Probe BSM physics with the interaction between the Higgs boson and top quark

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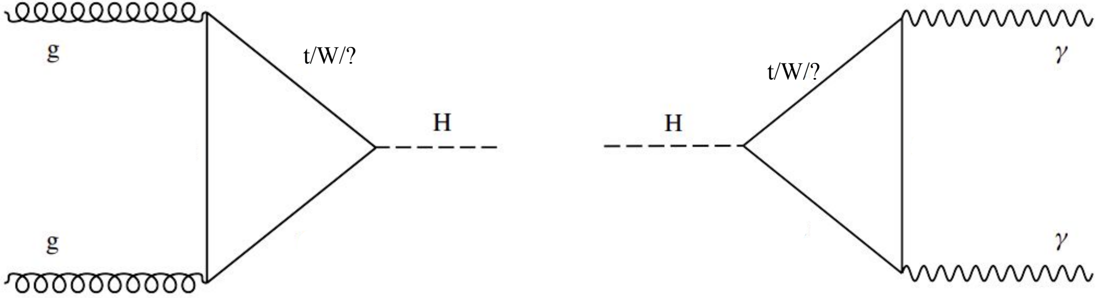
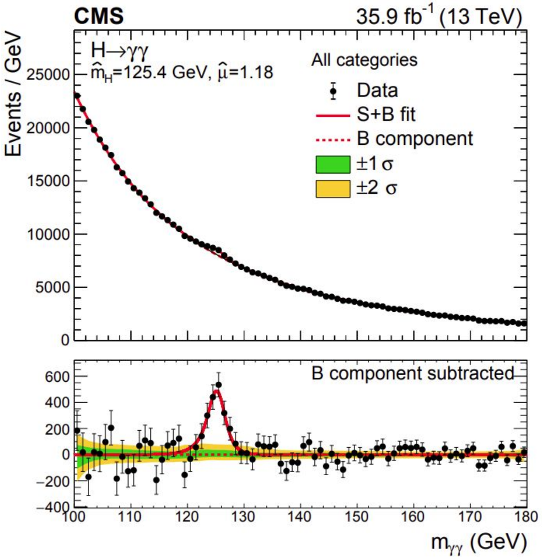
Top-Higgs Yukawa Interaction

- Yukawa interaction a **fundamental interaction** of the Standard Model (SM)
- In the SM, the Yukawa coupling between the Higgs boson and the fermion is proportional to the mass of the fermion
- Top-Higgs Yukawa coupling (Htt) being the largest



Indirect access to top-Higgs Yukawa coupling



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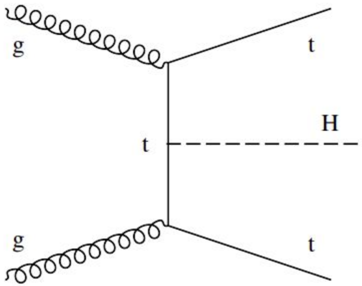
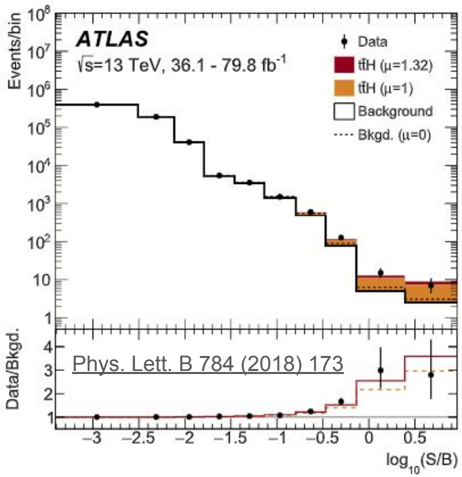
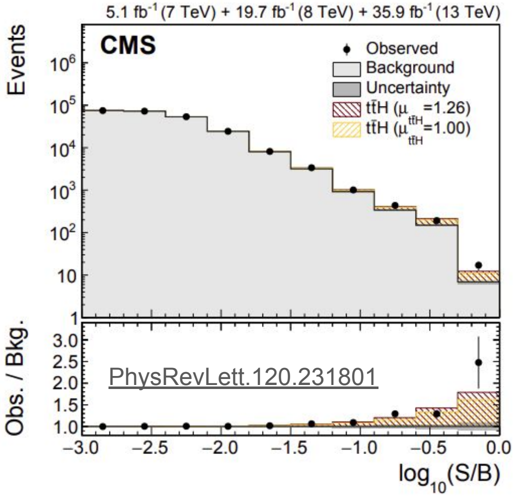
Direct probe of the top-Higgs Yukawa interaction



