

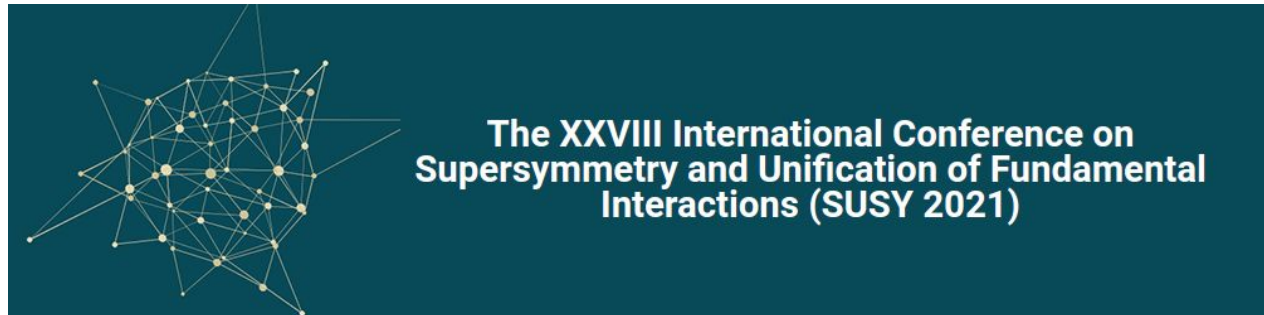


# Higgs boson measurements at CMS

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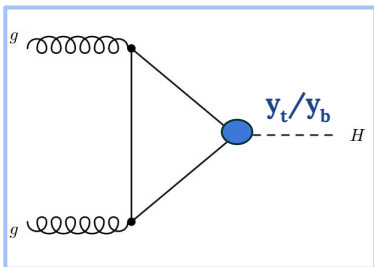
On behalf of  
CMS Collaboration, LHC, CERN.

*27 August, 2021*

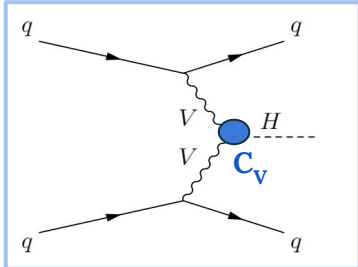


# Higgs productions, couplings and decays at the LHC

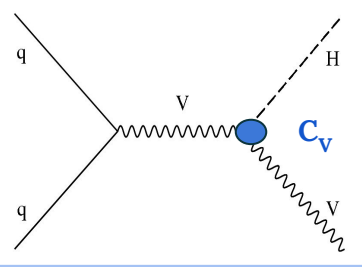
Production modes and cross sections @ 13 TeV



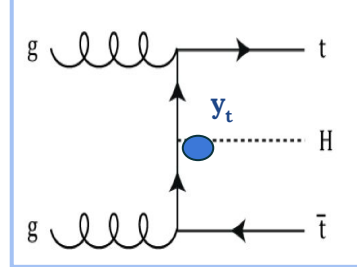
**Gluon gluon fusion (GGF)** X sec: 49 pb



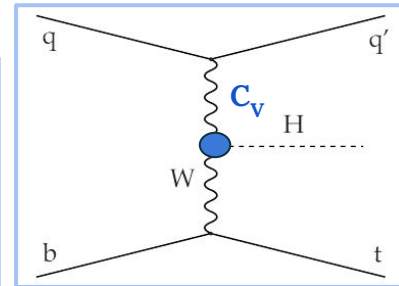
**Vector Boson fusion (VBF)** X sec: 3.8 pb



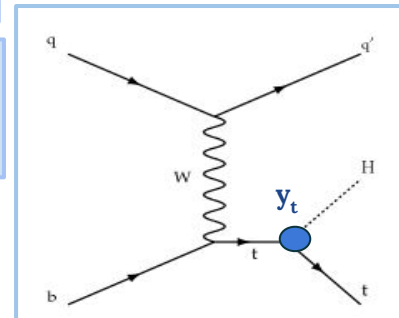
**Higgsstrahlung (VH)** X sec: 2.3 pb



**In association with a pair of top quark (ttH)** X sec: 0.5 pb

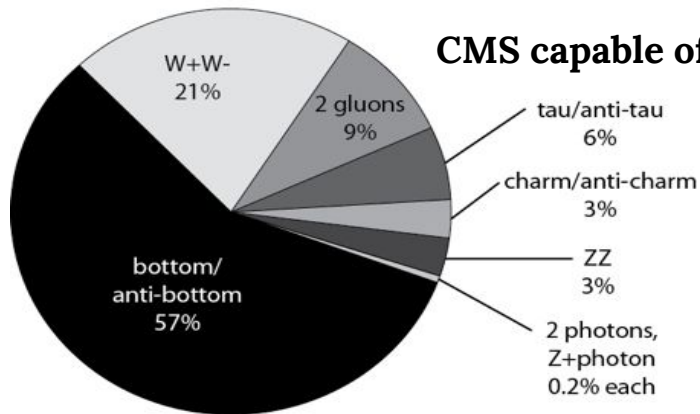


**In association with a single top quark (tH)+** X sec: 0.073 pb



Decays of a 125 GeV Standard-Model Higgs boson

**CMS capable of targeting large no. of decay modes**



Already established:

- $H \rightarrow b\bar{b}$
- $H \rightarrow W\bar{W}$
- $H \rightarrow \tau\bar{\tau}$
- $H \rightarrow Z\bar{Z}$
- $H \rightarrow \gamma\gamma$

- ❖  $H \rightarrow \mu\mu$  (evidence)
- ❖  $H \rightarrow Z\gamma$  (coming soon)

# Higgs searches at the LHC

**Run-1:**  $\sqrt{s}=7, 8 \text{ TeV}$   $\int \mathcal{L} dt = 5 \text{ fb}^{-1}, 19 \text{ fb}^{-1}$

- Discovery of Higgs bosons
- Measurement total cross sections in different modes
- Characterization: mass, spin, coupling with vector bosons

**Run-2:**  $13 \text{ TeV}$ ,  $\int \mathcal{L} dt = 137 \text{ fb}^{-1}$

- two fold gain
  - (i) increase in Higgs cross section
  - (ii) higher luminosity helps to probe and establish rarer decays
- Precision measurement of Higgs properties (mass, couplings)
- Differential cross sections
- ⇒ Use Higgs as a probe for new physics.

