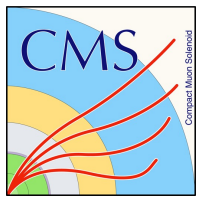
Recent couplings and cross-section measurements from ATLAS and CMS

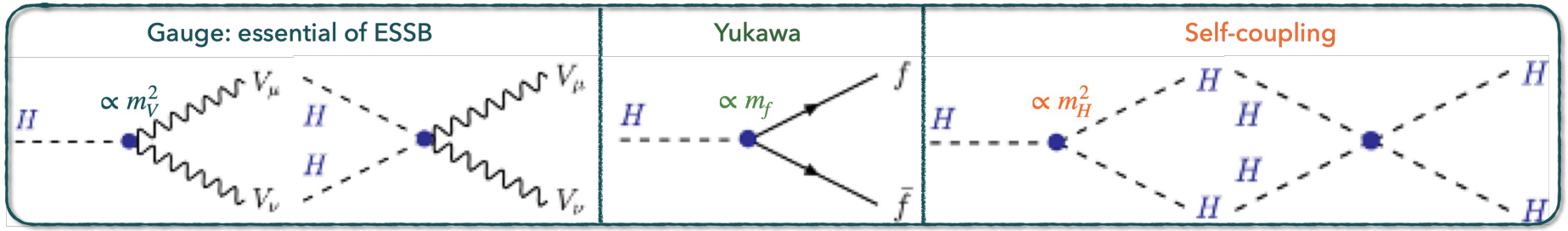
Kunlin Ran on behalf of ATLAS/CMS Collaborations
DESY

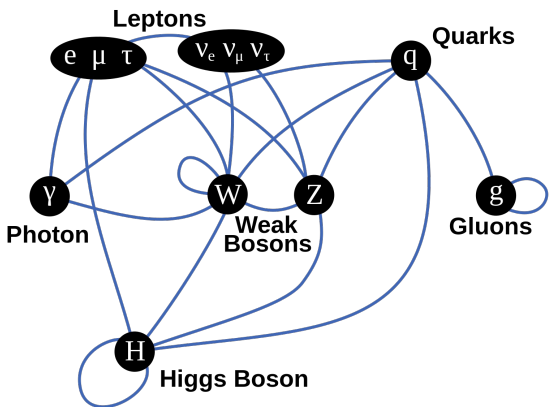
The 20th Workshop of the LHC Higgs Working Group, 13.11.2023

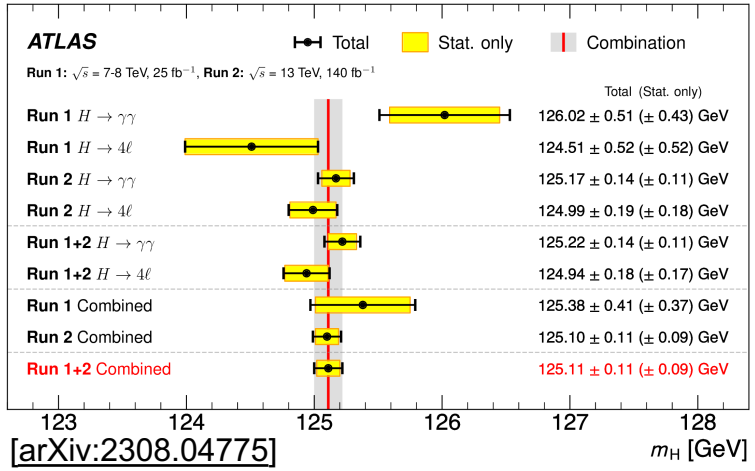


Introduction

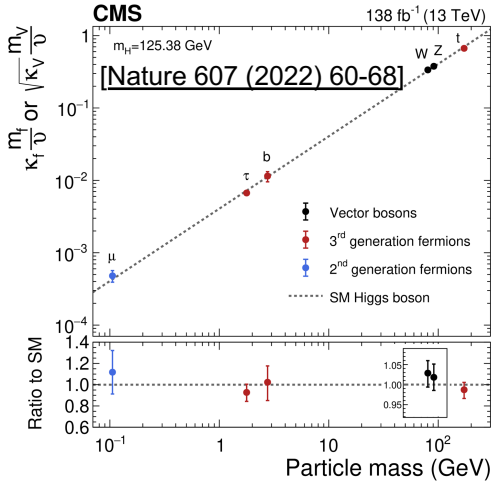
- **Higgs: scaler** field giving **mass to elementary particles**, central feature of SM
- **H coupling** can be precisely predicted once all masses/types of particles known
- Since H discovery, its measured properties (mass, quantum numbers, couplings) are **consistent with SM in an unprecedented accuracy**

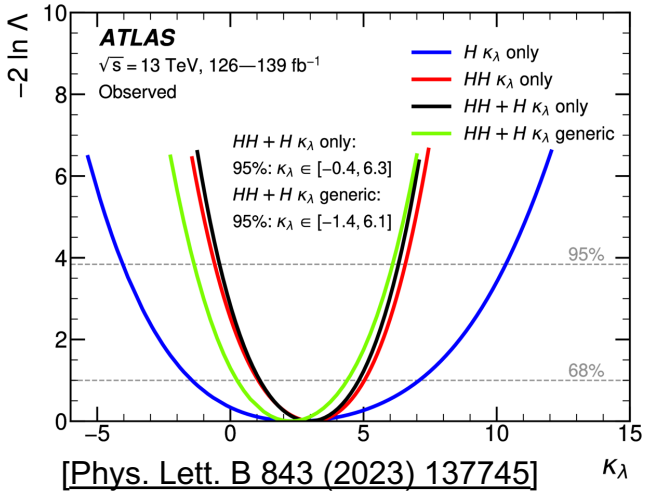






[arXiv:2308.04775]





[Phys. Lett. B 843 (2023) 137745]

- Summarize **recent couplings and XS measurements from ATLAS/CMS since last year!**

$H \to ZZ^* \to 4l$, $H \to \gamma\gamma$

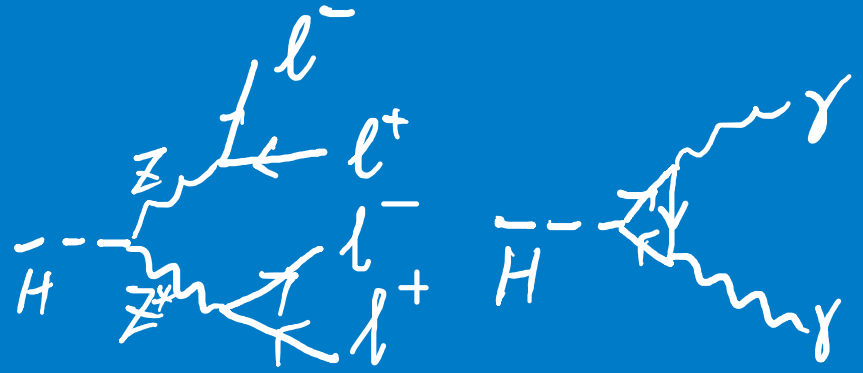
Small BR

Fully reconstructed final states, excellent mass resolution

Great photon/lepton RECO/ID efficiencies

Large signal-to-background ratio

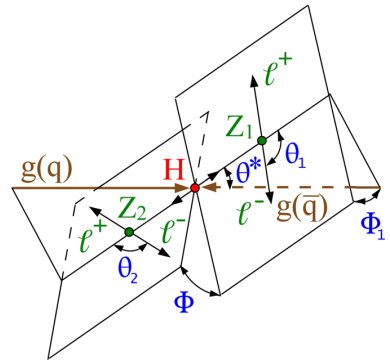
Golden channels for characterizing H!



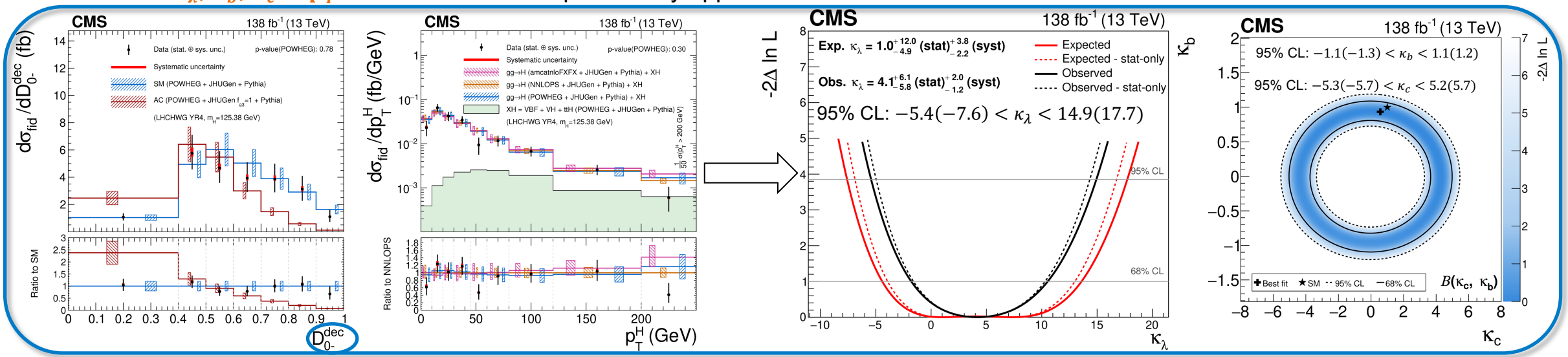
- Measurements of inclusive and differential cross sections for the Higgs boson production and decay to four-leptons in proton-proton collisions at $\sqrt{s} = 13$ TeV [JHEP 08 (2023) 040]
- Measurement of the $H \to \gamma\gamma$ and $H \to ZZ^* \to 4l$ cross-sections in pp collisions at $\sqrt{s} = 13.6$ TeV with the ATLAS detector [arXiv:2306.11379]
- Model-independent search for the presence of new physics in events including $H \to \gamma\gamma$ with $\sqrt{s} = 13$ TeV pp data recorded by the ATLAS detector at the LHC [JHEP 07 (2023) 176]
- Evidence of off-shell Higgs boson production from ZZ leptonic decay channels and constraints on its total width with the ATLAS detector [Phys. Lett. B 846 (2023) 138223]

Run 2 $H \to ZZ \to 4l$ inclusive/differential XS at CMS [JHEP 08 (2023) 040]

- **Fiducial phase space**
  - **Complementary** to characterize H production/decay
  - **Less model-dependence** to match detector acceptance and reco-level selections, corrected for detector effects (unfolding)
    - ➢ Allowing direct comparison with latest/wide variety of predictions (**insensitive to theory errors**)

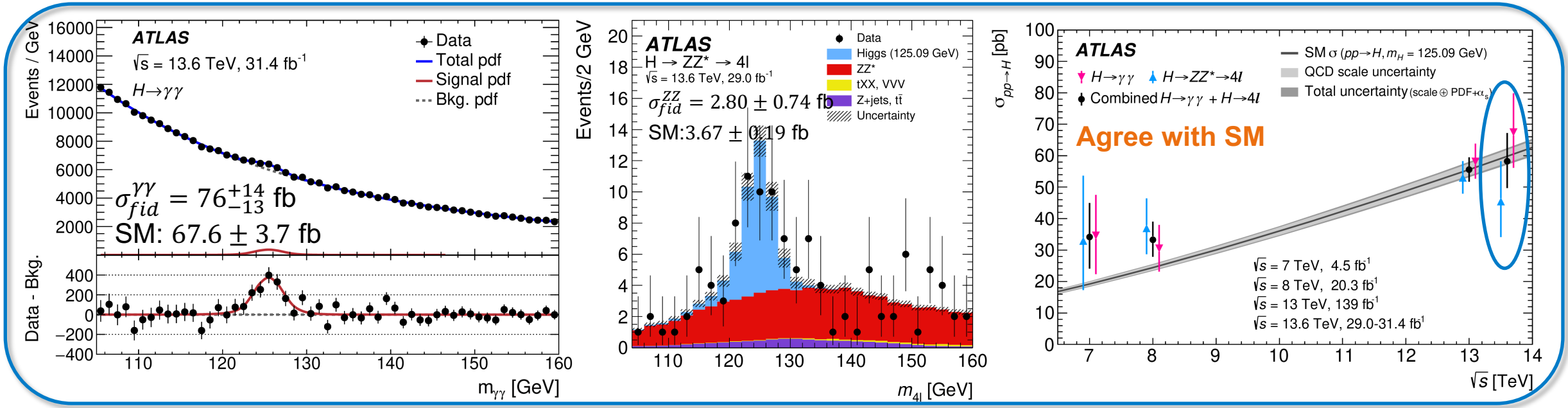


- **Inclusive:** $\sigma_{\text{fid}} = 2.73 \pm 0.26$ fb $= 2.73 \pm 0.22(stat) \pm 0.15(syst)$ fb, **agree with SM** $(2.86 \pm 0.15$ fb$)$
  - **Improved with latest CMS Run 2 calibrations** → ~40% reduction of dominant lepton RECO/selection efficiency systs wrt previous analysis
- **(Double-)Differential:** sensitive to **H production and decay to 4l** → comprehensive characterization of final states and fiducial phase space
  - Particularly include **ME**: Sensitive to **anomalous HVV couplings (ie D_{0-}^{dec})**, valuable test of SM/BSM
- **Constrain κ_λ, κ_b, κ_c in p_T^H**: alternative and complementary approach with differential information



