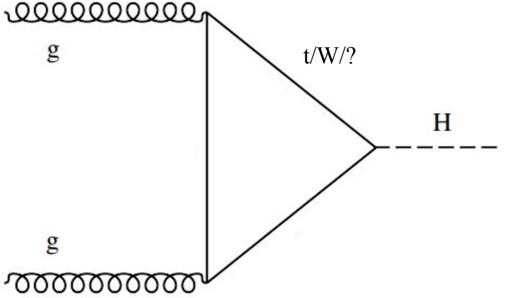
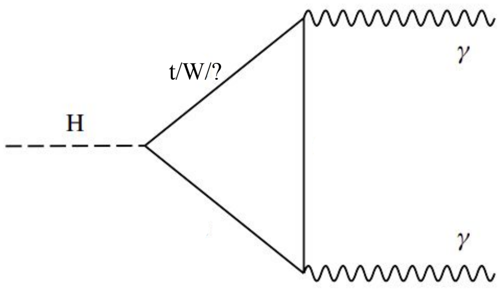
Studies of the top-Higgs interaction with the CMS experiment

梅华林
University of California, Santa Barbara

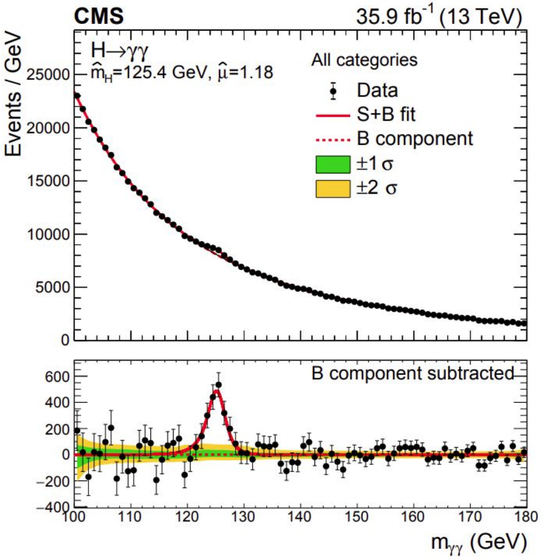
Top-Higgs Yukawa Interaction

- 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



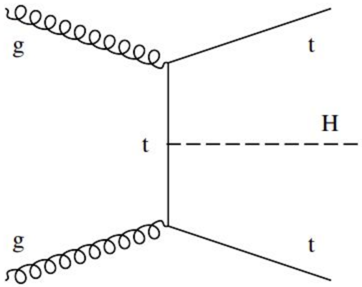


Indirect access to top-Higgs Yukawa coupling

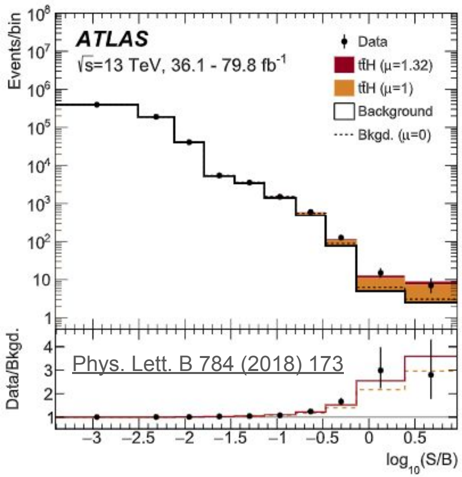


JHEP11(2018)185

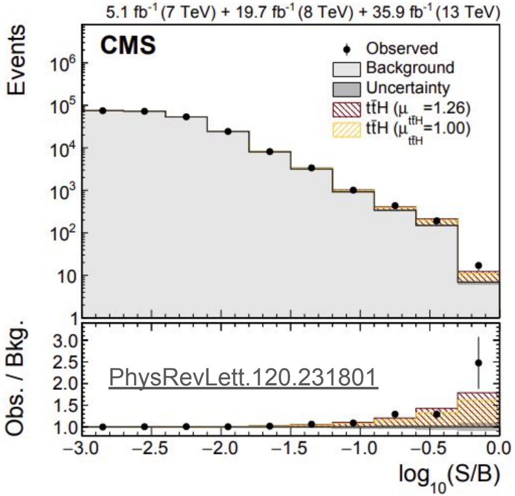
Direct probe of the top-Higgs Yukawa interaction



