SEARCH FOR RARE HIGGS DECAYS AND PRODUCTION MODES AT CMS

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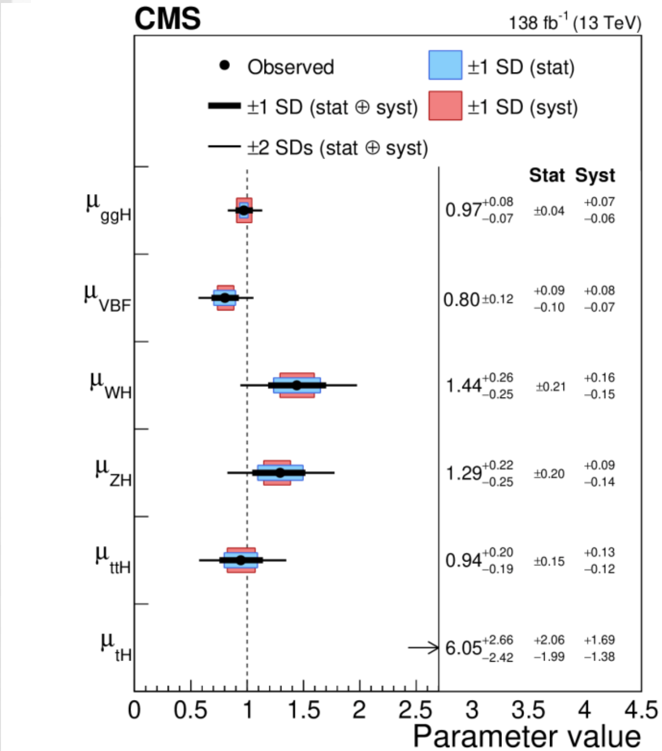
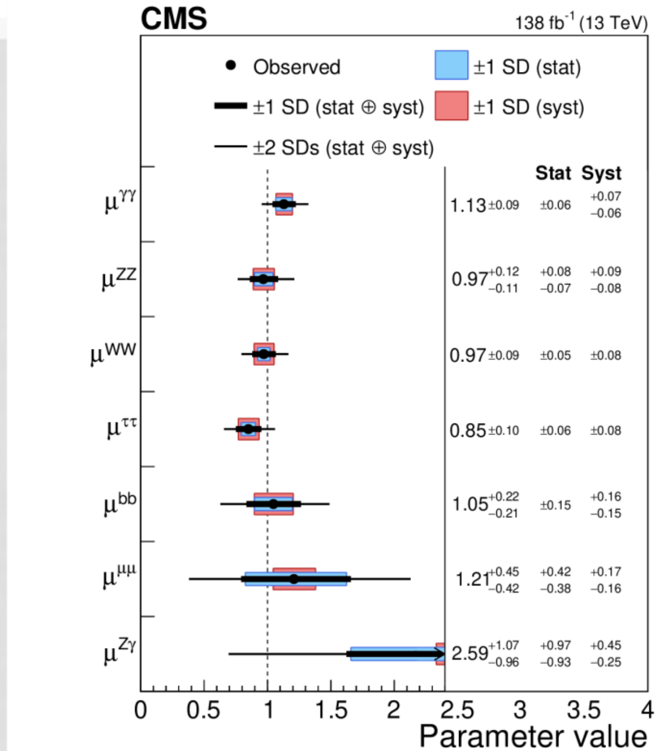
ON BEHALF OF THE CMS COLLABORATION

DIS 2024, HIGGS SESSION, 9 APRIL 2024

HIGGS BOSON: SM VS. MEASUREMENTS





Nature 607, 60 (2022)

$\mu = \sigma_{meas}/\sigma_{SM}$

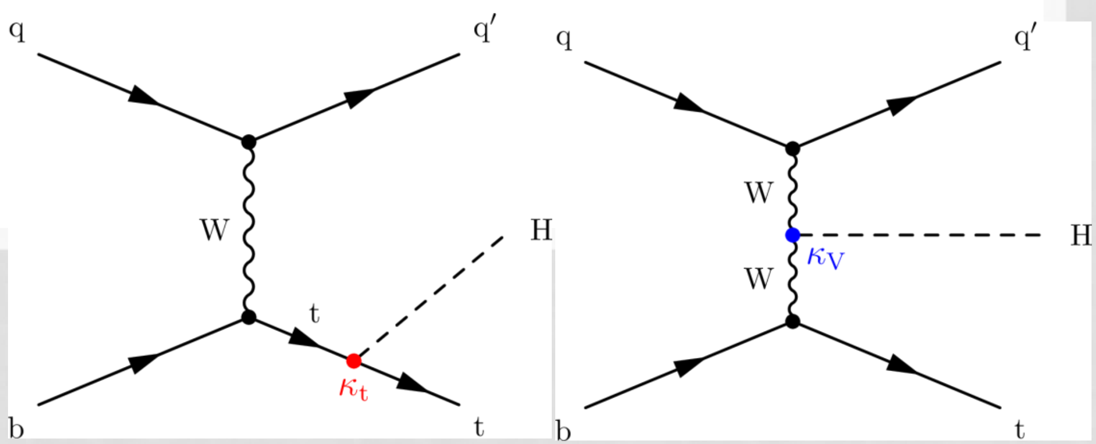
If NP in the Higgs sector, it may hide in **little-known couplings**

- PRODUCTION MODES:
  - **Several unmeasured (or barely explored) production modes: tH, bbH, γH…**
- DECAYS:
  - **Boson decay channels well established, except Zγ**
  - **Couplings with 1st and 2nd-generation fermions largely unknown**