- Using ttH production is the most direct way to probe the top-Higgs Yukawa interaction
- Production cross section for ttH at the 13 TeV LHC is ~0.5 pb, corresponding to ~1% of the total Higgs bosons produced



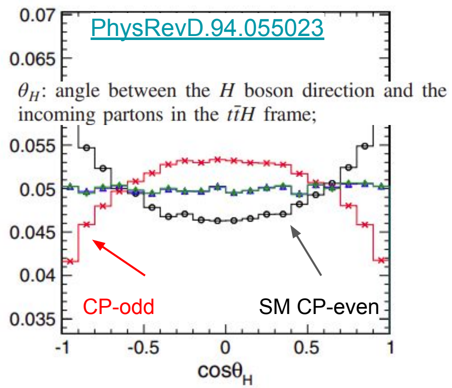


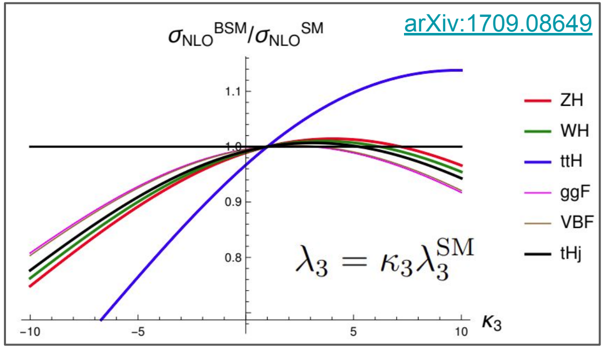
Both the CMS and ATLAS collaborations observed the ttH production with a combination of Run 1 and partial Run 2 dataset in 2017

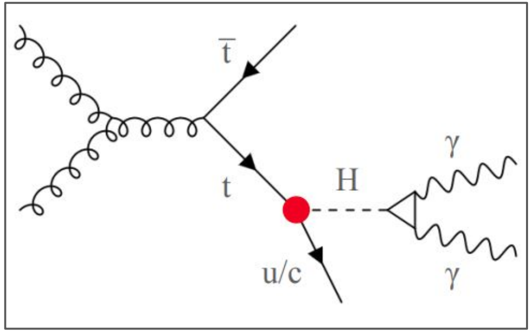
top-Higgs interaction as probes to BSM physics

This talk will use a collection of recent Run 2 CMS results, **based on H →γγ**, to illustrate 3 possible ways to explore BSM physics based on top-Higgs interaction

1. Measure the t-H Yukawa properties, test if there is small deviation from the SM
2. Use ttH production as a handle to better constrain the H trilinear self-coupling
3. Direct search of BSM t-H interactions

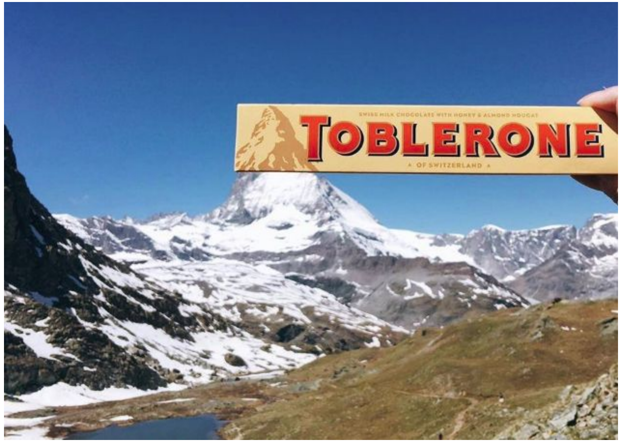




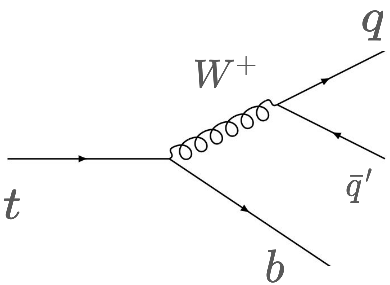


The foundation: a solid ttH(H→γγ) analysis

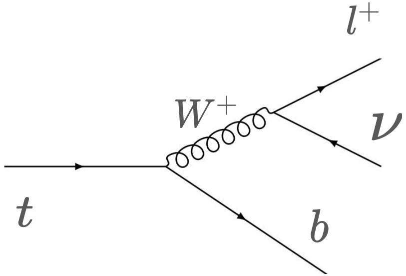
- Fit diphoton invariant mass distribution to extract parameters of interest
  - e.g., cross section, CP structure
- Utilize signatures from ttbar decay to improve S/B
  - Jet/lepton multiplicity
  - Jet triplet consistent with top quark decay
  - Event kinematics and flavour/top tagging information that are sensitive to differences between signal and background



