Higgs fermions couplings at the CMS experiment

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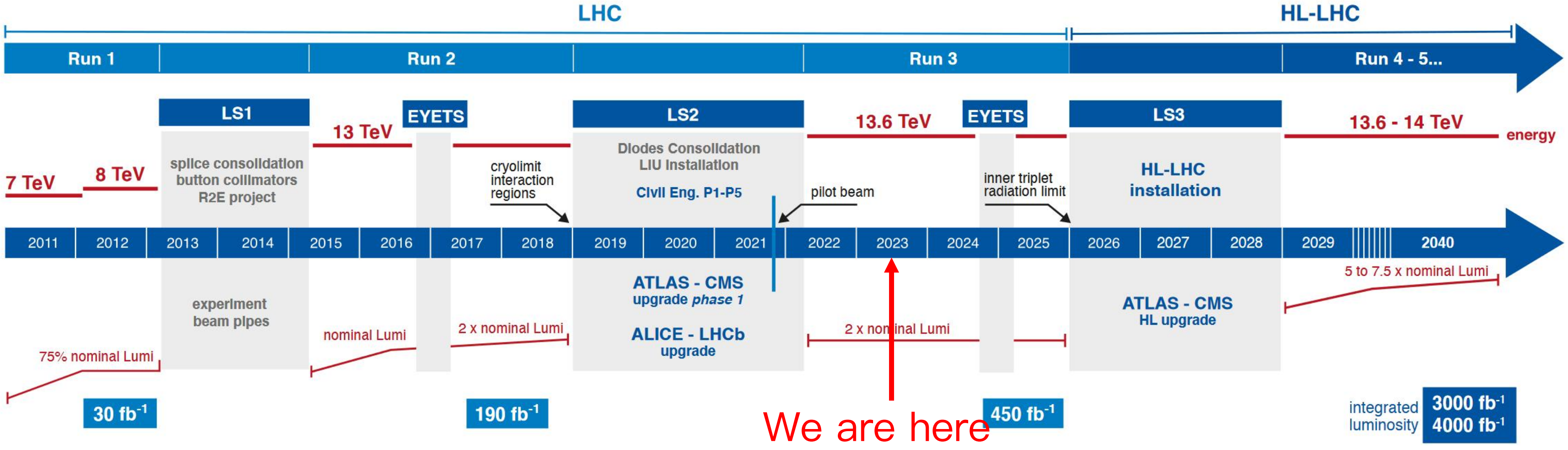
Overview

Why do we make Higgs fermion coupling measurements?

- Several open questions in particle physics call for a deeper understanding of the Higgs boson:
  - Dark matter, Asymmetry of matter vs antimatter in the universe, Hierarchy of fermion masses…
- Test compatibility with SM
  - Precise measurements of the main H production XS and decay BR
- Measurement of H coupling to fermions probes possible BSM effects inducing deviations from SM

Status

- In this presentation H fermions coupling measurements with CMS Run 2 data and perspectives for HL-LHC
- Run 3 ongoing → stay tuned for new exciting results!



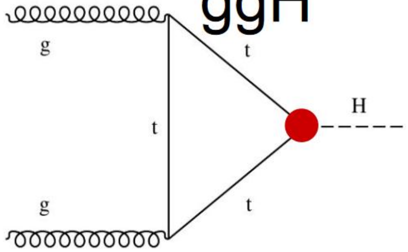
Nature 607, 60-68 (2022)

Higgs production

Main H production mechanisms at LHC

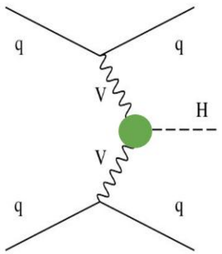
- ● fermionic coupling
- ● bosonic coupling

ggH



87%

VBF



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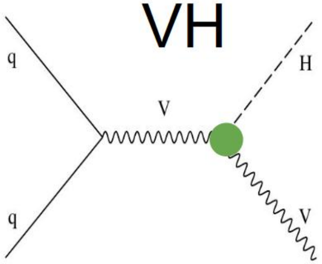
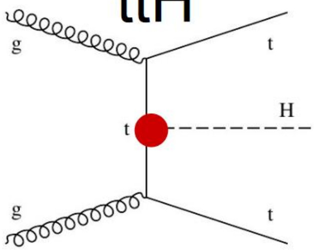
VH



5%

ttH



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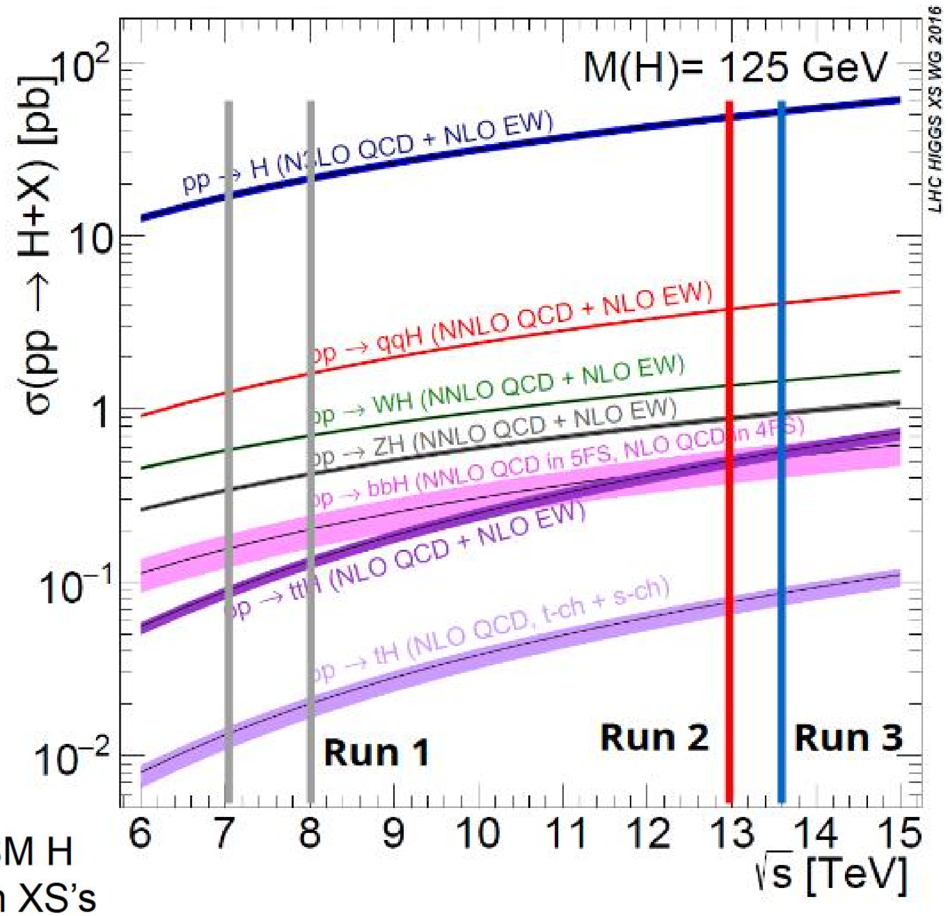
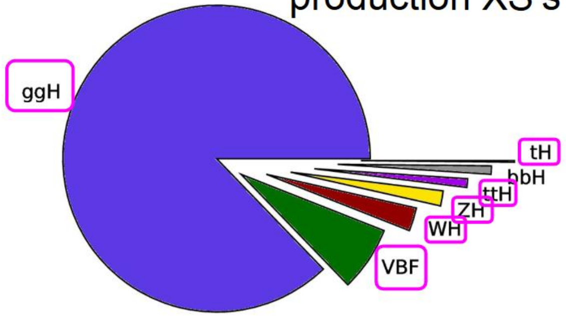
+ tH and bbH