- 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



Phys. Lett. B 784 (2018) 173

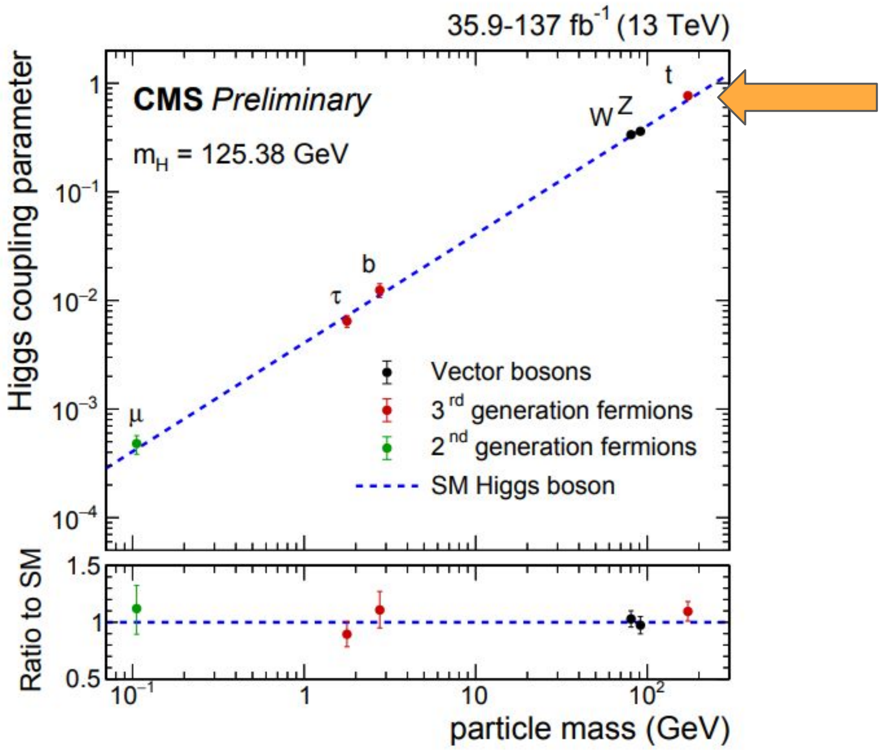


PhysRevLett.120.231801

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

Why studying top-Higgs interaction

- A basic test of the Standard Model

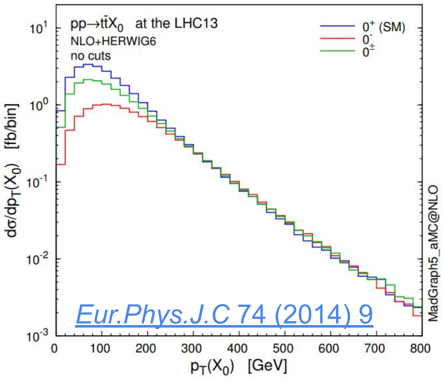


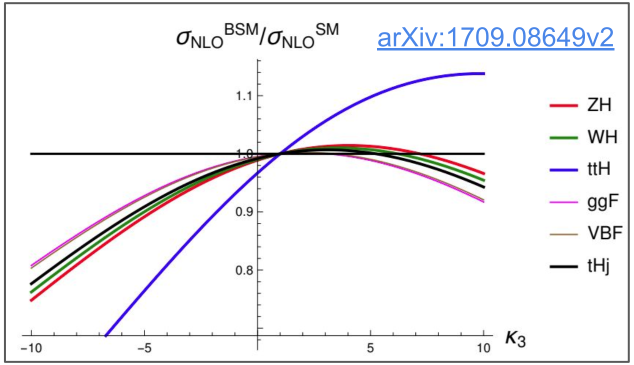
JHEP 01 (2021) 148

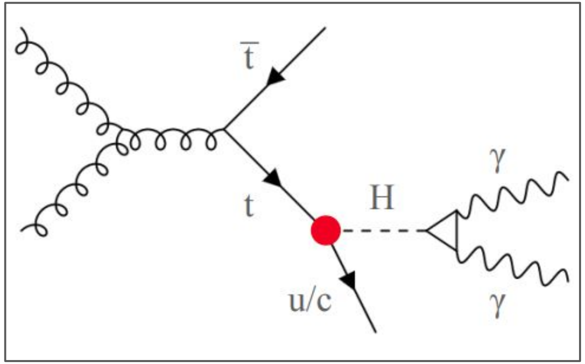
Why studying top-Higgs interaction

- A basic test of the Standard Model
- Opens up new opportunities to probe BSM physics, a few examples:

1. Precise measurement to probe 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







Why studying top-Higgs interaction

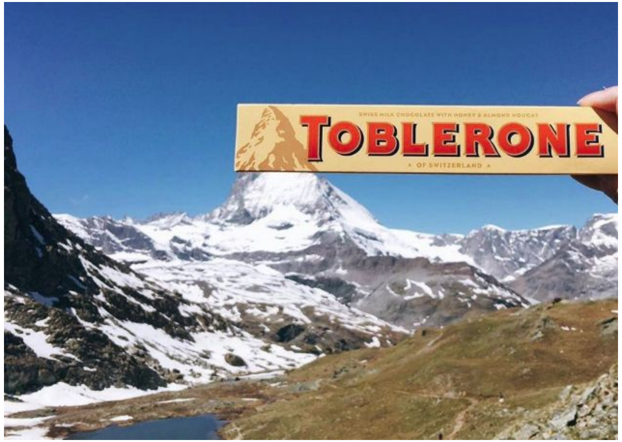
- A basic test of the Standard Model
- Opens up new opportunities to probe BSM physics, a few examples:

1. Precise measurement to probe 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

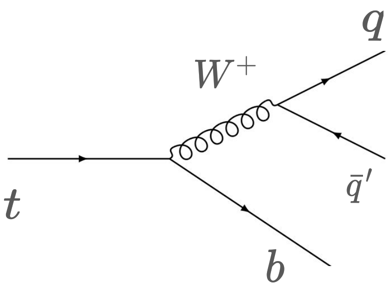
In this talk, I will discuss recent Run 2 results from the CMS collaboration featuring the study of top-Higgs interaction using the Higgs to diphoton decay channel

ttH(H→γγ) analysis: a brief introduction

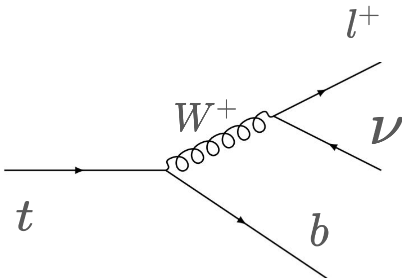
- Fit diphoton invariant mass distribution to extract parameters of interest
  - e.g., cross section, CP structure
- Utilize signatures from ttbar decay to improve S/B
  - Jet/lepton multiplicity
  - Jet triplet consistent with top quark decay
  - Event kinematics and flavour tagging information that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



Hadronic top decay:
no isolated lepton



Leptonic top decay:
1 isolated lepton

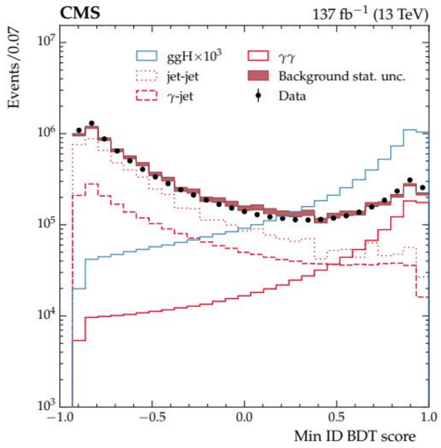


Main backgrounds

Leptonic

- ttbar + diphoton
- ttbar + 1/0 photon

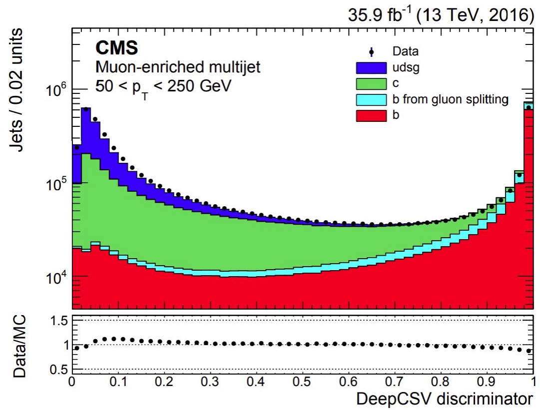
Use photon ID BDT score to suppress background with fake photons