Hadronic:
No isolated lepton
n-jet >= 3, n-bjet >= 1



Leptonic:
>= 1 isolated lepton
n-jet >= 1

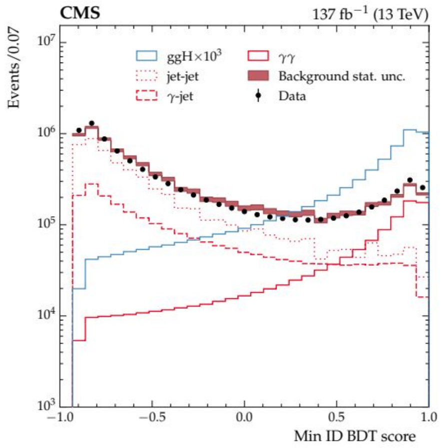


Main backgrounds

Leptonic

- ttbar + diphoton
- ttbar + 1/0 photon

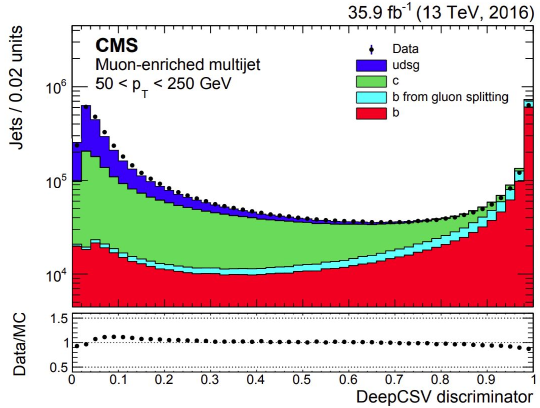
Use photon ID BDT score to suppress background with fake photons



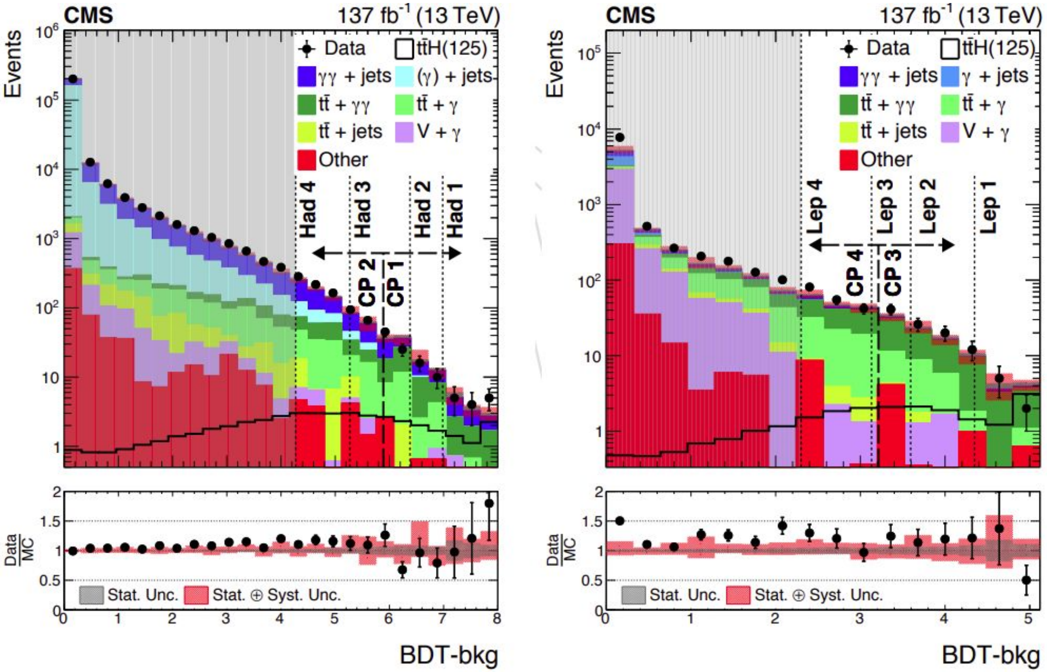
Hadronic

- Multi-jet + diphoton
- Multi-jet + 1/0 photon
- ttbar + diphoton
- ttbar + 1/0 photon

Use jet multiplicity and b-tagging score of individual jet to suppress non-ttbar background