Run 3 $H \to \gamma\gamma$ and $H \to ZZ^* \to 4l$ XS at ATLAS [arXiv:2306.11379]

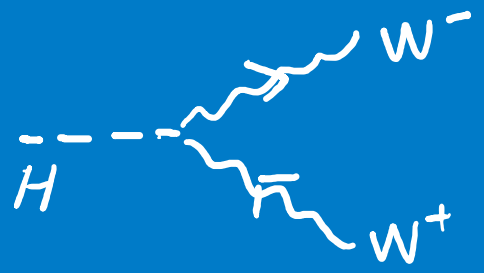
- **First $H \to \gamma\gamma$, $H \to ZZ^* \to 4l$ XS** measurements in **Run 3** with **new world-record $\sqrt{s} = 13.6$ TeV!**
- Fit observable: $m_{\gamma\gamma}$ or m_{4l}



- **Fiducial → Total XS**: assuming SM acceptances and BR
  - **$\gamma\gamma$/ZZ compatible** (p-value = 20%)

	$\gamma\gamma$	4l	Combination	SM
$\sigma(pp \to H)$ [pb]	67^{+12}_{-11}	46 ± 12	58.2 ± 8.7	59.9 ± 2.6

$H \rightarrow WW$



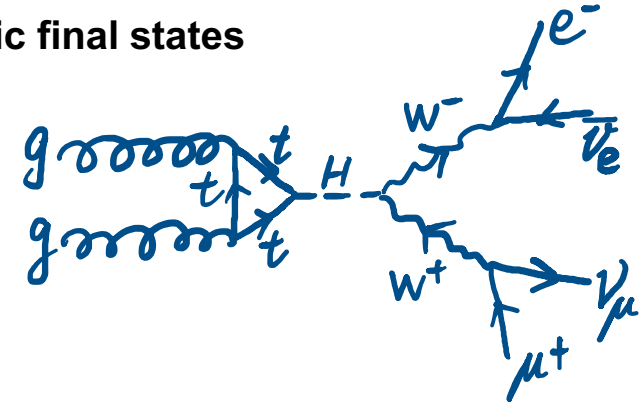
Second largest BR (21%, LHCHXS)

One of the most sensitive channels to fully characterize H properties!

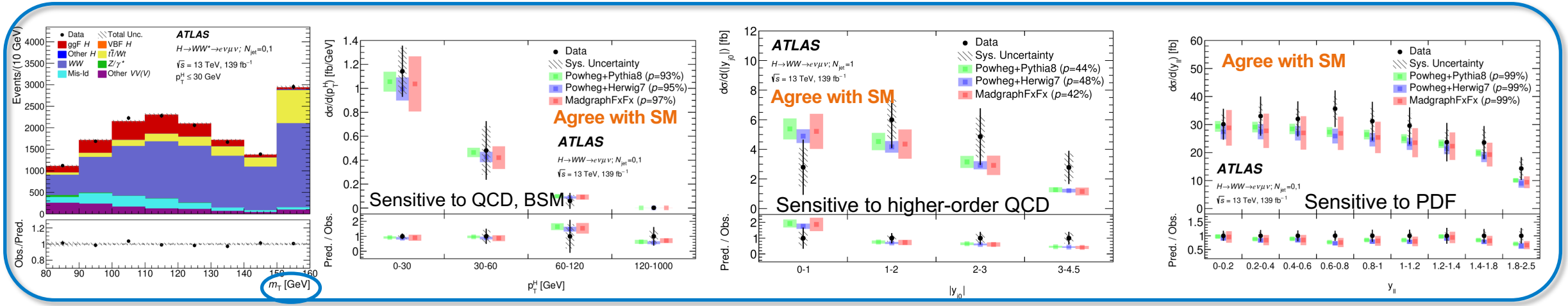
- Measurements of differential cross sections of Higgs boson production through gluon fusion in the $H \rightarrow WW^* \rightarrow e\nu\mu\nu$ final state at $\sqrt{s} = 13$ TeV with the ATLAS detector [Eur. Phys. J. C 83 (2023) 774]
- Fiducial and differential cross-section measurements for the vector-boson-fusion production of the Higgs boson in the $H \rightarrow WW^* \rightarrow e\nu\mu\nu$ decay channel at 13 TeV with the ATLAS detector [Phys. Rev. D 108, 072003]
- Measurements of the Higgs boson production cross section and couplings in the WW boson pair decay channel in proton-proton collisions at $\sqrt{s} = 13$ TeV [Eur. Phys. J. C 83 (2023) 667]
- Constraints on anomalous Higgs boson couplings from its production and decay in the WW channel [CMS-PAS-HIG-22-008]

Run 2 ggF $H \to WW^* \to e\nu\mu\nu$ differential XS at ATLAS [Eur. Phys. J. C 83 (2023) 774]

- $H \to WW^* \to e\nu\mu\nu$
  - ν in W decay → impossible to fully reconstruct final states ;-(
  - **Lower bkg in lepton final states → competitive with cleaner $\gamma\gamma$/ZZ! ;-)**
  - **ggF** production: good sensitivity in **full p_T^H → more comprehensive than boosted hadronic final states**
    - Other modes fixed as bkg
  - **DF lepton final states →** avoid **Drell-Yan** bkg; $N_j \leq 1$ → avoid **top** bkg

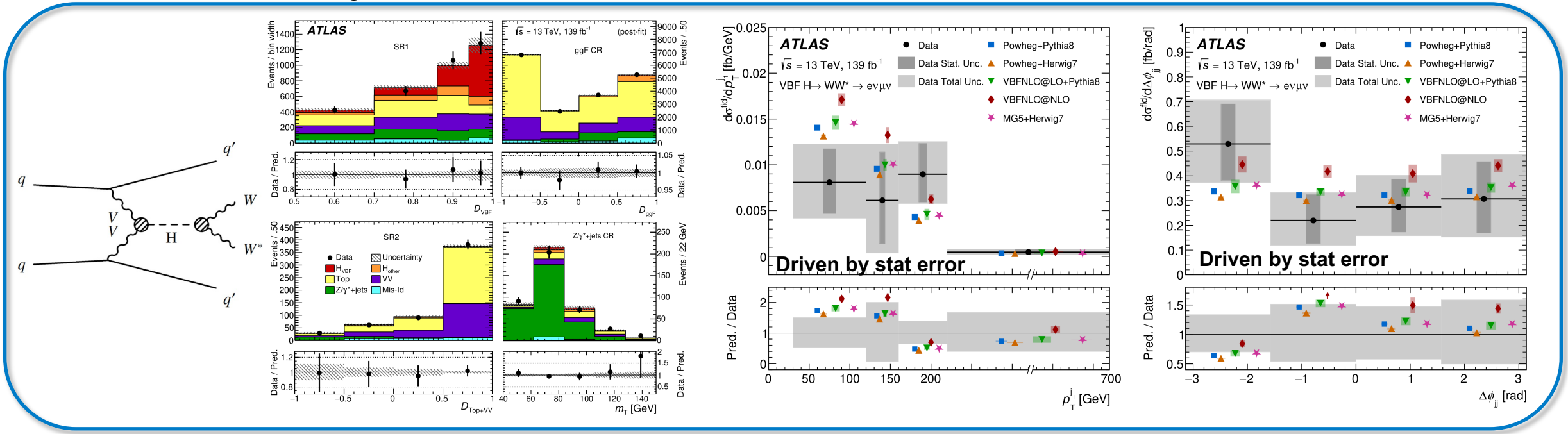


- **Improvements** comparing to previous analysis
  - More data, more **differential variables**
  - Previously used counting approach to subtract bkg → Now **fit to kinematic variable (m_T):** sensitivity improved, more **comprehensive syst treatments**



Run 2 VBF $H \to WW^* \to e\nu\mu\nu$ fiducial/differential XS at ATLAS [Phys. Rev. D 108, 072003]

- **VBF: second most** H production (3.78 pb, LHCHXS) with large Δy_{jj}, m_{jj}; **Directly probe H-V coupling**
  - Others modes as bkg

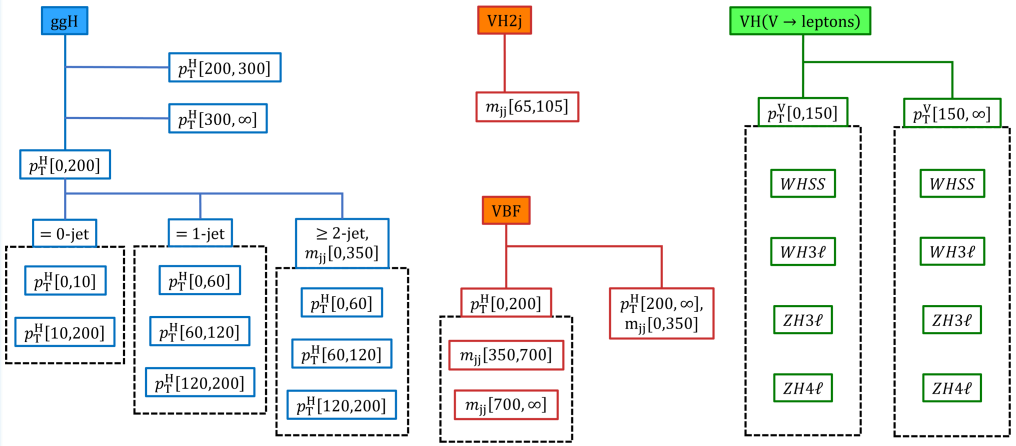


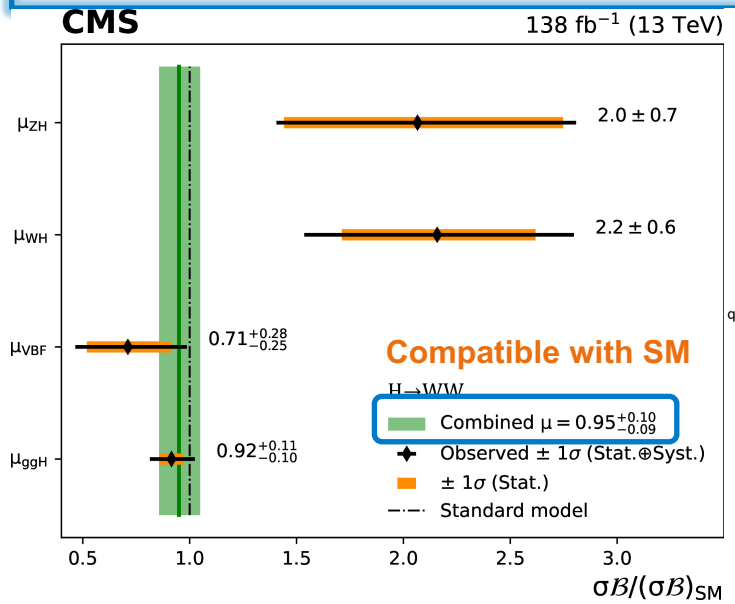
- $\sigma_{fid} = 1.68 \pm 0.33(stat) \pm 0.23(syst)$ fb, **consistent with SM**
- Constrain d-6 operators in EFT to probe anomalous couplings
- **Improvement** wrt previous VBF coupling analysis: **selections optimizied** to maximize sig significance in fiducial/differential regions, to minimize sig modelling/bkg uncertainties

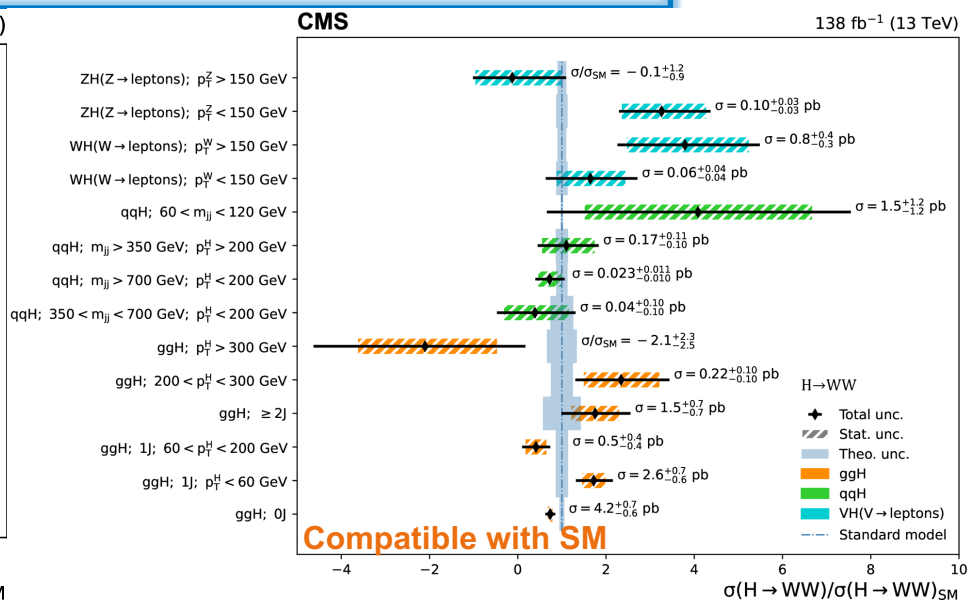
Run 2 $H \to WW$ coupling at CMS [Eur. Phys. J. C 83 (2023) 667]