Couplings with Vector bosons (V):

$$C_V \propto \frac{M_V^2}{v}$$

Couplings with fermions (f):  $y_f \propto \frac{m_f}{v}$

Measurement of Higgs couplings in

**$\kappa$ - framework** ( $\kappa_V, \kappa_t, \kappa_b, \kappa_\nu, \dots$ )

$\kappa = \frac{\text{(Observed Higgs coupling)}}{\text{(Standard Model predicted value)}}$

$\kappa = 1 \Rightarrow \text{Standard Model (SM)}$

Signal strength ( $\mu$ ) =  $(\sigma * \mathcal{B}_r)^{\text{obs}} / (\sigma * \mathcal{B}_r)^{\text{SM}}$

✓ Mass  $m_H$

✓ H couplings  
with f and V

H CP study

✓ Differential cross  
section

HH (H - self coupling)

**Common strategy for CMS analyses:**

- Multivariate analysis techniques based on **boosted decision trees (BDT)** or, **Deep Neural Network (DNN)** to discriminate signals from backgrounds
- Events categorized to achieve best sensitivity.

✓ **Today's discussion**

# Combined Higgs mass measurement

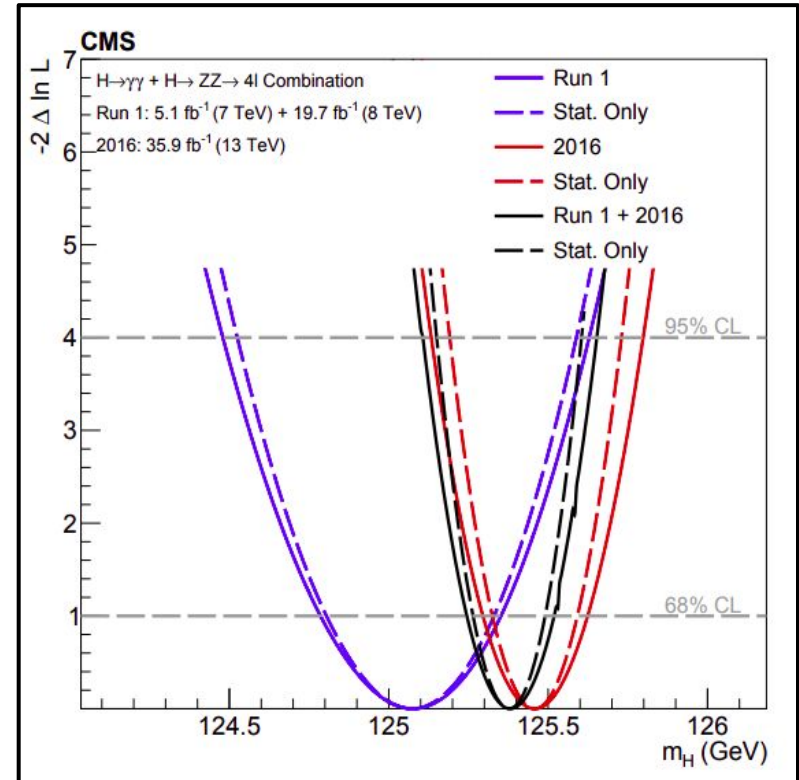
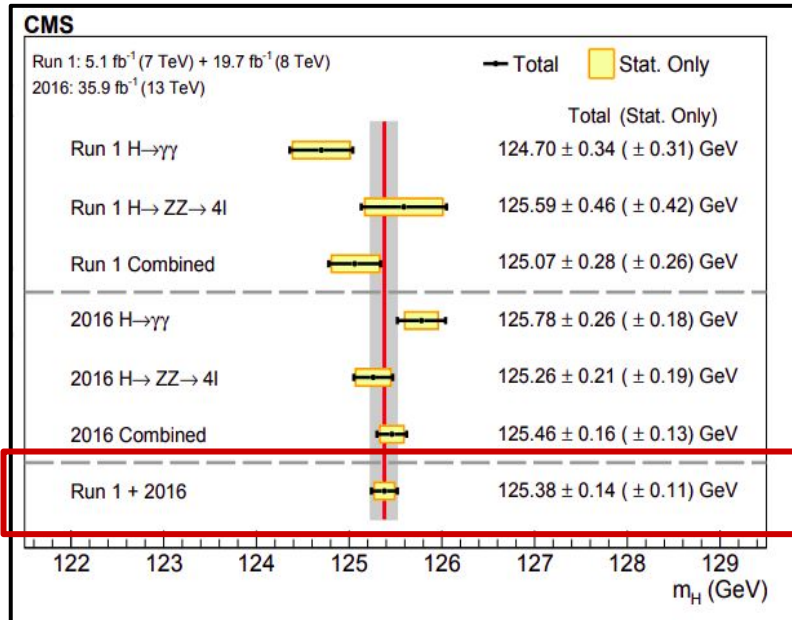
Phys Lett B. 805 (2020) 135425

Combination of 2 high resolution channels:  $H \rightarrow \gamma\gamma$  with  $H \rightarrow ZZ^* \rightarrow 4l$   
using 2016 data ( $\sim 36/\text{fb}$ ) and Run-1 data ( $\sim 25/\text{fb}$ )

$$m_H = 125.38 \pm 0.11 \text{ (stat)} \pm 0.08 \text{ (sys)} \text{ GeV}$$

→ total uncertainty  $\sim 0.21\%$ , dominated by stat (0.14%).