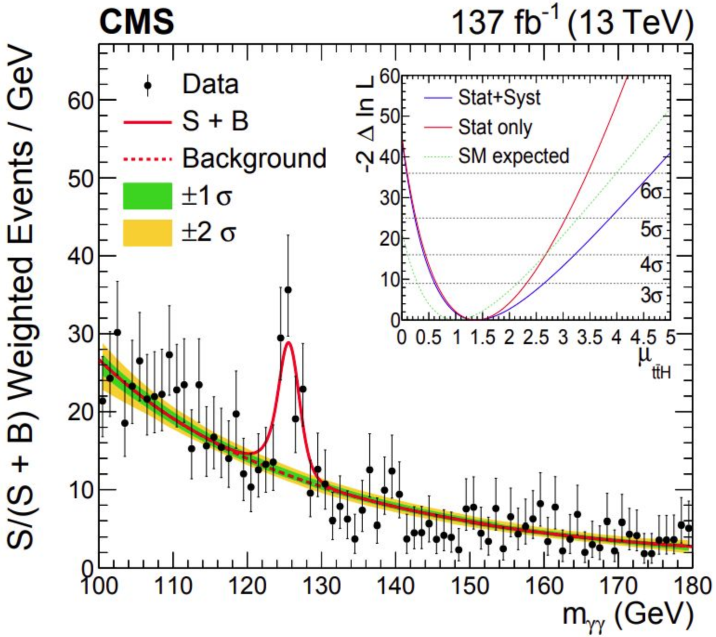
BDT-bkg performance



100 < $m_{\gamma\gamma}$ < 120 GeV or 130 < $m_{\gamma\gamma}$ < 180 GeV

- Events are either rejected or further divided into subcategories to maximize sensitivity
- The BDT-bkg score has good separation between signal and background
- Good data-MC agreement in the signal regions

Cross section measurement



- σ_{ttH}*$BR_{\gamma\gamma}$ = $1.56^{+0.34}_{-0.32}$ fb

  $1.56^{+0.33}_{-0.30}(\mathrm{stat})^{+0.09}_{-0.08}(\mathrm{syst})$ fb
- $(\sigma_{ttH}$*$BR_{\gamma\gamma})_{SM}$ = $1.13^{+0.08}_{-0.11}$ fb
- μ_{ttH} = $1.38^{+0.36}_{-0.29}$ = $1.38^{+0.29}_{-0.27}(\mathrm{stat})^{+0.21}_{-0.11}(\mathrm{syst})$
- Observed (expected) significance: 6.6σ (4.7σ)
- **First observation of the ttH production in a single Higgs decay channel**

CP structure of the Htt coupling

- By probing the interaction between the Higgs boson and vector bosons, CMS and ATLAS have determined that the H quantum numbers are consistent with J^{PC} = 0++
- However, the CP structure of H couplings to fermions has never been tested
- The CP structure of the Htt amplitude can be parameterized as:

$$\boxed{\mathcal{A}(\mathrm{Htt}) = -\frac{m_t}{v}\bar{\psi}_t \left(\kappa_t + i\tilde{\kappa}_t\gamma_5\right)\psi_t}$$

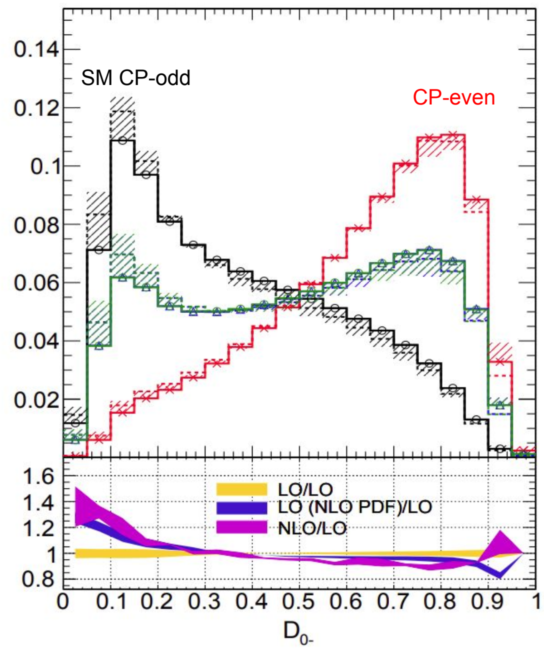
CP even yukawa coupling CP odd yukawa coupling

