Recent Higgs measurements in CMS

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On behalf of
CMS Collaboration, LHC, CERN.

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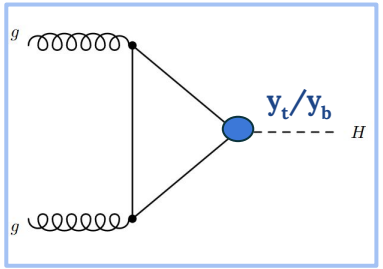
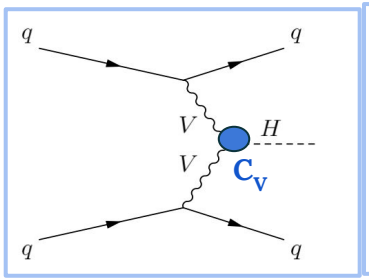
Higgs productions,couplings and decays at the LHC

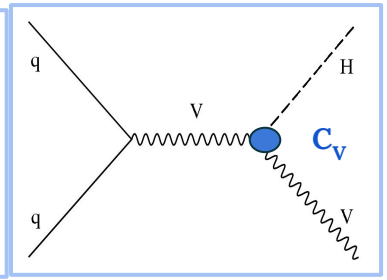
Production modes and cross sections @ 13 TeV



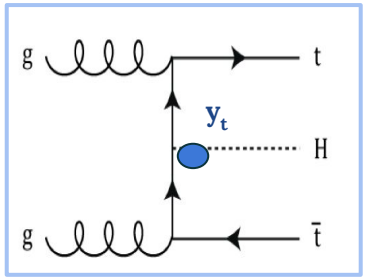
Gluon gluon fusion (GGF) X sec: 49 pb



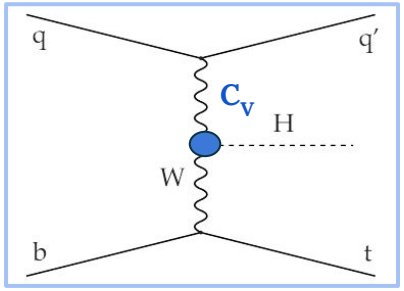
Vector Boson fusion (VBF) X sec: 3.8 pb

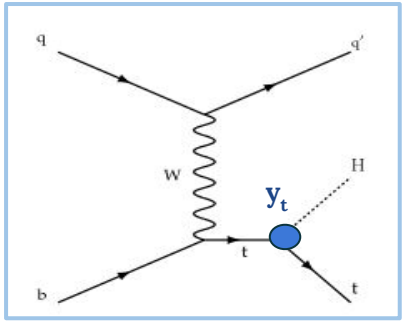


Higgstrahlung (VH) X sec: 2.3 pb



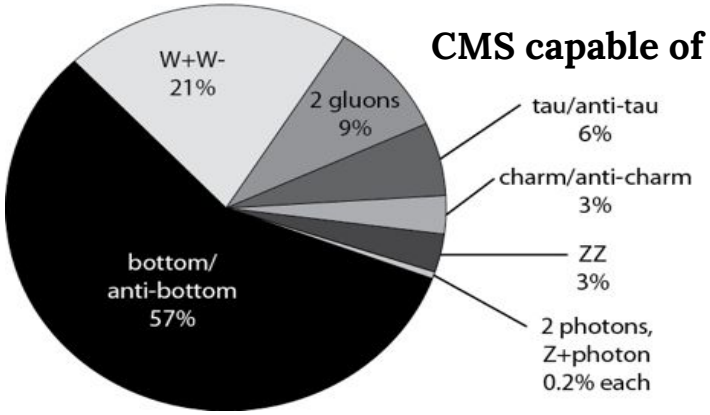
In association with a pair of top quark (ttH) X sec: 0.5 pb





In association with a single top quark (tH)+ X sec: 0.73 pb

Decays of a 125 GeV Standard-Model Higgs boson



CMS capable of targeting large no. of decay modes

Already established:

- ❑ H → bb
- ❑ H → WW
- ❑ H → $\tau\tau$
- ❑ H → ZZ
- ❑ H → $\gamma\gamma$

- ❖ H → $\mu\mu$ (evidence)
- ❖ H → Zγ (coming soon)

Higgs searches at the LHC

Run-1: $\sqrt{s}$=7, 8 TeV $\int L\,dt$ = 5 fb^{-1}, 19 fb^{-1}
→ Discovery of Higgs bosons
→ Measurement total cross sections in different modes
→ Characterization: mass, spin, coupling with vector bosons

Run-2: 13 TeV, $\int L\,dt$ = 137 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
κ- framework (κ_V, κ_t , κ_b, κ_γ . . . .)
κ = (Observed Higgs coupling) /
(Standard Model predicted value)
κ = 1 ⇒ Standard Model (SM)

Signal strength (μ) =(σ * $\mathcal{B}$r)^{obs} / (σ * $\mathcal{B}$r)^{SM}

Common strategy for CMS analyses:
(i) Multivariate analysis techniques based on **boosted decision trees (BDT)** or, **Deep Neural Network (DNN)** to discriminate signals from backgrounds
(ii) Events categorized to achieve best sensitivity.