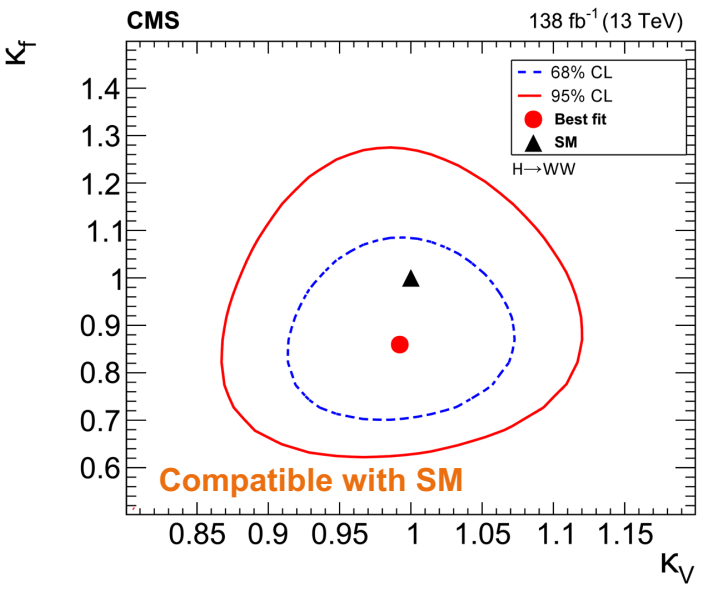
- **Phase space: ggF, VBF, VH**; With $N_l \geq 2$ (from associated V or $H \to WW$) → $\geq 1\ W_{lep}$ from H
- **Accuracy improved** wrt previous analysis besides larger LUMI
  - New analysis techniques to **increase VBF sensitivities (DNN approach)**
  - **New channels:** VBF/VH with SF leptons and V_{had}; ZH3l; WH with two SS leptons

Categorization





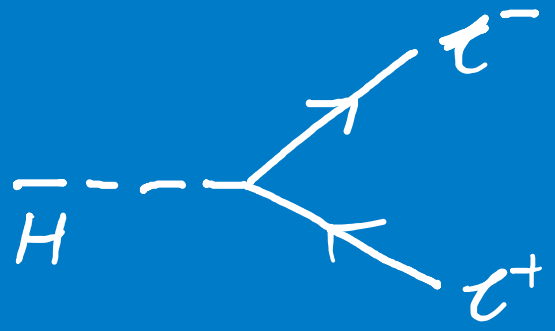




$H \rightarrow \tau\tau$

Largest BR (6%, LHCHXS) of H to leptonic decays

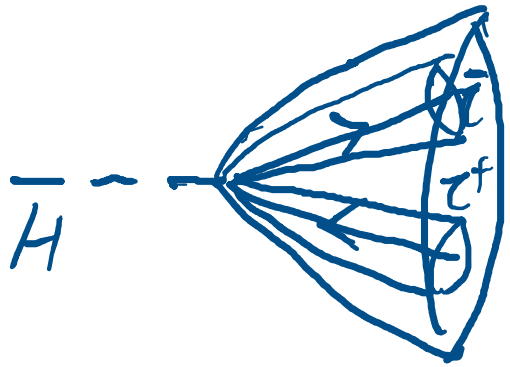
Unique opportunity to study Yukawa coupling

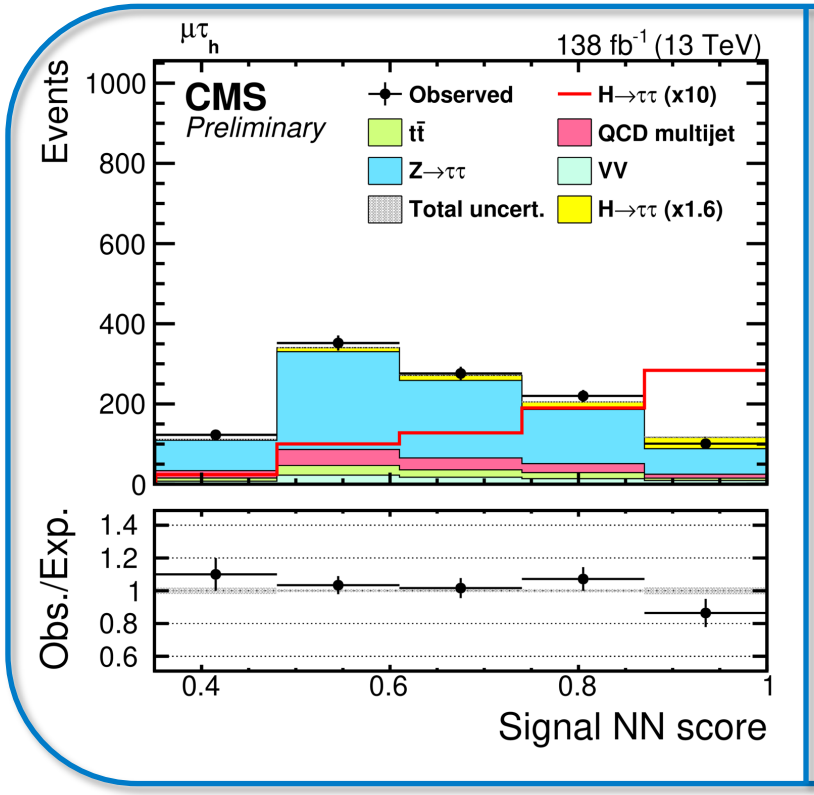


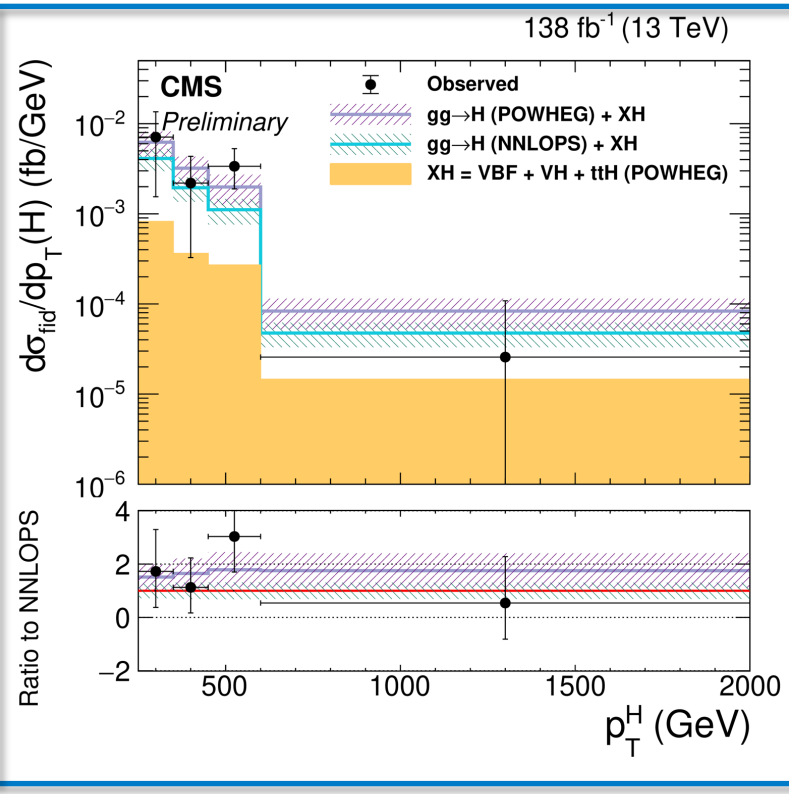
- Measurement of the highly Lorentz-boosted Higgs boson cross section in the decay mode of a pair of τ leptons in proton-proton collisions at $\sqrt{s} = 13$ TeV [CMS-PAS-HIG-21-017]
- Search for dark matter produced in association with a Higgs boson decaying to tau leptons at $\sqrt{s} = 13$ TeV with the ATLAS detector [JHEP 09 (2023) 189]
- Searches for lepton-flavour-violating decays of the Higgs boson into $e\tau$ and $\mu\tau$ in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector [JHEP 07 (2023) 166]
  - Search for the lepton-flavor violating decay of the Higgs boson and additional Higgs bosons in the $e\mu$ final state in proton-proton collisions at $\sqrt{s} = 13$ TeV [Phys. Rev. D 108 (2023) 072004]

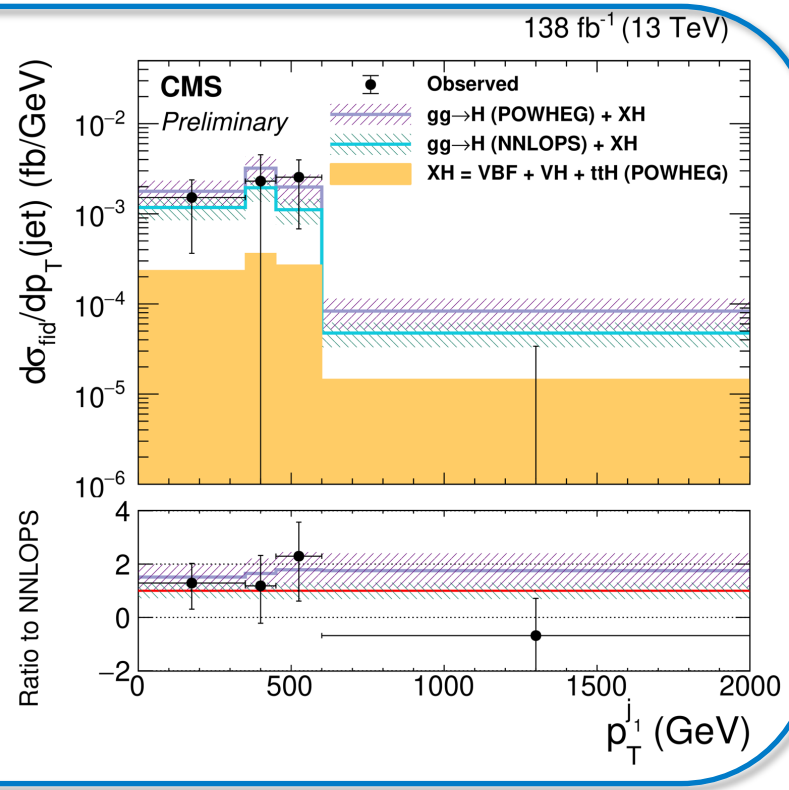
Run 2 boosted $H \to \tau\tau$ XS at CMS [CMS-PAS-HIG-21-017]

- Measure **boosted** $H \to \tau\tau$ XS for the **first time!** Sensitive to BSM
  - $p_T^H > 250$ **GeV**, $\Delta R_{\tau\tau} < 0.8$; τ decay: $\mu\tau_h$, $e\tau_h$, $\tau_h\tau_h$, $e\mu$
- **Collimated** τ_h **pair** → Single jet: dedicated algorithm to resolve
  - ➢ Clustered in a **large-R jet** → **Reversed** for **two sub-jets** consistent with τ → **identify** τ_h and reject bkg (HPS algorithm)
- Categorization: **multi-class NN**
- $\mu = 1.64^{+0.68}_{-0.54}$, **3.5$\sigma$ (2.2σ) significance**
- $\sigma_{fid} = 1.96^{+0.86}_{-0.69}$ fb, **consistent with SM** (1.20 ± 0.20 fb); Differential XS measured in p_T^H, p_T^{j1}

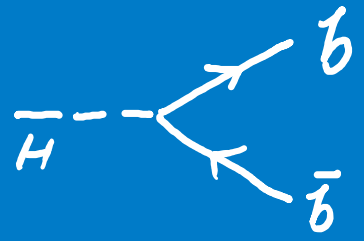








$H \to bb$

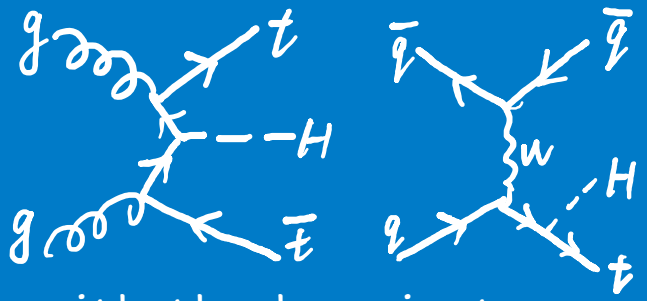


Largest BR (58%, LHCHXS)

Fully reconstructed

Overwhelmed by QCD background

ttH/tH



Yukawa coupling with the heaviest fermion, sensitive to test SM/BSM

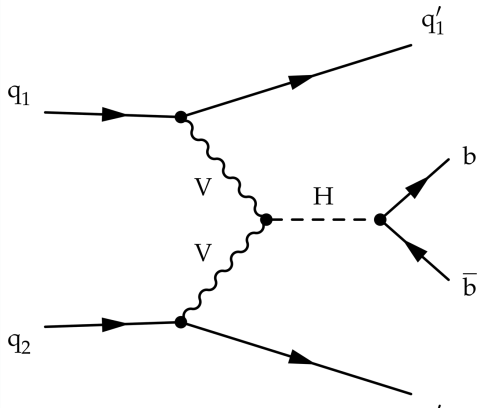
Probe $H-V/t$ coupling and interference in tH