- Production ratio shown for $\sqrt{s}$ = 13 TeV

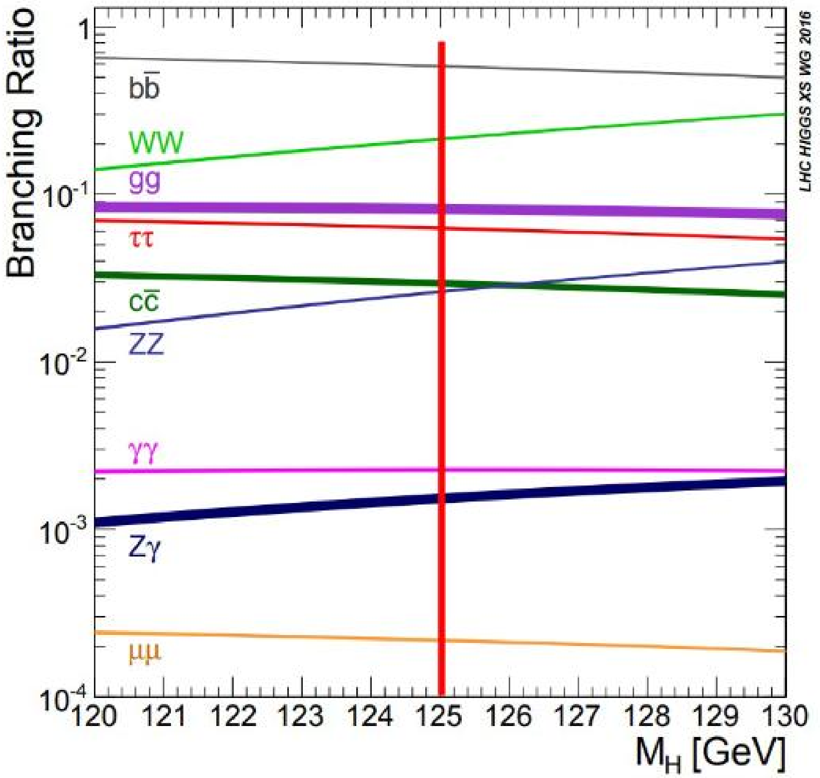
Relative SM H production XS's

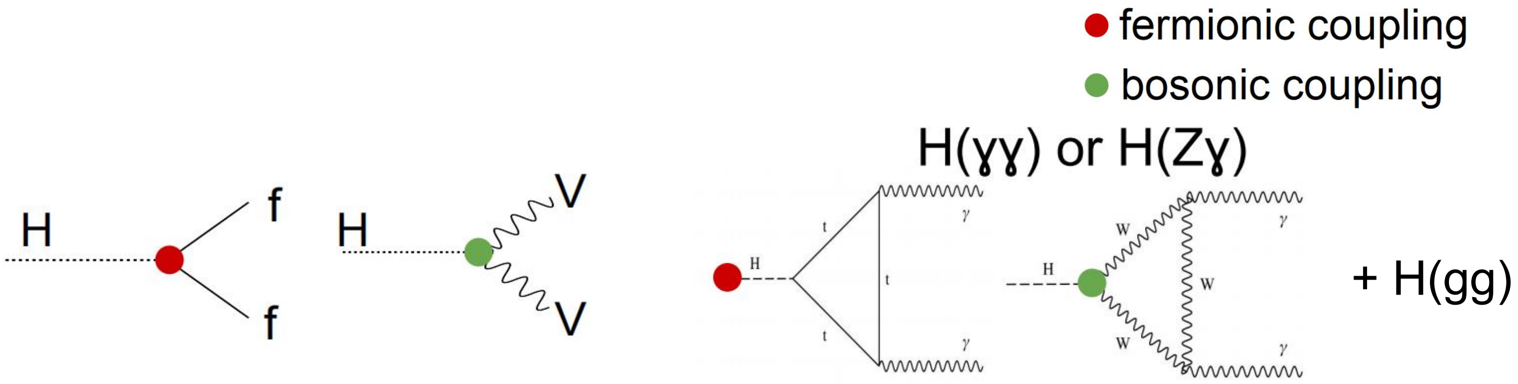


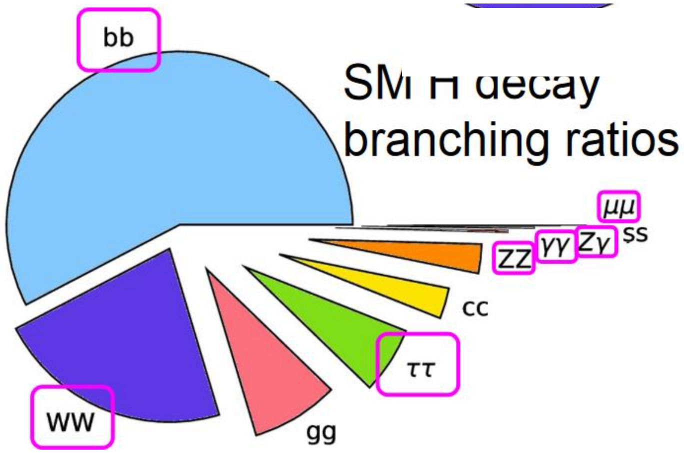
- ggH: gluon-gluon fusion Higgs production
- VBF: vector-boson fusion (Higgs) production
- VH: vector-boson associated Higgs production
- ttH: top-anti-top associated Higgs production

Higgs decay

Main H decay channels at L



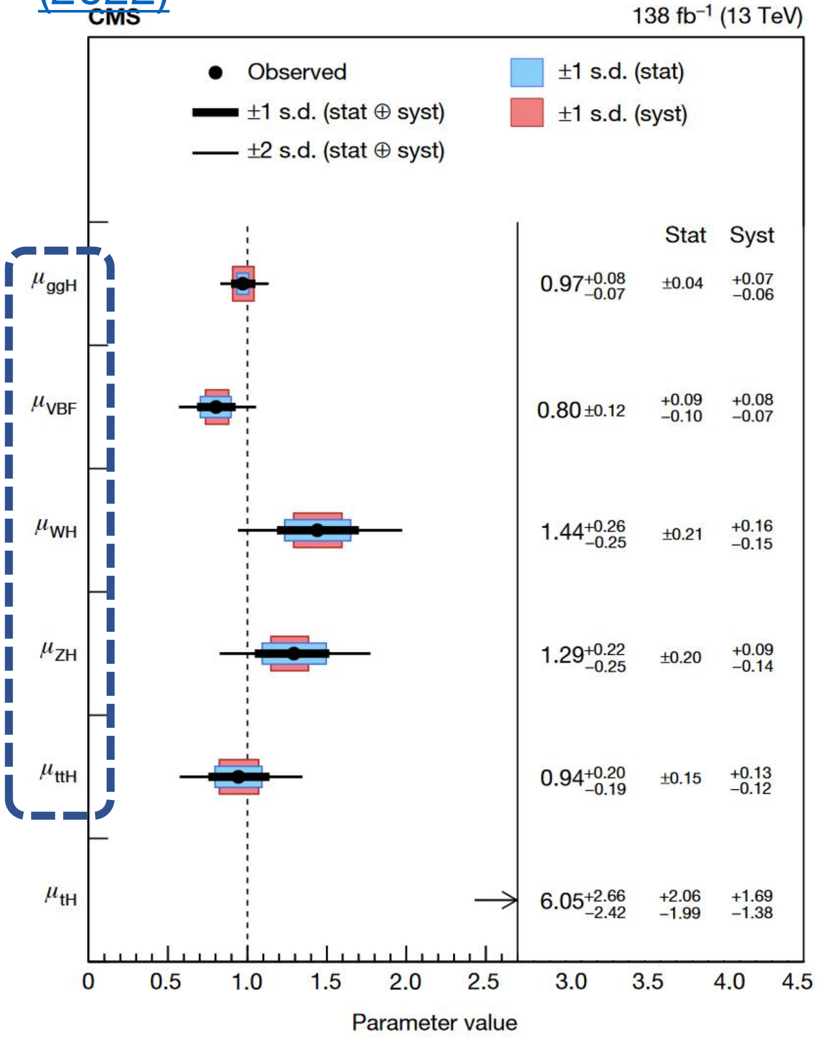


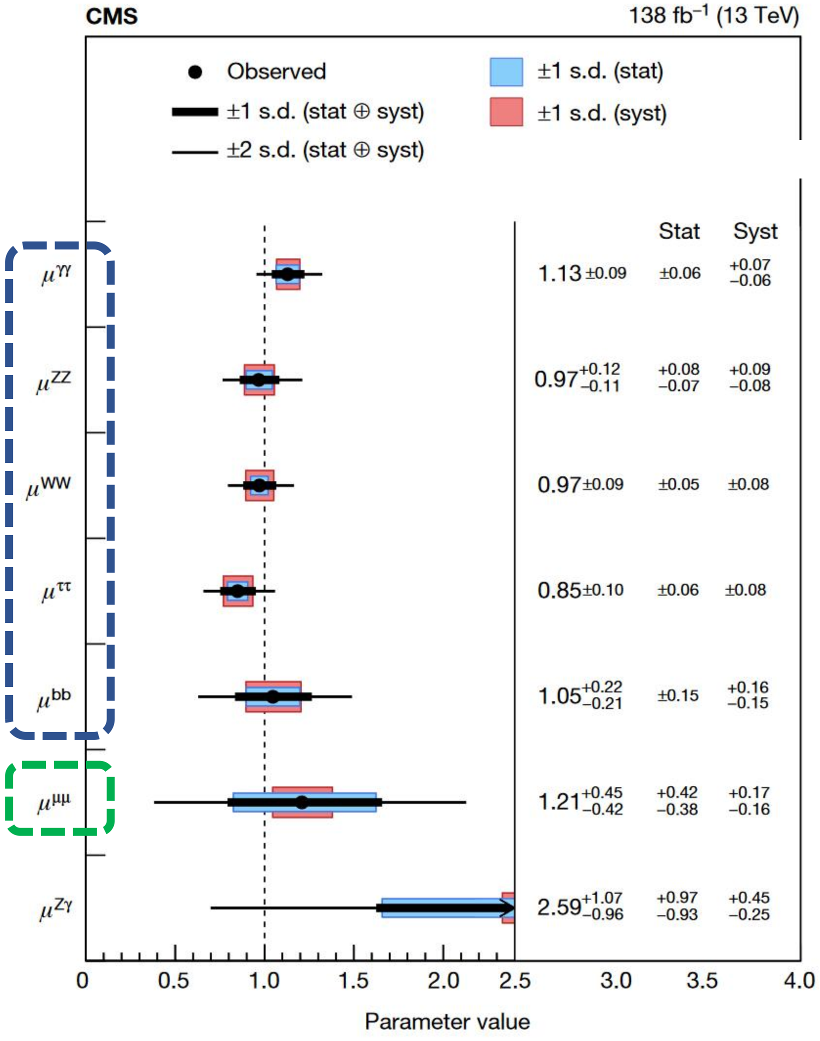


- Higgs boson first discovered mainly from the analysis of its decay into the bosonic channels: $H \to ZZ^*(\to 4\ell)$ and $H \to \gamma\gamma$
  - The latter provides indirect measurement of couplings to quarks (via virtual loops).
- Higgs decays into third generation fermions: $H \to \tau\tau$ and $H \to$ bb allow precise test the Yuwaka coupling.
- Evidence of interactions with muons are emerging

