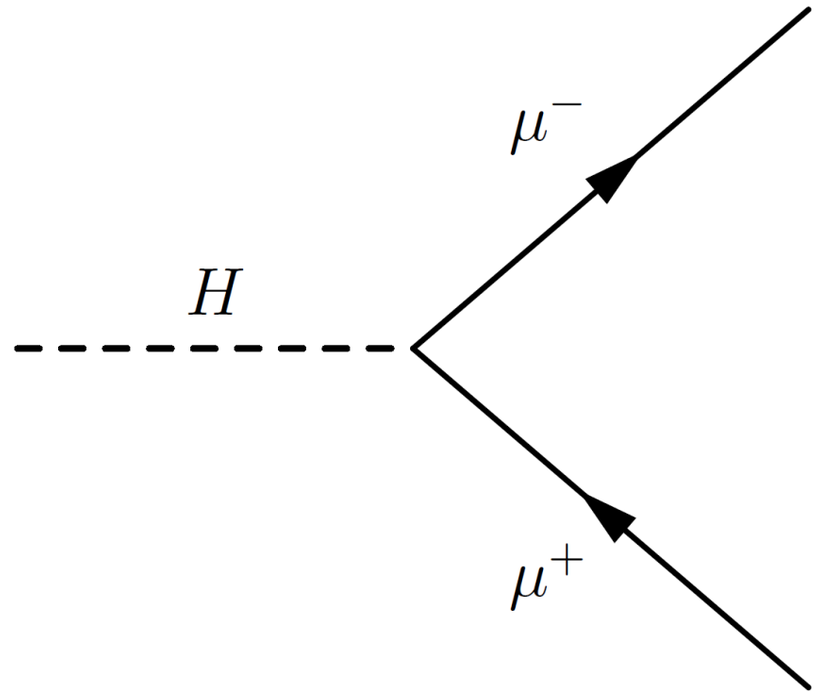



- Yukawa interactions are “a new kind of fundamental interaction”
  - **important to study the Yukawa sector, which may provide important indication for the origin of the fermion mass pattern**
- Experimental signatures: **$t\bar{t}H$ production**, **$H\to\tau\tau$ decay**, **$H\to b\bar{b}$ decay**, etc.
  - In SM, Yukawa couplings are proportional to fermion masses; BSM physics can modify coupling strengths

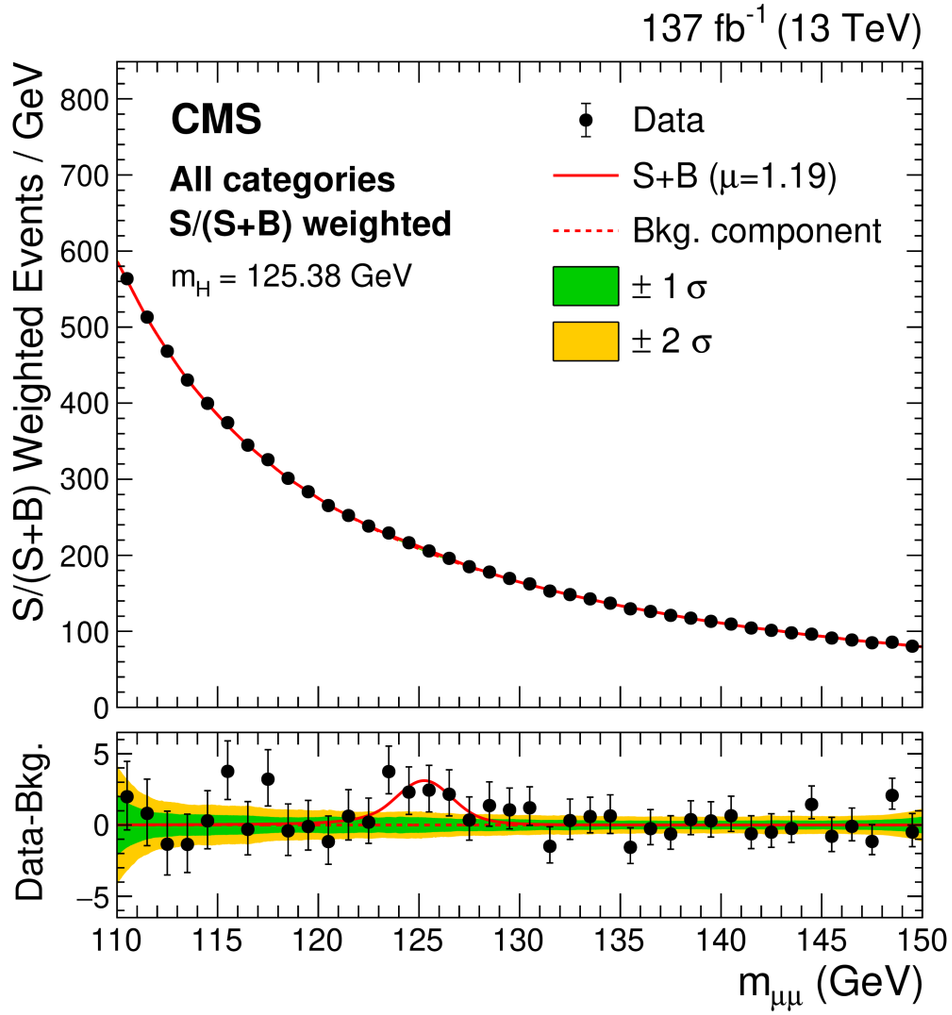


# H→*μμ* decay

- The couplings between the Higgs boson and third-generation fermions (top quark, bottom quark, $\tau$ lepton) have already been observed
  - The Higgs couplings with fermions of the other generations have not been established
- **The Higgs decay to two muons offers the best opportunity to observe the Higgs couplings with second-generation fermions at the LHC**
  - Small branching ratio in SM ($2\times10^{-4}$), physics beyond the SM could modify it