Combined Higgs mass measurement

Phys Lett B. 805 (2020)135425

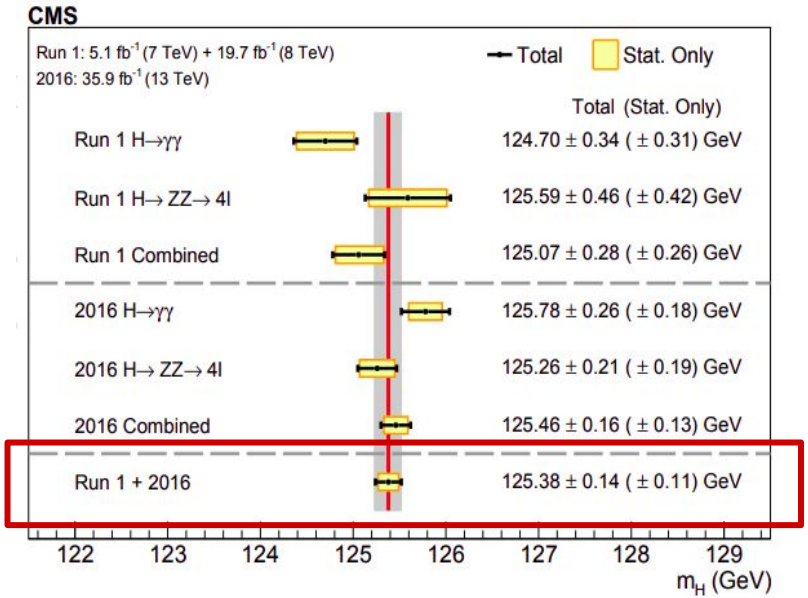
Combination of 2 high resolution channels: H→ γγ with H→ ZZ* → 4l

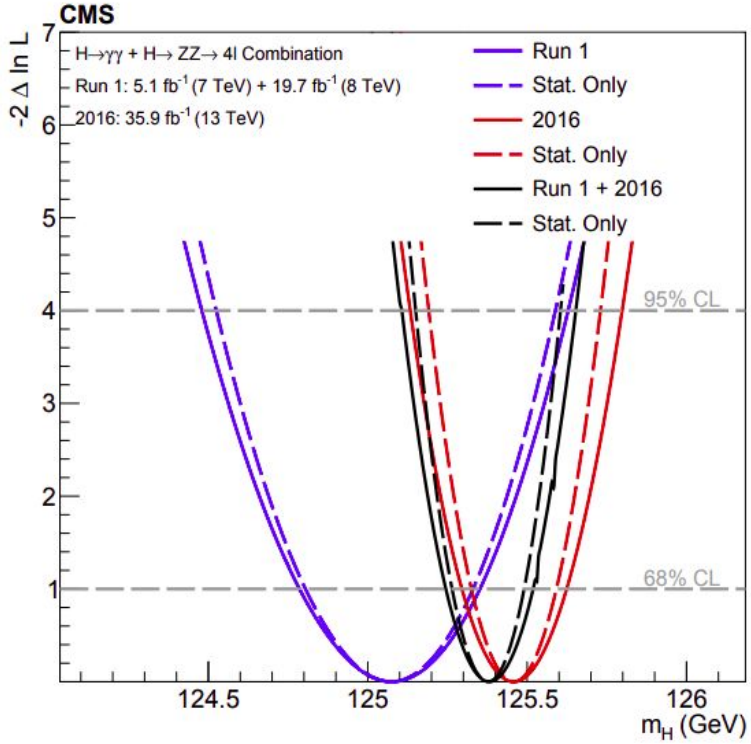
using 2016 data (~36/fb) and Run-1 data (~25/fb)

m_H = 125.38± 0.11 (stat) ± 0.08 (sys) GeV

→ total uncertainty ~ 0.21% , dominated by stat (0.14%).