XS and BR compatibility with the SM

[Nature 607, 60-68 (2022)]





Observed with 5σ significance

Evidence at 3σ significance

- Good compatibility with SM
- Evidence of H-> $\mu\mu$ at 3σ significance (and excess in μ_{tH}, $\mu^{Z\gamma}$): interesting to see with Run 3 data
- Inclusive H cross section:
- μ = 1.002 ± 0.057 [± 0.036 (theory) ± 0.033 (exp.) ± 0.029 (stat.)]
- Systematic uncertainties becoming crucial
- Need for reducing exp. uncertainties with new or improved approaches and more precise theory predictions

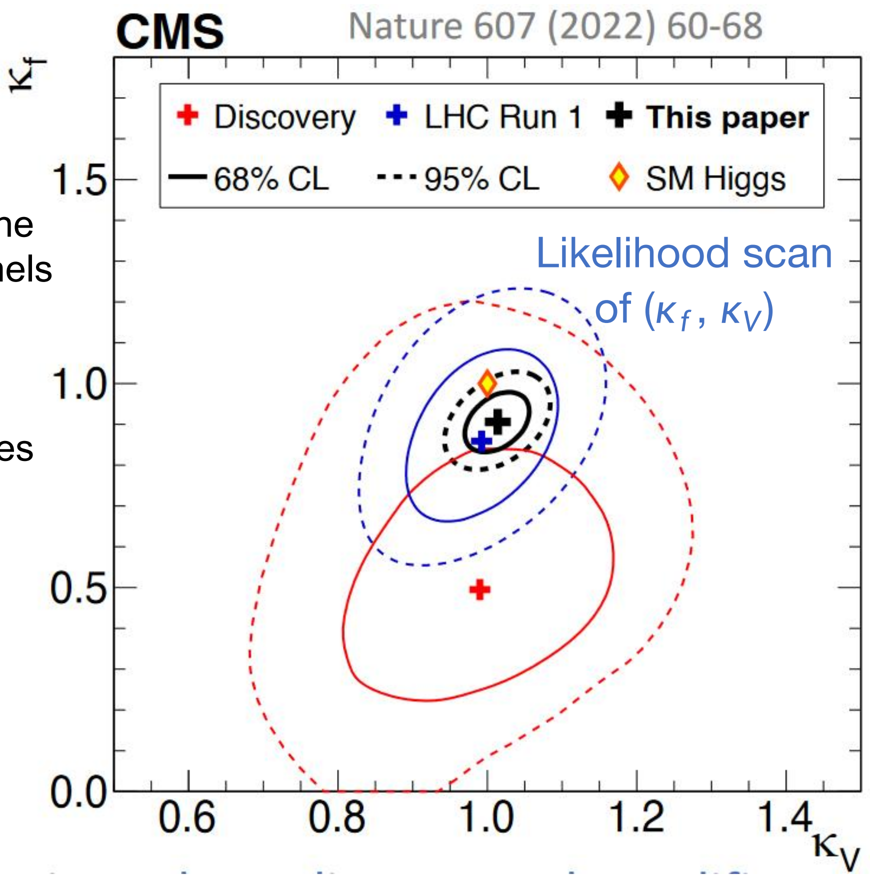
CMS Searches for fermionic decay

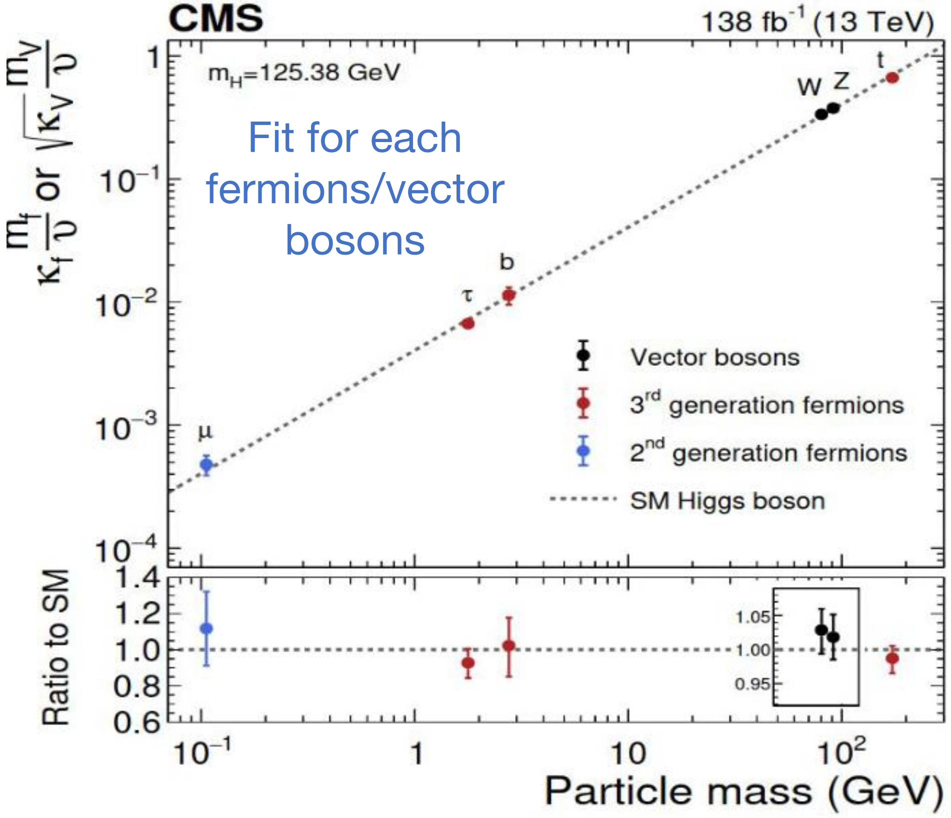
Analyses	Integrated lumi (fb^{-1})	Reference
H(bb)	36(ttH) 77(VH) 91 (VBF) 138(ggH)	JHEP03(2019)026 Phys. Rev. Lett. 121, 121801 HIG-22-009 JHEP12(2020)085
H($\tau\tau$)	138	CMS-HIG-19-010
H(cc) Boosted H(cc)	138 138	HIG-21-008 HIG-21-012
H($\mu\mu$)	138	JHEP01(2021)148
H(ee)	138	HIG-21-015
H($e\mu$)	138	HIG-22-0002

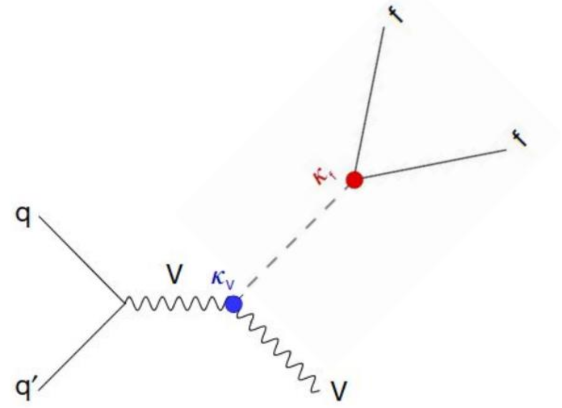
- Fruitful results produced by CMS!
- We will focus on second generation interactions in the following, and highlighting the most recent results

kappa framework and Higgs couplings

- BSM physics is expected to affect the production modes and decay channels in a correlated way
- Any modification in the Higgs' interaction affect not only decay-rates but also production cross sections