→ **currently the most precise measurement**



# H $\rightarrow\mu\mu$ study using full Run-2 data

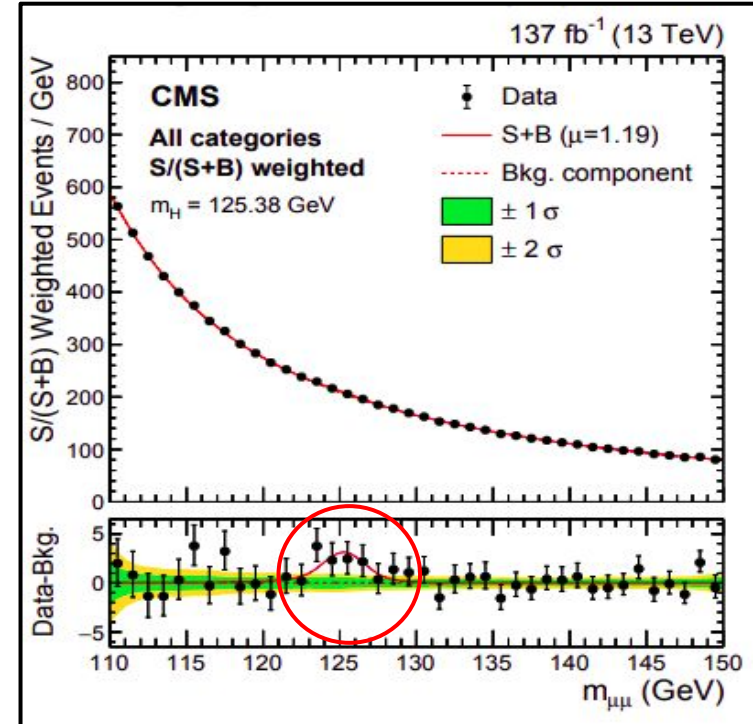
Experimental confirmation of H $\rightarrow\mu\mu$  decay is crucial to establish Higgs interaction with 2nd generation fermions.

But extremely low branching fraction:  $2.18 \cdot 10^{-4}$

- requires high luminosity
- used complete Run-2 data
- Targets all production modes
- overwhelming continuum background from **Drell-Yan**

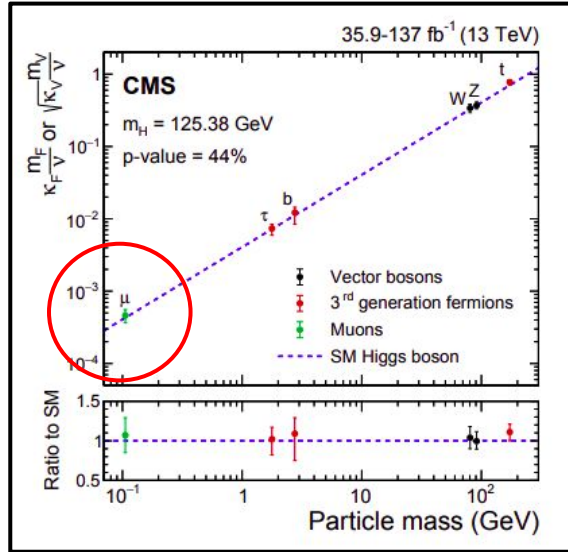
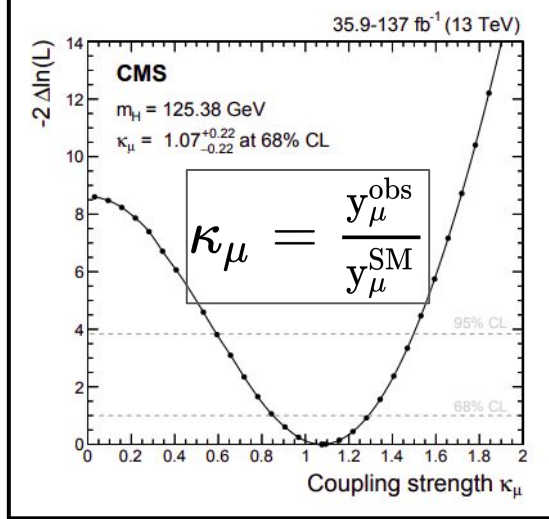
Signal extraction:

- VBF categories by performing template fit of DNN output score.
- For other production modes (ggH, VH, ttH), by fitting dimuon invariant mass ( $m_{\mu\mu}$ ) spectrum



# Results from $H \rightarrow \mu\mu$ study

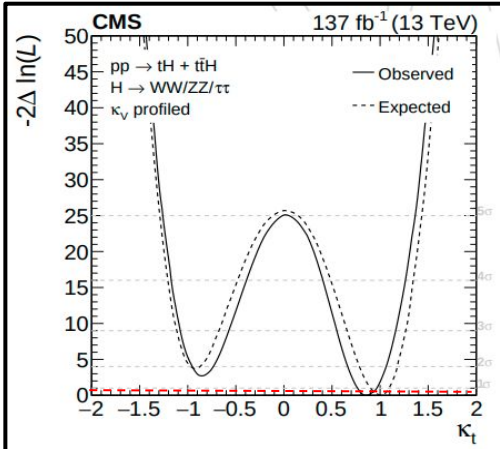
- **First evidence of  $H \rightarrow \mu\mu$  process at the LHC**
- Observed (expected) signal significance: **3.0** (2.5) $\sigma$
- Signal strength  $\mu = 1.19^{+0.44}_{-0.42}$  @68%
- Observed best fit value of  $\kappa_\mu : 1.07^{+0.29}_{-0.15}$  @ 68% CL
- **Most constrained measurement of  $\kappa_\mu$  till date.**