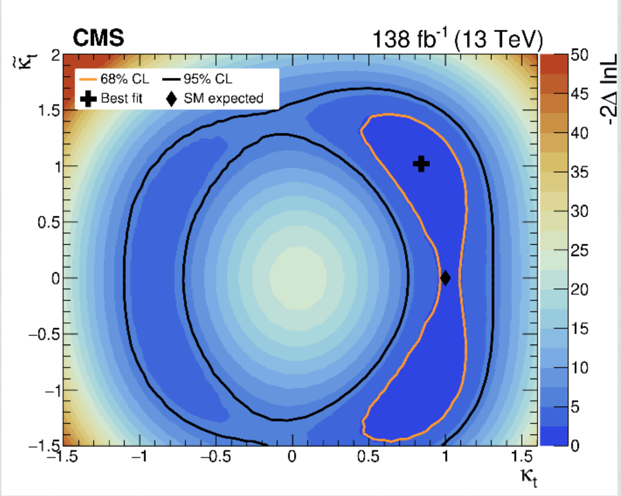
RARE PRODUCTION MODES

- NOTE: Unless differently specified, all results are based on the CMS dataset from LHC Run2 (L = 138 fb^{-1} at $\sqrt{s}$ = 13 TeV)

tH SEARCHES



- Single-top + Higgs production
  - tHq
  - tHb
  - tHW
  - Total cross-section of the 3 contributions ~80 fb @ 13 TeV
- Theoretically and experimentally linked to $t\bar{t}H$ production mode
  - The two processes interfere (at different levels depending on 4- or 5-flavor scheme description)
  - Combined measurement is a probe of CP admixtures in the top-Higgs coupling
  - Very close final states, typically tH is a subdominant contribution in the ttH event yields → dedicated selection categories
- Current best CMS tH results from b-jet + multi-lepton final states ($H \rightarrow WW$, $\tau\tau$ etc.)
  - μ_{tH} **= 5.7 ± 2.7 (stat.) ± 3.0 (syst.)**
  - First limits on CP-odd couplings

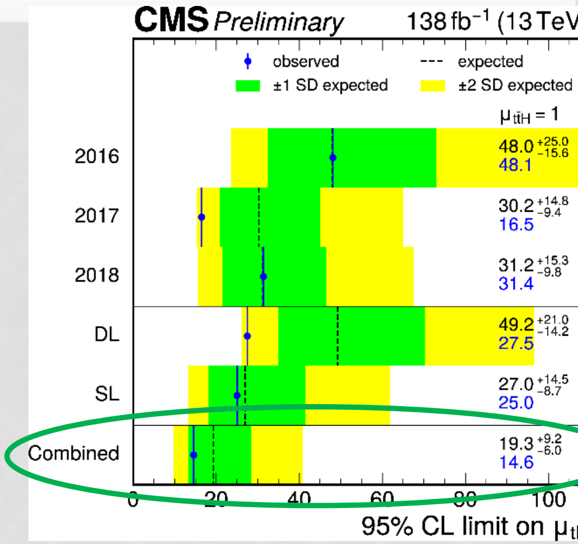


CMS coll., Eur. Phys. J. C81 (2021) 378
CMS coll., JHEP 07 (2023) 092

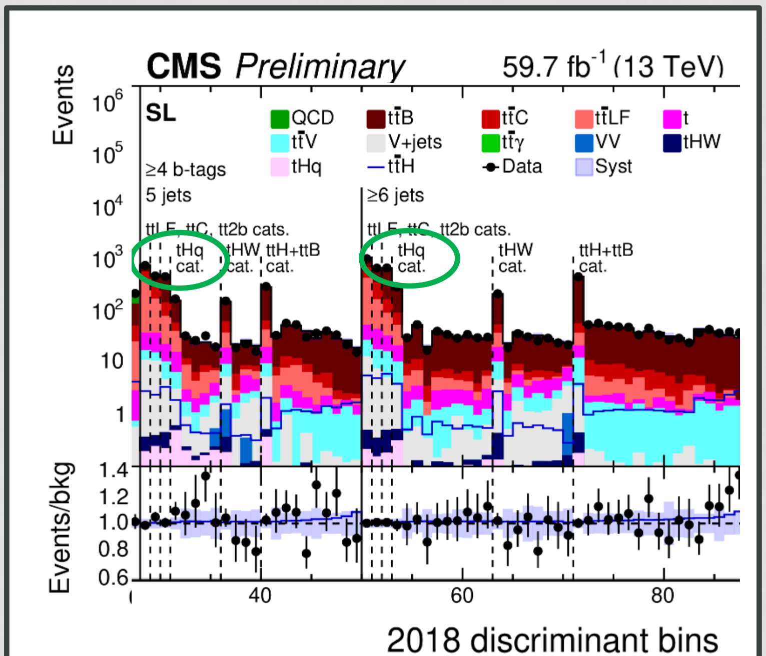
tH IN THE H → $b\bar{b}$ FINAL STATE

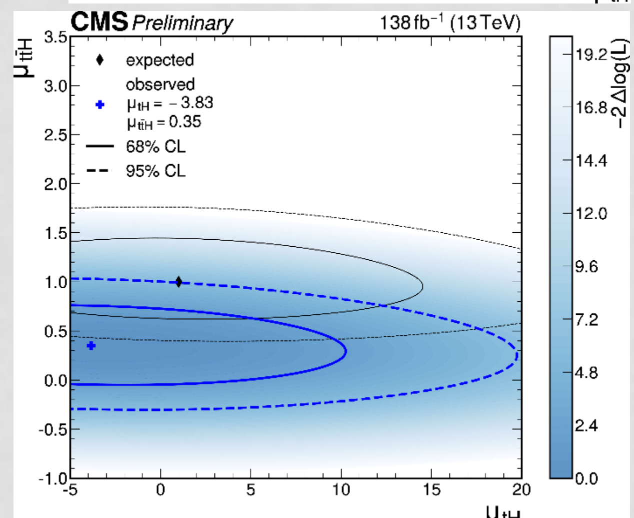
CMS-PAS-HIG-19-011 (2023)

- Largest sensitivity in semileptonic categories (1 lepton from W decay + n jets, of which at least m are b-tagged)
- Dedicated categories enriched in tHq or tHW in multi-class ANNs based on many variables related to kinematics and b-tagging



- Fits of event yields or ANN shape templates in categories
- SM signal strength determined in two hypotheses:
  - $\mu_{ttH} = 1$
  - Both μ free