Sensitive to the relative sign of κ_t/κ_V

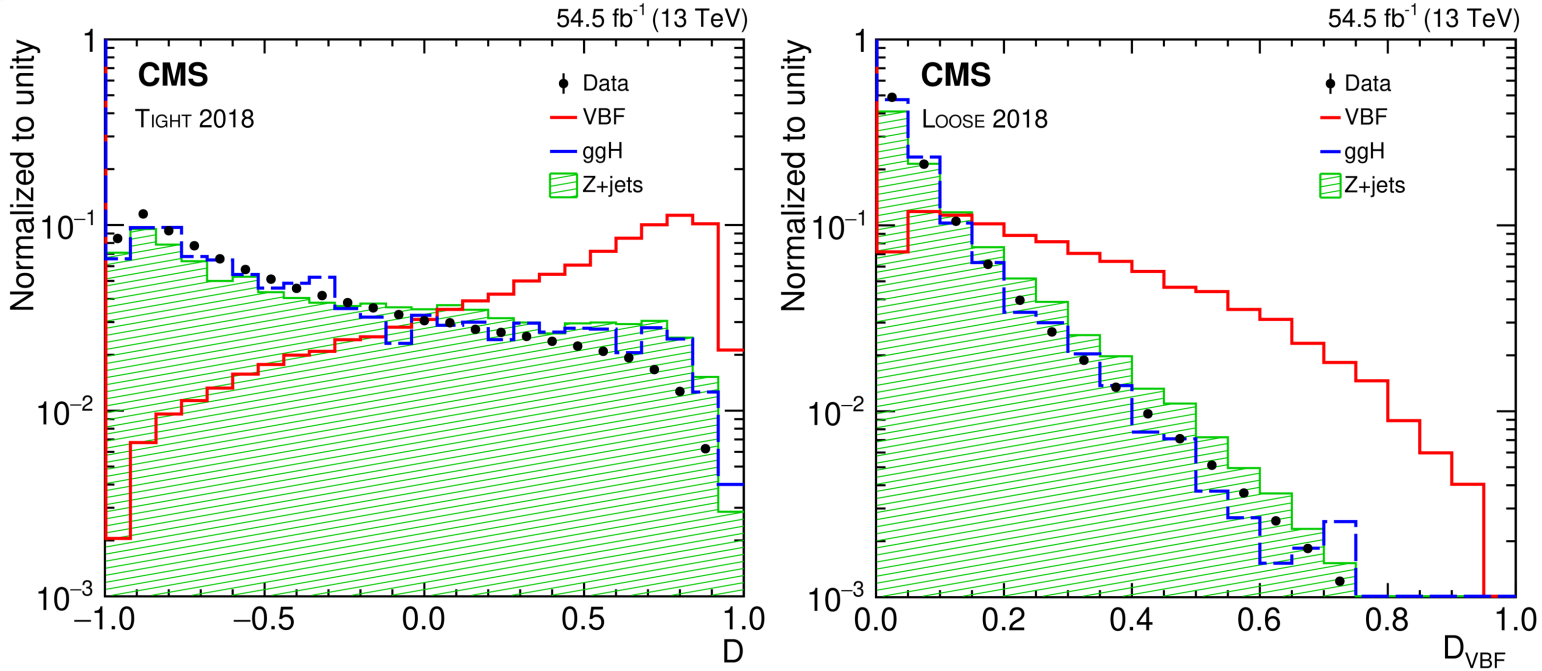
- Measurement of the Higgs boson production via vector boson fusion and its decay into bottom quarks in proton-proton collisions at $\sqrt{s} = 13$ TeV [arXiv:2308.01253]
- Search for boosted Higgs bosons produced via vector boson fusion in the $H \to b\bar{b}$ decay mode using LHC proton-proton collision data at $\sqrt{s} = 13$ TeV [CMS-PAS-HIG-21-020]
- Measurement of high-momentum Higgs boson production in association with a vector boson in the $qqbb$ final state with the ATLAS detector [ATLAS-CONF-2023-067]
- Measurement of the ttH and tH production rates in the $H \to b\bar{b}$ decay channel with 138 fb^{-1} of proton-proton collision data at $\sqrt{s} = 13$ TeV [CMS-PAS-HIG-19-011]

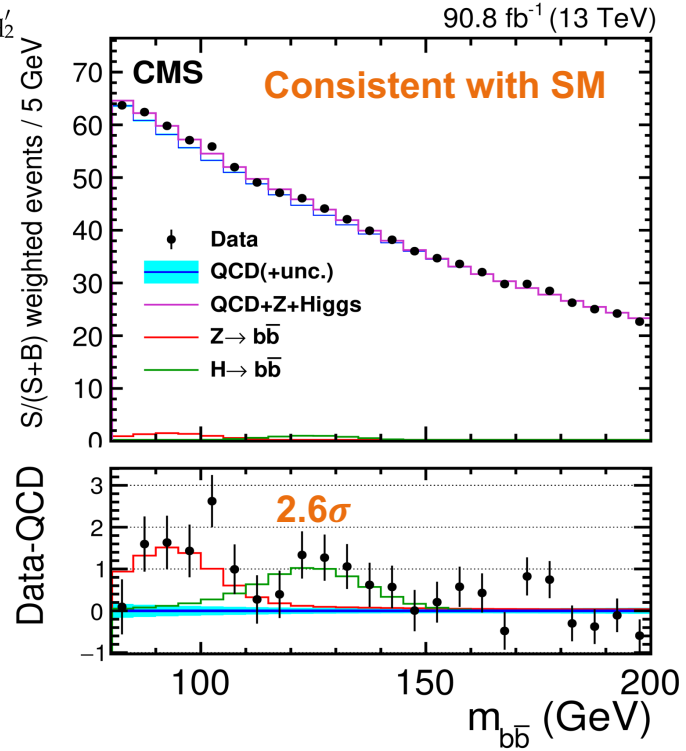
Run 2 VBF $H \to bb$ coupling at CMS [arXiv:2308.01253]

- **VBF:** interact via **colorless particle (V)** exchanges, color connection of quarks suppressed → Relatively small hadronic activity between VBF-/b-jets → **Suppress QCD bkg**
- **MVA (BDT)** used to discriminate sig/bkg



		Significance
μ_{Hbb}^{qqH}	$1.01^{+0.55}_{-0.46}$	2.4σ (2.7σ)
μ_{Hbb}^{incl}	$0.99^{+0.48}_{-0.41}$	2.6σ (2.9σ)





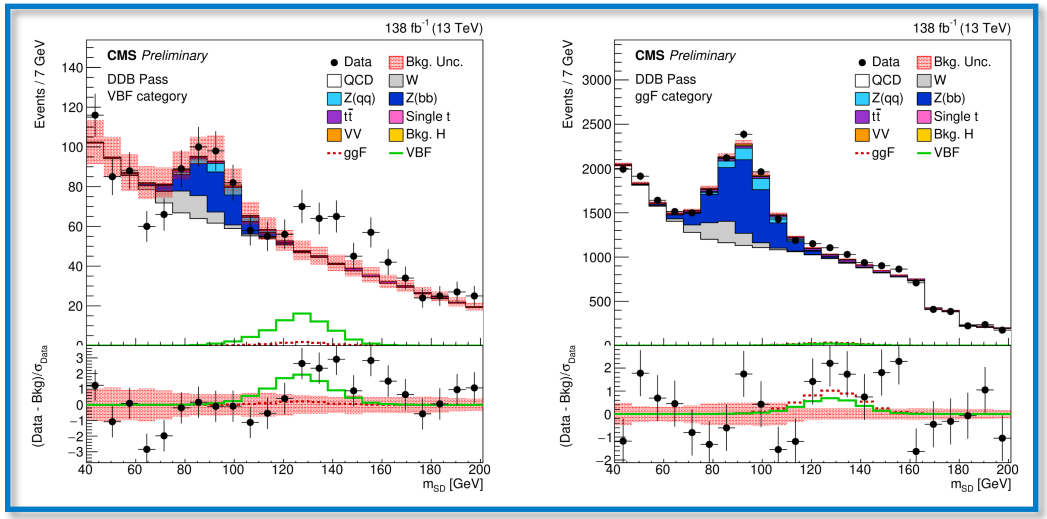
Run 2 boosted VBF $H \rightarrow bb$ at CMS [CMS-PAS-HIG-21-020]

- When $p_T^H > 450$ **GeV**, dominant **ggF** production fraction **decreases** from 87% to 50%

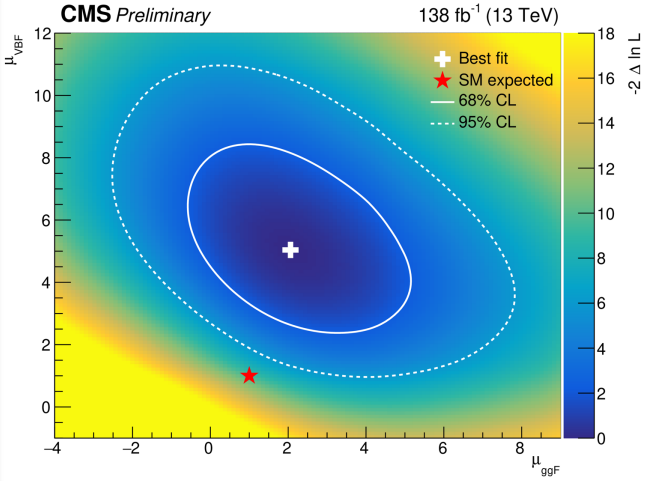
➢ Measure **boosted VBF $H \rightarrow bb$ for the first time ($p_T^H > 450$ GeV)!**

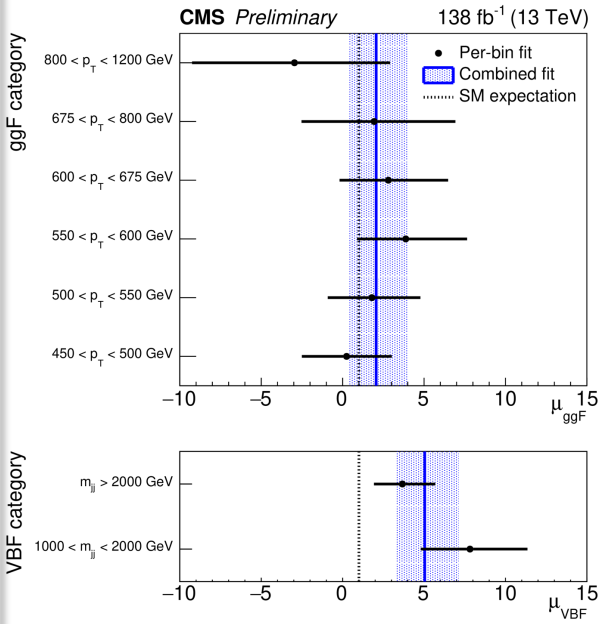
- **Boosted bb:** single large-R jet, efficient b-tagging, reduced bkg and improved m_{bb} resolution wrt resolved
  - bb pair isolated by **DeepDoubleBvL-v2 jet tagger**, improving sig significance by a factor of 2 wrt previous search
  - ➢ **Most powerful to explore H at high pT!** Not only the first boosted VBF measurement, but also the **most precise boosted ggF measurement** to date!

➢ Fit variable: soft drop mass of large-R jet m_{SD}



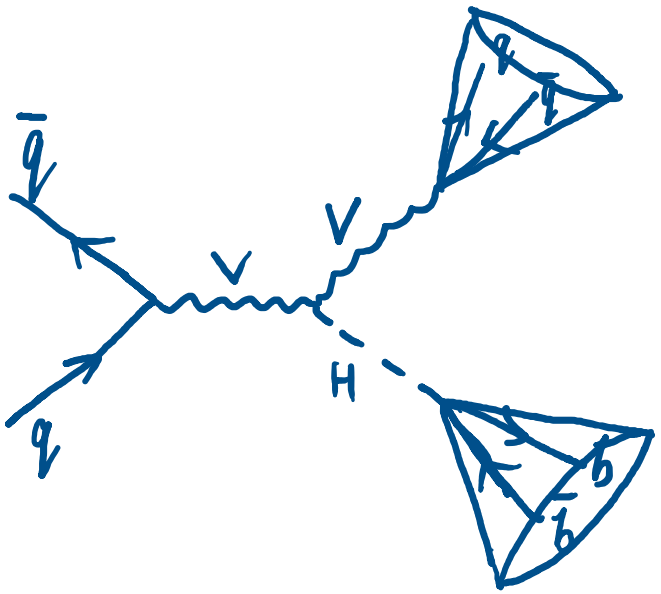
		Significance
μ_{ggF}	$2.1^{+1.9}_{-1.7}$	1.2σ (0.9σ)
μ_{VBF}	$5.0^{+2.1}_{-1.8}$	3.0σ (0.9σ)