# ttH + tH: multilepton study

EPJC 81 (2021) 378

- **ttH**: probe magnitude of top Yukawa coupling ( $y_t$ )
- tH**: provides the sign of  $y_t$  wrt  $C_V$
- Categories based on flavour and number of final state leptons (L: e,  $\mu$ , hadronic tau  $\tau_h$ )
  - (i)  $H \rightarrow WW$ : In final state:  $2L SS + 0\tau_h$ ,  $3L SS + 0\tau_h$ ,  $4L SS + 0\tau_h$
  - (ii)  $H \rightarrow ZZ$ : In final state  $3L + 0\tau_h$ ,  $4L + 0\tau_h$
  - (iii)  $H \rightarrow \tau\tau$ : In final state  $2L SS + 1\tau_h$ ,  $0L + 2\tau_h$ ,  $1L + 1\tau_h$ ,  $1L + 2\tau_h$ ,  $2L + 2\tau_h$
 SS: same sign  $\rightarrow$  reduced background by large factor
- BDT output score used for the extraction of signal for each category



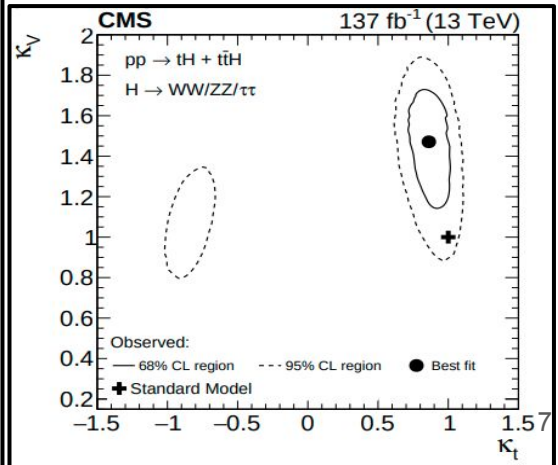
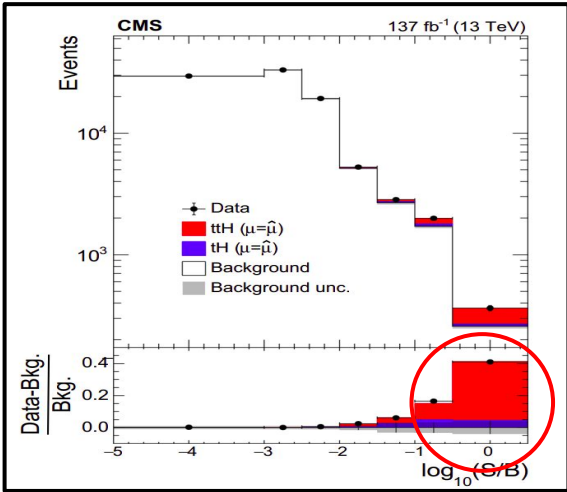
$\kappa_V = 1$ , @ 95% CL  
 $-0.9 < \kappa_t < -0.7, 0.7 < \kappa_t < 1$

1.1

Observed (expected) signal significance:  $4.7(5.2) \sigma$

Signal strength:

- $\mu(\text{ttH}) = 0.92^{+0.19}_{-0.19} \text{ (stat)}^{+0.17}_{-0.13} \text{ (syst)}$
- $\mu(\text{tH}) = 5.7^{+02.7}_{-2.7} \text{ (stat)}^{+3.0}_{-3.0} \text{ (syst)}$

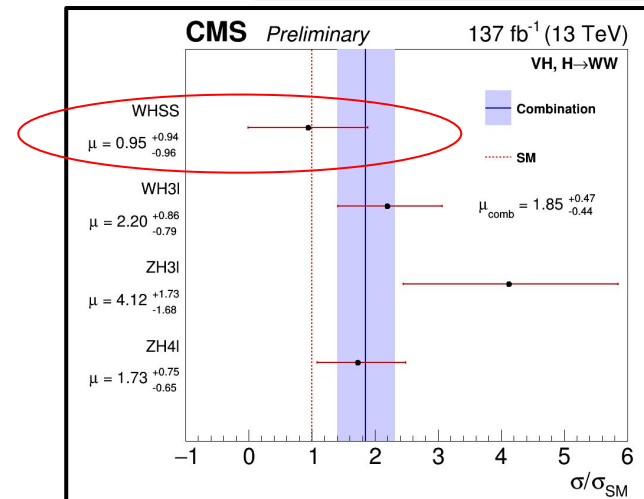
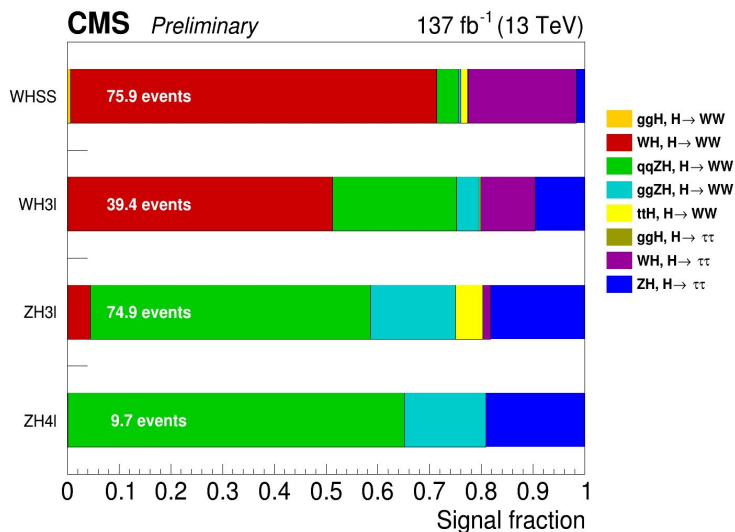
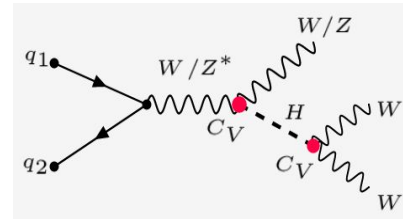