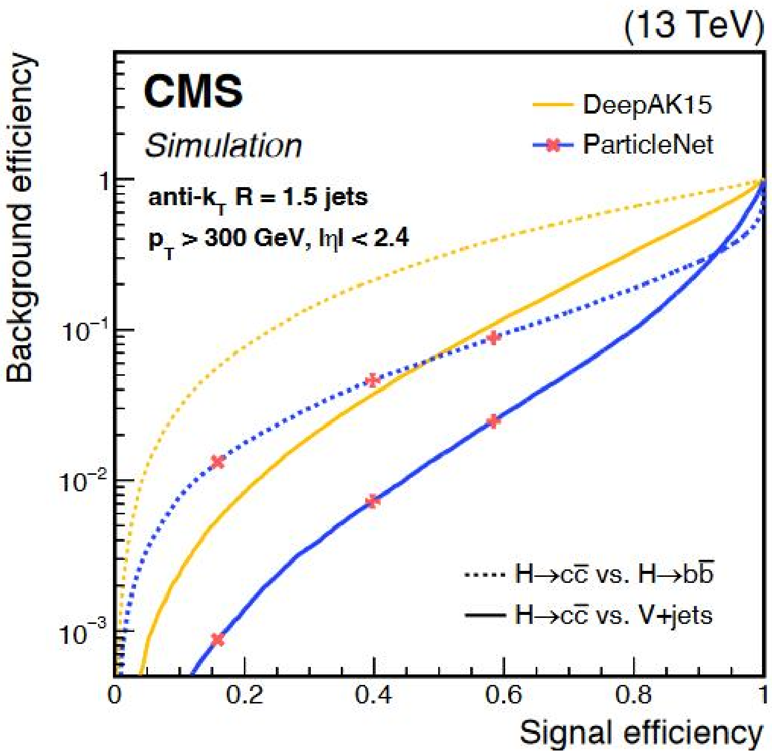


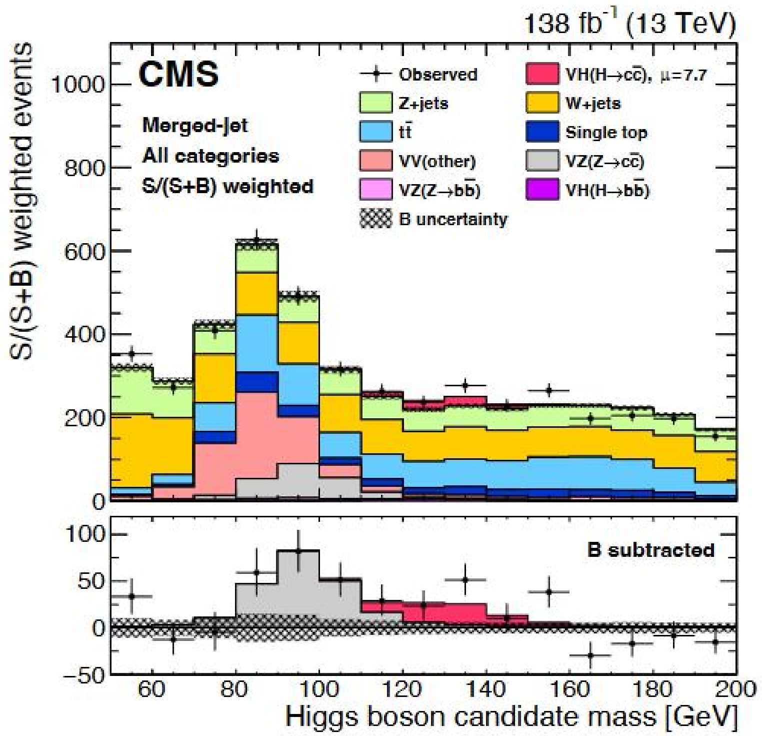




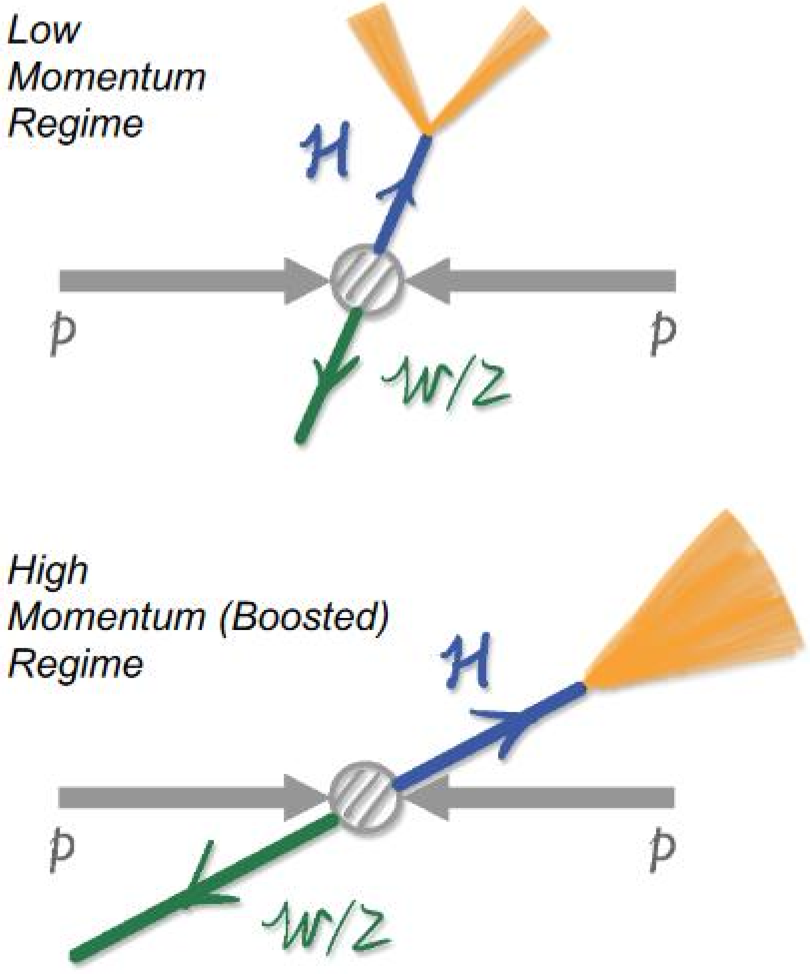
- Coupling modifiers κ to quantify couplings deviations from SM predictions
- Factorize deviations of H production XS's & decay widths $\sigma(i \to \mathrm{H} \to f) = \sigma_i(\vec{\kappa}) \frac{\Gamma_f(\vec{\kappa})}{\Gamma_H(\vec{\kappa})}$
- Scaling inclusive XS's & partial decay widths $\sigma_i(\vec{\kappa}) = k_i^2 \cdot \sigma_i^{SM}$ $\quad \Gamma_j(\vec{\kappa}) = k_j^2 \cdot \Gamma_j^{SM}$

Recent highlights: H–>cc





[HIG-21-008](), accepted by PRL



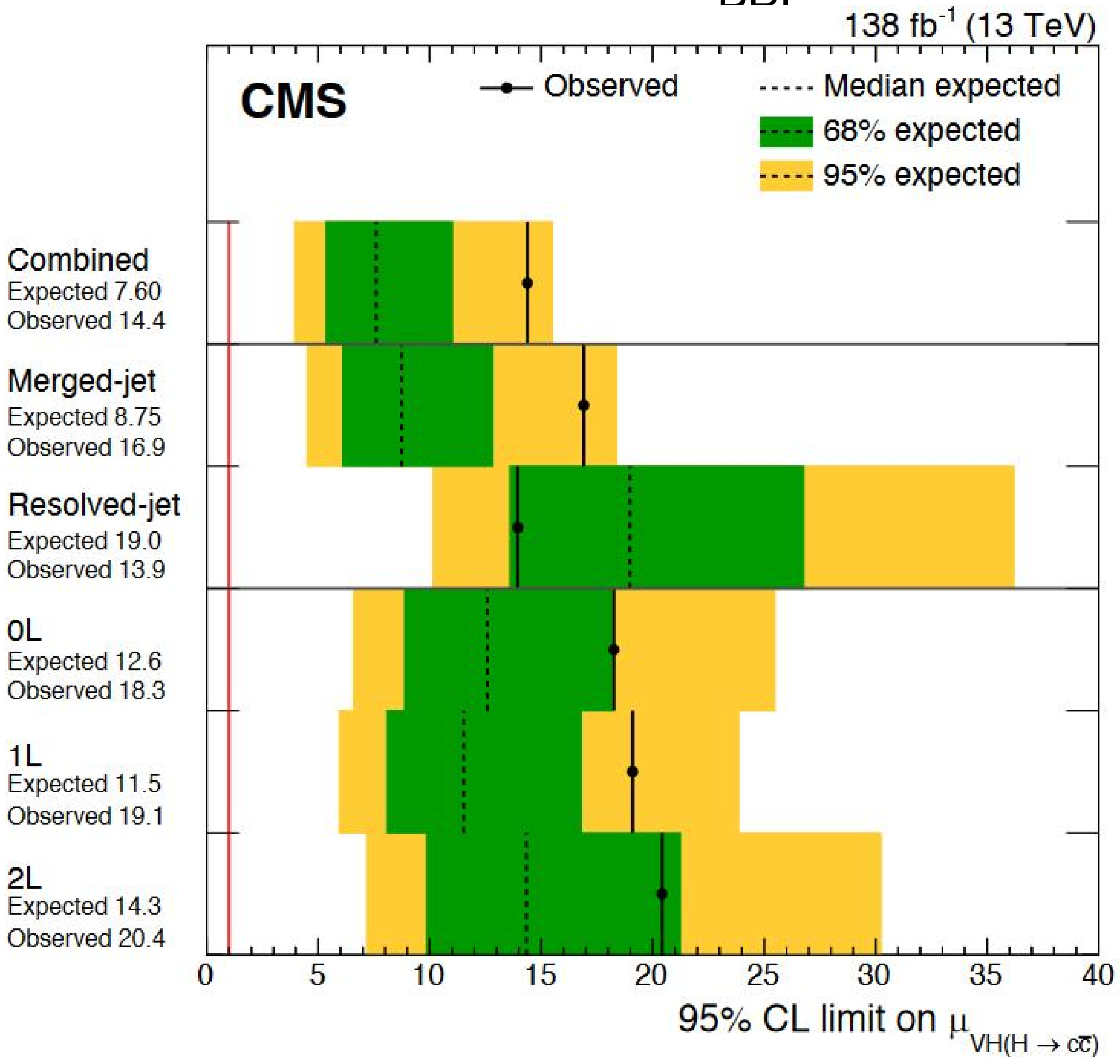
- VH production with W/Z boson decaying leptonically
- Expected BR: ~3%