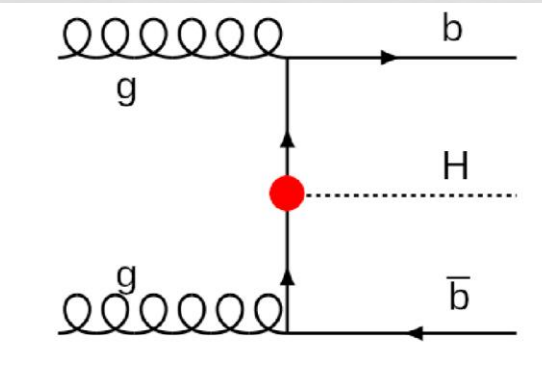




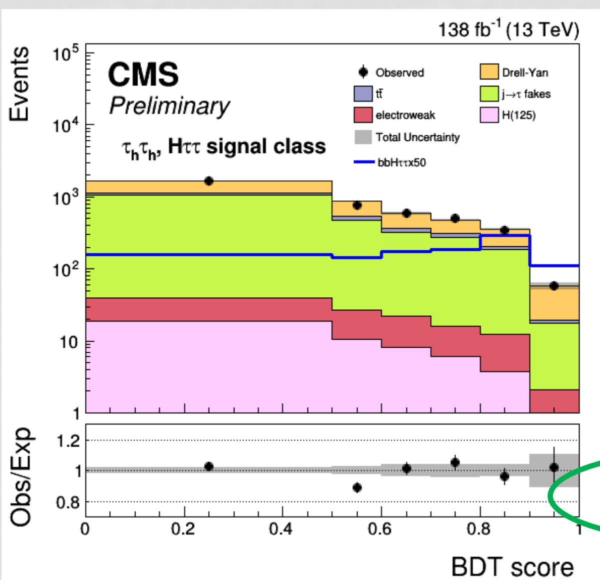
$b\bar{b}$H WITH MULTILEPTONS

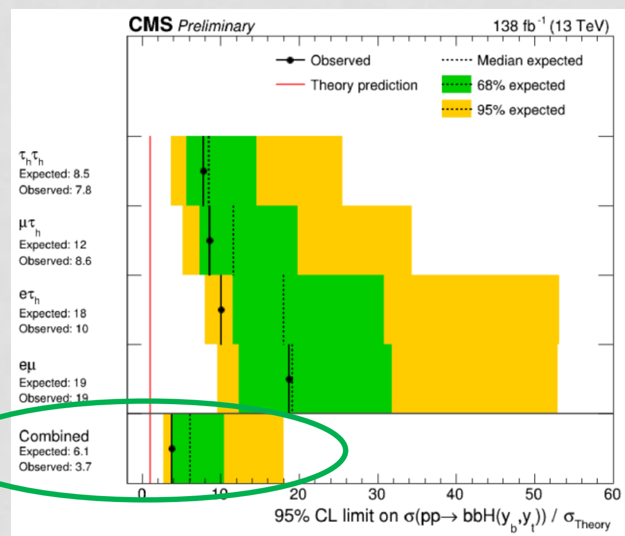
New!

CMS-PAS-HIG-23-003 (2024)



- Cross-section similar to ttH, but more challenging experimentally
  - Less distinguishing event signature
  - Destructive interference with other production modes
- Multilepton final states (including τ with hadronic decays)
  - State-of-the-art DNN-based τ and b-jet identification

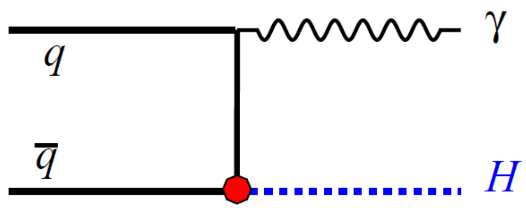


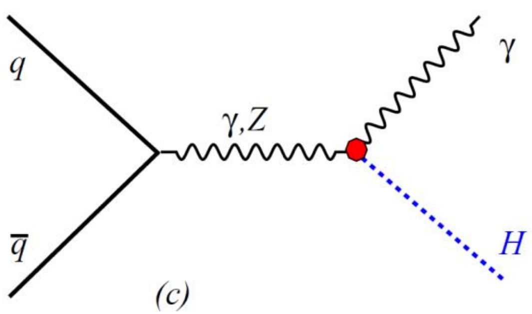


- BDTs trained in 4 event categories ($e\mu$, $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$)
- Output scores values defining event "classes" (HWW, H$\tau\tau$, other)
- Template fits in classes

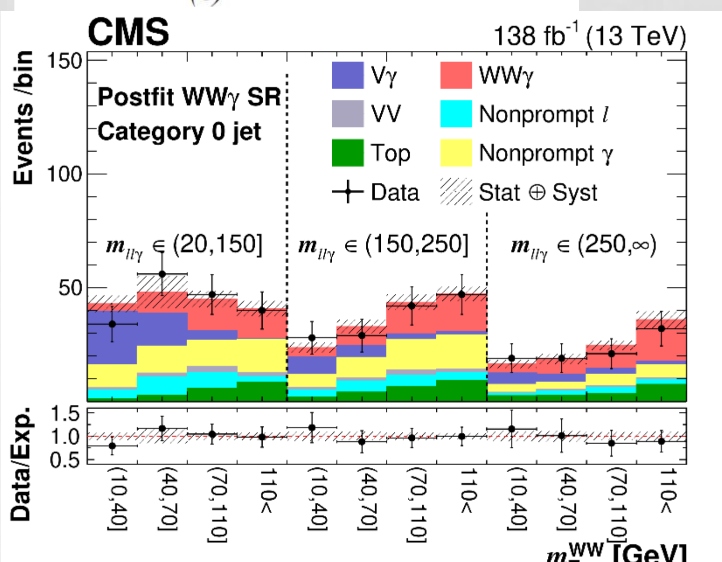
γH WITH H → W⁺W⁻

CMS coll., Phys.Rev.Lett. 132 (2024) 121901





- Vanishing cross-section for gg → γH
  - Dominant diagrams sensitive to anomalous Hqq or Hγγ/HZγ couplings
- Very clean final state ($e\mu\gamma + p_{T,miss}$)
  - Non-prompt lepton/γ fraction from data
  - 2-dimensional fit in $m_{T,WW}$, $m_{e\mu\gamma}$
    - Result interpreted in terms of constraints to multipliers of SM Hqq couplings (κ_q)