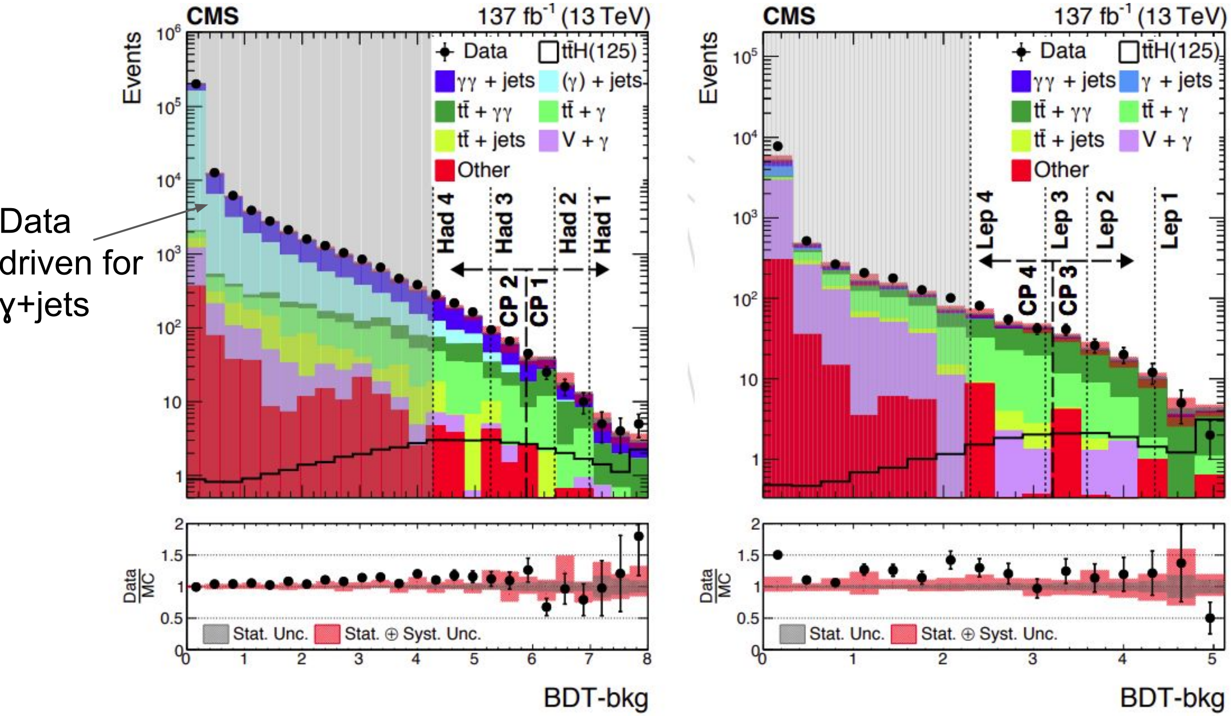
Hadronic

- 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



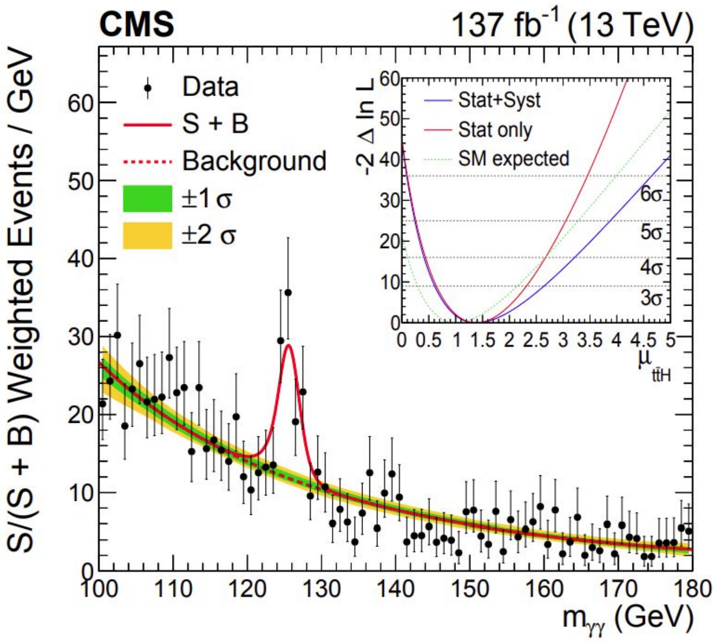
BDT-bkg performance



$100 < m_{\gamma\gamma} < 120$ 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