- Two regimes:
  - Low momentum: resolved charm quark jets
  - Boosted (p T > 300 GeV): merged, single jet

- Novel charm jet identification and analysis methods using ML (GNN)
- Validated by searching for Z → cc in VZ events

Recent highlights: H–>cc

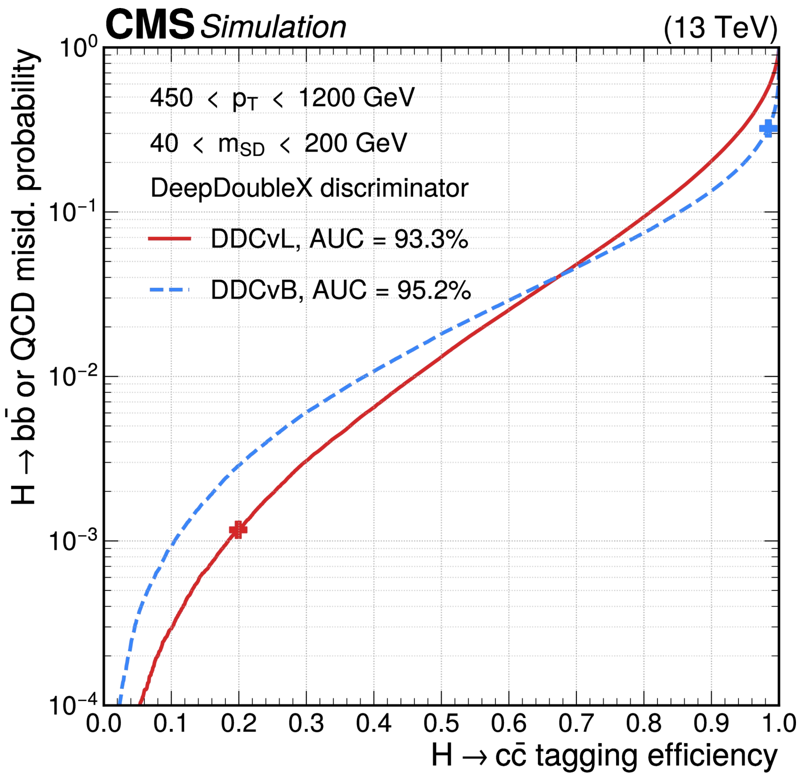
HIG-21-008, accepted by PRL

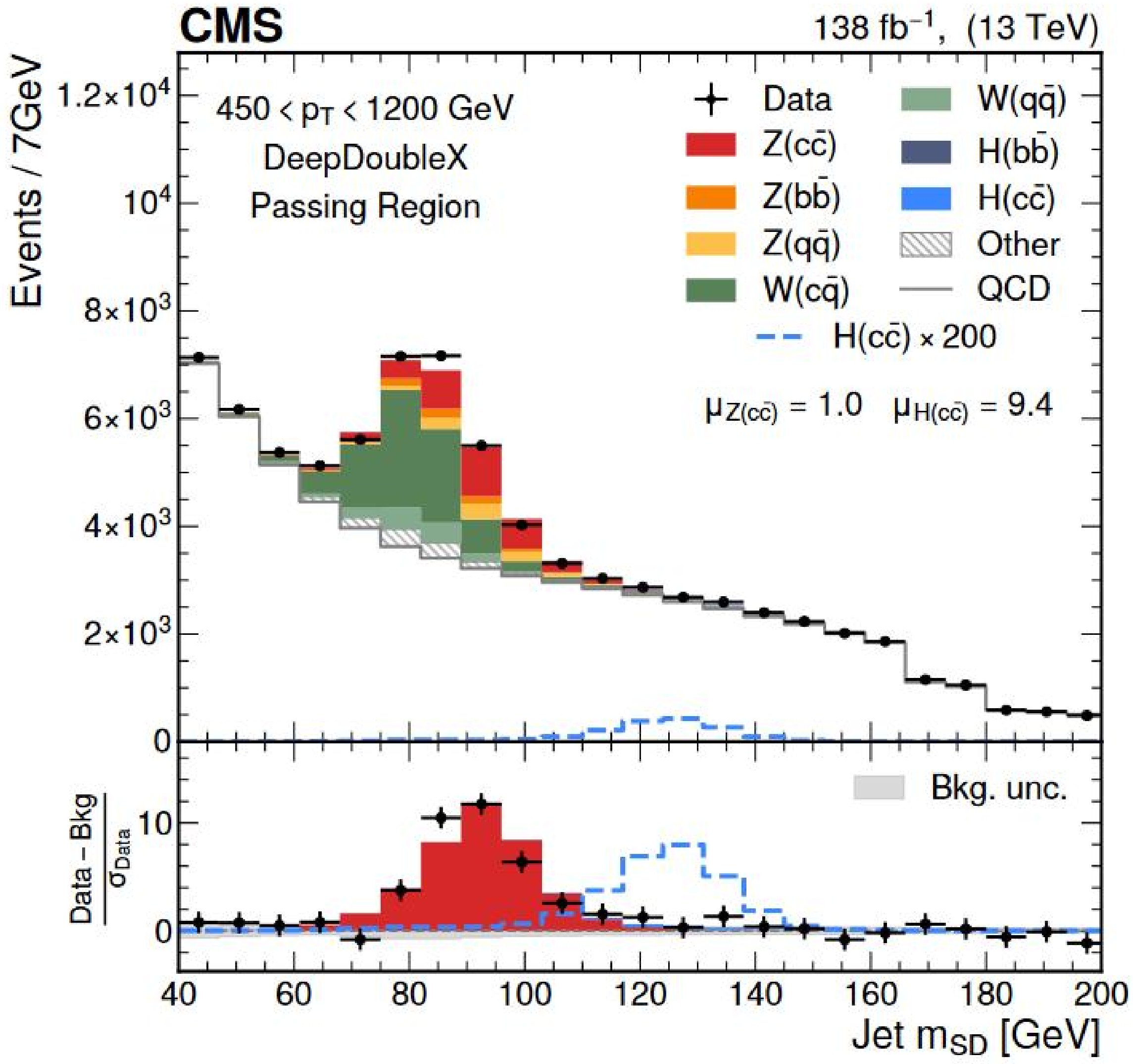


- Observed (expected) upper limit on σ(VH) B(H→cc) is 0.94 ($0.50^{+0.22}_{-0.15}$) pb at 95% CL
  - Corresponding to 14 ($7.6^{+3.4}_{-2.3}$) x SM
- For Higgs-charm Yukawa coupling modifier (κ_C), observed expected) 95% CL interval is $1.1 < |\kappa_c| < 5.5$ ($|\kappa_c| < 3.4$)
- **Most stringent constraint to date**