# VH ( $V = W/Z$ ), $H \rightarrow WW$ to multileptons

CMS PAS HIG-19-017

- ❖ Pure process for probing H coupling to vector bosons ( $C_V$ )
- ❖ Events with at least one leptonically decaying W in e/ $\mu$  modes.
- ❖ Final states marked by number, charge and flavour of leptons
- ❖ WH same-sign (SS) lepton category has the best sensitivity  
→ compatible with SM



Observed signal significance:  $4.7\sigma$

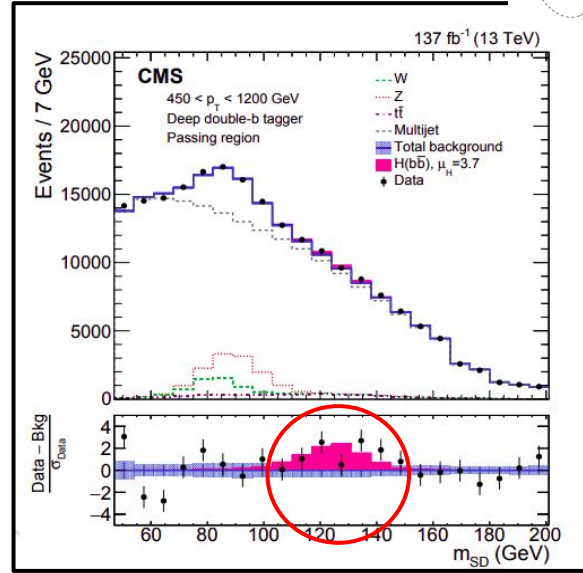
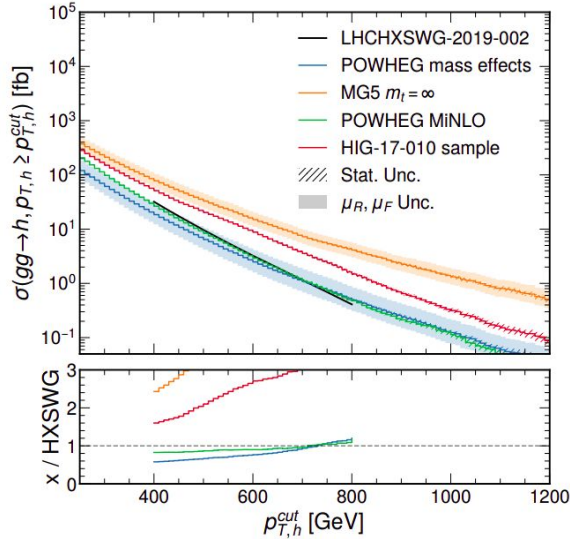
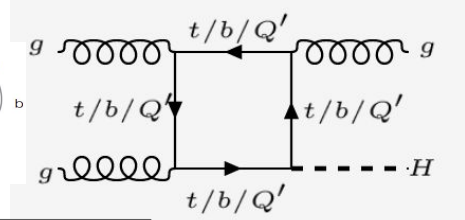
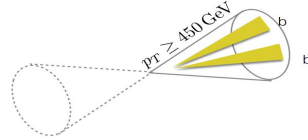
Signal strength:

$$\mu = 1.85^{+0.33}_{-0.32} \text{ (stat)}^{+0.25}_{-0.25} \text{ (syst)}^{+0.10}_{-0.07} \text{ (theo)}$$

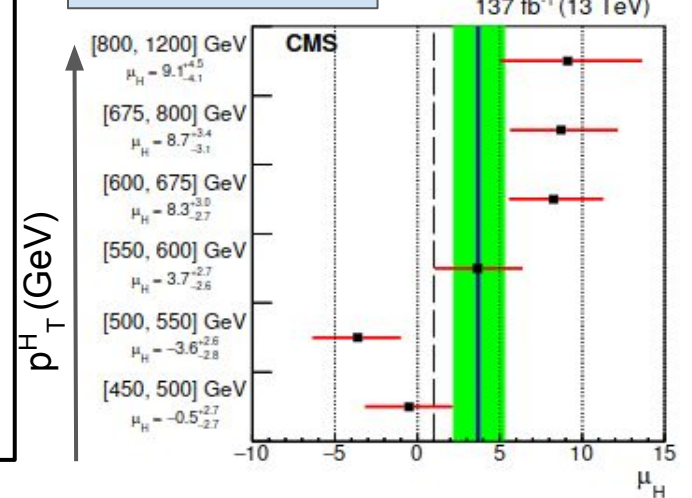


# Inclusive boosted Higgs production and decay to bb

- ☐ Suitable to measure Hbb Yukawa coupling ( $y_b$ )
- ☐ High end  $p_T^H$  can resolve loop-induced contributions to the  $ggH$  process from new particles



JHEP 12 (2020) 085



## Analysis strategy:

- Serious background from  $tt$  production, controlled by
  - missing transverse energy < 140 GeV
  - lepton veto, no  $b$ -jets in opposite hemisphere

Signal extraction by fitting jet mass distribution

Obs. (exp. ) signal significance: **2.5 (0.7)  $\sigma$**

Signal strength:

$$\mu = 3.7^{+1.2}_{-1.2} \text{ (stat)} +^{+0.6}_{-0.7} \text{ (syst)} +^{+0.8}_{-0.5} \text{ (theo)}$$