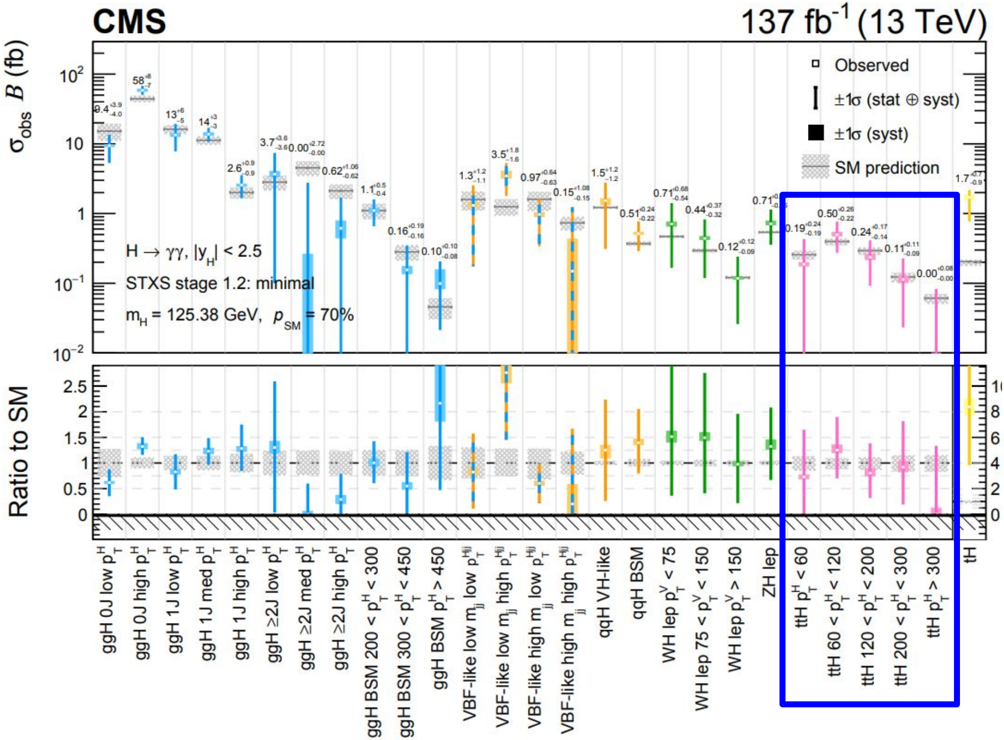
Cross section measurement



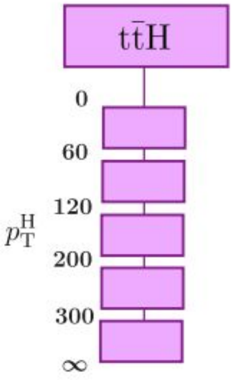
- σ_{ttH}*$BR_{\gamma\gamma}$ = $1.56^{+0.34}_{-0.32}$ fb

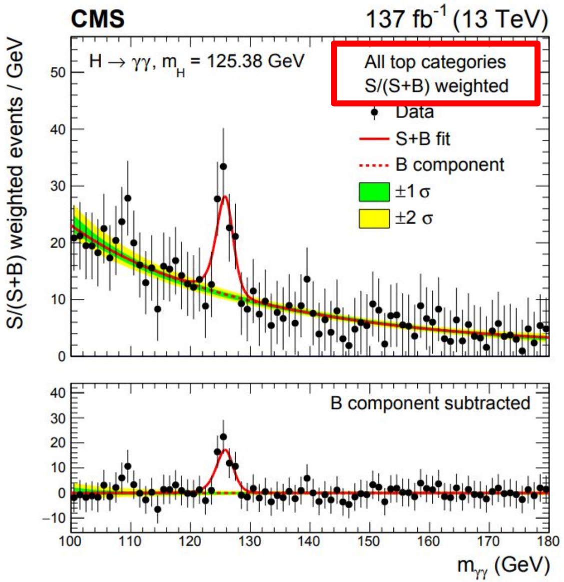
  $1.56^{+0.33}_{-0.30}(\text{stat})^{+0.09}_{-0.08}(\text{syst})$ fb
- $(\sigma_{ttH}$*$BR_{\gamma\gamma})_{SM} = 1.13^{+0.08}_{-0.11}$ fb
- $\mu_{ttH} = 1.38^{+0.36}_{-0.29} = 1.38^{+0.29}_{-0.27}(\text{stat})^{+0.21}_{-0.11}(\text{syst})$
- Observed (expected) significance: 6.6σ (4.7σ)
- **First observation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

ttH production under STXS stage 1.2



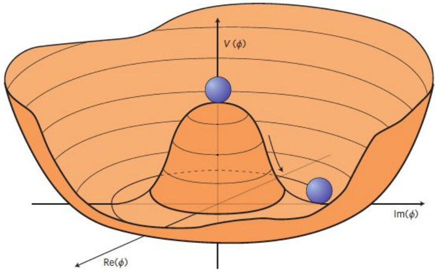
Extend sensitivity to BSM physics

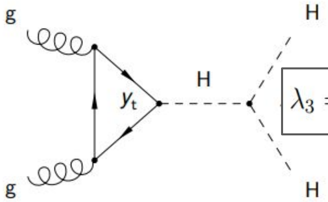




First measurement of ttH production cross section in 5 regions of the Higgs boson p_T, so far everything consistent with SM

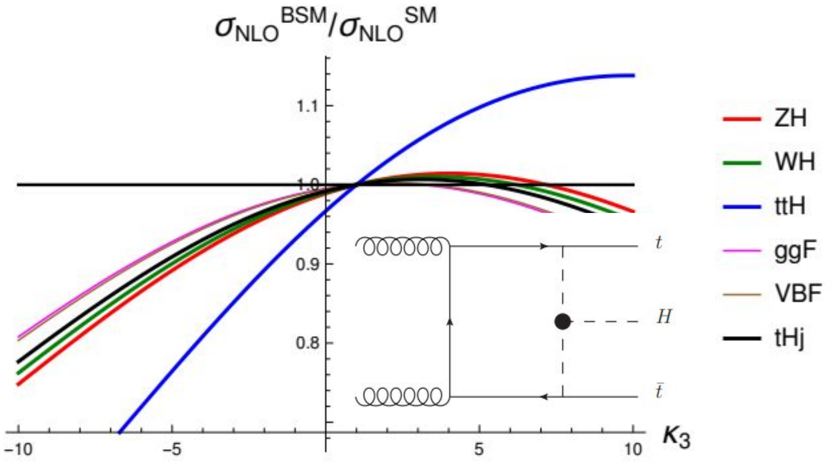
Use ttH process to probe the H self-coupling