Recent highlights: boosted H–>cc

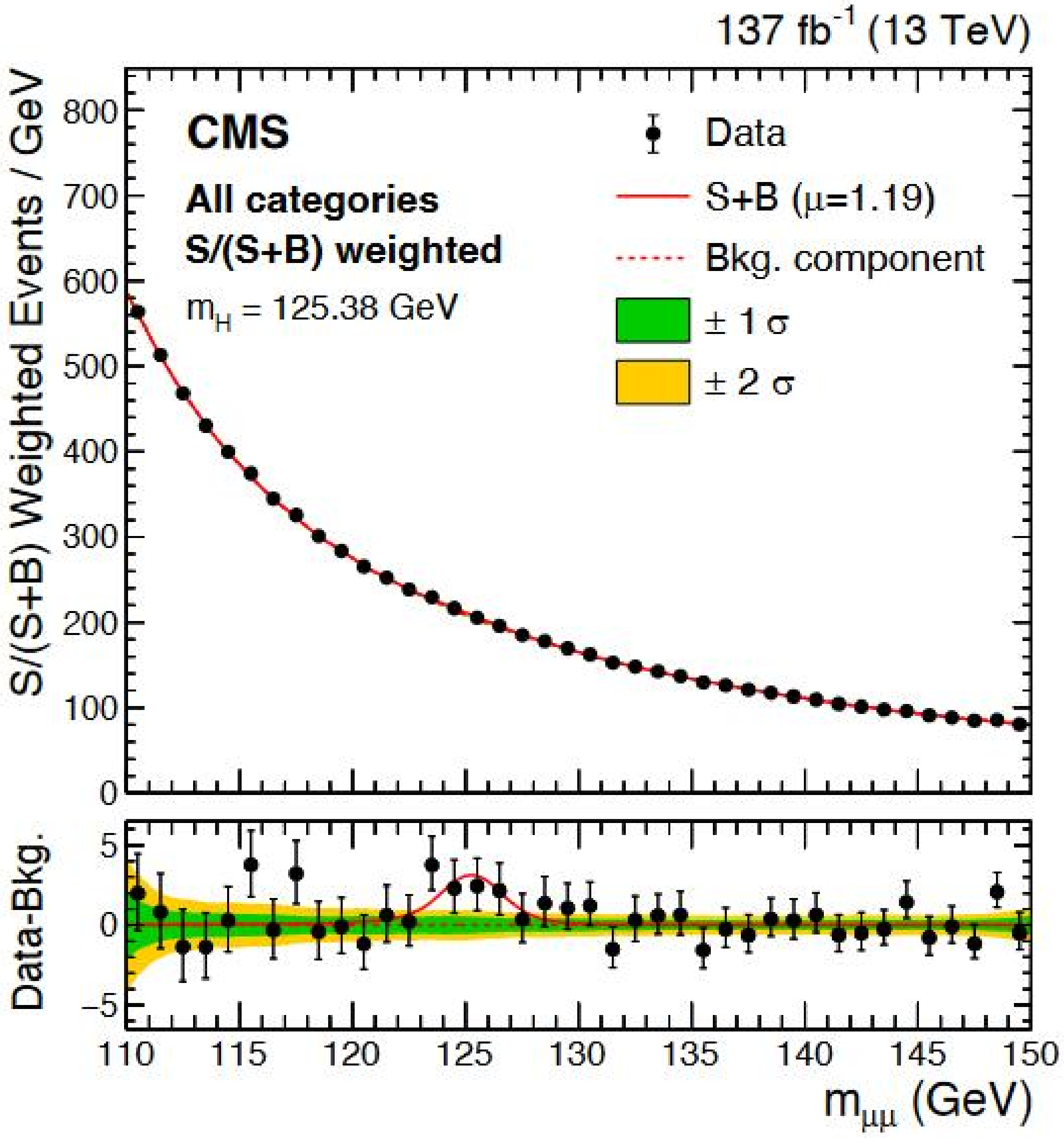
HIG-21-012, submitted PRL





- Boosted H→cc reconstructed as a single large-radius jet Identified using a deep neural network charm tagging technique
- Validated by measurement of Z→cc, observed with signal strength of: $1.00^{+0.17}_{-0.14}$ (syst) ± 0.08 (theo) ± 0.06 stat (stat)
- Observed (expected) upper limit on σ(H) B(H→cc) is 47 (39) x SM

Recent highlights: H–>$\mu\mu$

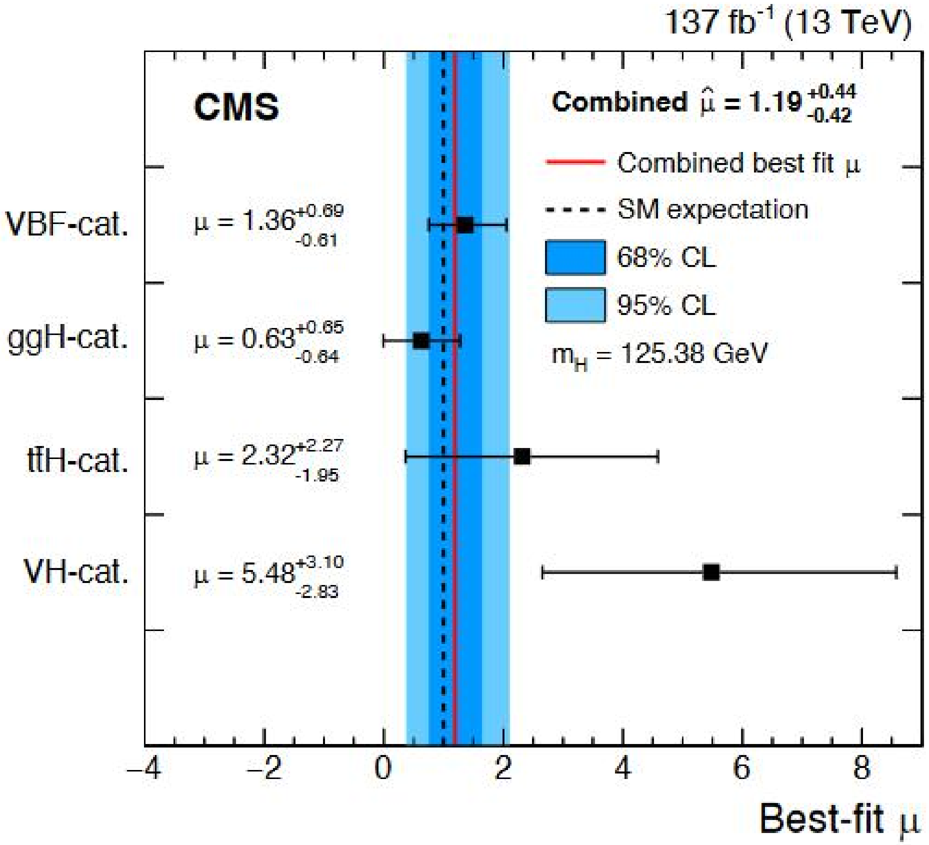


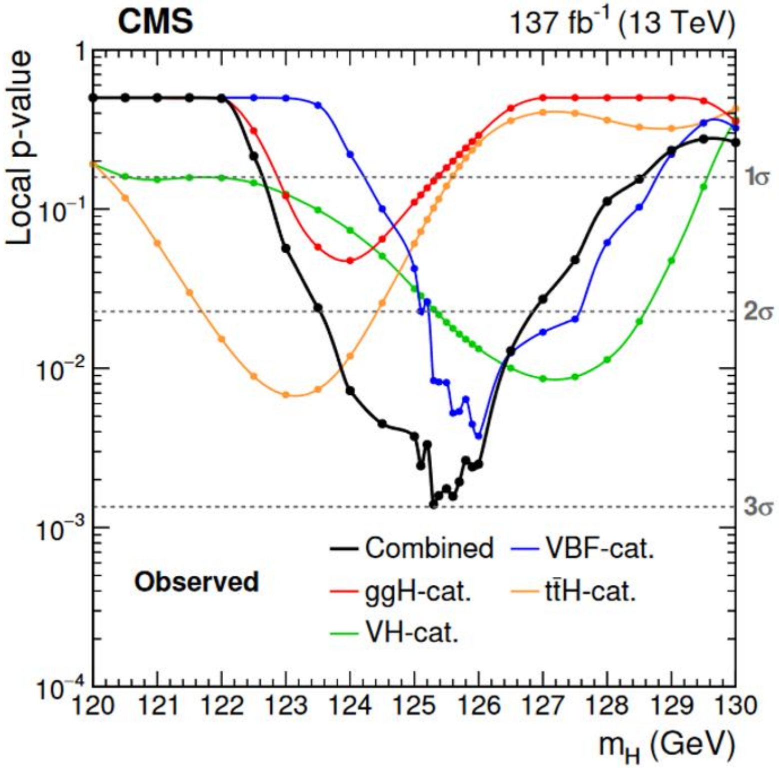
[JHEP 01 (2021) 148]

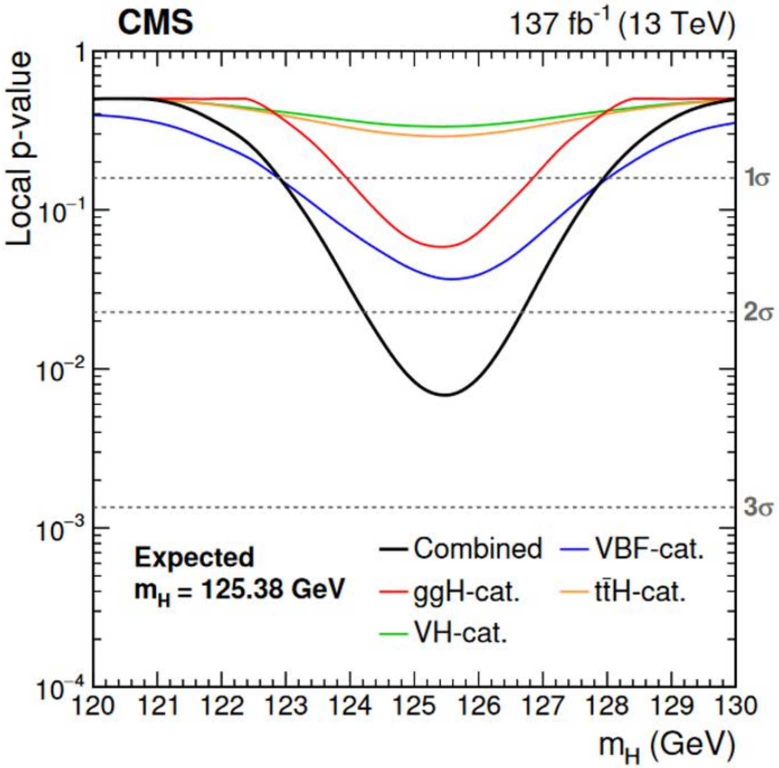
- Production: ggF, VBF, ttH and VH
- Selections applied in order of ttH, VH, VBF and ggH.
  - ttH: at least one medium or two loose b-tagged jets
  - VH: WH: 3μ or $2\mu 1e$, ZH: 4μ or $2\mu 2e$
  - VBF: 2 jets with VBF-like kinematic
  - ggH: events not selected by the other channels
- Expected BR: 2.17×10^{-4}
- Categories designed based on production processes
- Multivariate analysis (BDTs, DNN) is used in all channels