$* \text{ In SM, } \kappa_t = 1 \text{ and } \tilde{\kappa}_t = 0$

- Experimentally, we can test the CP structure by measuring $\boxed{f_{CP}^{Htt} = \frac{|\tilde{\kappa}_t|^2}{|\kappa_t|^2 + |\tilde{\kappa}_t|^2}\,\mathrm{sign}(\tilde{\kappa}_t/\kappa_t)}$

CP measurement strategy

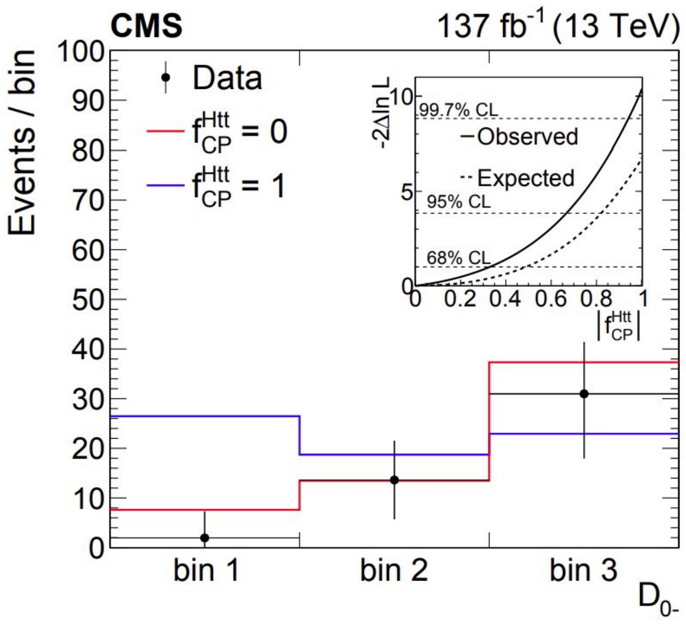
- In principle, one can use matrix element based technique to distinguish CP-even from CP-odd hypothesis
- This may not be practical for studying ttH, given the final state particles can be either mis-tagged or not reconstructable
- In practice, two BDTs were used in both Hadronic and Leptonic channels to separate CP-even from CP-odd
    - Utilize kinematic properties of jets/diphoton, b-tagging information and lepton multiplicity as input variables



PhysRevD.94.055023

PhysRevLett.125.061801

CP measurement result



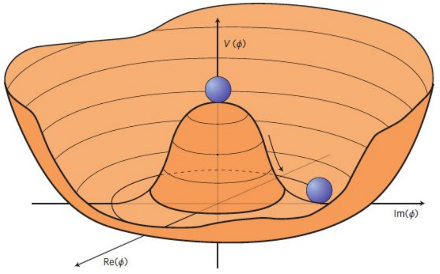
D0- represents the CP BDT output

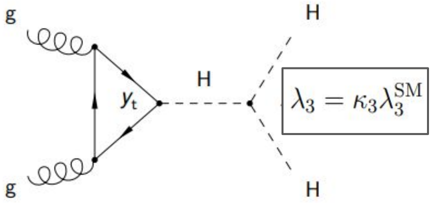
- Possible fractional CP-odd contribution

$$f_{CP}^{Htt} = 0.00 \pm 0.33$$

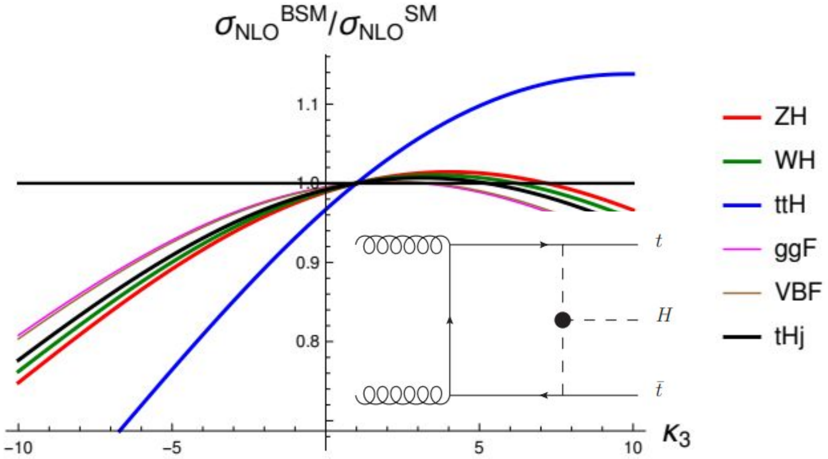
- $|f_{CP}^{Htt}|$ is constrained to be smaller than 0.67 at 95% confidence level (CL)
- Observed (expected) significance for the exclusion of pure CP-odd hypothesis: 3.2σ (2.6σ)
- **First test of CP structure of the Htt coupling**