# Simplified template cross section (STXS)

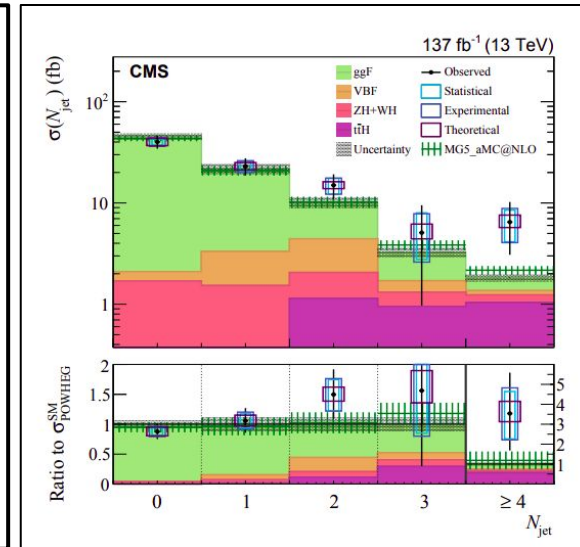
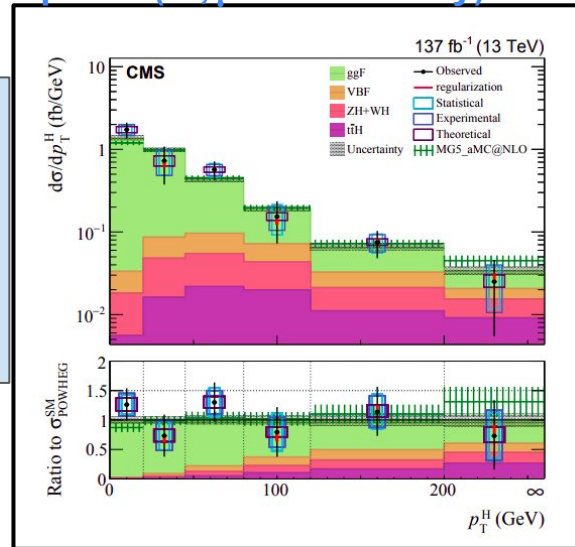
- ❖ Increased luminosity of Run-2 → probe BSM using H measurement as a tool
- ❖ Fine-grained measurements for individual or inclusive Higgs production modes in various kinematic regions
- ❖ Differential distributions in  $p_T^H$ ,  $n_{\text{jets}}$ , ..
- ❖ Minimizing theory dependence
- ❖ Maximizing experimental sensitivity
- ❖ Used as common framework in all decay modes → optimum for combined interpretation

## Inclusive production of $H+X \rightarrow WW^* \rightarrow \text{leptons}$ ( $e^\pm, \mu^\pm$ modes only) stage: 1.0

Signal strength:

$$\mu = 1.05 \pm 0.05 \text{ (stat)} \pm 0.07 \text{ (exp)} \\ \pm 0.01 \text{ (signal)} \pm 0.07 \text{ (bkg)} \pm 0.03 \text{ (lumi)}$$

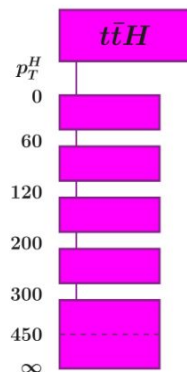
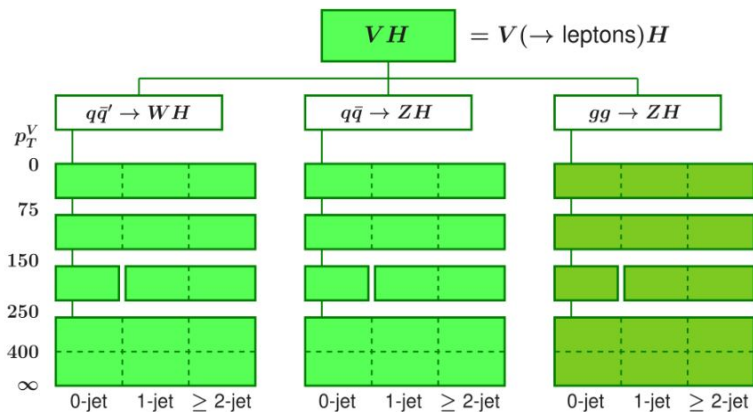
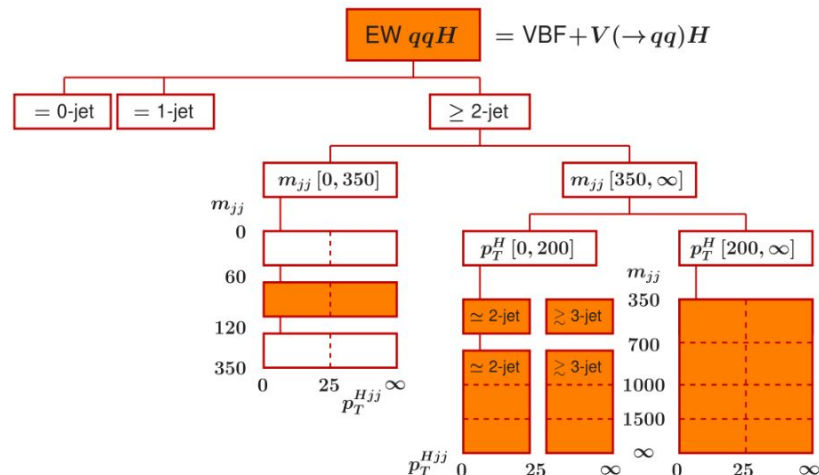
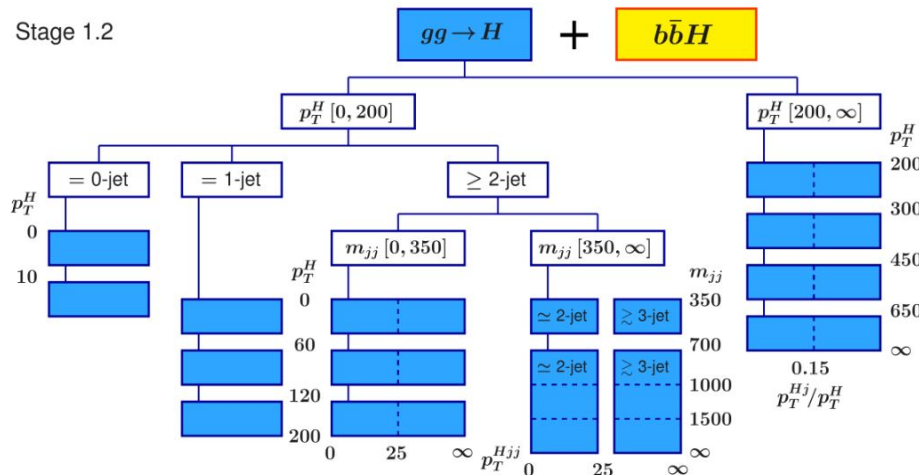
Measured cross section:  $86.5 \pm 9.5 \text{ fb}$   
SM prediction:  $82.5 \pm 4.2 \text{ fb}$