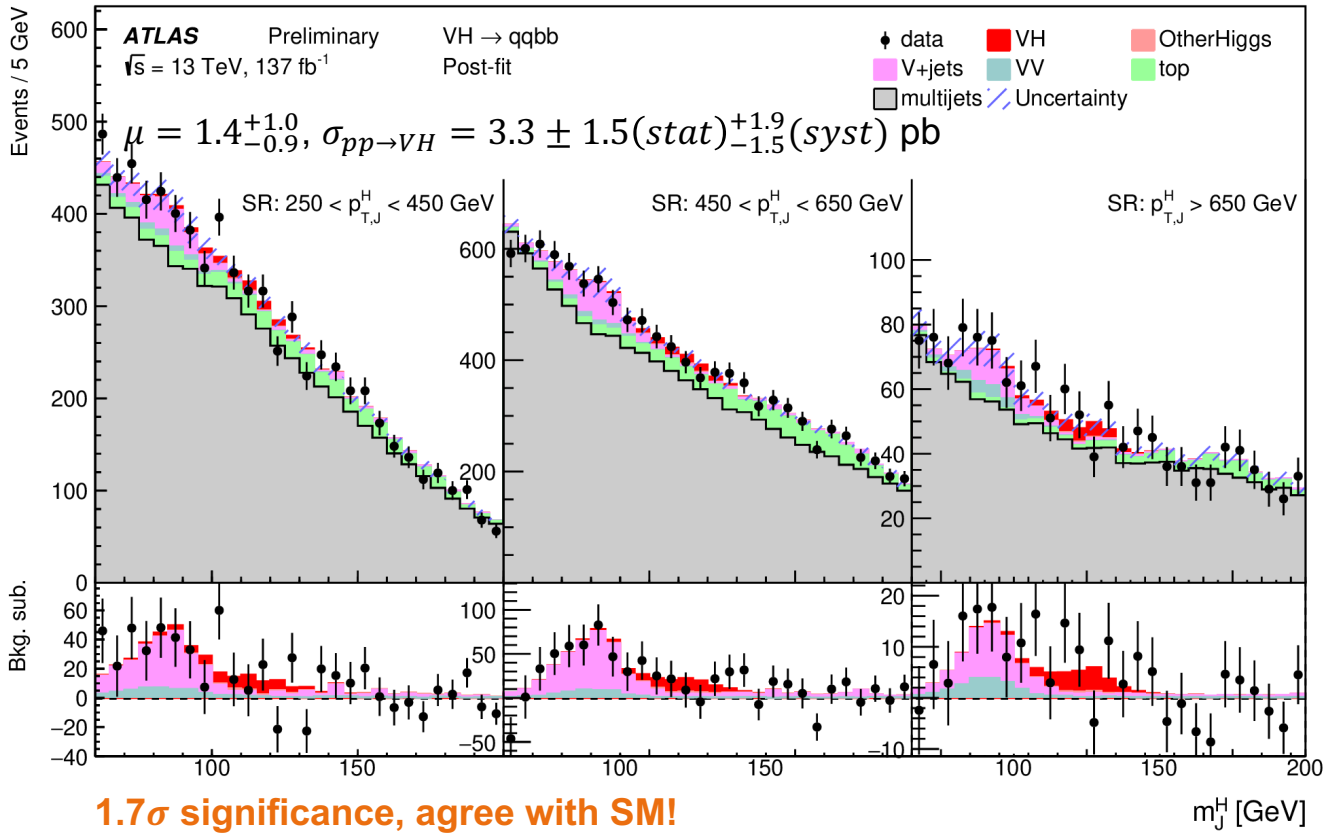




Run 2 boosted V(qq)H(bb) at ATLAS [ATLAS-CONF-2023-067]

- **V(lep)H(bb): most sensitive for $H \to bb$ observation** [ATLAS, CMS]
  - Effective triggers, suppress large QCD bkg
- **First V(qq)H(bb) measurement at high p_T^H!** Larger $B(V \to qq)$, sensitive to new physics
  - Both **large-R jets**, efficient W/Z, $H \to bb$ tagging algorithms
- Bkg: dominant data-driven QCD, others modeled by MC

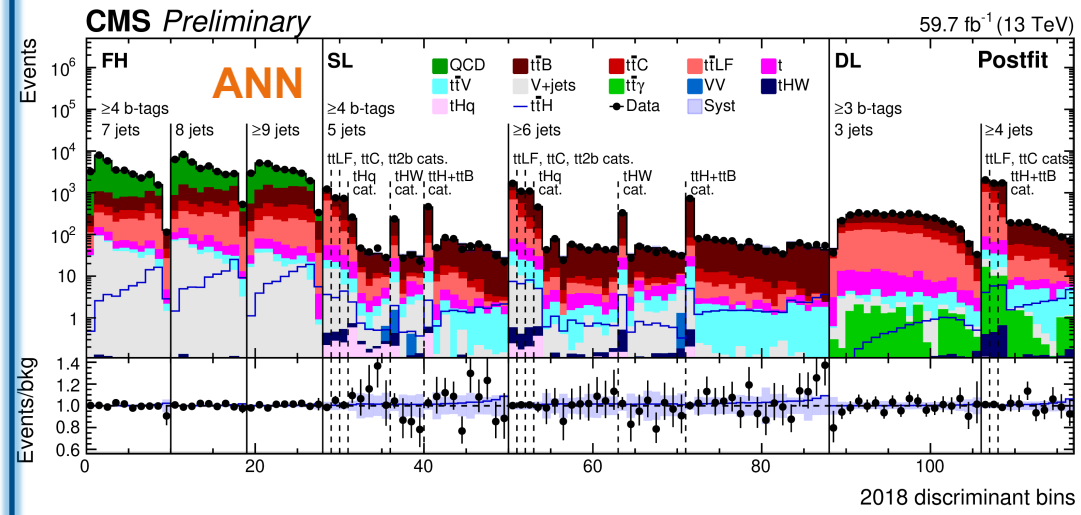


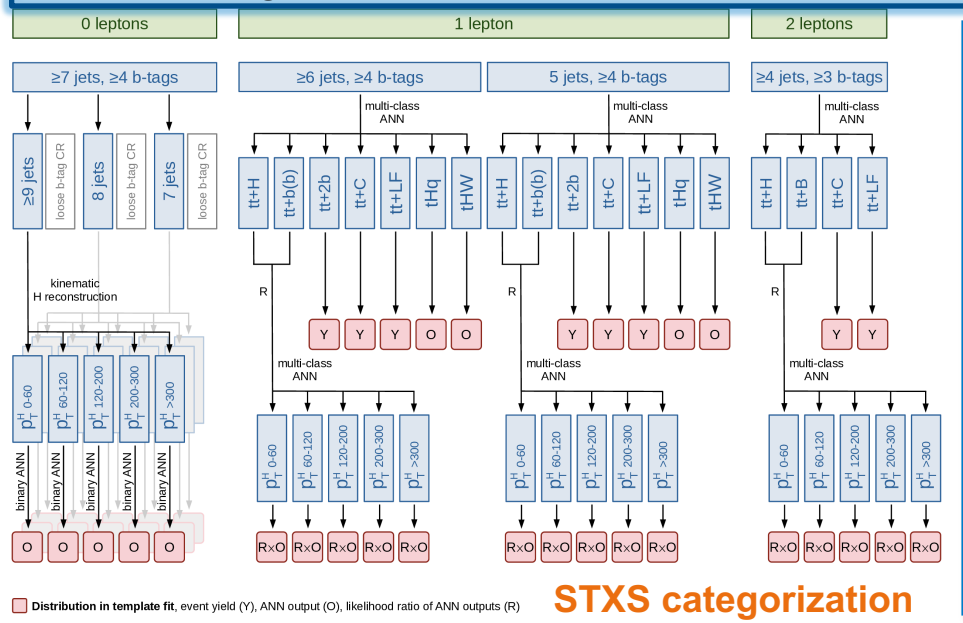


1.7σ significance, agree with SM!

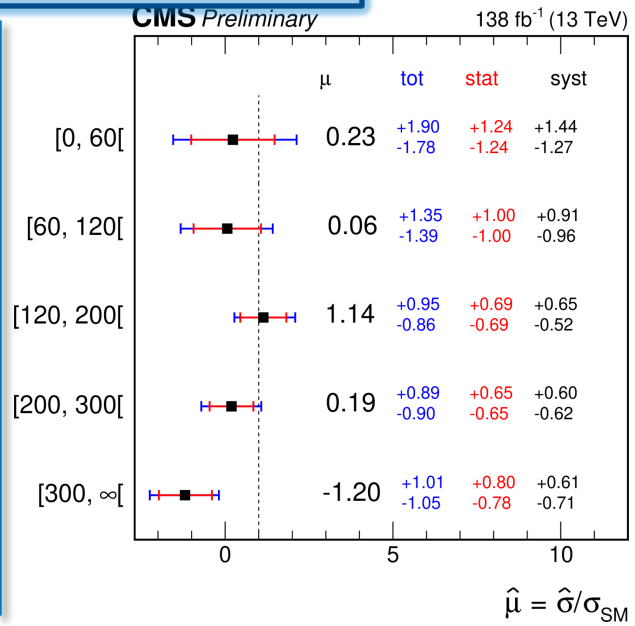
Run 2 ttH/tH(bb) at CMS [CMS-PAS-HIG-19-011]

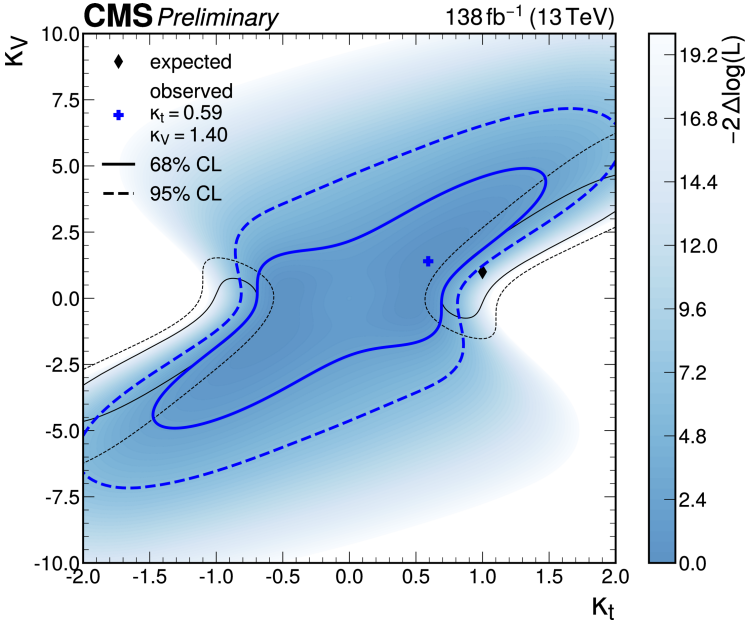
- **ttH/tH(bb):** **directly** probe $H-t/b$ coupling
- **Challenge:** combinatorial bkg with **multiple b jets → no unambiguous way to reconstruct m_H → ANNs** approach
- $\mu_{ttH} = 0.33 \pm 0.26\left(\pm 0.17(stat) \pm 0.21(syst)\right)$
- $\mu_{tH} < 14.6\ (19.3^{+9.2}_{-6.0})$ at 95% CL
- **Improvements** wrt previous analyses: Cover **all $t\bar{t}$ decays**; ANN approach; **Improved b-tagging**; Latest $t\bar{t} + b\bar{b}$ bkg modelling





STXS categorization





Rare process; Higgs to invisible decay

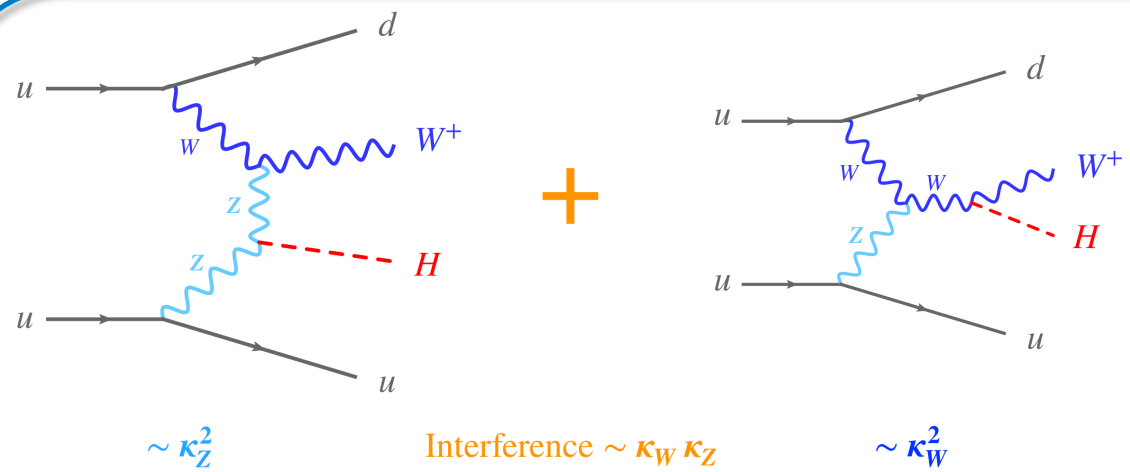
- Determining the relative sign of the Higgs boson couplings to W and Z bosons using VBF WH production with the ATLAS detector [ATLAS-CONF-2023-057]
- Evidence for the Higgs boson decay to a Z boson and a photon at the LHC [arXiv:2309.03501]