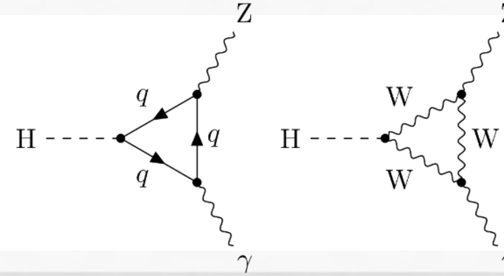


Process	κ_q limits obs. (exp.) at 95% CL
$u\bar{u} \to H + \gamma \to e\mu\nu_e\nu_\mu\gamma$	$\lvert\kappa_u\rvert \leq 16000$ (13000)
$d\bar{d} \to H + \gamma \to e\mu\nu_e\nu_\mu\gamma$	$\lvert\kappa_d\rvert \leq 17000$ (14000)
$s\bar{s} \to H + \gamma \to e\mu\nu_e\nu_\mu\gamma$	$\lvert\kappa_s\rvert \leq 1700$ (1300)
$c\bar{c} \to H + \gamma \to e\mu\nu_e\nu_\mu\gamma$	$\lvert\kappa_c\rvert \leq 200$ (110)

RARE DECAYS

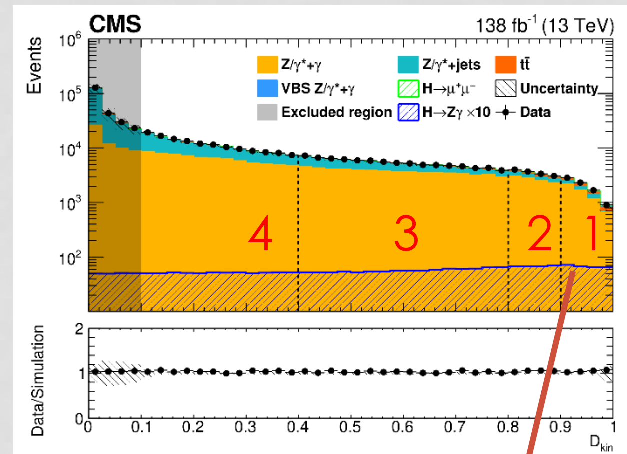
- NOTE: Unless differently specified, all results are based on the CMS dataset from LHC Run2 (L = 138 fb^{-1} at $\sqrt{s}$ = 13 TeV)

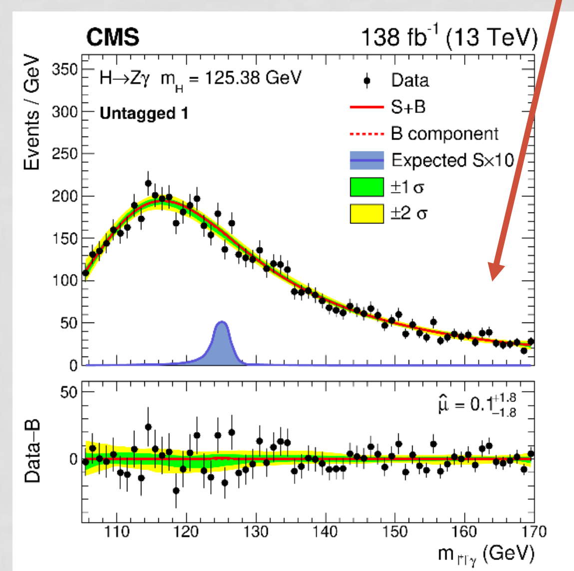
$H \rightarrow Z\gamma$ CMS



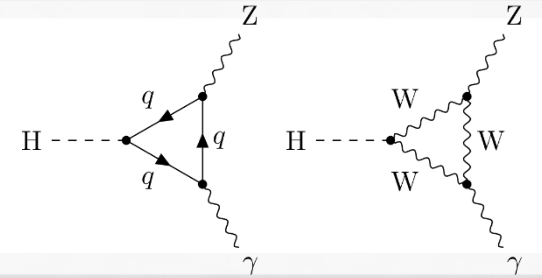
CMS coll., JHEP 05 (2023) 233

- Use $Z \rightarrow l^{+}l^{-}$ decay
- Event classification by production mode to isolate larger-purity categories
  - One additional lepton (targeting WH/ZH)
  - Two additional jets (targeting VBF)
    - Kinematic BDT discriminant trained → events further split in 3 categories based on output score
  - Untagged (targeting ggH)
    - 4 BDT categories
- Large background from Z+jets estimated from fits on $m_{ll\gamma}$ data sidebands