Use ttH process to probe the H self-coupling





$$V = \frac{m_h^2}{2} h^2 + \lambda_3 v h^3 + \frac{\lambda_4}{4} h^4$$



- Understand the shape of the Higgs potential is one of the most important goals of the HL-LHC physics program
- Both the HH and H production cross section depends on κ_λ
- In the case of anomalous values of κ_λ, <u>which are signs of new physics</u>, the single H process with the largest modification of the cross section is ttH

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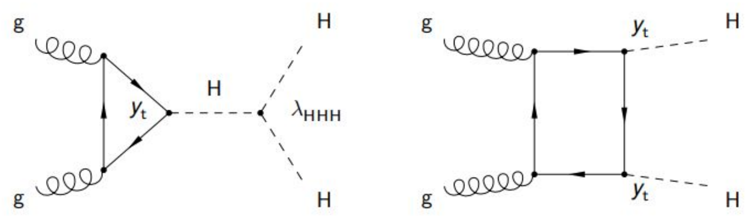
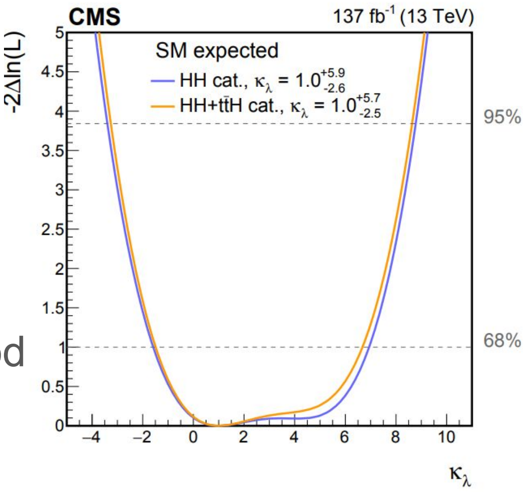
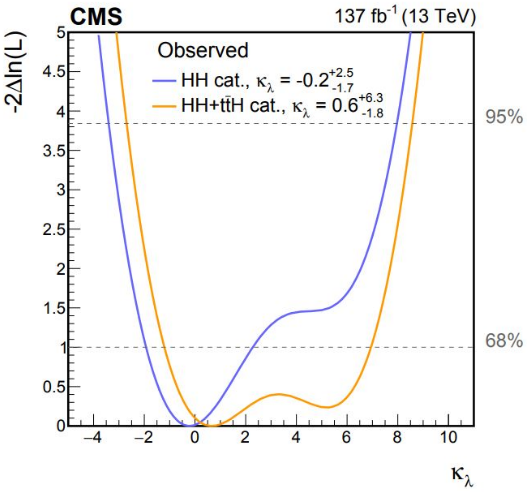
Application in CMS Run 2 HH→bbγγ result



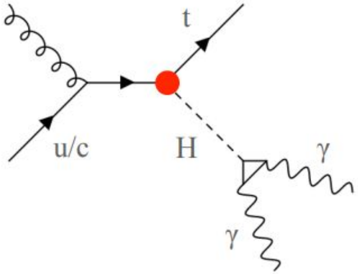
One of the most sensitive channels to HH production due to large Br(H→bb) and good mass resolution of the H → γγ channel

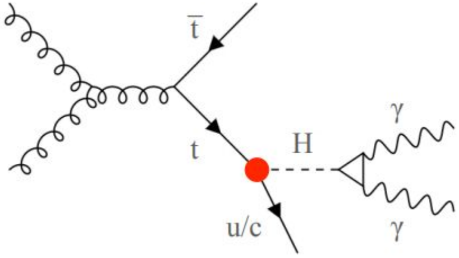




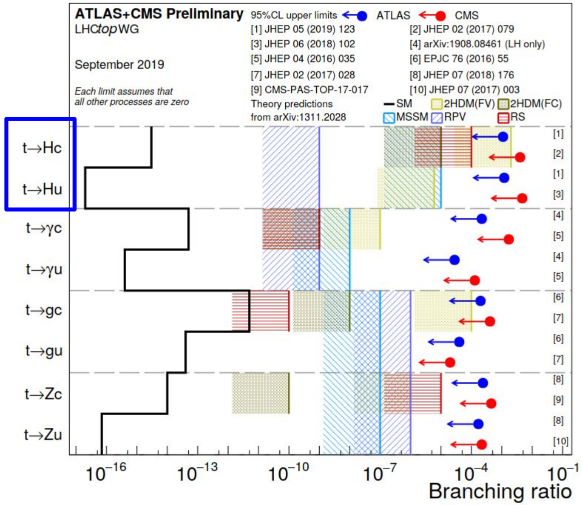
- Additional orthogonal categories targeting the ttH process are included
- ttH leptonic and hadronic categories are developed and optimized for the measurement of the ttH production cross section
- **The sensitivity of constraining κ_λ increases by 5% when fitting the HH and ttH categories simultaneously**