# H→μμ decay

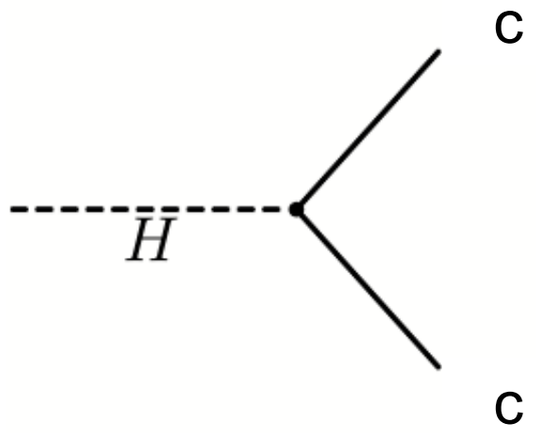


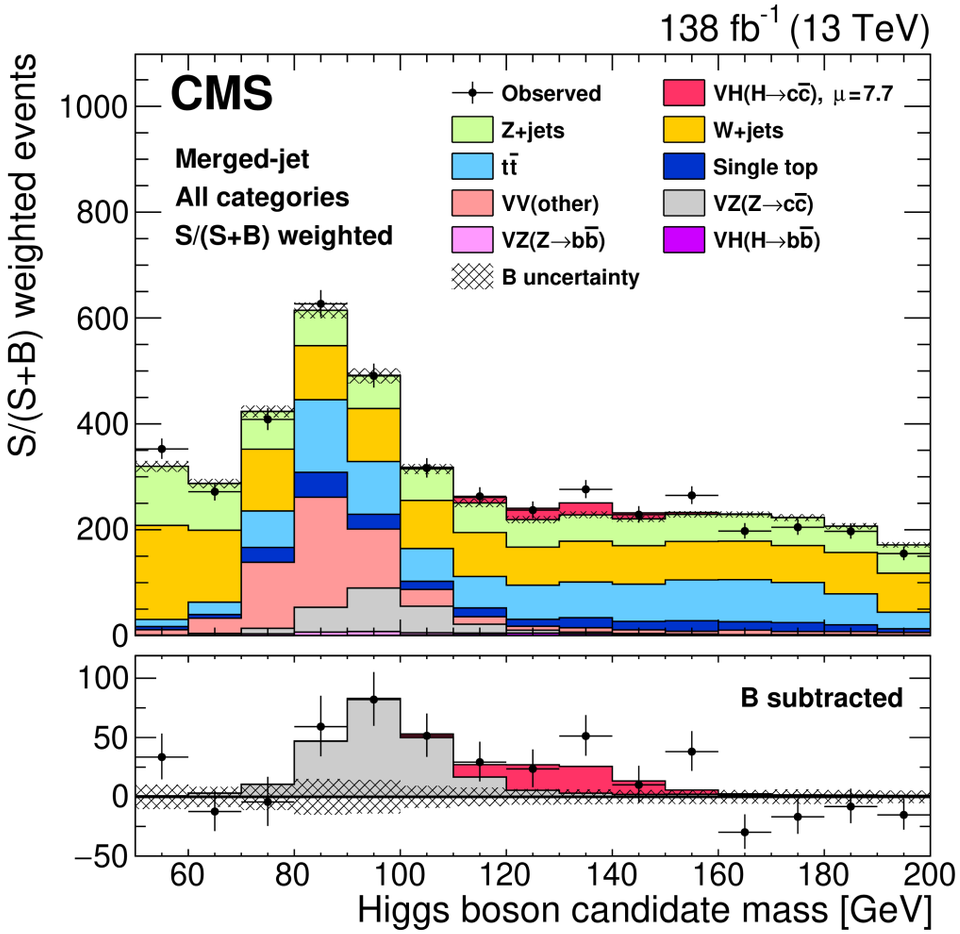

JHEP 01 (2021) 148

- The observed H→μμ significance in CMS full Run 2 result is **3.0σ** (expected 2.5σ)
- These results provide **first evidence** for the Higgs couplings to second generation fermions
- Working to observe H→μμ decay with >=5σ in Run-3

# H→cc̄ decay

- **H→cc̄ decay** is currently the main channel to probe Higgs coupling to c quarks
  - branching ratio in SM: 2.8%

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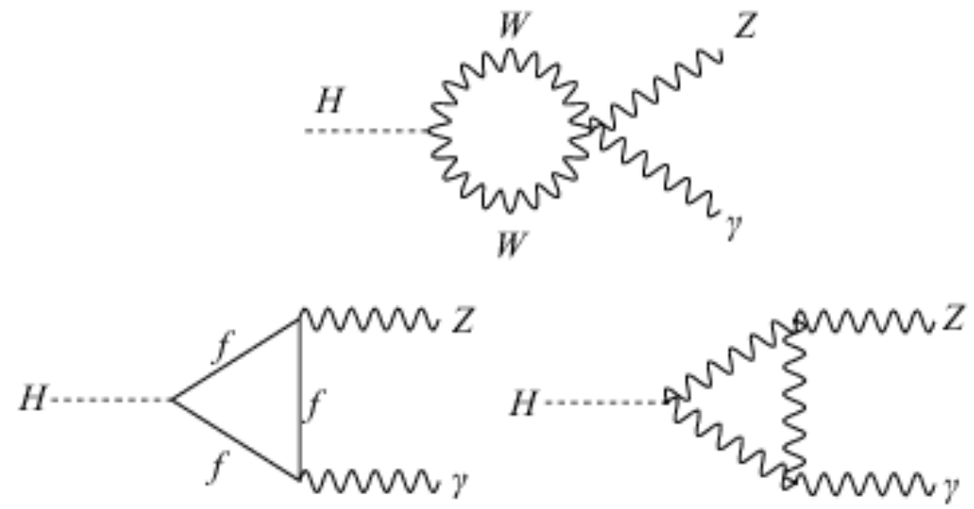
## VH H→cc̄