→ **currently the most precise measurement**





H→ $\mu\mu$ study using full Run-2 data

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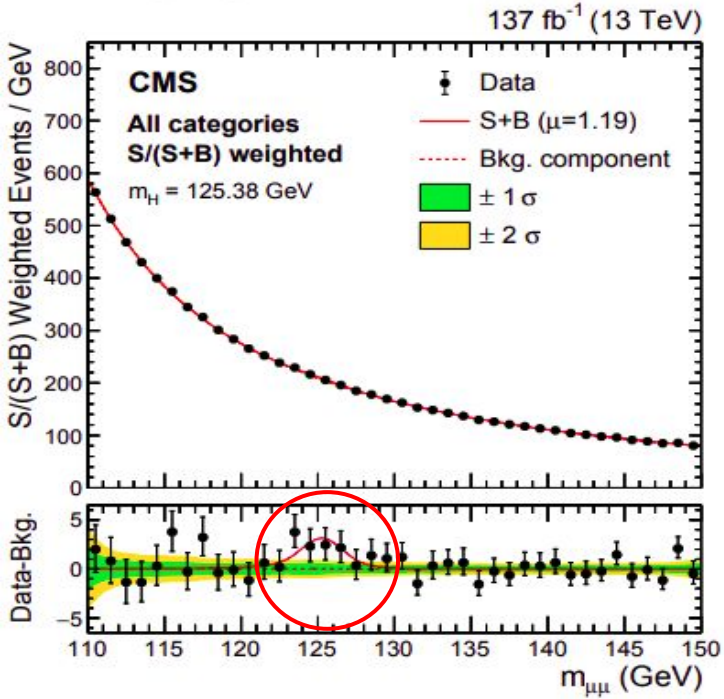
Experimental confirmation of H→ $\mu\mu$ decay is crucial to establish Higgs interaction with 2nd generation fermions.

But extremely low branching fraction: **$2.18 * 10^{-4}$**
→ requires high luminosity
→ used complete Run-2 data
→ Tragets 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→ $\mu\mu$ study

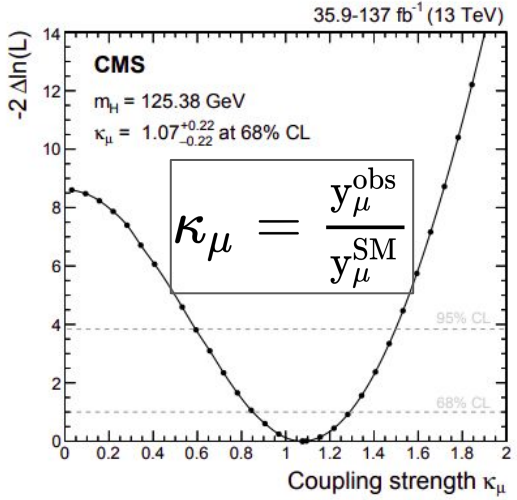
→ **First evidence of H→ $\mu\mu$ process at the LHC**

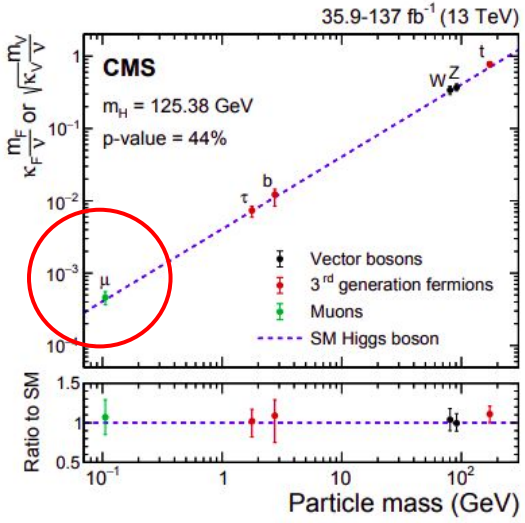
→ Observed (expected) signal significance: **3.0** (2.5)σ

→ Signal strength **μ = 1.19 $^{+44}_{-0.42}$ @68%**

→ Observed best fit value of κ_μ : **1.07 $^{+0.29}_{-0.15}$** @ 68% CL

→ **Most constrained measurement of κ_μ till date.**





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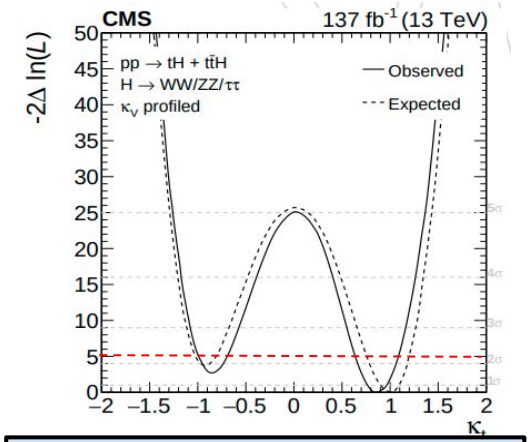
ttH + tH: multilepton study

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, μ , hadronic tau τ_h)
  (i) H → WW : **2L SS + 0τ_h**, 3L SS + 0τ_h, 4L SS + 0τ_h
  (ii) H → ZZ : 3L + 0τ_h , 4L + 0τ_h
  (iii) H →$\tau\tau$: 2L SS + 1τ_h , 0L + 2τ_h , 1 L + 1τ_h , 1L + 2τ_h, 2L + 2τ_h
  SS: same sign → reduced background by large factor