# STXS analysis for $H \rightarrow \gamma\gamma$

arXiv: 2103.06956  
Accepted by JHEP

Stage 1.2



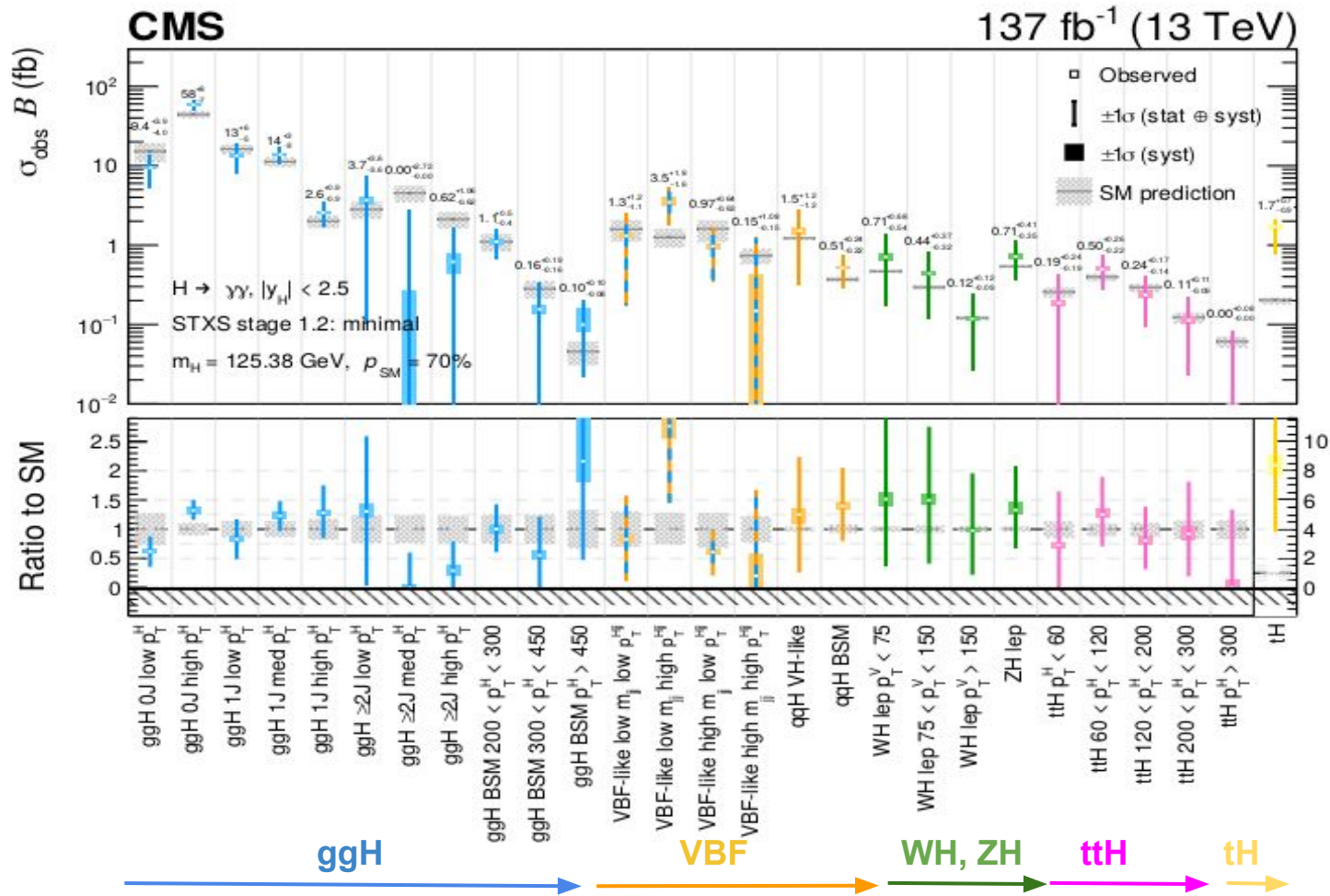
$tH$

Newly added in  
 $H \rightarrow \gamma\gamma$  analysis

# STXS study for $H \rightarrow \gamma\gamma$

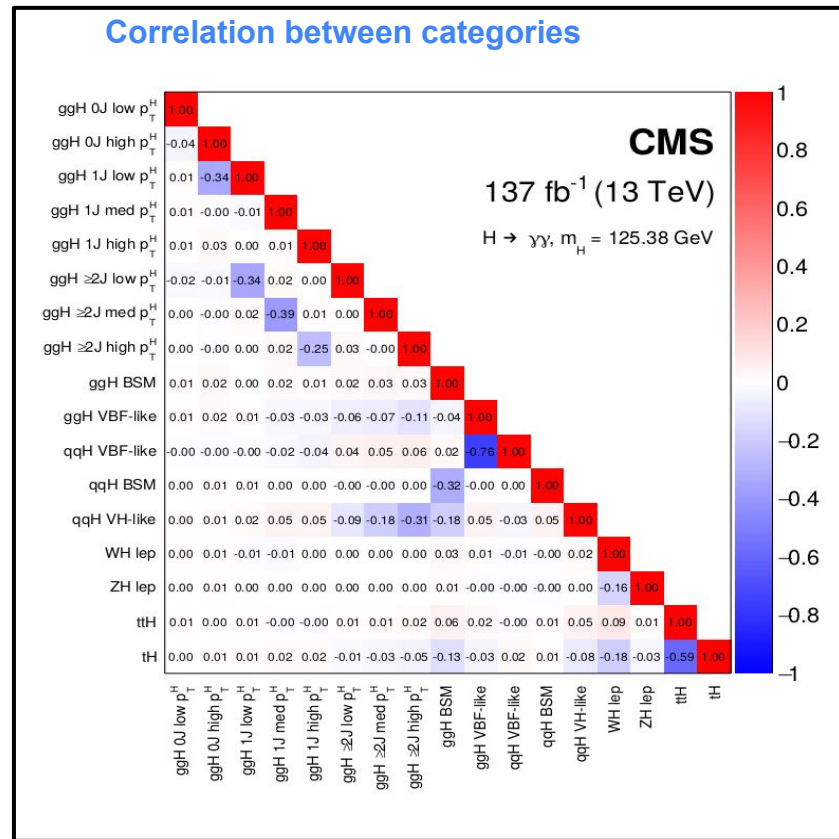
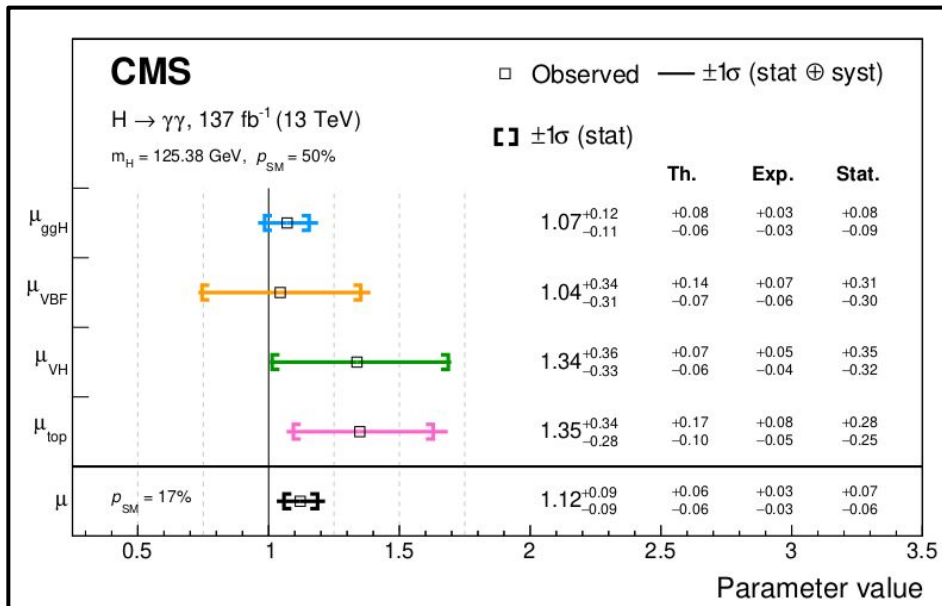
arXiv: 2103.06956

Accepted by JHEP



Decent sensitivity for STXS bins in all production modes

# Results of STXS study of $H \rightarrow \gamma\gamma$ study



**Measured signal strength**  
 $\mu : 1.12^{+0.06}_{-0.06} \text{ (theo)} + 0.03^{+0.07}_{-0.03} \text{ (syst)} + 0.07^{+0.06}_{-0.06} \text{ (stat)}$

# Summary

- ❑ CMS continues to explore various aspects of Higgs physics from abundant to rare decay modes.
- ❑ The standard model predicted H interaction with lower mass particles are coming into view:  
**First evidence of  $H \rightarrow \mu\mu$**
- ❑ Exploring more detailed kinematic regions to probe BSM from STXS study (recently in  $H \rightarrow \gamma\gamma$ )
- ❑ Understanding of Higgs potential from HH studies are also being carried in various final states:

## What's next?

- ❑ Even after 2.5 years of completing Run-2 data taking, analyses not yet over in several fronts of Higgs  $\rightarrow$  stay tuned!