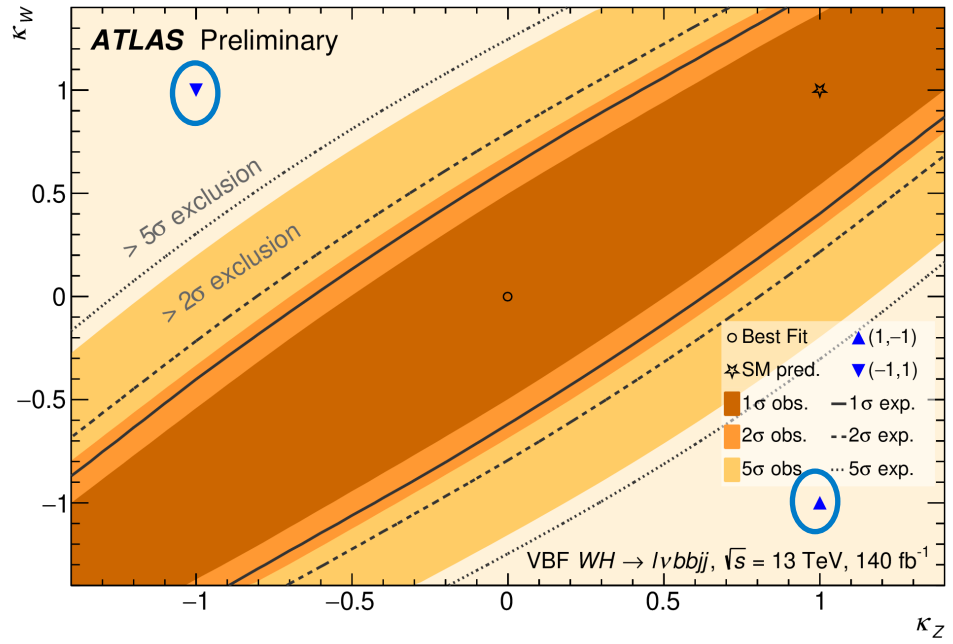
- A search for decays of the Higgs boson to invisible particles in events with a top-antitop quark pair or a vector boson in proton-proton collisions at $\sqrt{s} = 13$ TeV [Eur. Phys. J. C 83 (2023) 933]
- Combination of searches for invisible decays of the Higgs boson using 139 fb^{-1} of proton-proton collision data at $\sqrt{s} = 13$ TeV collected with the ATLAS experiment [Phys. Lett. B 842 (2023) 137963]

- Exotic Higgs decay
  - Search for exotic Higgs boson decays to a pair of pseudoscalars in the $\mu\mu bb$ and $\tau\tau bb$ final states in proton-proton collisions with the CMS experiment [CMS-PAS-HIG-22-007]
  - Search for an exotic decay of the Higgs boson into a Z boson and a pseudoscalar particle in proton-proton collisions at $\sqrt{s} = 13$ TeV [arXiv:2311.00130]

Relative sign of the κ_W/κ_Z determination in VBF WH at ATLAS [ATLAS-CONF-2023-057]

- Relative sign of κ_W/κ_Z is nearly unconstrained in current H coupling measurements
- **VBF WH: constructive interference for negative κ_W/κ_Z → Enhancement in high pT → Sensitive to the sign at tree level, no further loop assumptions!**
- Final state: $qq \rightarrow qq\boldsymbol{W}(\rightarrow \boldsymbol{l\nu})H(\rightarrow bb)$



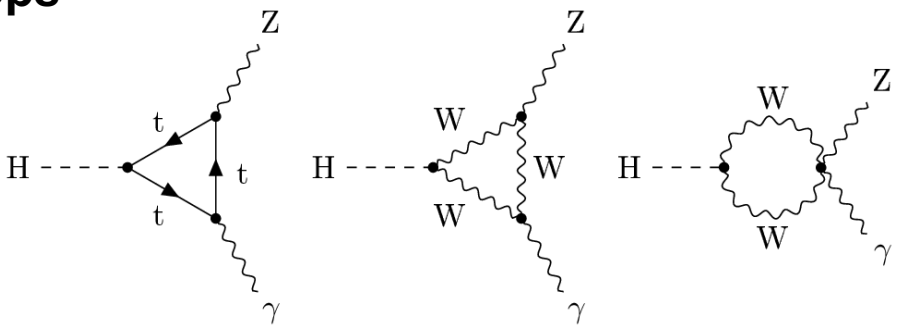


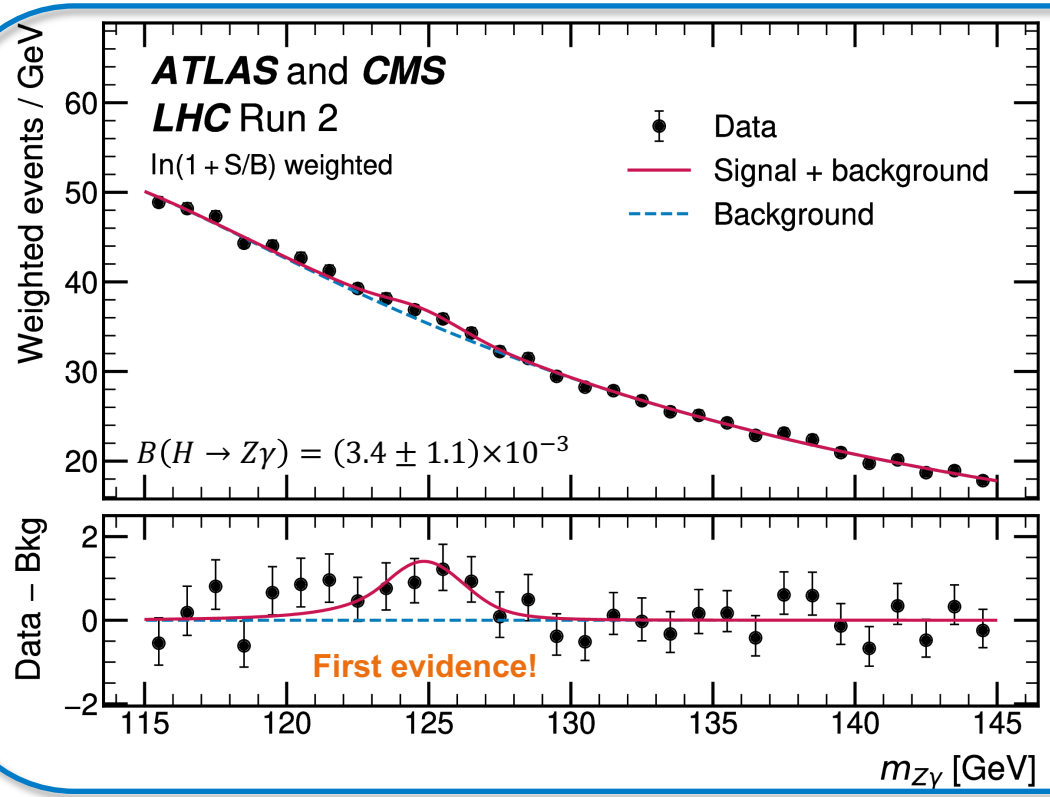
- With Run 2 data, $\boldsymbol{\mu_{\lambda_{WZ}=1} < 11.2\ (9.4)}$ **at 95% CL, no excess above SM**
- **Negative sign of κ_W/κ_Z ($\lambda_{WZ} = -1$) excluded with significance > 8σ!**

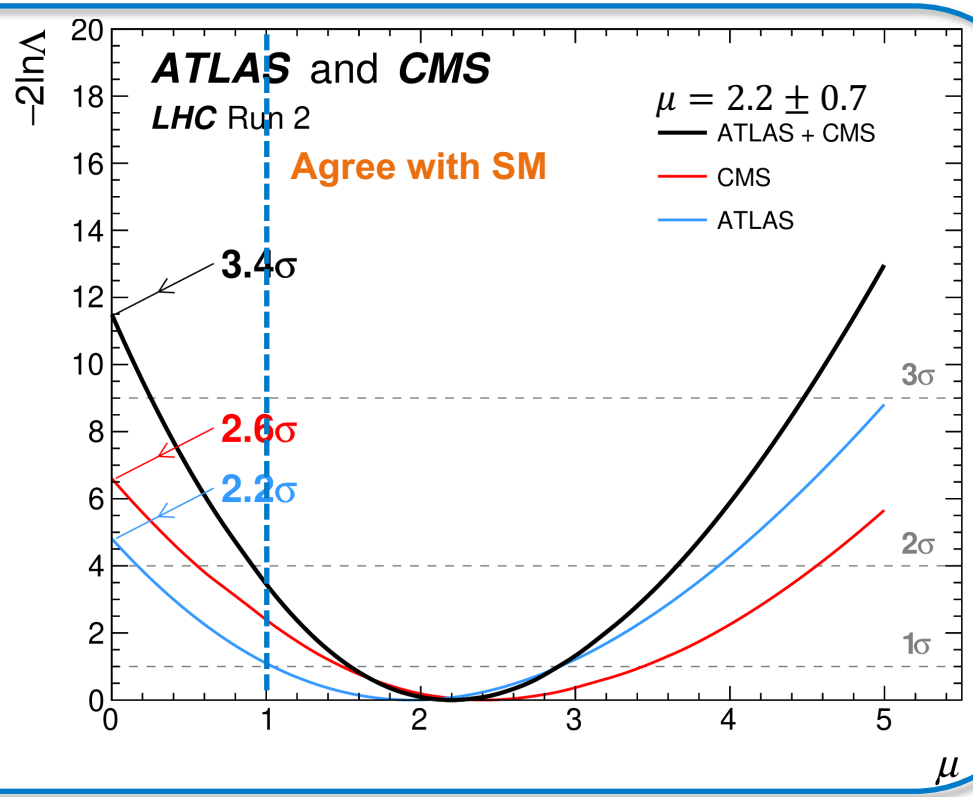
$H \to Z\gamma$ evidence at the LHC [arXiv:2309.03501]

- $H \to Z\gamma$: **rare decay**, not observed; Sensitive to BSM via **loops**
- **Combine** ATLAS + CMS Run 2 $H \to Z(\to ll)\gamma$ analyses

➢ **3.4σ significance, first evidence!**

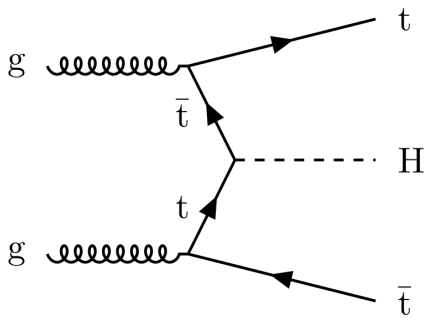


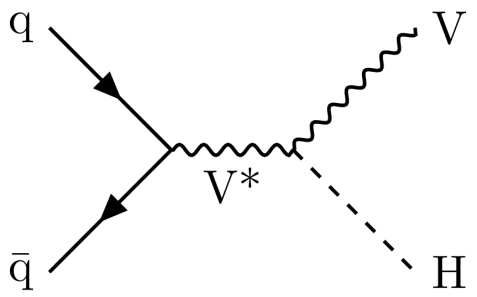




Run 2 VH/ttH to invisible search at CMS [Eur. Phys. J. C 83 (2023) 933]

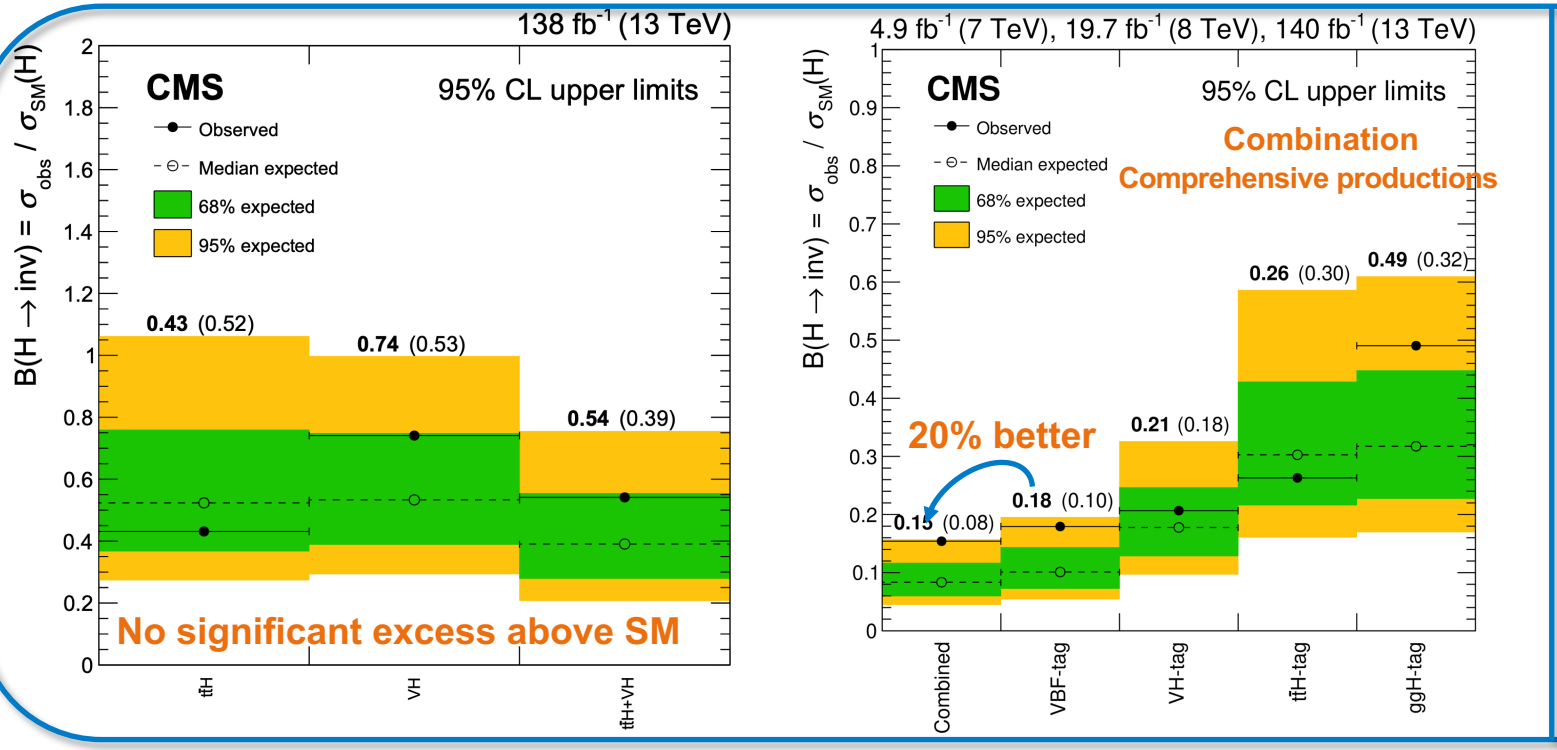
- **H → inv:** $H \to ZZ^* \to 4\nu$ is the only decay in SM, BR = 0.1%
- **VH/ttH: fully hadronic final states, first time at CMS**
  - Boosted/Resolved ttH; Resolved VH complementing previous boosted search