Recent highlights: H–>$\mu\mu$

[JHEP 01 (2021) 148]



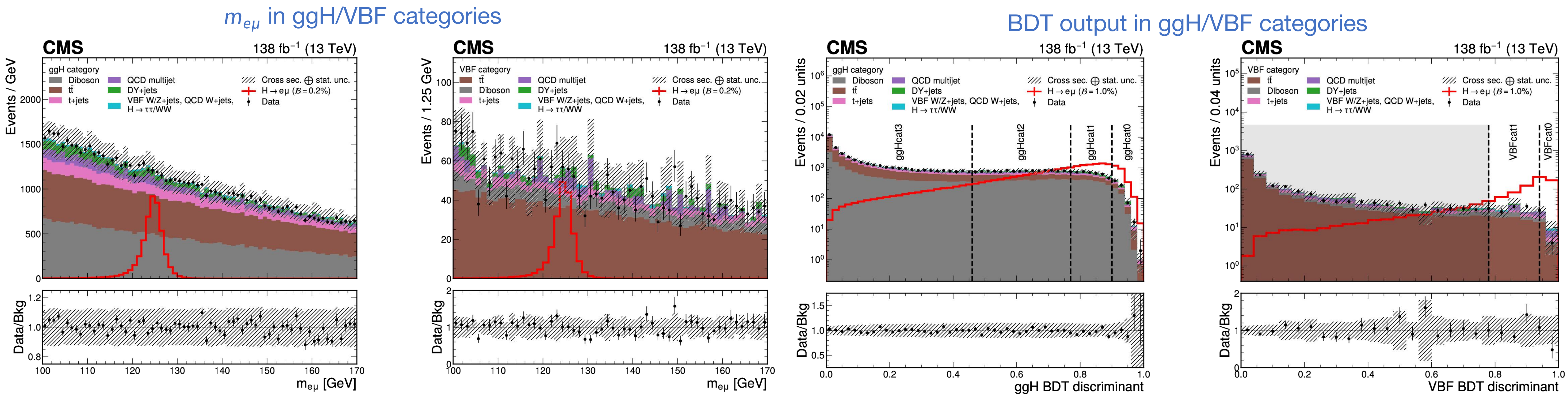




- Measured signal strength, relative to SM: $1.19^{+0.40}_{-0.39}$(stat)$0^{+0.15}_{-0.14}$(syst)
- First evidence for H $\rightarrow \mu\mu$: 3.0 (2.5)σ observed (expected)

Recent highlights: LF violating H–> eμ

HIG-22-0002 ,submitted to PRD

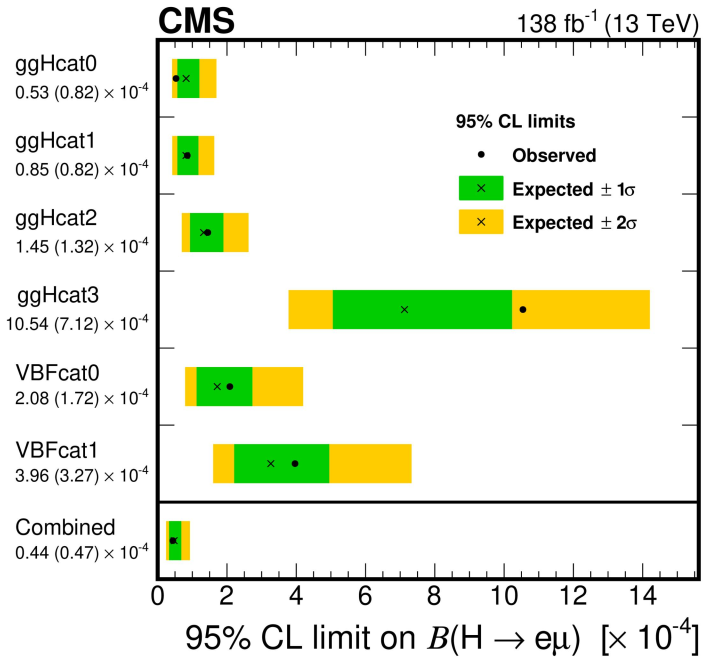


- The lepton-flavor violating (LFV) decays $H \to e\mu$, $H \to e\tau$, or $H \to \mu\tau$ are forbidden in the SM but may arise in BSM theories with more than one Higgs boson doublet
- Search for the lepton-flavor violating decay of the Higgs boson and potential additional Higgs bosons with a mass in the range 110-160 GeV to an $e^{\pm}\mu^{\mp}$ using 138 fb^{-1}
- Events are first divided into two broad categories to enhance the signal from either the ggH or the VBF
  - Then further split using output of boosted decision trees (BDTs)

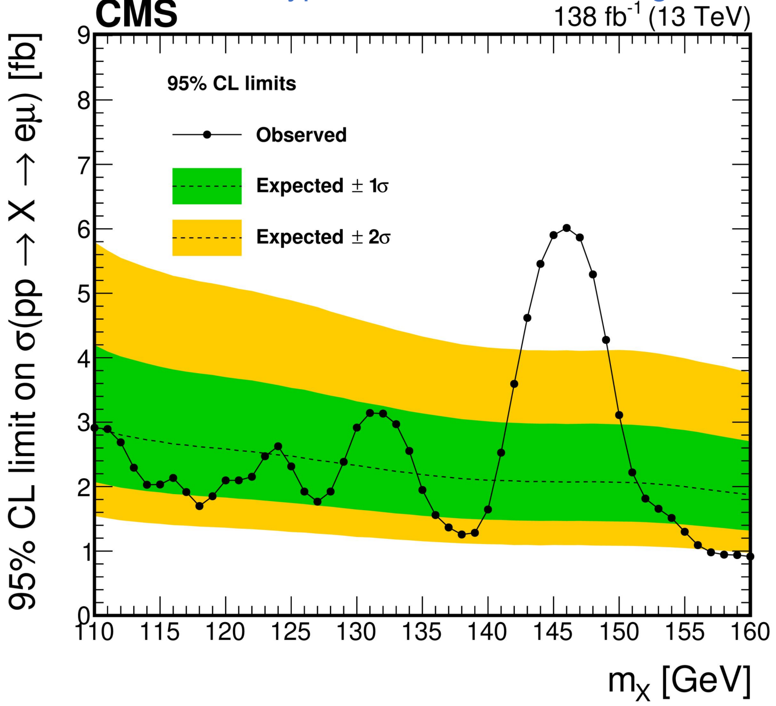
Recent highlights: LF violating H–> eμ

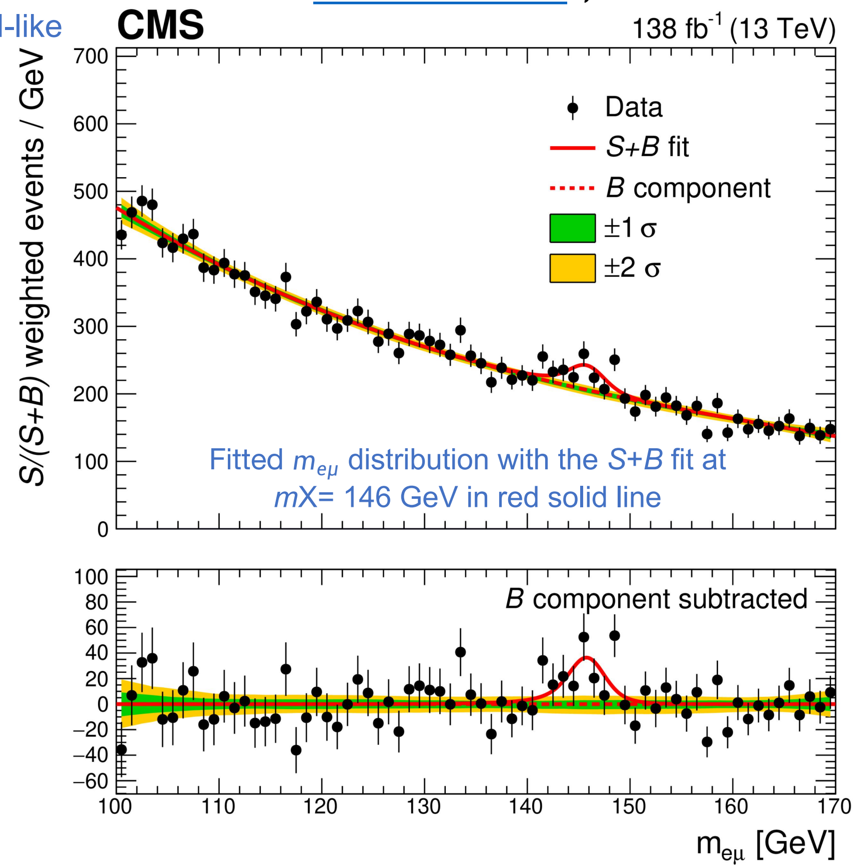
[HIG-22-002](#) ,submitted to PR

Observed (expected) 95% CL upper limits on B(H→eμ) category and the combination



95% CL upper limits on σ(pp→X→eμ) as a function of the hypothesised mX, assuming relatively SM-like