- ❑ Continue precision measurements
- ❑ Focus to establish other rare processes
- ❑ Rigorous searches for BSM signature
- ❑ More interesting physics results and bold understandings will come in next run.

*Thank you and be safe*



# HH searches in CMS

Higgs potential :  $V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$

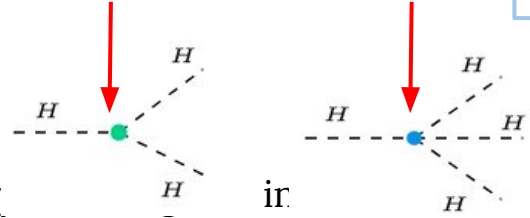
Expanding about the minimum:  $V(\phi) = -V(v + h)$

$$V = V_0 + \frac{1}{2}m_h^2 h^2 + \frac{m_h^2}{2v^2}vh^3 + \frac{1}{4}\frac{m_h^2}{2v^2}h^4$$

↓ Higgs mass term    
 ↓ Tri-linear Higgs self coupling ( $\lambda_{HHH}$ )    
 ↓ Quasi-linear Higgs self coupling ( $\lambda_{HHHH}$ )

In SM :

$$\lambda_{HHH} = \lambda_{HHHH} = \frac{m_H^2}{2v^2} = 0.13$$



- ❖ HH decay modes being explored using **full Run2 (137 fb<sup>-1</sup>)** data:
- ❖ Modes with large branching ratios (BR) utilized for at least one of the H decays :
  - bb (58%) and WW\*(21%)
- ❖ HH → 4b, bbττ, **bbγγ**, bbWW, bbZZ, 4W, WWττ, 4τ, WWγγ

- Leads to EWK symmetry breaking
- Measuring  $\lambda$  important because it probes the shape of the Higgs potential
- HH production at the LHC provides access to  $\lambda$  : → **Detailed talk by Lata Panwar**