- BDT output score used for the extraction of signal for each category

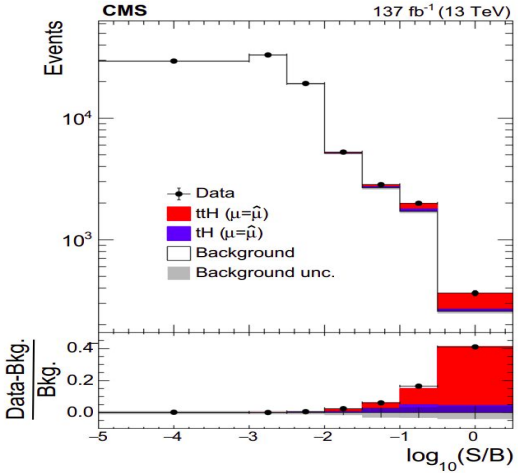


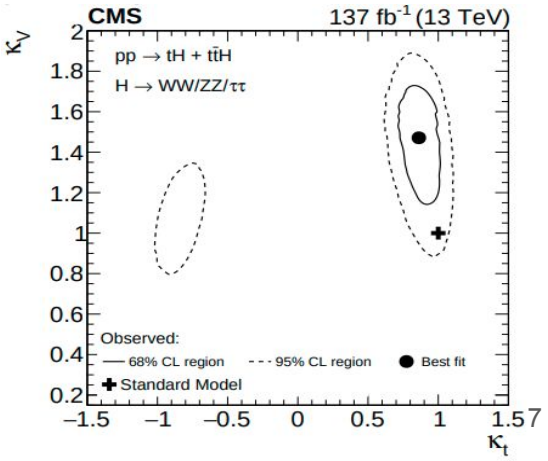
κ_V =1 , @ 95% CL
-0.9 < κ_t < -0.7, 0.7 < κ_t < 1.1

Observed (expected) signal significance: 4.7(5.2) σ

Signal strength:

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

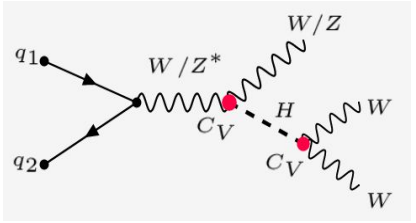


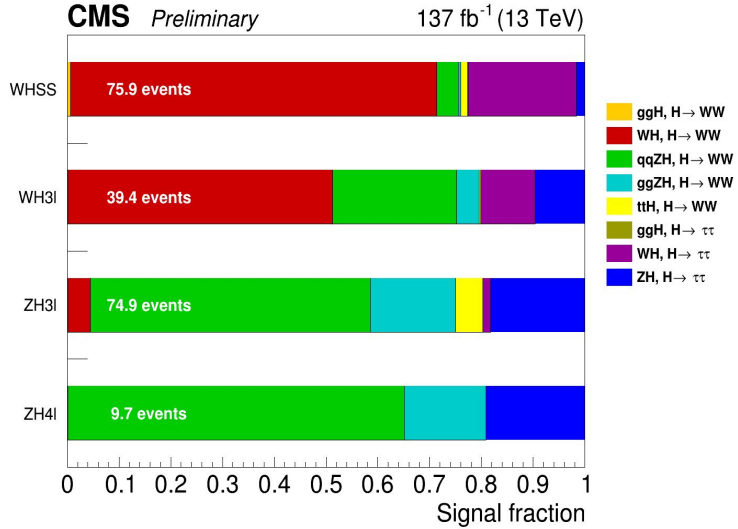


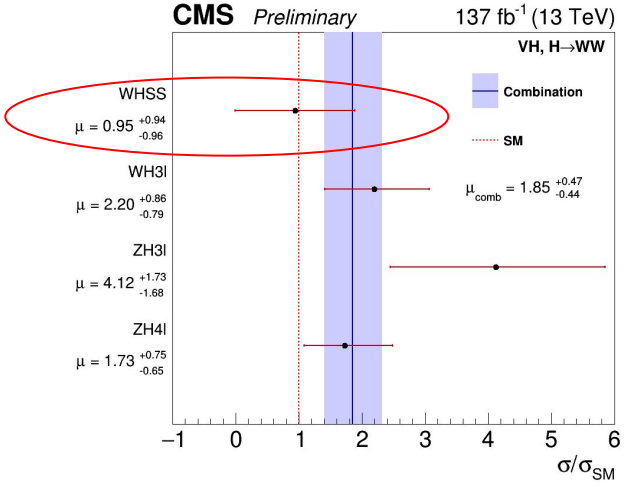
VH (V = W/Z), H → WW to multileptons

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 eμ modes.
- Final states marked by number, charge and flavour of leptons
- WH same-sign (SS) lepton category has the best sensitivity
  → compatible with SM