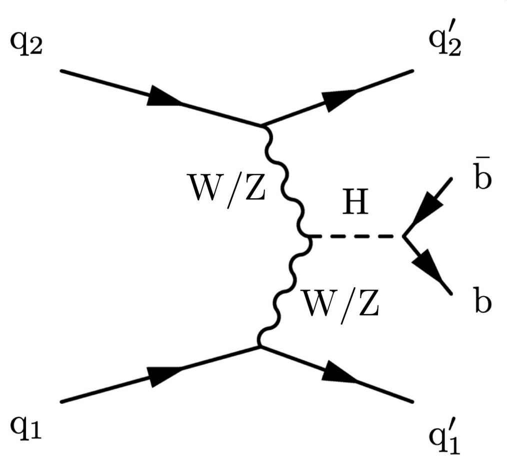


Fitted $m_{e\mu}$ distribution with the S+B fit at mX= 146 GeV in red solid line

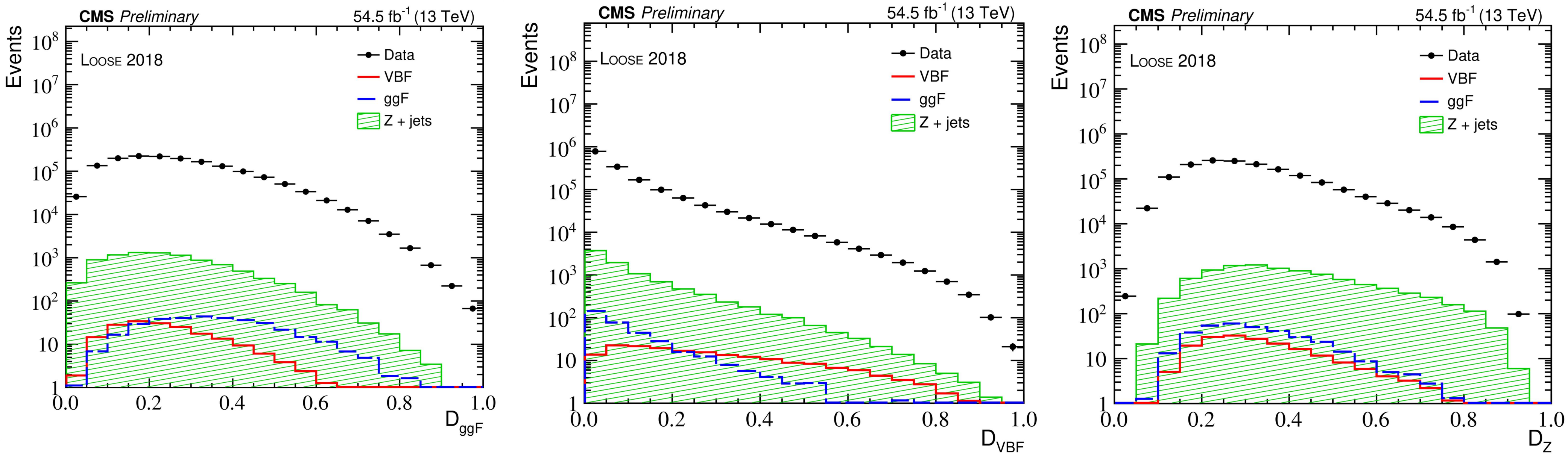
- Observed (expected) limit on B(H→eμ): 4.4 (4.7) × 10^{-5} at 95% confidence level
  - The most stringent direct limit set thus far.
- The observed (expected) upper limits on the cross sections of pp→X→eμ are set in the mX range 110-160 GeV at 95% confidence level.
- Largest excess: local (global) significance of 3.8 (2.8) σ at an $m_{e\mu}$ around 146 GeV.
  - This is the first result of a direct search for X→eμ, with mX below twice the W boson mass.

Recent highlights: VBF H–>bb

[HIG-22-009]



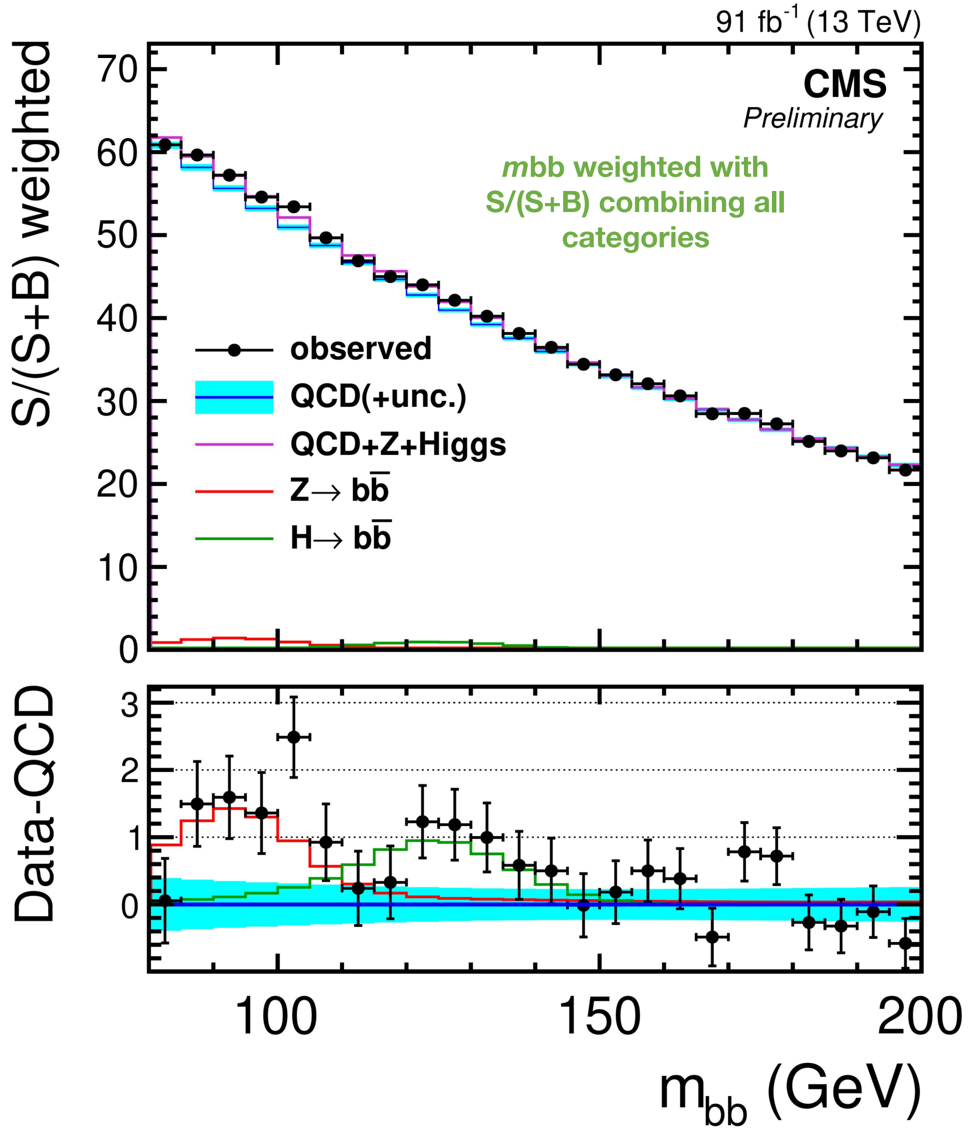
- VBF H->bb search using 91 fb^{-1} (2016+2018) at 13 TeV.
    - 2017: No trigger path suitable for this analysis
- Treating ggF as a background and constraining its rate to SM
- The analysis employs BDT to discriminate signal against major background processes - QCD multijet production and Z + jets events
- Based on the BDT: multiple event categories are introduced, targeting VBF, ggF and Z + jets



BDT outputs for each processes
Data is dominated by QCD

Recent highlights: VBF H->bb

HIG-22-009



- Observed (expected) significance of μ_{qqH}: 2.4 (2.7) σ, $\mu_{\mathrm{qqH}} = 0.97^{+0.53}_{-0.45}$
- Inclusive measurement of H production followed by decaying into 2b: Observed (expected) significance 2.5 (2.9) σ, $\mu_{\mathrm{qqH}} = 0.92^{+0.45}_{-0.39}$

Summary

- H measurements are essential to LHC physics program
- XS and BR: overall good compatibility with SM predictions
  - Precision better than 10% for most of the considered coupling modifiers
  - Statistical uncertainties comparable to systematics ones for main H production and decay channels
- **CMS have also made impressive progress in rare decay searches**
- Improvements not only come from a larger data set, but also from using innovative analysis techniques
- Run 3 will consolidate the evidence in some decay channels and will bring further improvement in sensitivity