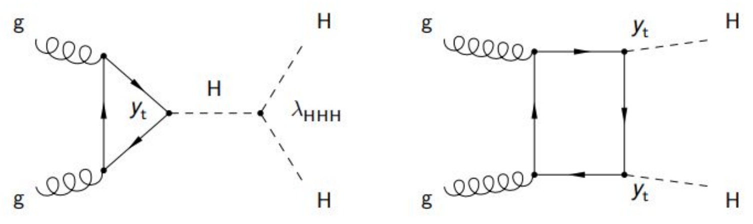
$$\lambda_3 = \kappa_3 \lambda_3^{SM}$$

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

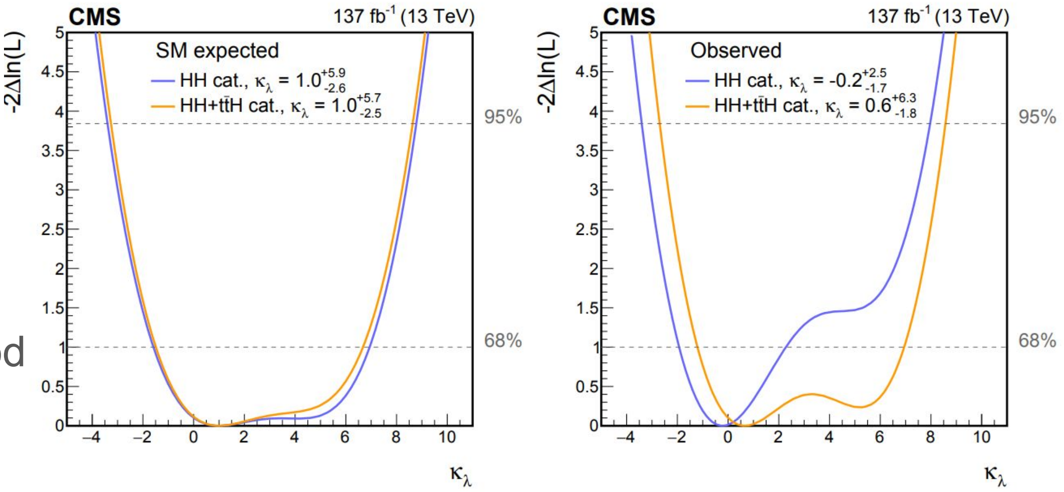


- Understanding the shape of the Higgs potential is one of the most important goals of the future LHC physics program
- Both the HH and H production cross section depends on κ_λ
- In the case of anomalous values of κ_λ, <u>which are signs of new physics</u>, the single H process with the largest modification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

Application in CMS Run 2 HH→bbγγ result

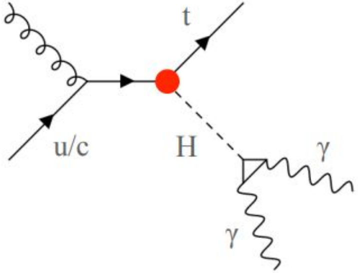


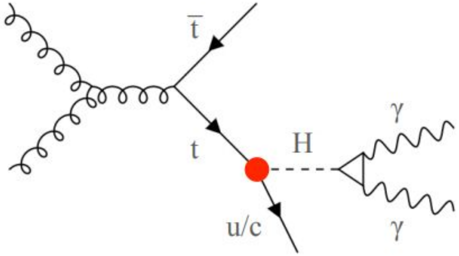
One of the most sensitive channels to HH production due to large Br(H→bb) and good mass resolution of the H → γγ channel



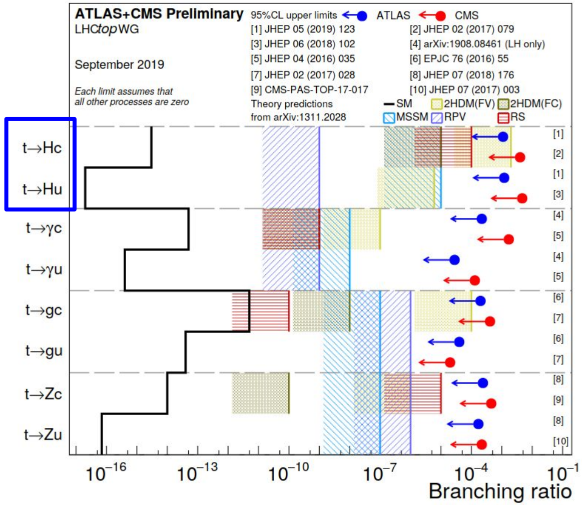
- Additional orthogonal categories targeting the ttH process are included
- Use ttH categories developed for ttH cross section measurement
- **The sensitivity of constraining κ_λ increases by 5% when fitting the HH and ttH categories simultaneously**