- Tag leptonically decaying W/Z boson
- **Combine both resolved and boosted jet analyses**
- Boosted analysis benefits from ParticleNet based charm tagging
- Observed limit at 95% CL on H→cc̄ signal strength: 14 times SM prediction
- Constraint on Higgs-charm Yukawa coupling modifier: **1.1 < |Kc| < 5.5**

# $H \to ll\gamma$

# H→Zγ decay

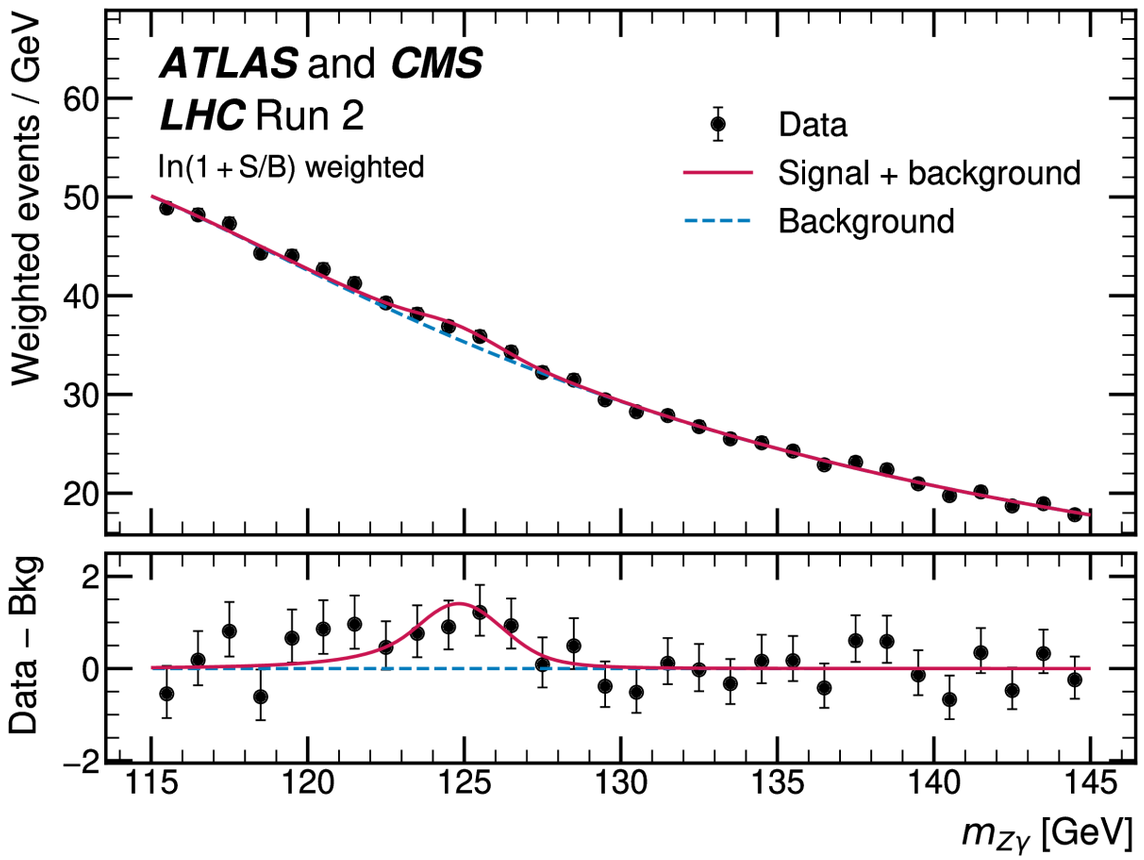
- BSM particles & couplings could be present in the quantum loops
- Difference between H→Zγ decay and H→γγ/H→ZZ decay sensitive to new physics
  - (e.g. Qing-Hong Cao et al. *Phys. Lett. B* 789 (2019) 233 )
  - Small branching ratio in SM ($1.6\times10^{-3}$); main bkg: non-Higgs Zγ, Z+jets