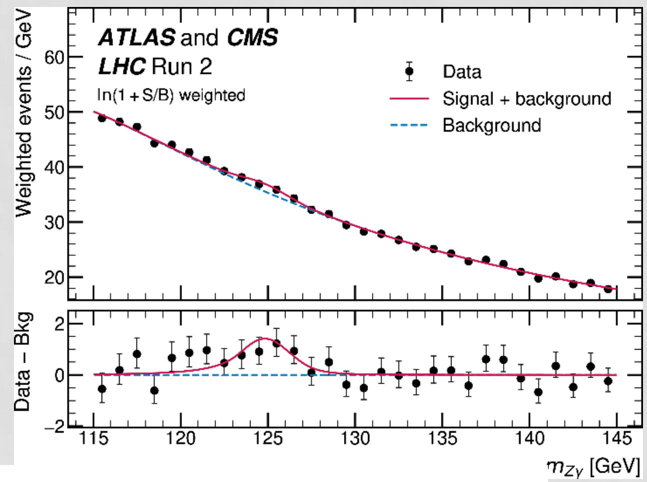


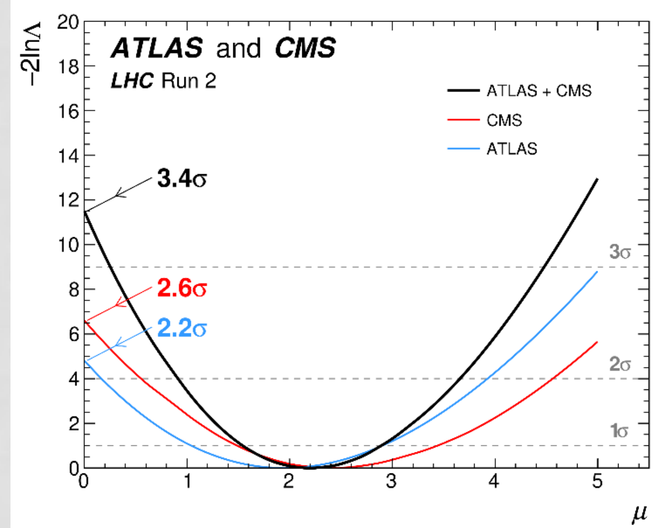
$H \rightarrow Z\gamma$ COMBINATION



ATLAS and CMS colls., Phys.Rev.Lett. 132 (2024) 021803

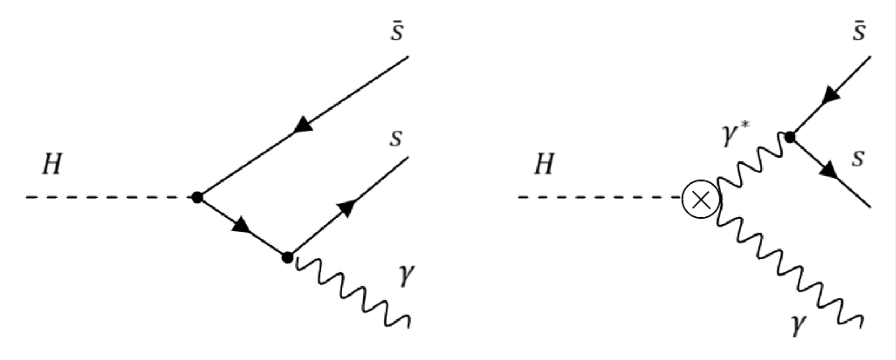
- Result combination with similar ATLAS analysis
  - Independent datasets, theory systematics correlated, experimental uncorrelated
- Both experiments consistently measuring small (non-significant) excess over SM
  - 3.4σ combined evidence
  - Best combined fit: $\mu = 2.2 \pm 0.7$
  - Agreement with SM expectation at the 1.9σ level

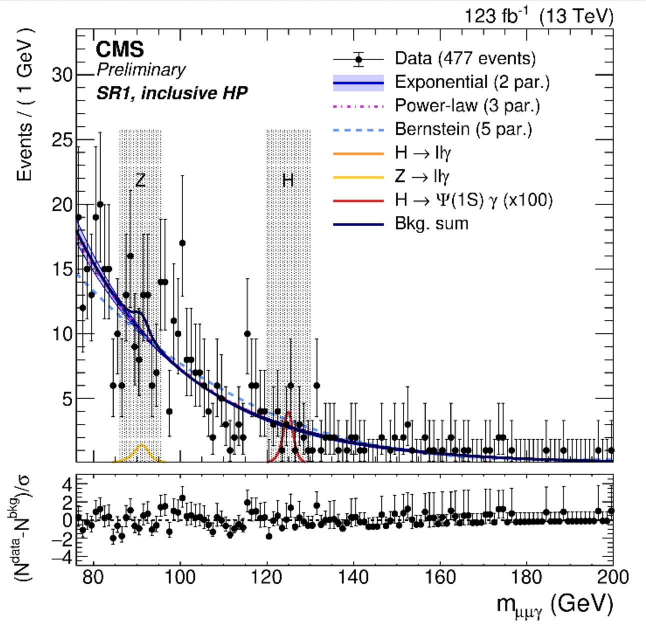




H → VECTOR MESON + γ

- Expected BRs in the 10^{-5}-10^{-6} range
  - Unique sensitivity to light-quark coupling through interference with dominant γγ* diagram
- J/ψγ and ψ(2S)γ → $\mu^+\mu^-\gamma$: similar strategy as Zγ
  - Event categorization based on production modes
    - 1 b-jet (ttH + bbH); 2 jets (VBF); untagged (ggH)
  - Likelihood discriminant for ggH based on spin-correlation variables
  - Upper limits @95% CL from $m_{\mu\mu\gamma}$ fits
    - BR(H → J/ψγ) < $2.6 \cdot 10^{-4}$
    - BR(H → ψ(2S)γ) < $9.9 \cdot 10^{-4}$



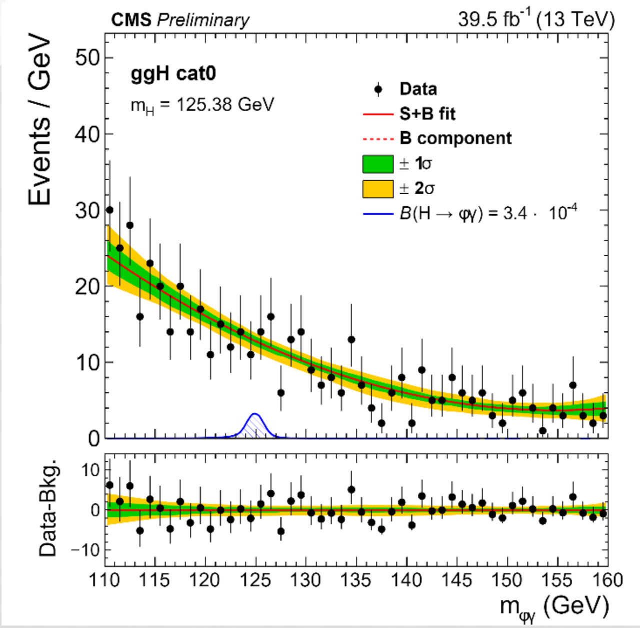


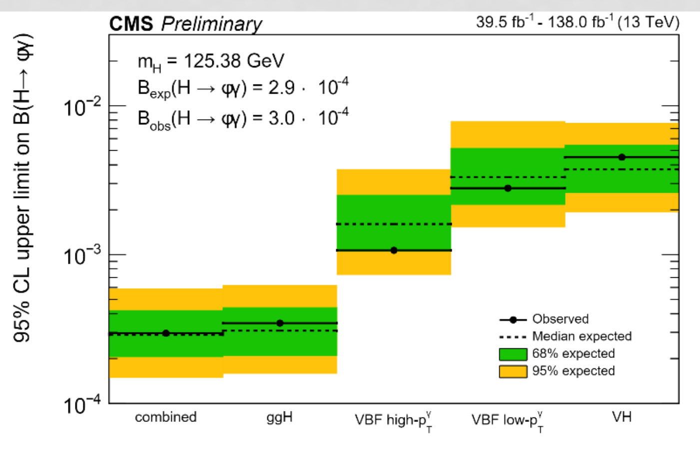
CMS-PAS-SMP-22-012 (2023)

New!