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





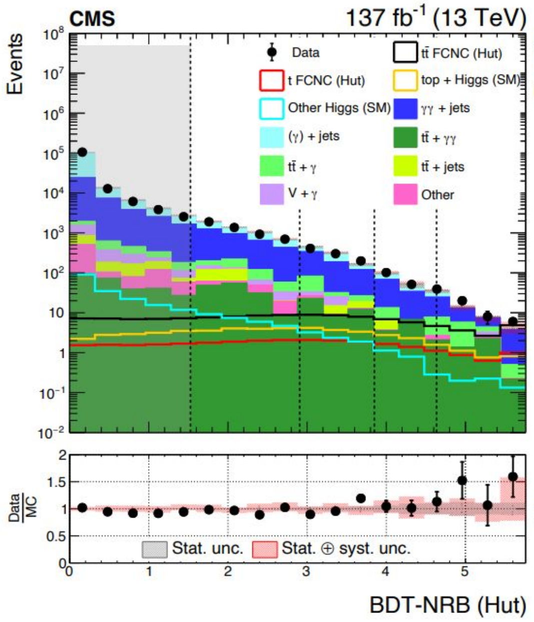
Status of top FCNC results as in 2019



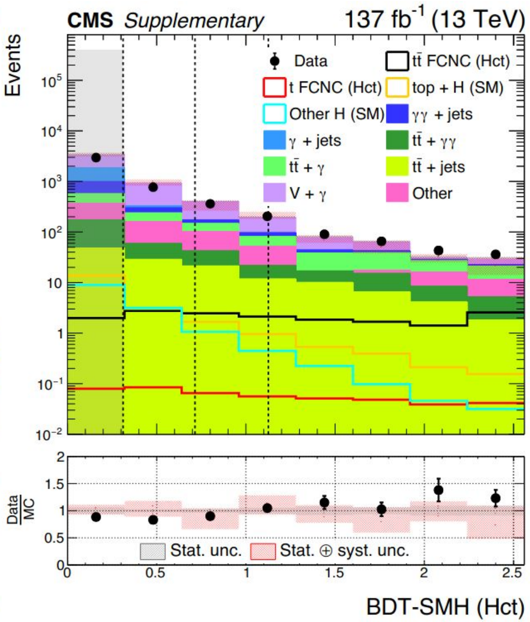
- $t \rightarrow H + u/c$ through a Flavour Changing Neutral Current (FCNC) is highly suppressed in the SM (BR < $O(10^{-15})$)
- In many scenarios of BSM model, the $t \rightarrow Hq$ branching fractions are enhanced by many orders of magnitude, thus motivates the search for top-Higgs FCNC process

arXiv:2111.02219

Search strategy



BDT targets non-resonant bkg

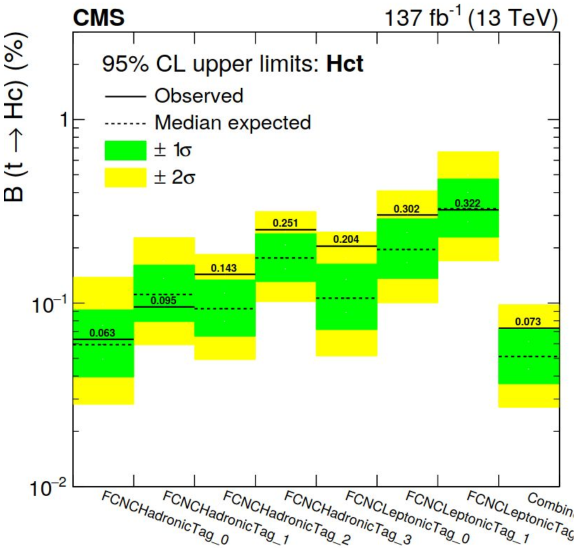


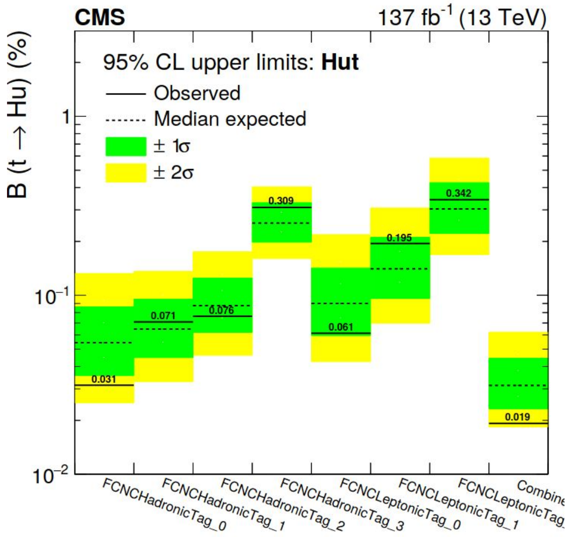
BDT targets SM Higgs bkg

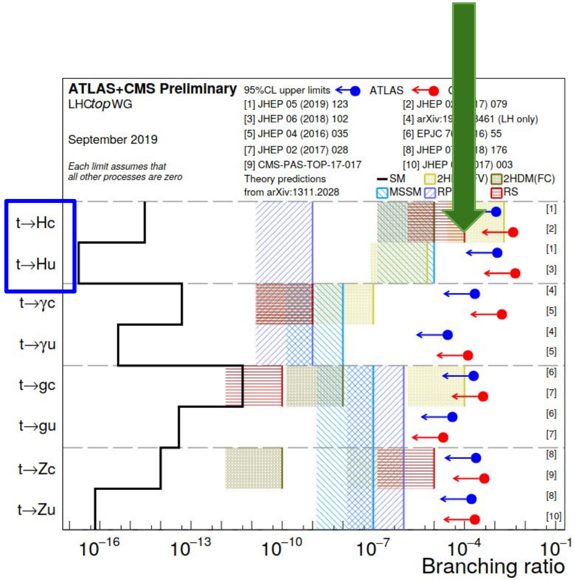
- Recent search of t-H FCNC with H→γγ, strategy is largely based on ttH(H→γγ) xs measurement
- Multiple methods (MVA/kinematic fit) to reconstruct the top candidate
- Two dedicated BDTs targeting both non-resonant (ttbar, GJets etc) and SM Higgs backgrounds (ttH)

arXiv:2111.02219

New CMS limit with using Run 2 dataset



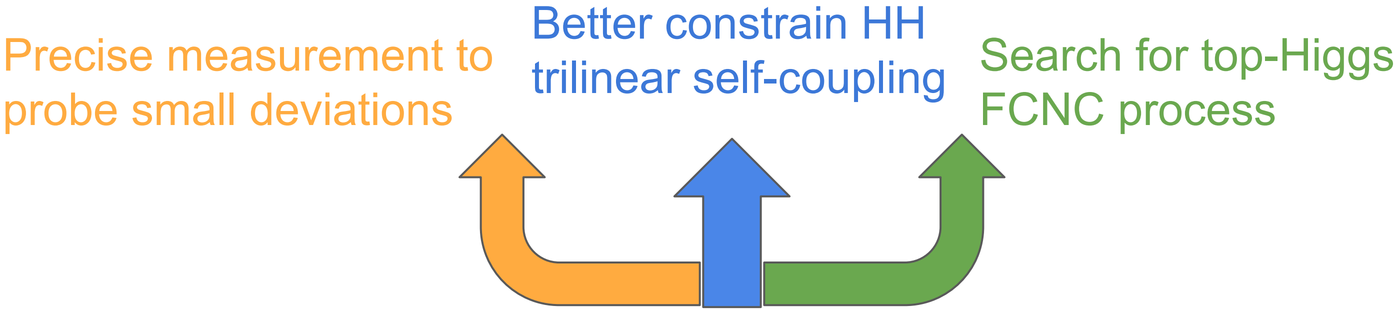




- The observed (expected) upper limits on B(t → Hu) and B(t → Hc) are 1.9×10^{-4} (3.1×10^{-4}) and 7.3×10^{-4} (5.1×10^{-4}), respectively
- **Current world's best limits**, almost an order of magnitude better than previous results with partial (2016) Run 2 data combination (H→γγ + H→bb + H→leptons)