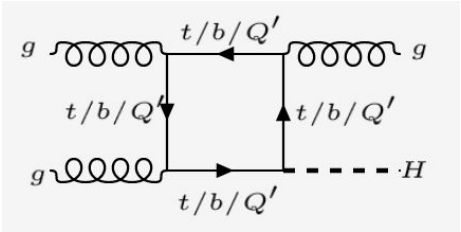


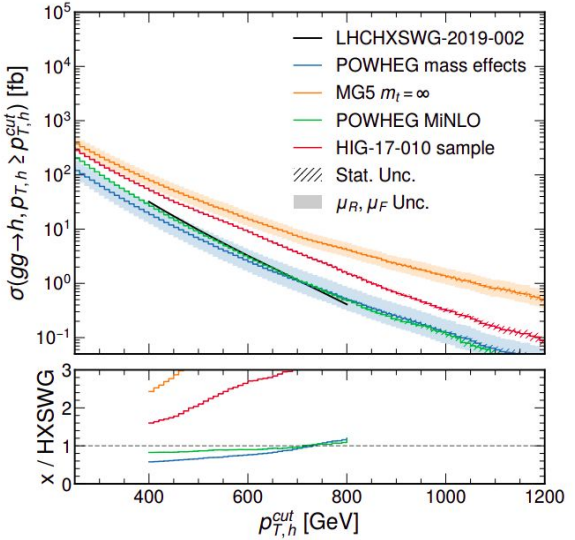
Observed signal significance: 4.7σ
Signal strength:
$\mu = 1.85^{+0.33}_{-0.32}\,(\text{stat})\,^{+0.25}_{-0.25}\,(\text{syst})^{+0.10}_{-0.07}(\text{theo})$

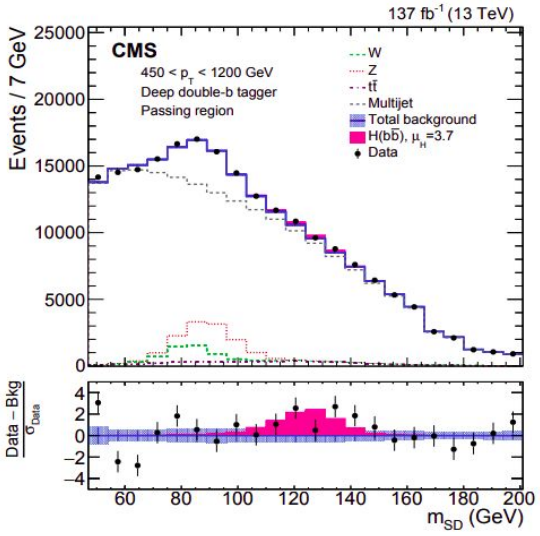
Inclusive boosted Higgs production and decay to bb

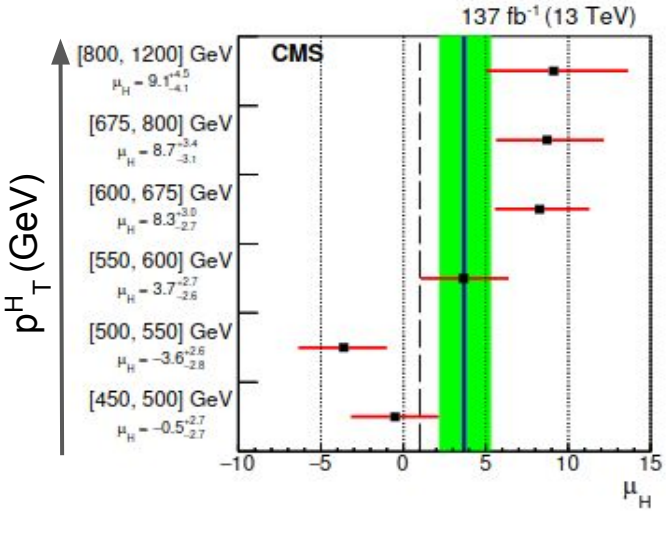
JHEP 12 (2020) 085

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









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) σ**

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)