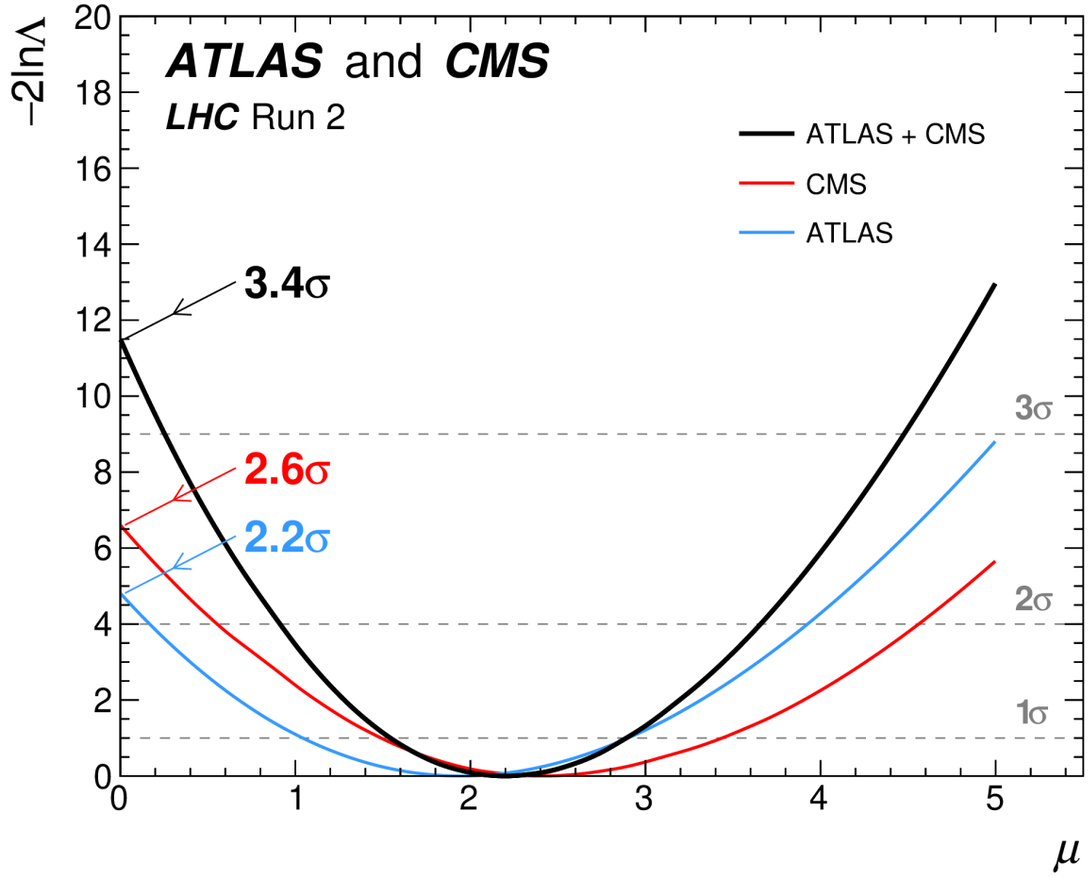



- Select events with two leptons (mll ~90 GeV) and one photon and separate them to multiple categories to target various production modes
- Fit in llγ mass distribution over all categories

# H→Zγ decay

Phys. Rev. Lett. 132 (2024) 021803, Featured in Physics



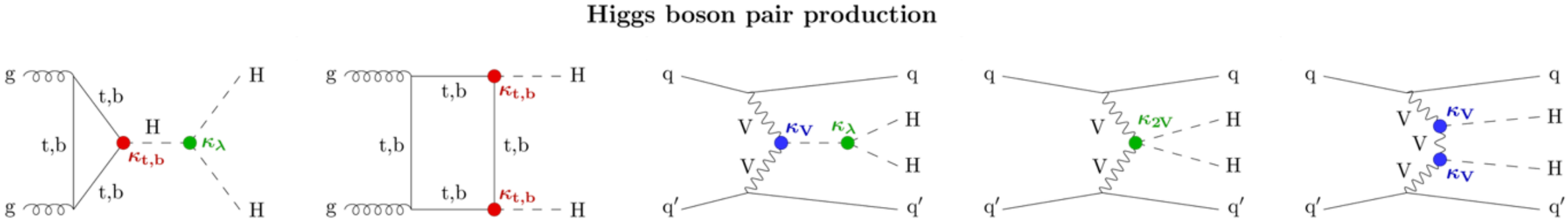

- In ATLAS+CMS combined result, the observed H→Zγ significance is **3.4σ** (expected 1.6σ)
  - **First evidence** of the H→Zγ decay
- Signal strength is 2.2 ± 0.7: agrees with theoretical expectation within **1.9σ**
- With the ongoing Run-3, we will be able to improve the precision of this rare Higgs decay

# *Double Higgs production*

# Higgs boson self-couplings

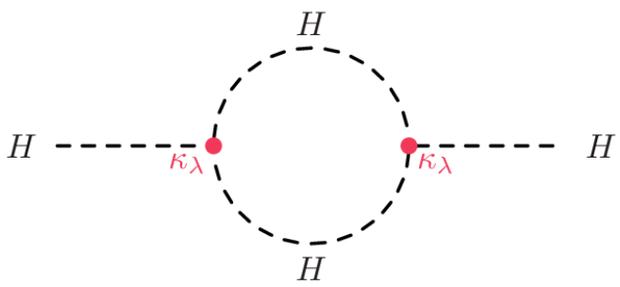
- **Higgs self-coupling is one of the deepest questions of SM and may provide a portal to new physics beyond it**
  - Vacuum stability, early universe evolvement, …
- **Double Higgs production is the way to directly probe Higgs self-couplings at the LHC**
  - Extremely low cross-section in the SM
  - Non-SM self-coupling strength can change cross-section and kinematics of double Higgs production
  - Many final states are analyzed: bbbb, bb$\tau\tau$, bbγγ, …