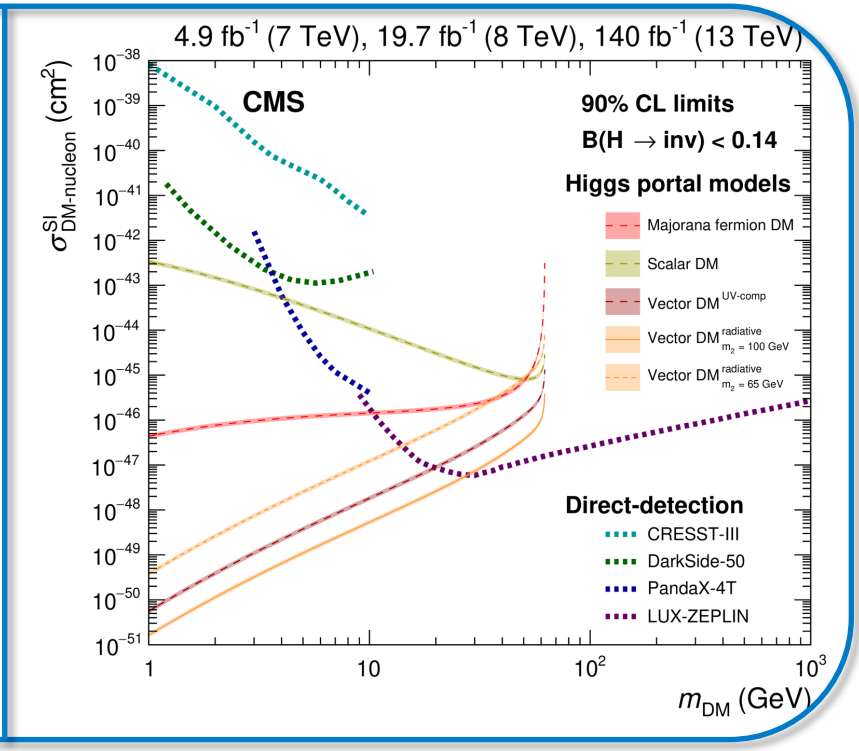




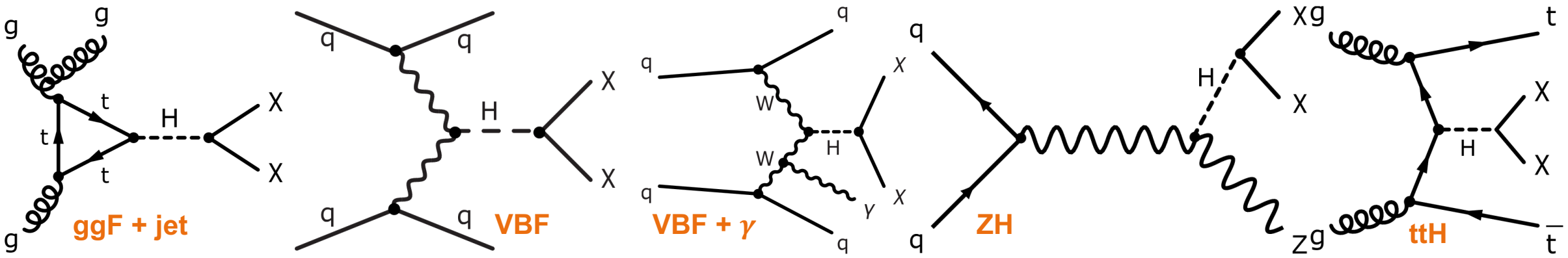
- **DM** comprises **most of matter in universe**, while its nature is unknown
  - Possible candidate: **WIMP (weakly interacting massive particle)**

➢ **Interpretation:** Higgs as a portal between DM and SM particles for m_{DM} in [0.1 GeV, $m_H/2$] → **Complementary to direct light DM searches**

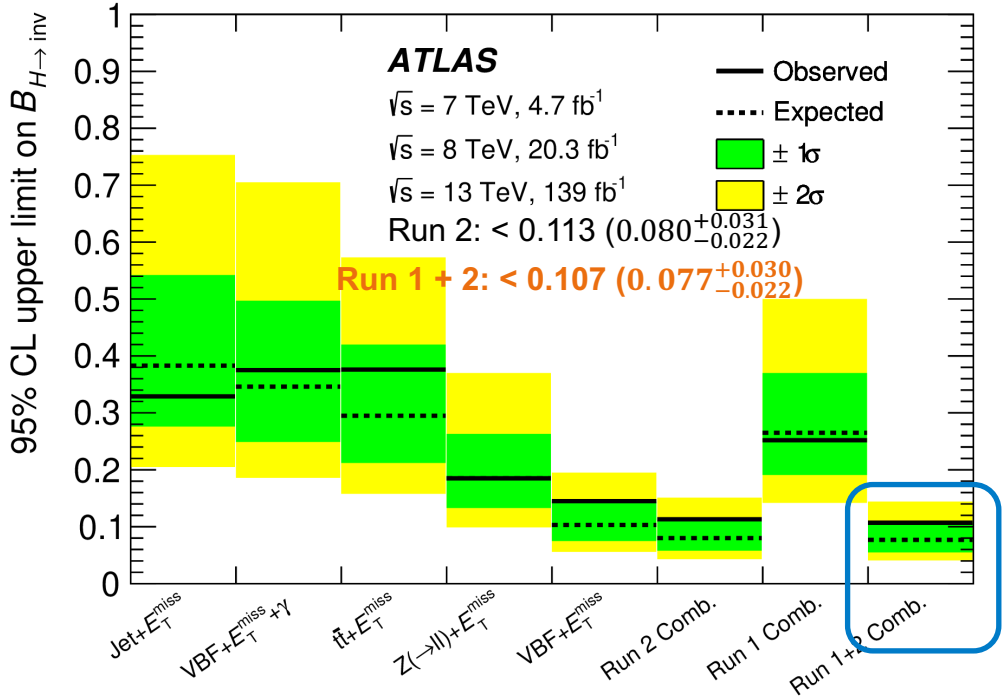


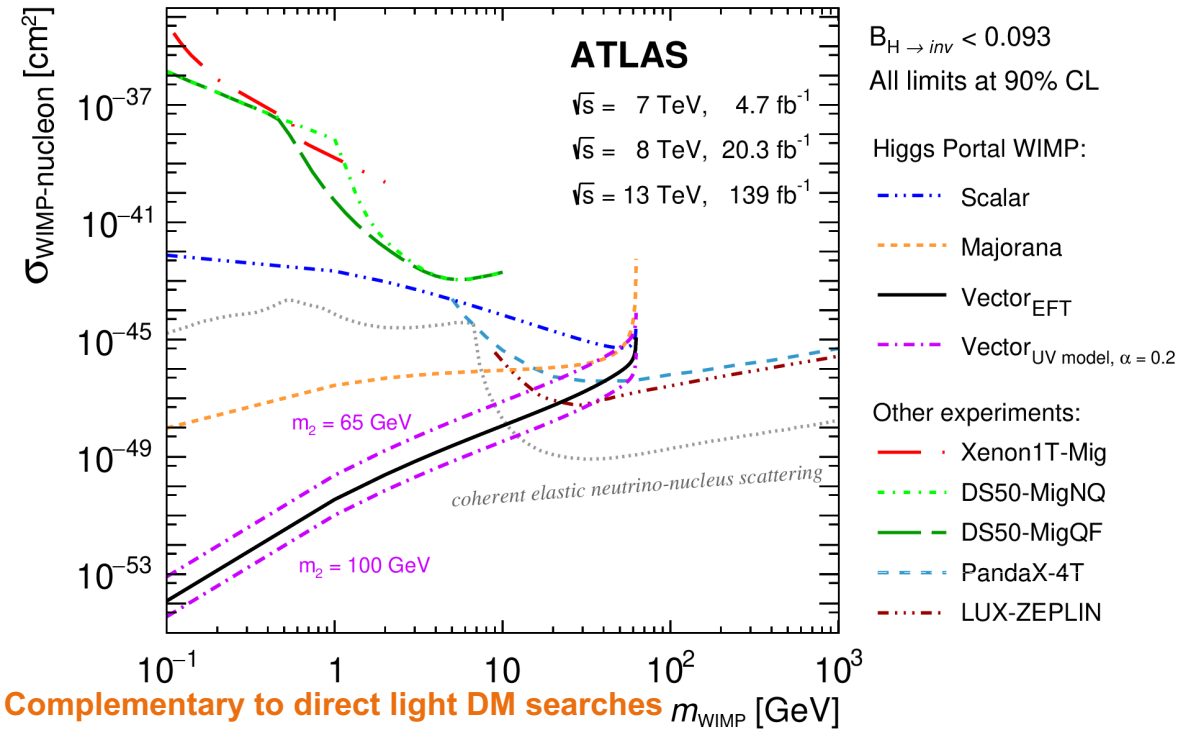


H → inv combination at ATLAS [Phys. Lett. B 842 (2023) 137963]



- **Run 1 + Run 2 combination: Most sensitive direct constraints in ATLAS**





Complementary to direct light DM searches

Summary

- Since **Higgs discovery**, its measured properties are **consistent with SM in an unprecedented accuracy**
- Summarized **recent couplings and XS measurements from ATLAS/CMS since last year!**

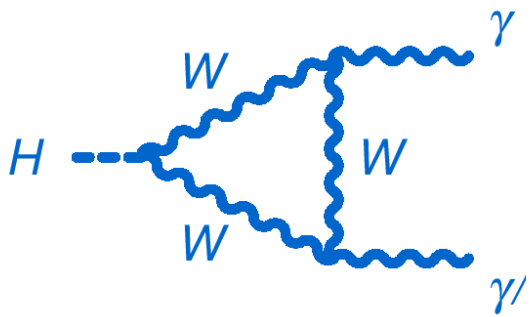
- $H \to \gamma\gamma$, $H \to ZZ^* \to 4l$
  - Total/Fiducial XS firstly measured with early Run 3 data at ATLAS!
- $H \to WW$
  - ggF/VBF differential XS measured at ATLAS, coupling properties probed at CMS
- $H \to \tau\tau$: Measured boosted XS for the first time at CMS!
- $H \to bb$
  - Measured boosted VBF $H \to bb$ for the first time at CMS, most precise boosted ggF results to date!
  - First V(qq)H(bb) measurement at high p_T^H at ATLAS!
  - CMS released ttH/tH coupling results
- **Rare process; Higgs to invisible decay**
  - ATLAS excluded negative sign of κ_W/κ_Z ($\lambda_{WZ} = -1$) with significance > 8σ!
  - Observed first evidence of $H \to Z\gamma$ by combining ATLAS/CMS analyses!
  - Fully hadronic final states of VH/ttH to inv. particles measured first time at CMS
  - Most sensitive direct constraints of H → inv obtained in ATLAS by combing Run 1 + 2 datasets

- **Stay tuned with more exciting results!**

Backup

Search for new physics in $H \to \gamma\gamma$ at ATLAS [JHEP 07 (2023) 176]

- Most analyses have certain model assumptions, either targeting a Higgs production or a BSM process
- Large fraction of signals may populate SR probed by SM measurements, while unknown BSM Higgs production can be outside those regions