H → VECTOR MESON + γ

CMS-PAS-HIG-23-005 (2024)



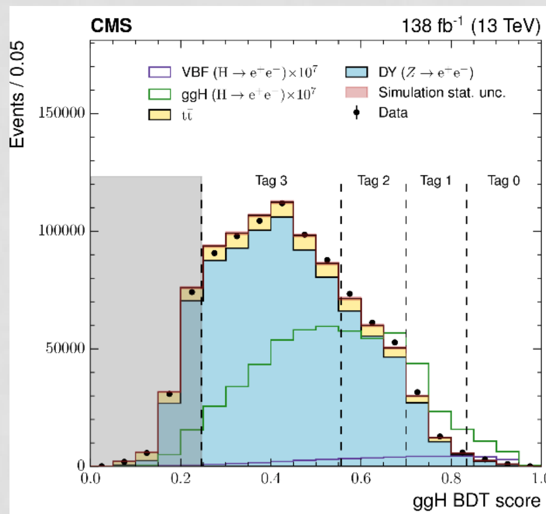


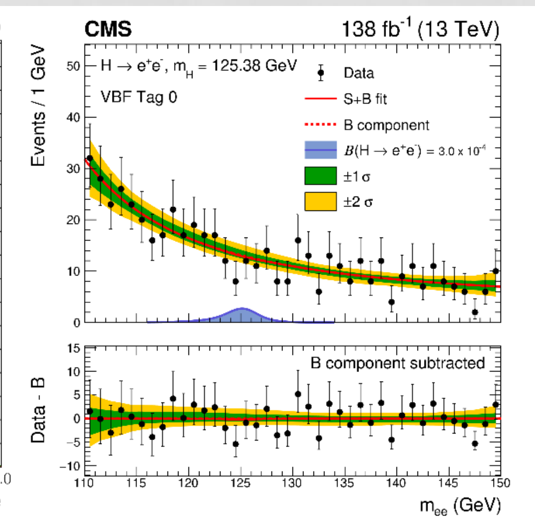
- ργ, ϕγ, $K^{*0}\gamma \to \gamma$ + di-track
  - Also targeting FCNC in final state
- Needs a dedicated high-level triggering technique
  - Definition of an isolated-meson object using similarities with hadronic τ reconstruction
- Event categorization using production modes
  - 1 lepton (WH + ZH); 2 jets (VBF); untagged (ggH)
- BDT discriminants for less pure categories
- Upper limits @95% CL from $m_{t+t-\gamma}$ fits
  - $BR(H \to \rho\gamma) < 3.7 \cdot 10^{-4}$
  - $BR(H \to \phi\gamma) < 3.0 \cdot 10^{-4}$
  - $BR(H \to K^{*0}\gamma) < 1.7 \cdot 10^{-4}$

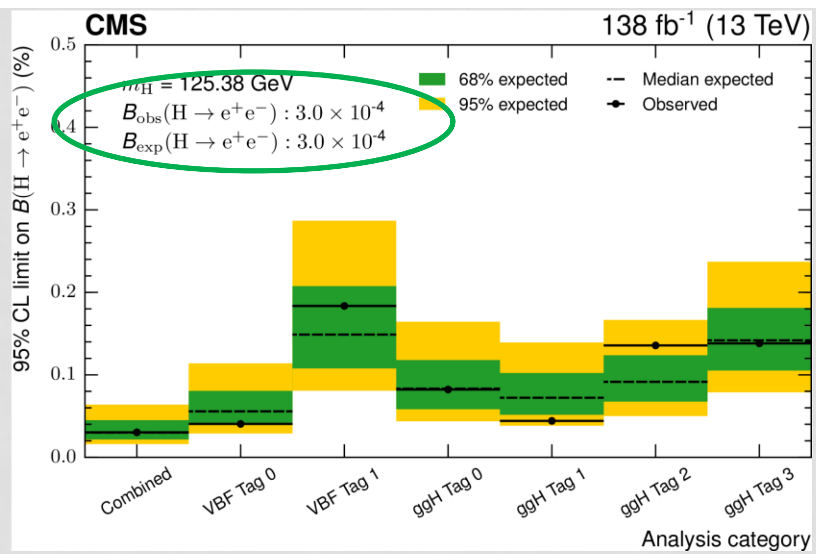
$H \rightarrow e^+e^-$

CMS coll., Phys.Lett. B846 (2023) 137783

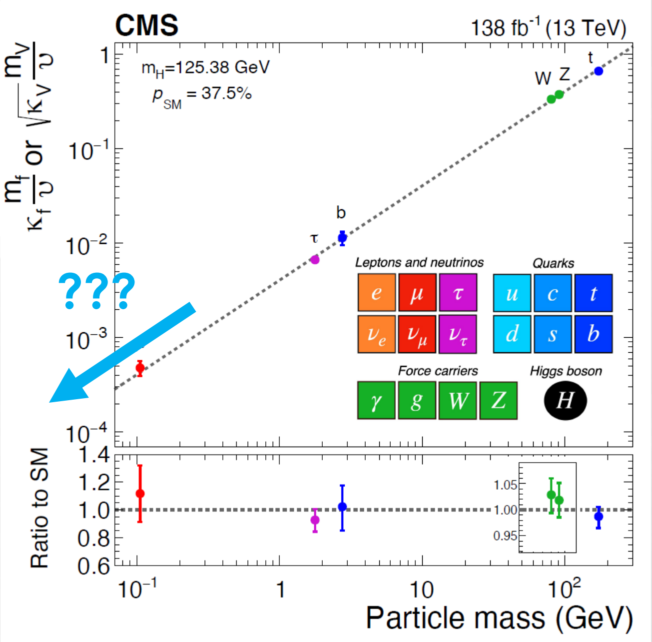
- $BR_{SM}(H \rightarrow e^+e^-) = 5 \cdot 10^{-9}$
- Event classification:
  - Two additional jets (targeting VBF)
    - Kinematic BDT discriminant trained → events further split in 2 categories based on output score
  - Untagged (targeting ggH)
    - 4 BDT categories
- Large background from DY directly fit from data
- Systematics/calibration/ resolution… etc. largely constrained from large $Z \rightarrow e^+e^-$ data samples