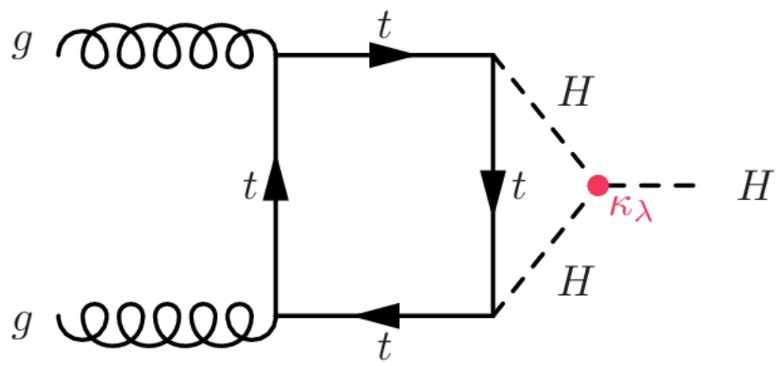
Higgs boson pair production

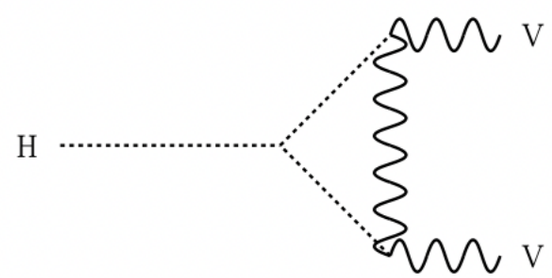


# Higgs boson self-couplings

- **Single Higgs boson production and decays can be modified by self-coupling modifier through NLO EW correction**