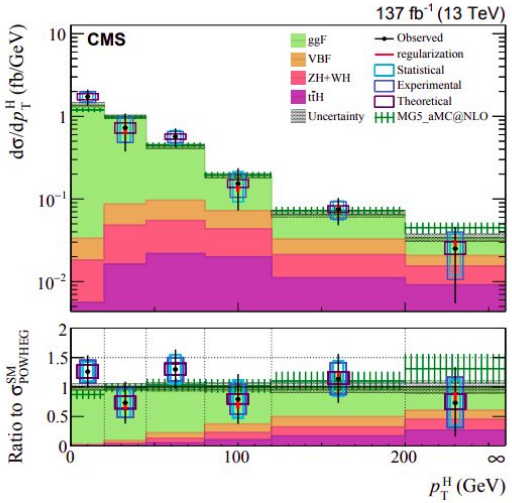
JHEP 03 (2021) 003

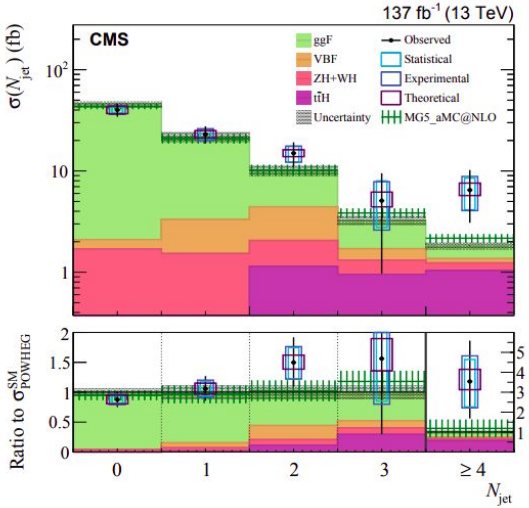
- Increased luminosity of Run-2 → probe BSM using H measurement as a tool
- Fine-grained measurements for individual or inclusive Higgs production modes in various kinematic regions
- Differential distributions in p^{H}_{T} , njets, ..
- Minimizing theory dependence
- Maximizing experimental sensitivity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

Inclusive production of H+X → WW* → leptons ($e^{\pm}$, $\mu^{\pm}$ modes only)

Signal strength:
μ = 1.05 ±0.05 (stat) ± 0.07 (exp)
± 0.01 (signal) ± 0.07 (bkg) ± 0.03 (lumi)

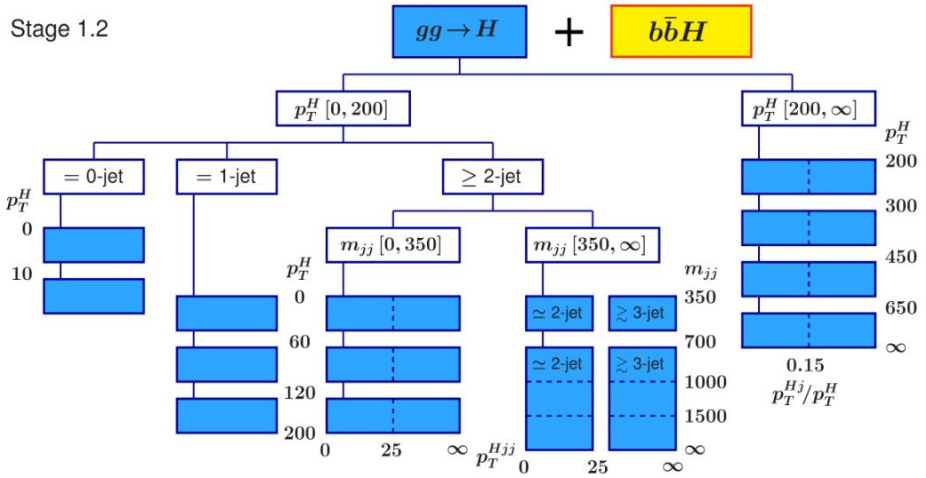
Measured cross section: **86.5 ± 9.5 fb**
SM prediction: **82.5 ± 4.2 fb**