Direct search of BSM t-H interactions (e.g. FCNC)



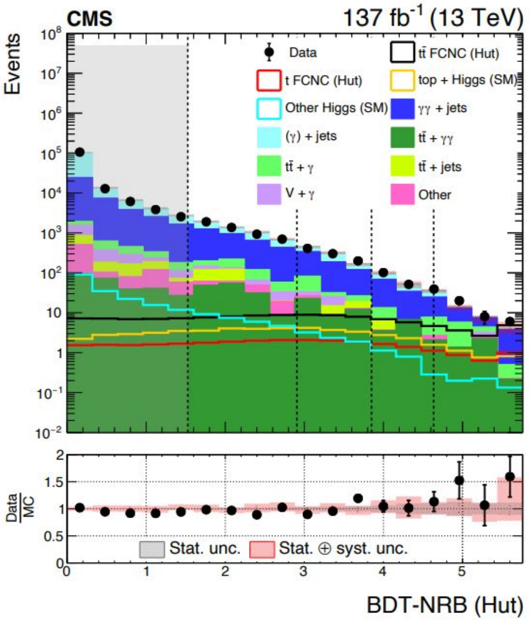


Status of top FCNC results as in 2019

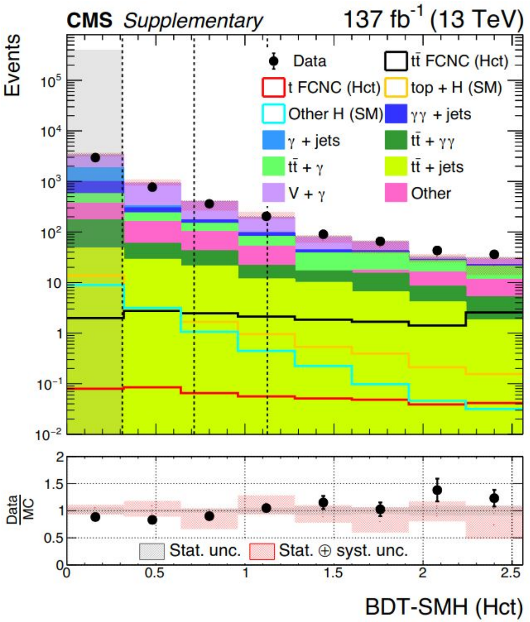


- $t \rightarrow H + u/c$ through a Flavour Changing Neutral Current (FCNC) is forbidden at tree level and suppressed through the GIM mechanism (BR < $O(10^{15})$)
- In many scenarios of BSM model, the $t \rightarrow Hq$ branching fractions are enhanced by many orders of magnitude w.r.t SM values, thus motivates the search for top-Higgs FCNC process