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 using t-H interaction



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

Backup

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:

$$\mathcal{A}(\mathrm{Htt}) = -\frac{m_\mathrm{t}}{v}\bar{\psi}_\mathrm{t}\left(\kappa_\mathrm{t} + \mathrm{i}\tilde{\kappa}_\mathrm{t}\gamma_5\right)\psi_\mathrm{t}$$

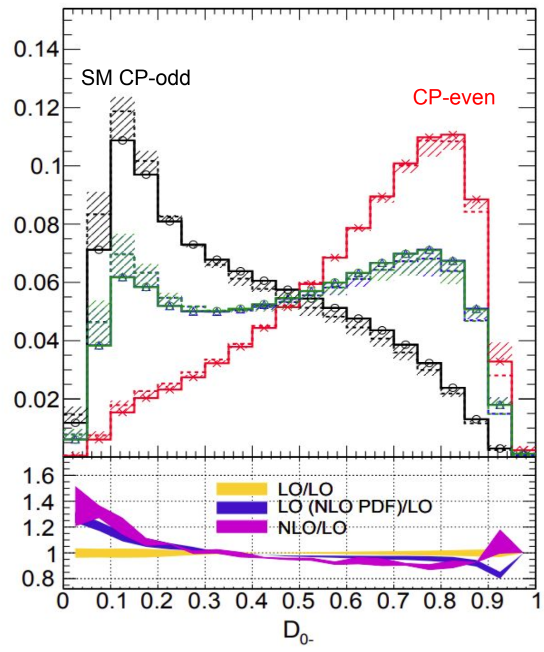
CP even yukawa coupling (→ κ_t)   CP odd yukawa coupling (→ $\tilde{\kappa}_\mathrm{t}$)

$*$ In SM, $\kappa_\mathrm{t} = 1$ and $\tilde{\kappa}_\mathrm{t} = 0$

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

CP measurement strategy

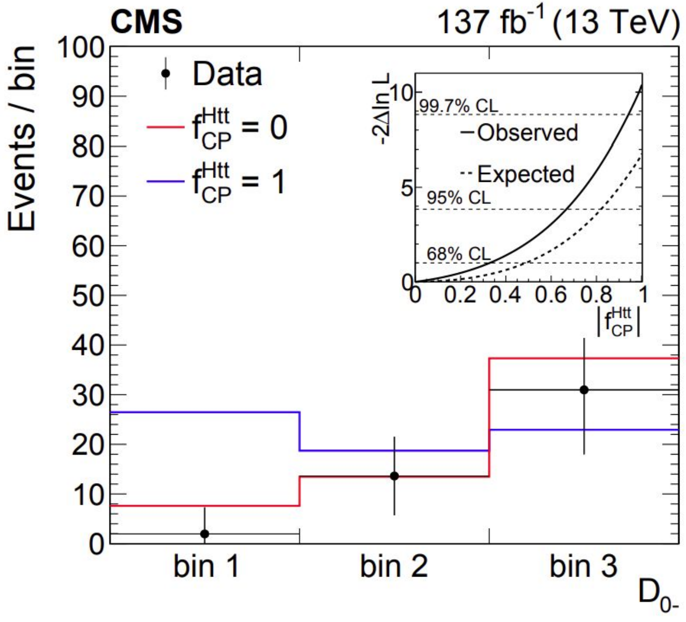
- In principle, one can use matrix element based technique to distinguish CP-even from CP-odd hypothesis
- This may not be practical for studying ttH, given the final state particles can be either mis-tagged or not reconstructable
- In practice, two BDTs were used in both Hadronic and Leptonic channels 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