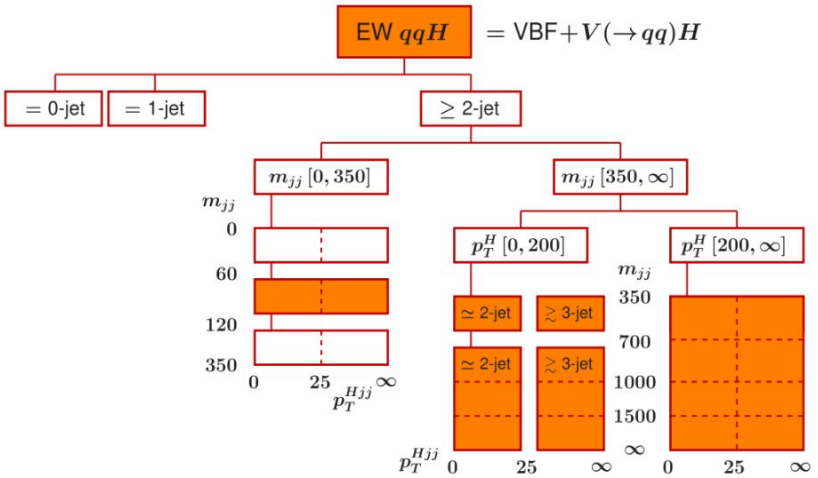


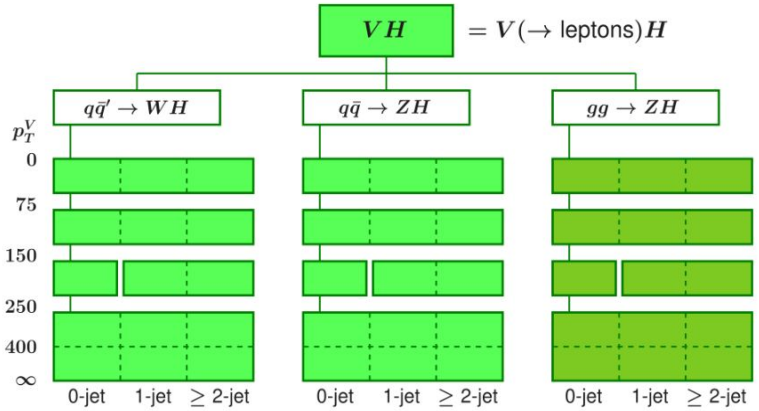


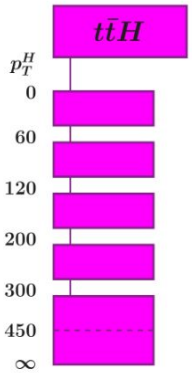
STXS analysis for H→ γγ

arXiv: 2103.06956
Accepted by JHEP







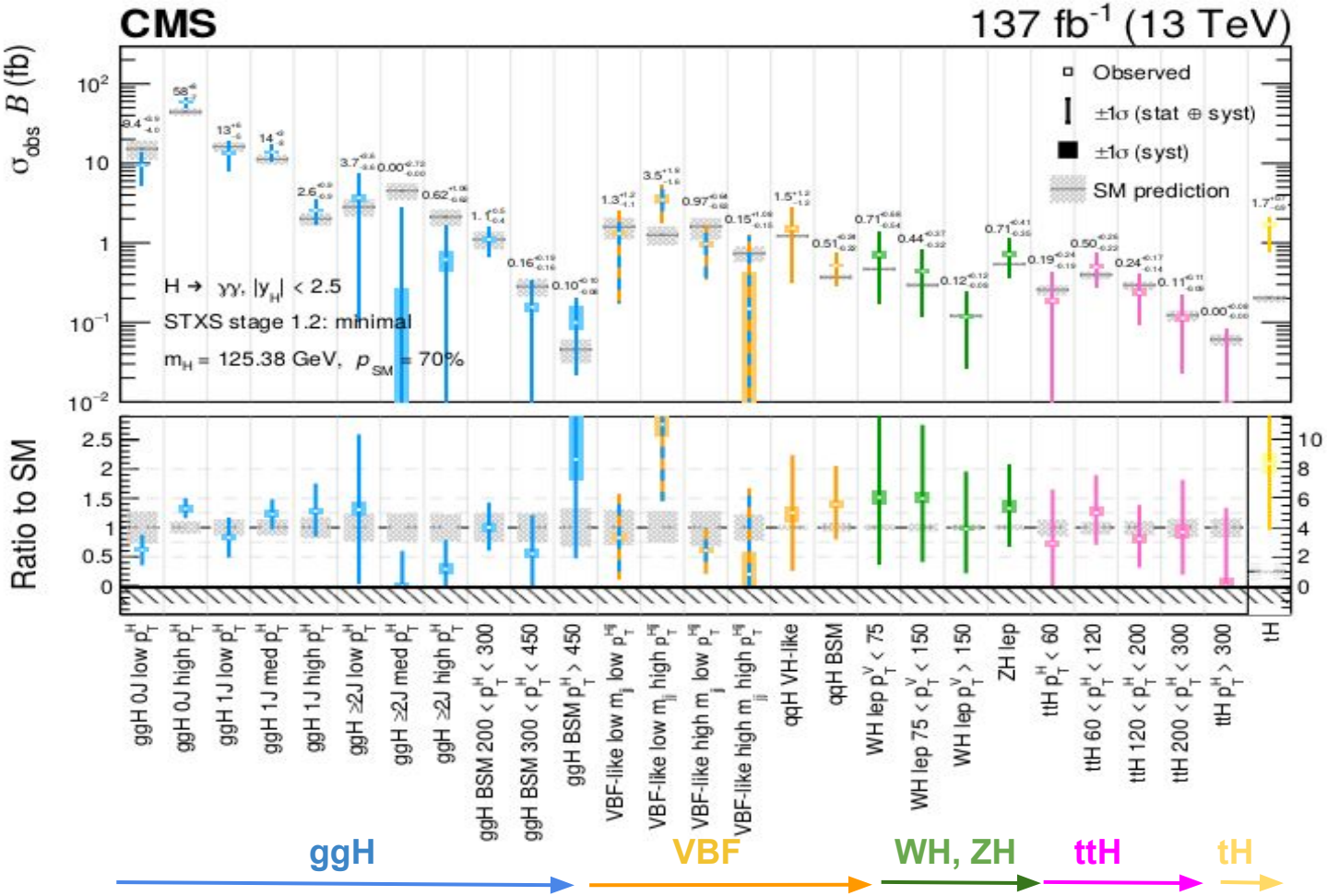


tH

Newly added in H→ γγ analysis

STXS studv for H→ γγ

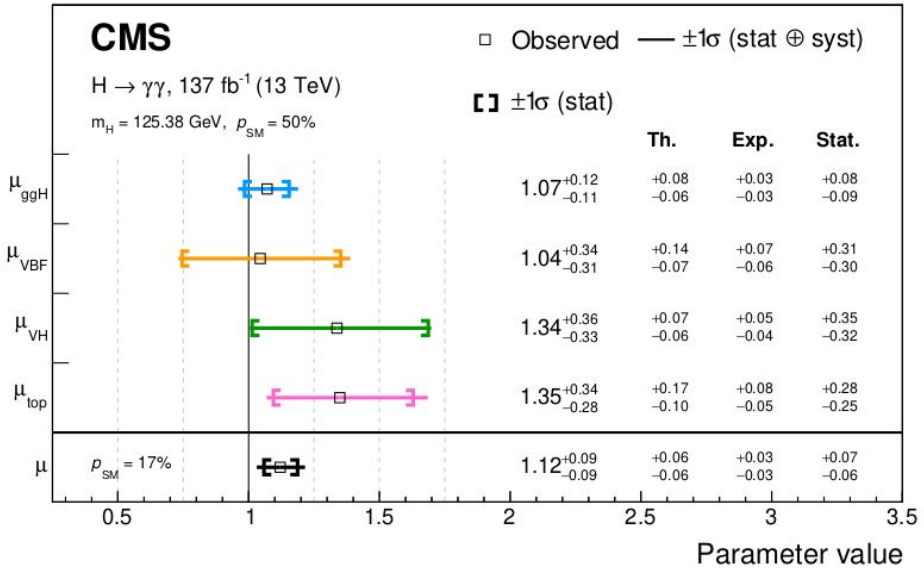
arXiv: 2103.06956
Accepted by JHEP



Decent sensitivity for STXS bins in all production modes

Results of STXS study of H→ γγ study

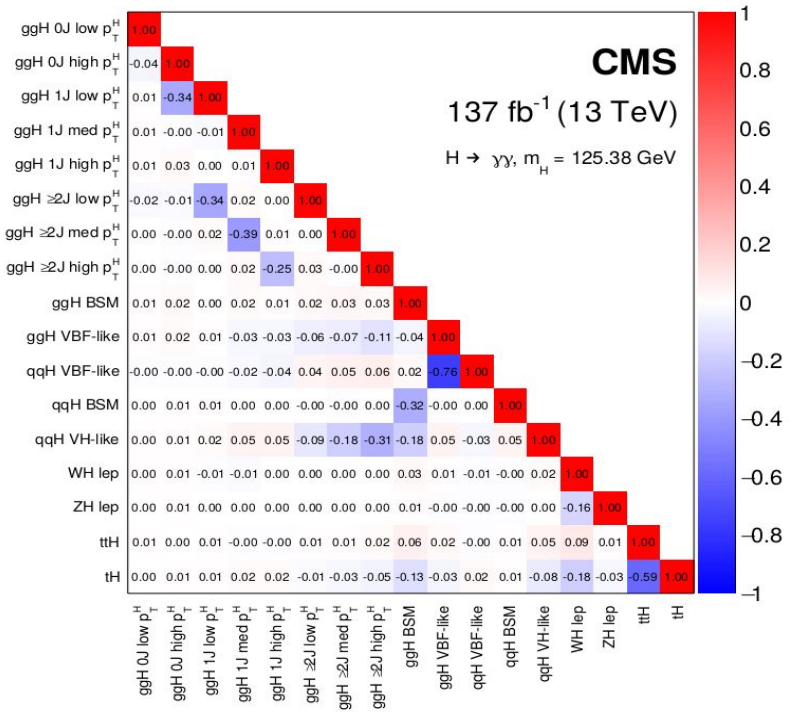
arXiv: 2103.06956
Accepted by JHEP



Measured signal strength:

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

Correlation between categories



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 → *μμ*
- Exploring more detailed kinematic regions to probe BSM from STXS study (recently in **H→ γγ)**
- Understanding of Higgs potential from HH studies are also being carried in various final states:

→ *talk by Lata Panwar*

What's next?

- Even after 2.5 years of completing Run-2 data taking, analyses not yet over in several fronts of Higgs → 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: $V(\phi) = -V(v+h)$

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

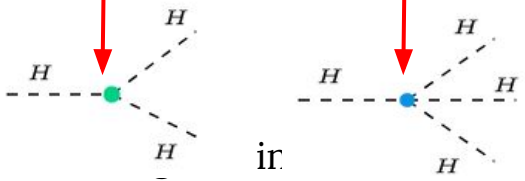
Higgs mass term

Tri-linear Higgs self coupling (λ_{HHH})

Quarti-linear Higgs self coupling (λ_{HHHH})

In SM :

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



- Leads to EWK symmetr ir asses of other standard model particles
- Measuring λ important because it probes the shape of the Higgs potential
- HH production at the LHC provides access to λ : → ***Detailed talk by Lata Panwar***

- HH decay modes being explored using **full Run2 (137 fb^{-1})** data:
- Modes with large branching ratios (BR) utilized for at least one of the H decays :
  - bb (58%) and WW*(21%)
- HH→ 4b , bb$\tau\tau$, **bb$\gamma\gamma$**, bbWW, bbZZ, 4W, WW$\tau\tau$, 4τ, WW$\gamma\gamma$