CONCLUSIONS



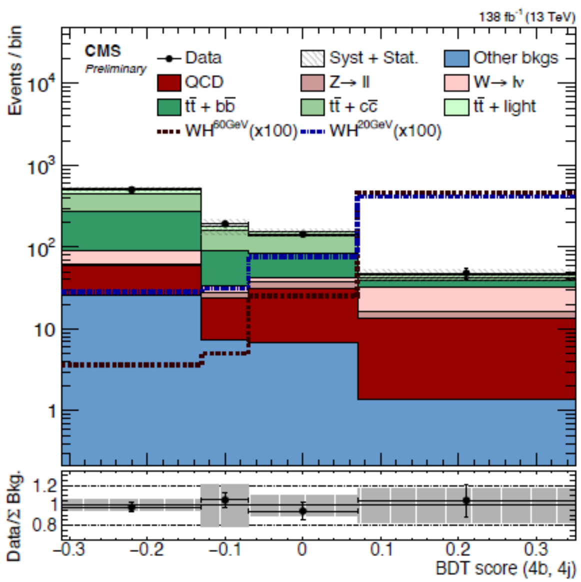
- Higgs boson measurements in CMS have reached precisions of 10-20% on main production/decay modes
  - Corresponding to tight constraints on possible deviations from SM Higgs-boson couplings
- Rare production modes and decays are the key to accessing less explored couplings
  - Closing in on tH and bbH production modes (limits are a few times the SM predictions)
  - Evidence for Zγ sheds light on the last Higgs-to-bosons decay
  - Couplings to lightest particles (electrons, light quarks)? SM beyond CMS reach both now and in the future → signal observations would be clear hints of BSM physics
  - Rare-decay measurements statistically limited, expect large improvements from Run3 and high-luminosity phase

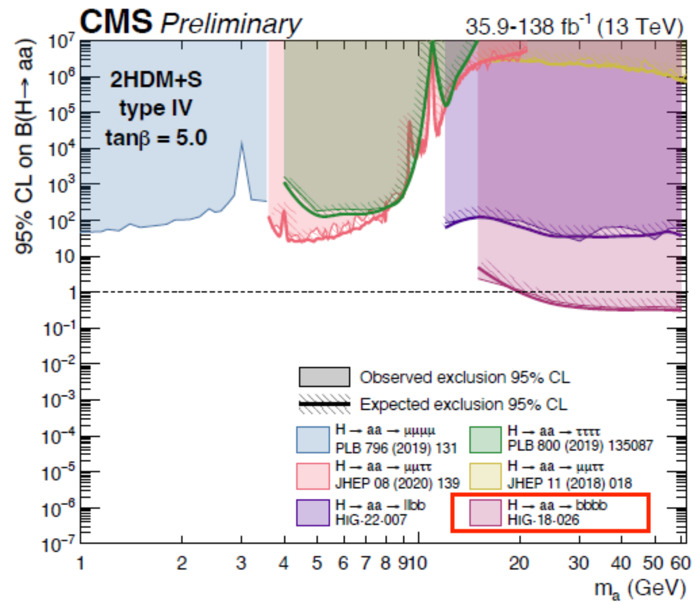
BACKUP

H → AA → 4B

Challenging fully hadronic final state, consider mass range 12 < m_a < 60 GeV HIG-18-026

- Feasible reconstruction in VH production mode, events selected using single or double-lepton trigger
- Resolved analysis: at least 3 jets in the selected events, categorised based on number of jets and b-jets
- Signal-to-background discrimination using a BDT, score distribution compared to data