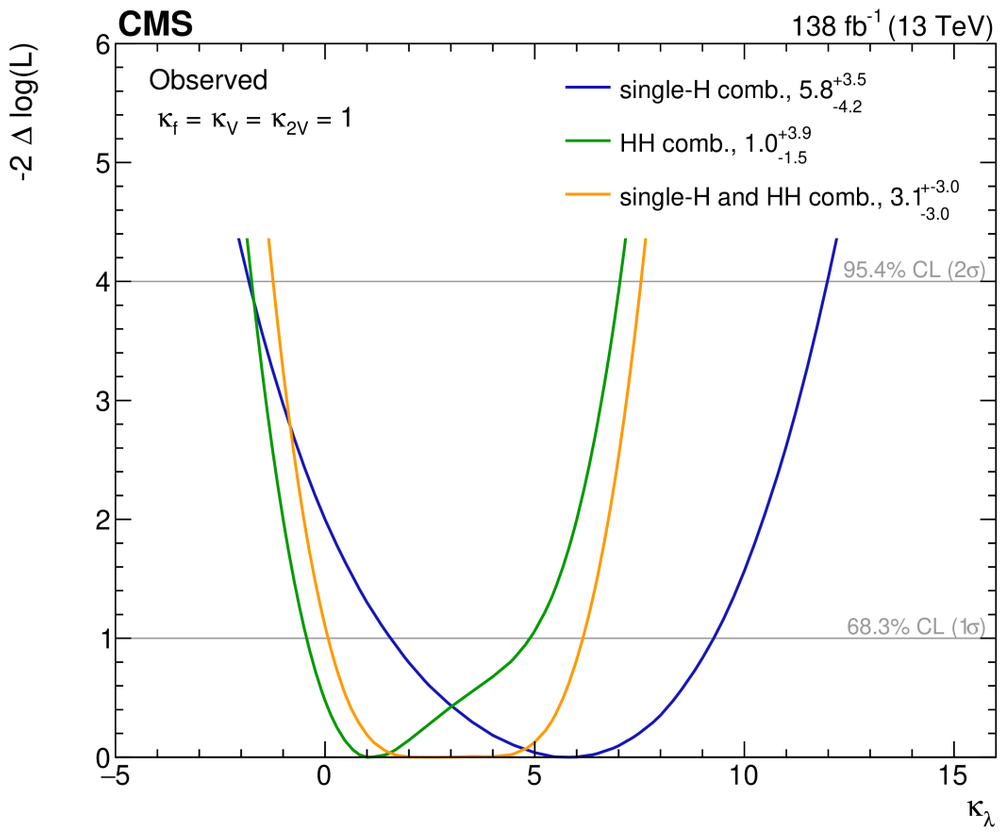


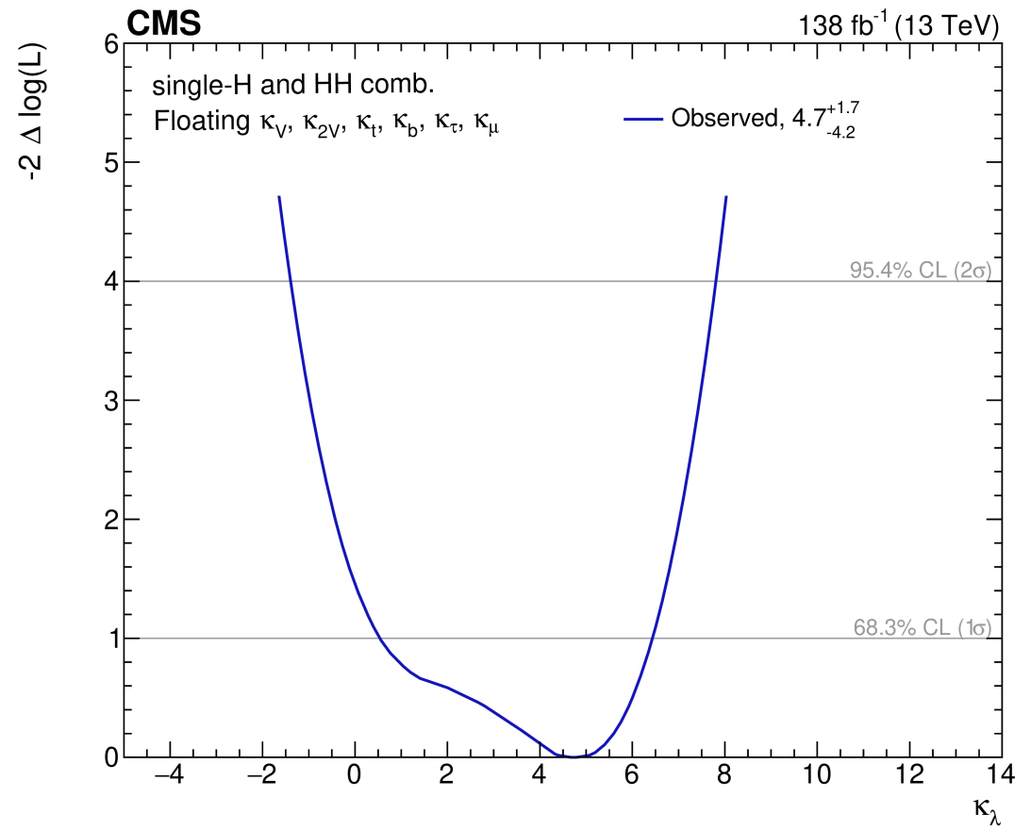



# Double Higgs + Single Higgs Combination

arxiv:2407.13554




- **Strongest constrain on Higgs self coupling with CMS:**
  - $-1.2 < \kappa_\lambda < 7.5$ under the assumption that the other Higgs couplings are fixed to SM
  - $-1.4 < \kappa_\lambda < 7.8$ if relaxing the assumption