Search strategy



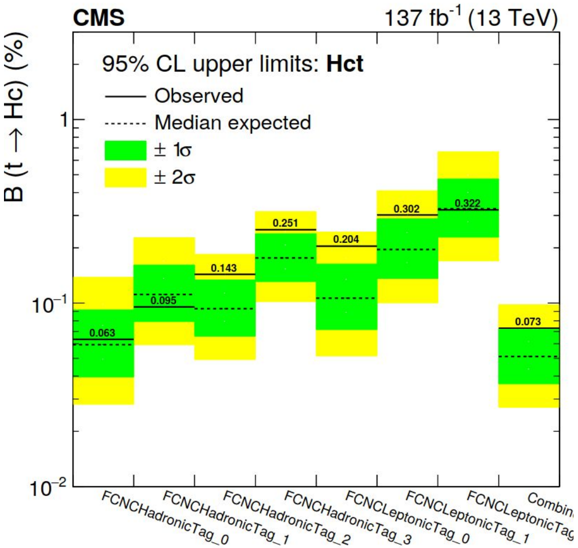
BDT targets non-resonant bkg

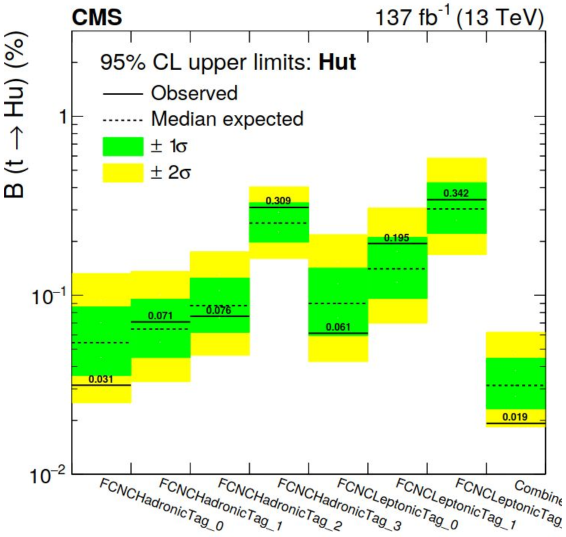


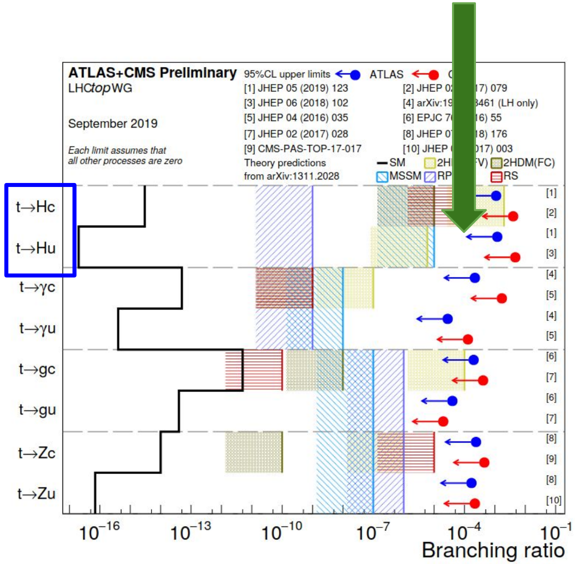
BDT targets SM Higgs bkg

- In a recent search of t-H FCNC based on H→γγ, the strategy is largely based on previous SM ttH(H→γγ) measurement
- Utilize multiple methods (MVA+kinematic fit) trying to reconstruct the top candidate
- Use two dedicated BDTs targeting both non-resonant background (ttbar, GJets etc) and SM Higgs backgrounds (ttH)

New CMS limit with using Run 2 dataset



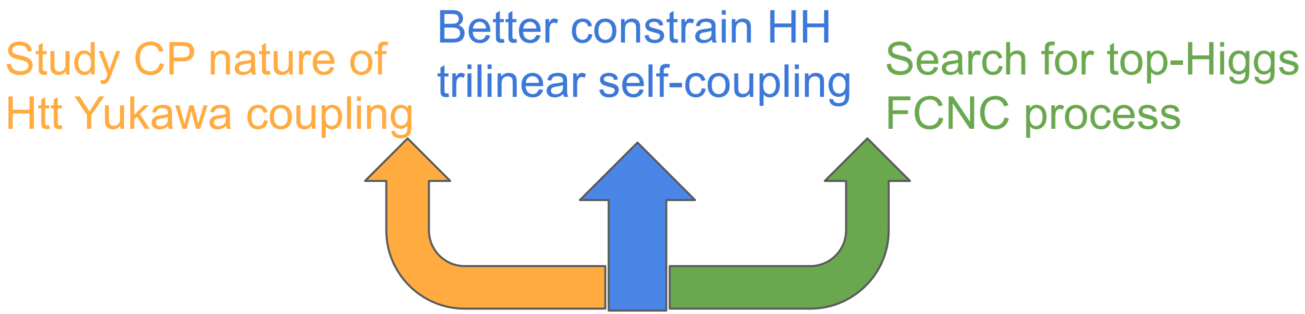




- The observed (expected) upper limits on B(t → Hu) and B(t → Hc) are 1.9×10^{-4} (3.1×10^{-4}) and 7.3×10^{-4} (5.1×10^{-4}), respectively
- **Current world's best limits**, almost an order of magnitude better than previous results with partial (2016) Run 2 data combination (H→γγ + H→bb + H→leptons)

Summary

- Since of observation of ttH production in 2018, the top-Higgs interaction has opened up many new opportunities for the probe of new physics beyond the standard model
- This talk has summarized 3 examples to explore potential BSM physics



- More opportunities are ahead of us in the future LHC runnings, stay tuned!