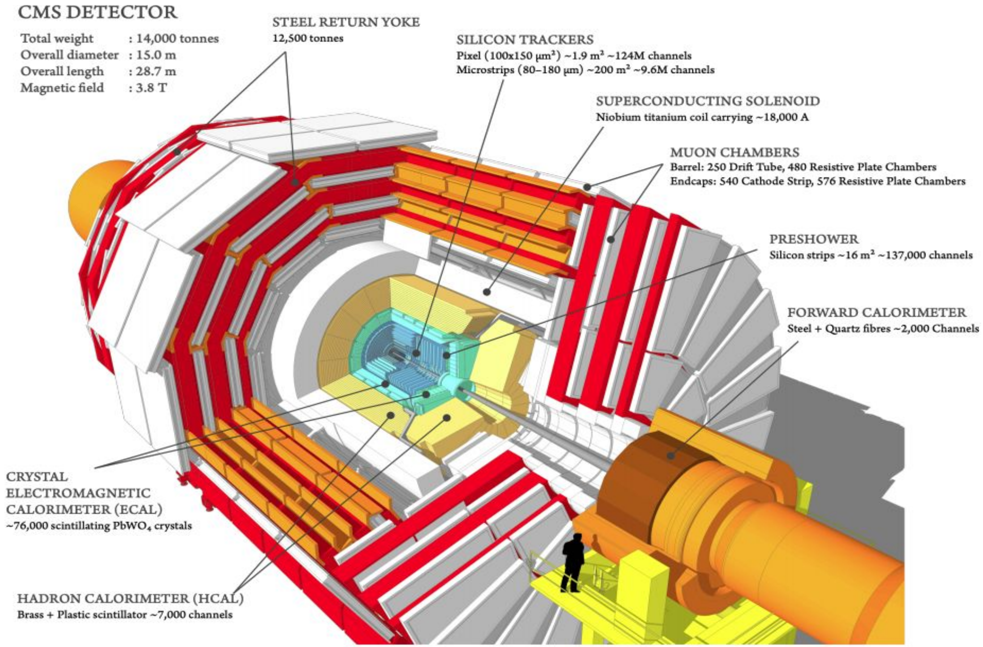
D0- represents the CP BDT output

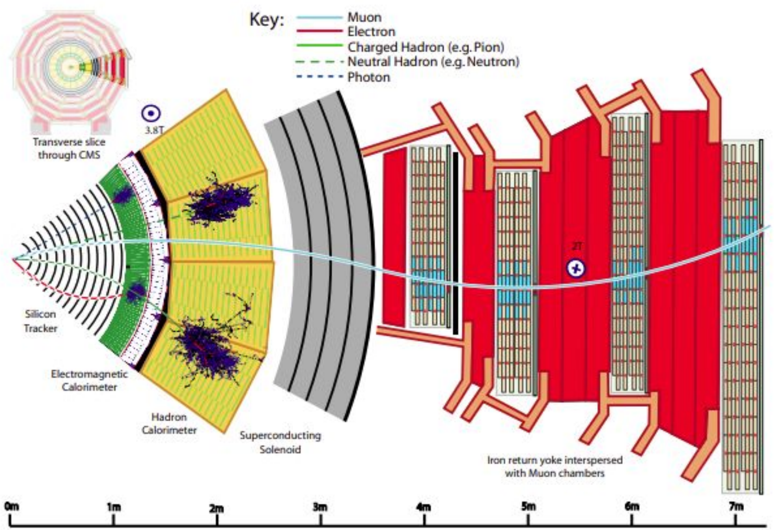
- Possible fractional CP-odd contribution

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

- $|f_{CP}^{Htt}|$ 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 (2.6 σ)
- **First test of CP structure of the Htt coupling**

The CMS detector

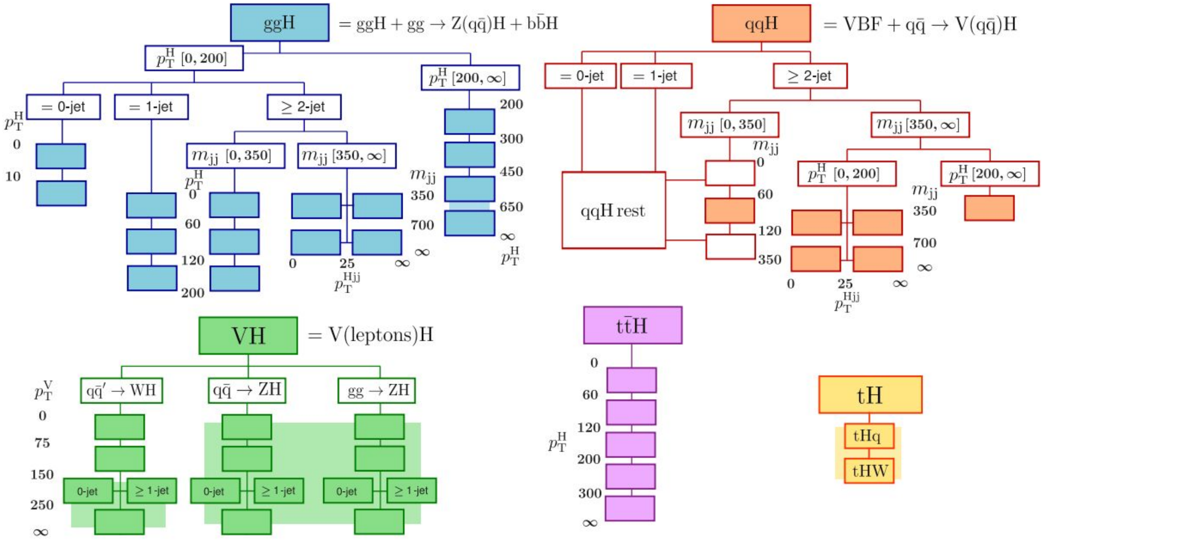


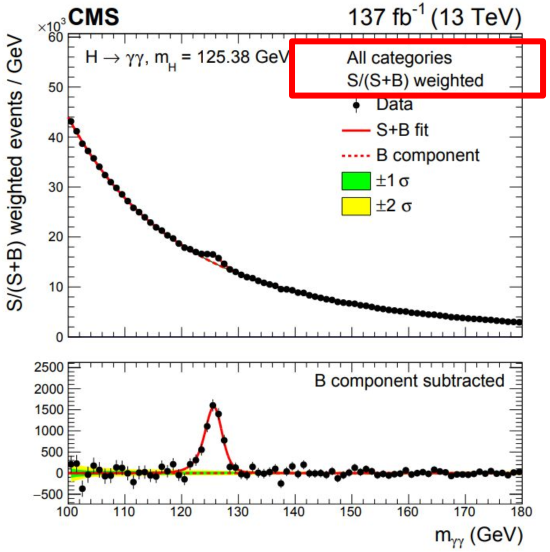


What is new in this result

- In 2018, CMS released a ttH(H→γγ) measurement with partial Run 2 dataset ($77fb^{-1}/137fb^{-1}$), **exp/obs significance: 2.7σ/4.1σ** (CMS PAS HIG-18-018)
- If considering only statistical effect (with ~2 times more data), naively one would get **3.6σ expected significance** with full Run 2 dataset
- In the end, we got **4.7σ expected**, that is **30% improvement in sensitivity**
  - Better control background estimation when training the BDT, especially using data-driven γ+jets to improve training statistics in hadronic channel
  - Better utilization of modern machine learning techniques: both the analysis level BDTs and introduced various useful input features (hadronic top-tagging BDT, dedicated DNNs for difficult backgrounds)

CMS H→ γγ Run 2 legacy result





- Under the simplified template cross section (STXS) framework, produced a comprehensive measurement of the Higgs boson properties with H → γγ channel (signal strength, STXS stage 1.2, coupling modifier) with the full Run 2 dataset (2016 + 2017 + 2018)

[JHEP 07 (2021) 027]