# Double Higgs + Single Higgs Combination

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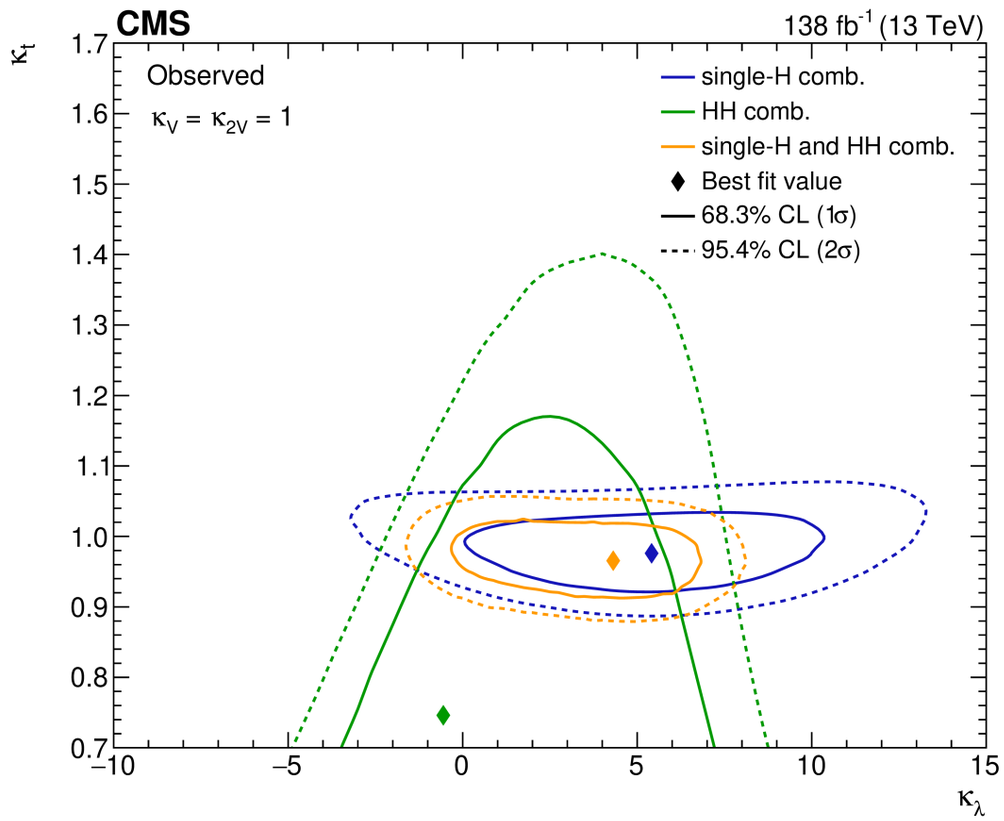
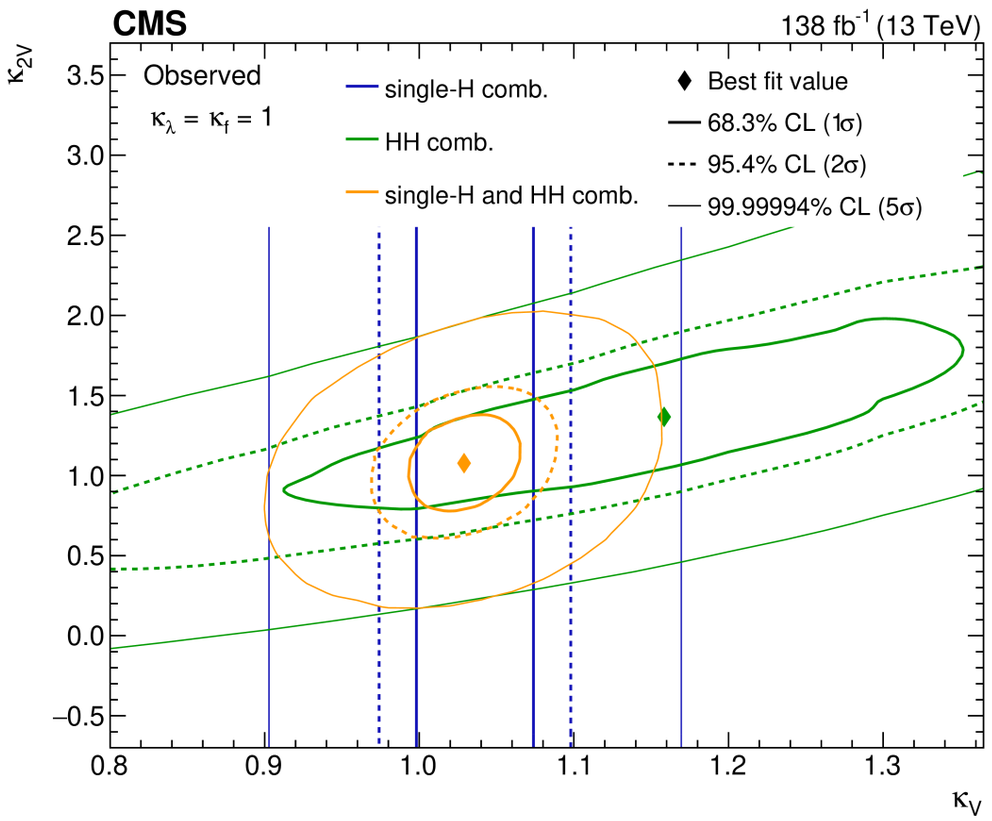
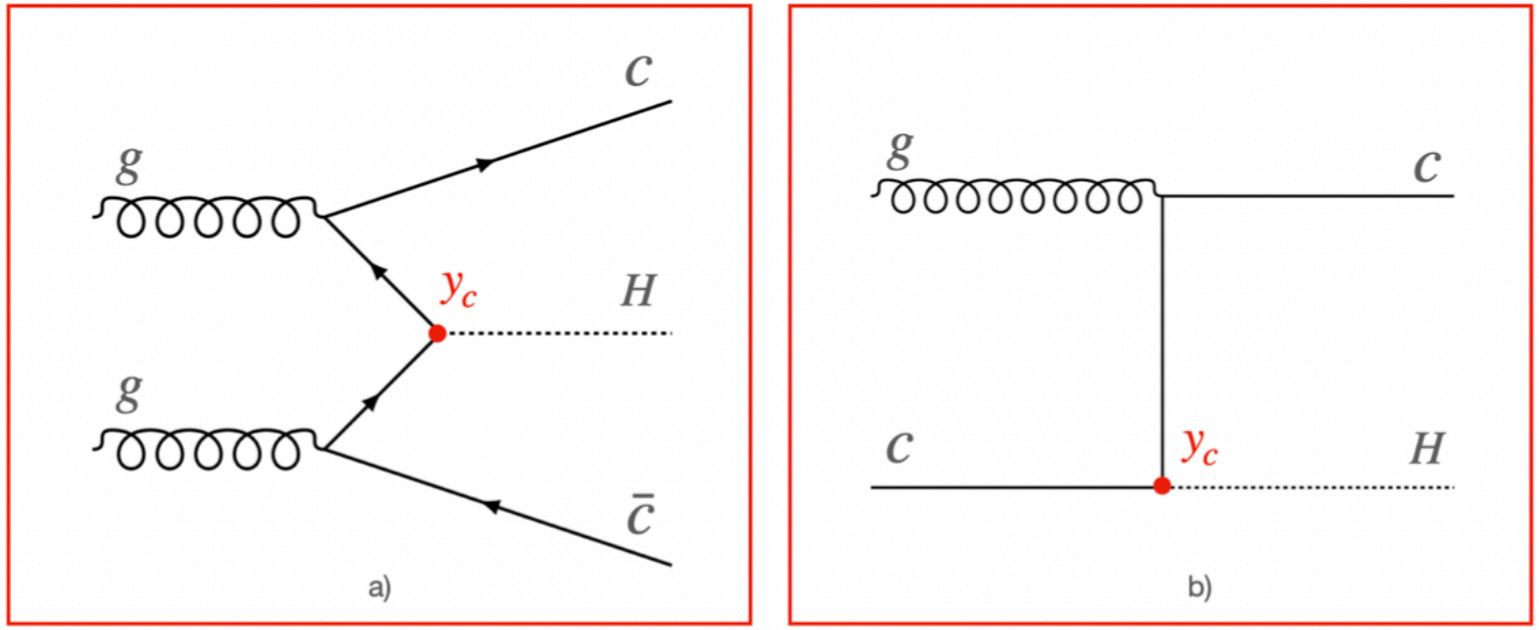



- **Excluded $\kappa_{2V} = 0$**
- Combined single-Higgs and double-Higgs analyses provide results with fewer assumptions

# *c(c)H production*

# c(c)H production




- To improve the experimental sensitivity for Higgs coupling to c quarks, one possibility is to look for c(c)H production
  - Challenging because of ggH background