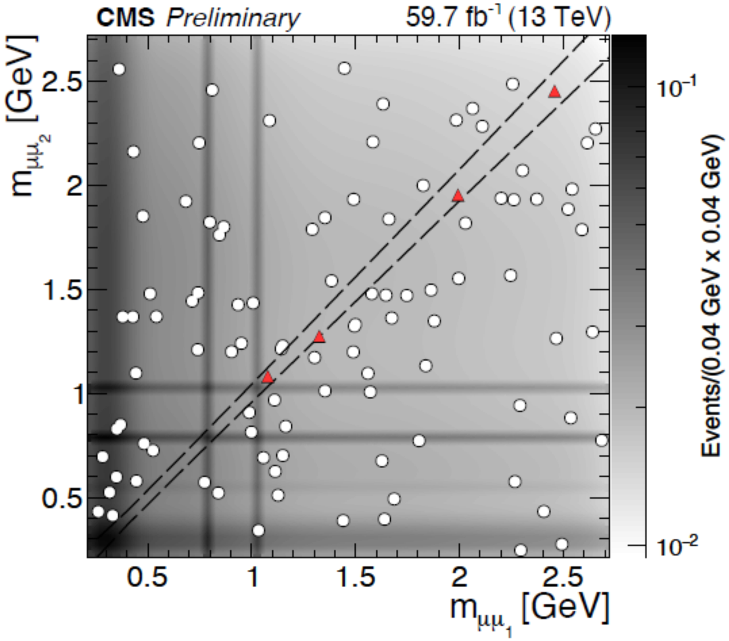


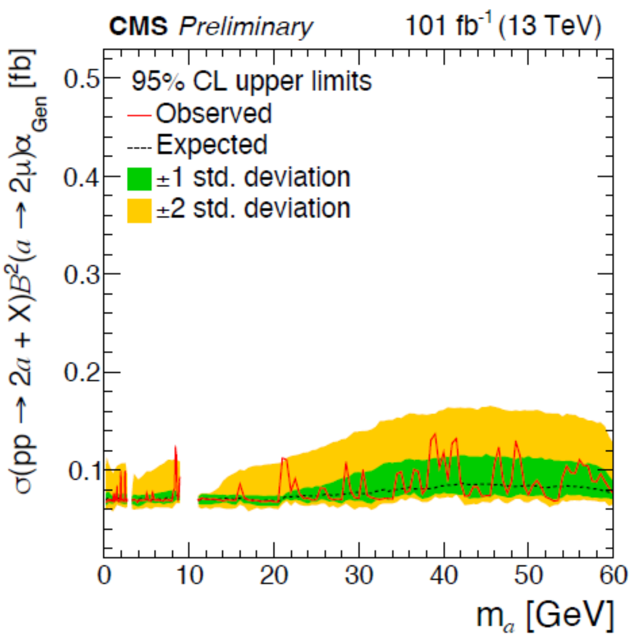
Assuming B(H→aa→4b) = 100%, m_a values between 21-60 GeV are excluded at 95% CL

H → AA → 4MU

Model-independent search considering **0.21 < m_a < 60 GeV and 0 < cτ < 100 mm** [HIG-21-004]

- Interpreted in terms of vector-portal, ALPs, NMSSM, dark-SUSY models
- Long-lived muon trigger utilised for 2018 data
- Reconstruct two dimuon pairs per event where $|m_{(\mu\mu)1} - m_{(\mu\mu)2}| < f\,(m_{(\mu\mu)1} + m_{(\mu\mu)2})/2$



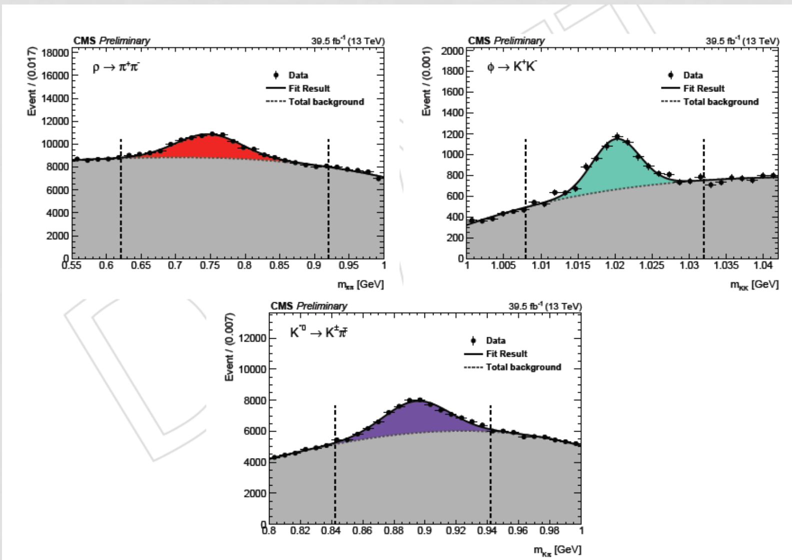


95% CL upper limit on $\sigma(H\to 2a+X)\times BR^2(a\to 2\mu)$, constrained within 0.049 and 0.247 fb

BBH BDT

Variable	$e\mu$	$e\tau_h$	$\mu\tau_h$	$\tau_h\tau_h$
$m_{\tau\tau}$	×	✓	✓	✓
m_{vis}	✓	✓	✓	✓
Collinear mass	×	✓	✓	×
D_ζ	✓	✓	✓	×
$\Delta\eta$ between lepton and τ_{h}	×	✓	✓	×
Total transverse mass	✓	×	×	×
Di-τ p_{T}	✓	✓	✓	✓
Electron p_{T}	✓	×	×	×
Muon p_{T}	✓	×	×	×
p_{T} of leading τ_{h}	×	×	×	✓
p_{T} of trailing τ_{h}	×	×	×	✓
Transverse mass	×	✓	✓	×
Number of b-jets	✓	×	×	✓
p_{T} of leading b-jet	✓	✓	✓	✓
p_{T} of trailing b-jet	×	✓	✓	×
B-tag score for leading b-jet	×	✓	✓	✓
$\Delta\eta$ between di-τ p_{T} and leading b-jet	×	✓	✓	×
B-tag score for trailing b-jet	×	✓	✓	✓
Number of jets	✓	×	×	✓
p_{T} of leading jet	✓	×	×	✓
p_{T} of trailing jet	✓	×	×	✓
Di-jet invariant mass	×	×	×	✓
Di-jet $\Delta\eta$	✓	×	×	✓
$p_{\mathrm{T}}^{\mathrm{miss}}$	×	×	×	✓

PHI,RHO,K* GAMMA BREAKDOWN



	U.L. $\mathcal{B}(H \to \rho^0\gamma)$		U.L. $\mathcal{B}(H \to \phi\gamma)$		U.L. $\mathcal{B}(H \to K^{*0}\gamma)$	
category	Exp. (10^{-4})	Obs. (10^{-4})	Exp. (10^{-4})	Obs. (10^{-4})	Exp. (10^{-4})	Obs. (10^{-4})
VH	$62.3^{+25.6}_{-17.9}$	73.7	$37.3^{+16.9}_{-11.3}$	45.0	$25.3^{+11.4}_{-7.3}$	48.5
low-p_T^γ VBF	$49.6^{+22.5}_{-15.0}$	35.6	$33.1^{+18.7}_{-11.5}$	27.9	$18.8^{+8.90}_{-5.7}$	12.3
high-p_T^γ VBF	$22.9^{+10.5}_{-6.9}$	16.0	$16.0^{+9.0}_{-5.5}$	10.7	$9.13^{+4.25}_{-2.75}$	6.66
ggH	$6.01^{+2.53}_{-1.72}$	4.37	$3.08^{+1.33}_{-0.98}$	3.46	$2.20^{+0.94}_{-0.62}$	1.93
combined	$5.71^{+2.37}_{-1.63}$	3.74	$2.88^{+1.33}_{-0.83}$	2.97	$2.10^{+0.90}_{-0.58}$	1.71