# c(c)H production

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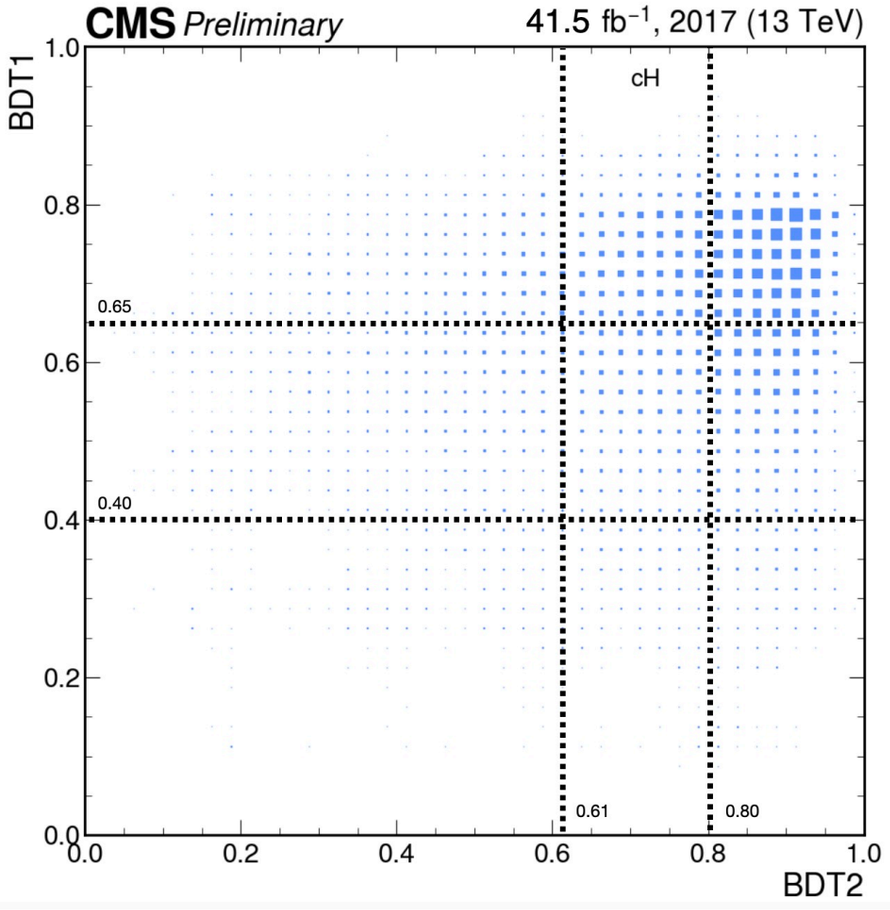


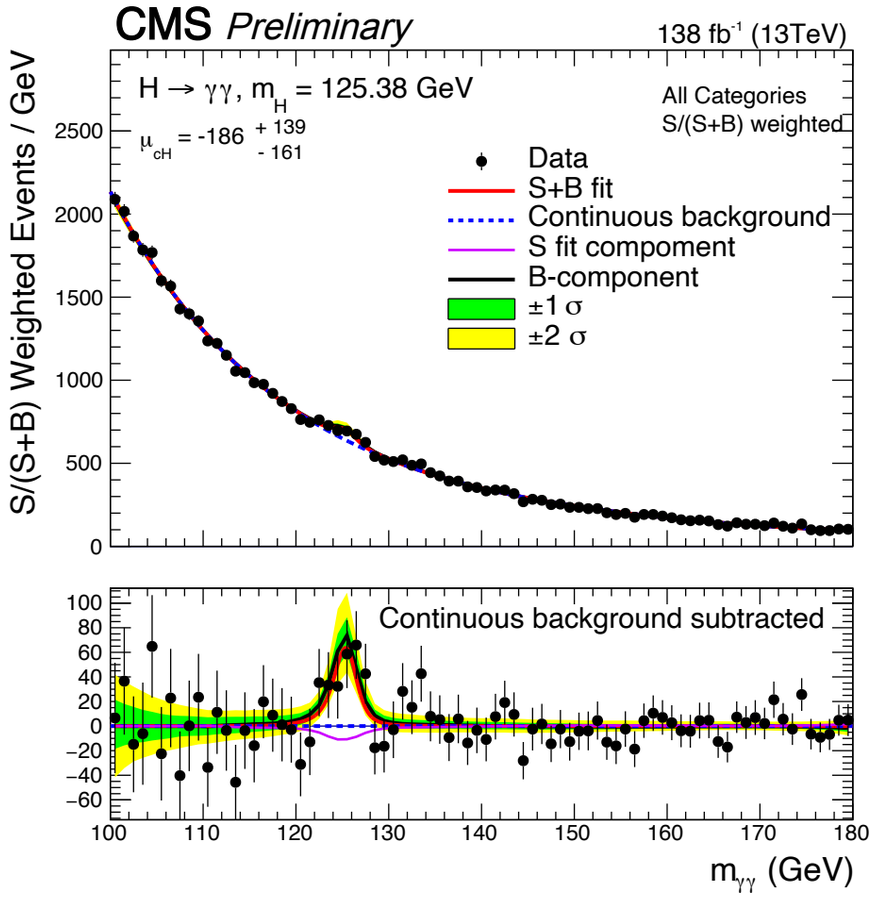


- CMS presents the first search for cH, focusing on the diphoton decay channel of the Higgs boson
- The observed upper limit on the cH signal strength is 243 times the SM prediction
- The observed allowed interval on $\kappa_c$, the Higgs boson-charm quark coupling modifier, is **|Kc | < 38.1**

# Summary

- **CMS experiment has a large program to study Higgs boson rare productions and decays and keep improving sensitivities**
  - Results are so far consistent with the SM predictions
  - First evidence of $H \to \mu\mu$ and $H \to Z\gamma$
  - Excluded $\kappa_{2V} = 0$ (using HH)
- **Run 3 is ongoing. Stay tune for the new results!**
- Also see Yongfeng Zhu's talk on Higgs rare decays with future colliders

*Thank you!*