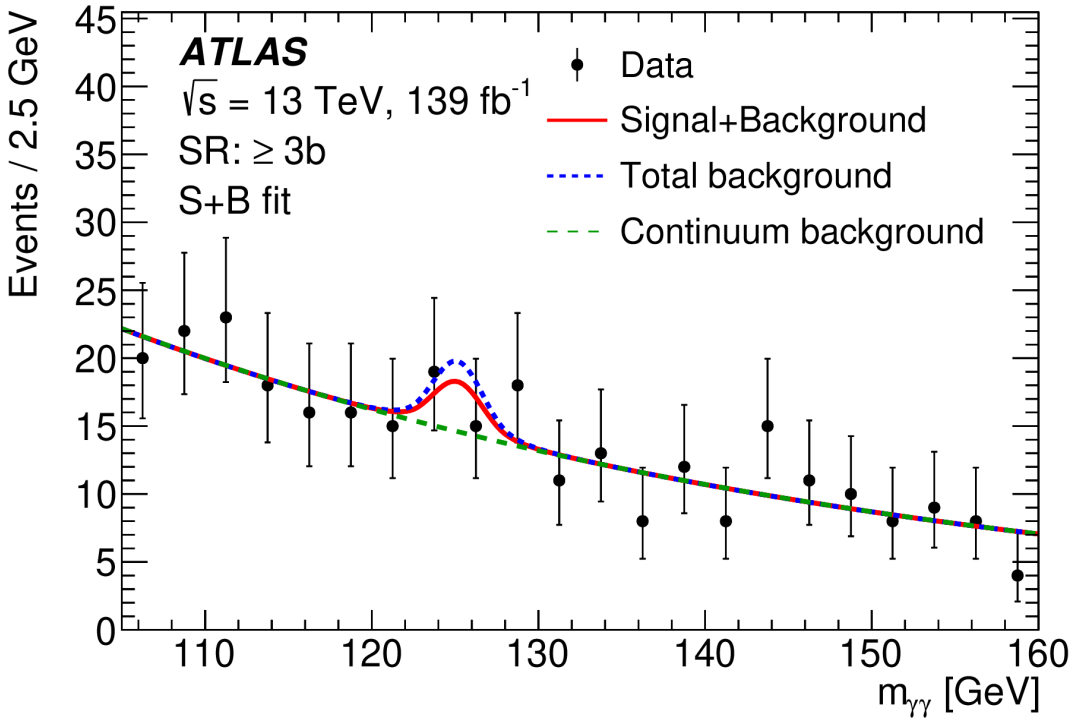
➢ Model-independent search for new physics in $H \to \gamma\gamma$ in Run 2 at ATLAS

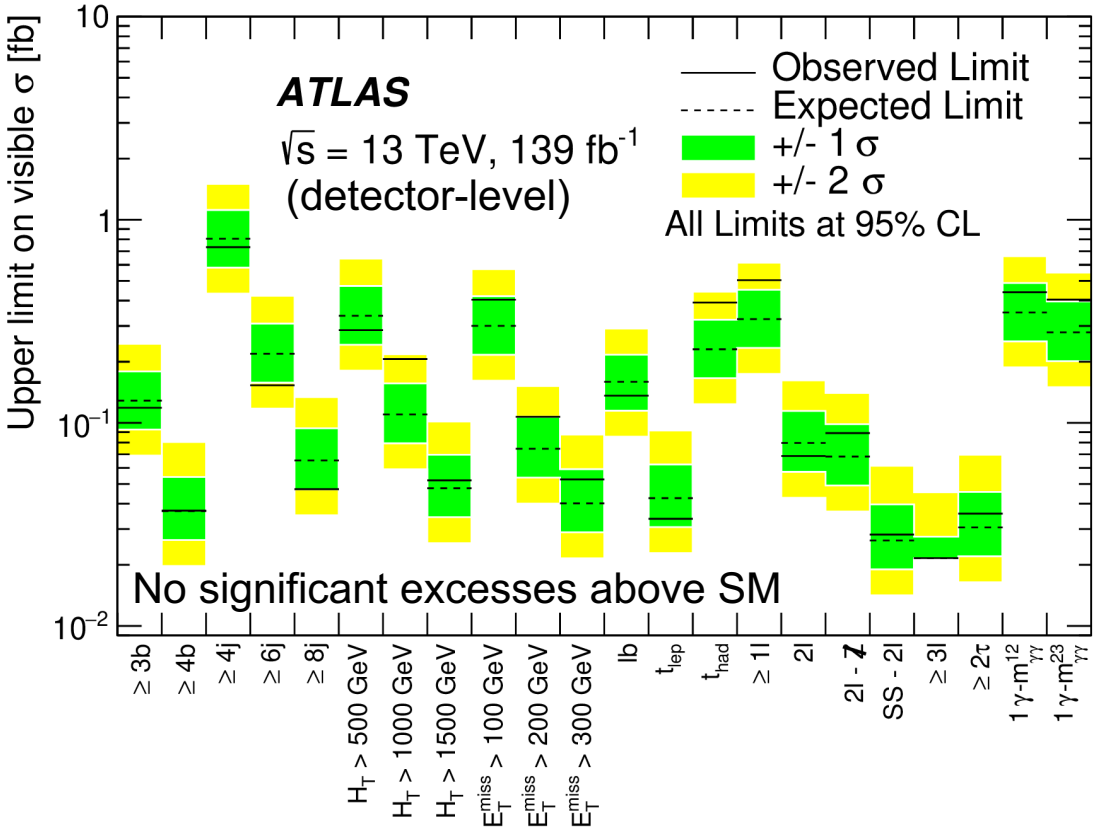
- Sensitivity of $H \to \gamma\gamma$ competitive: Better m_H resolution → Relatively small bkg
- SR: defined to cover a wide range of signatures in association with Higgs (e, μ, τ_{had}, γ, MET, (b-)jets) with simple and mostly inclusive selections → Minimize model dependence

Target	Region	Detector level
Heavy flavour	$\geq 3b$	$n_{b\text{-jet}} \geq 3$, 85% WP
	$\geq 4b$	$n_{b\text{-jet}} \geq 4$, 85% WP
High jet activity	≥ 4j	$n_{\text{jet}} \geq 4$, $\lvert\eta_{\text{jet}}\rvert < 2.5$
	≥ 6j	$n_{\text{jet}} \geq 6$, $\lvert\eta_{\text{jet}}\rvert < 2.5$
	≥ 8j	$n_{\text{jet}} \geq 8$, $\lvert\eta_{\text{jet}}\rvert < 2.5$
	$H_{\text{T}} > 500$ GeV	$H_{\text{T}} > 500$ GeV
	$H_{\text{T}} > 1000$ GeV	$H_{\text{T}} > 1000$ GeV
	$H_{\text{T}} > 1500$ GeV	$H_{\text{T}} > 1500$ GeV
$E_{\text{T}}^{\text{miss}}$	$E_{\text{T}}^{\text{miss}} > 100$ GeV	$E_{\text{T}}^{\text{miss}} > 100$ GeV
	$E_{\text{T}}^{\text{miss}} > 200$ GeV	$E_{\text{T}}^{\text{miss}} > 200$ GeV
	$E_{\text{T}}^{\text{miss}} > 300$ GeV	$E_{\text{T}}^{\text{miss}} > 300$ GeV
Top	ℓb	$n_{\ell=e,\mu} \geq 1$, $n_{b\text{-jet}} \geq 1$, 70% WP
	t_{lep}	$n_{\ell=e,\mu} = 1$, $n_{\text{jet}} = n_{b\text{-jet}} = 1$, 70% WP
	t_{had}	$n_{\ell=e,\mu} = 0$, $n_{\text{jet}} = 3$, $n_{b\text{-jet}} = 1$, 70% WP, $\text{BDT}_{\text{top}} > 0.9$
Lepton	$\geq 1\ell$	$n_{\ell=e,\mu} \geq 1$
	2ℓ	$ee, \mu\mu$, or $e\mu$
	2ℓ–$\not{Z}$	$ee, \mu\mu, e\mu$; $\lvert m_{\ell\ell} - m_Z\rvert > 10$ GeV for same-flavour leptons
	SS-2ℓ	ee, $\mu\mu$, or $e\mu$ with same charge
	$\geq 3\ell$	$n_{\ell=e,\mu} \geq 3$
	$\geq 2\tau$	$n_{\tau,\text{had}} \geq 2$
Photon	1γ–$m_{\gamma\gamma}^{12}$	$n_\gamma \geq 3$, $m_{\gamma\gamma}$ defined with γ_1,γ_2
	1γ–$m_{\gamma\gamma}^{23}$	$n_\gamma \geq 3$, $m_{\gamma\gamma}$ defined with γ_2,γ_3

Search for new physics in $H \to \gamma\gamma$ at ATLAS [JHEP 07 (2023) 176]

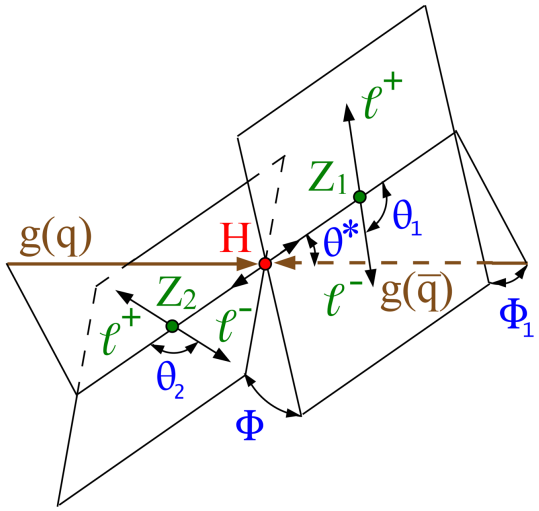
- The same bkg modelling strategy applied to most SR: fit analytic functions of $m_{\gamma\gamma}$ in data
  - Exception in $\geq 3l$ SR : no sufficient statistics constraining bkg → event count
- Measure $\sigma(pp \to H \to \gamma\gamma)$ (detector-level) for all SR, no significant excesses above SM; Detector efficiencies for several BSM benchmarks also performed to convert σ to particle-level





Run 2 $H \to ZZ \to 4l$ inclusive/differential XS at CMS [JHEP 08 (2023) 040]

- $H \to ZZ \to 4l$: Fully reconstructed; Large sig-to-bkg ratio → one of the pillars for characterizing H!
- Fiducial
  - Complementary to characterize H production/decay
  - Less model-dependence to match detector acceptance and reco-level selections, corrected for detector effects (unfolding)
    - ➢ Allowing direct comparison with latest/wide variety of predictions (insensitive to theory errors)



Requirements for the H $\to$ ZZ $\to 4\ell$ fiducial phase space

Lepton kinematics and isolation	
Leading lepton p_T	$p_T > 20$ GeV
Sub-leading lepton p_T	$p_T > 10$ GeV
Additional electrons (muons) p_T	$p_T > 7(5)$ GeV
Pseudorapidity of electrons (muons)	$\lvert\eta\rvert < 2.5$ (2.4)
Sum of scalar p_T of all stable particles within $\Delta R < 0.3$ from lepton	$< 0.35 p_T$
Event topology	
Existence of at least two same-flavor OS lepton pairs, where leptons satisfy criteria above	
Inv. mass of the Z_1 candidate	$40 < m_{Z_1} < 120$ GeV
Inv. mass of the Z_2 candidate	$12 < m_{Z_2} < 120$ GeV
Distance between selected four leptons	$\Delta R(\ell_i, \ell_j) > 0.02$ for any $i \neq j$
Inv. mass of any opposite sign lepton pair	$m_{\ell^+\ell'^-} > 4$ GeV
Inv. mass of the selected four leptons	$105 < m_{4\ell} < 160$ GeV

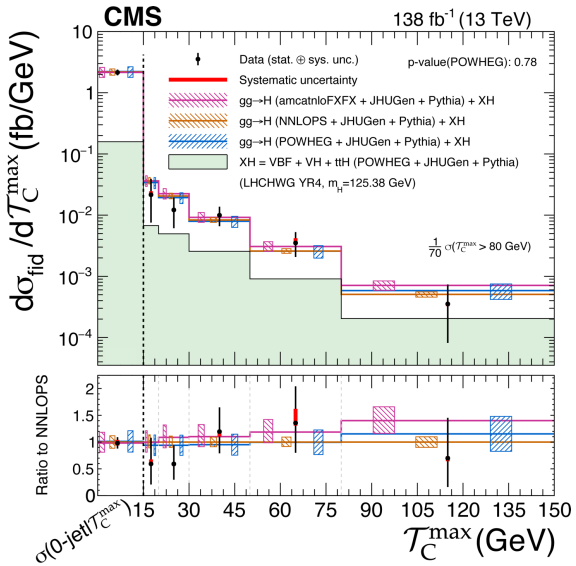
Run 2 H inclusive/differential XS in $H \to ZZ \to 4l$ at CMS

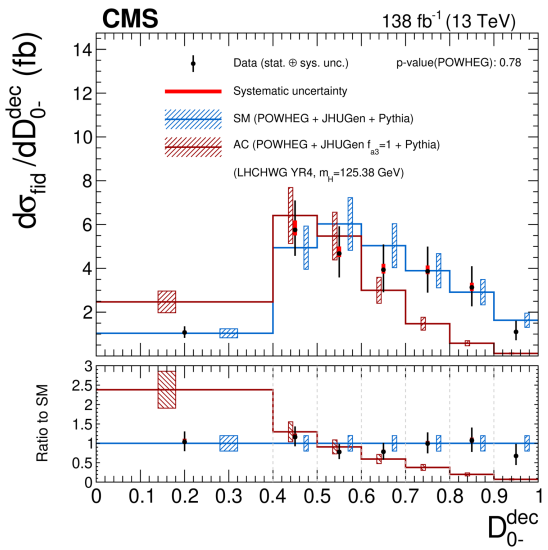
- Inclusive: $\sigma_{\text{fid}} = 2.73 \pm 0.26$ fb $= 2.73 \pm 0.22(stat) \pm 0.15(syst)$ fb, agree with SM (2.86 ± 0.15 fb)
  - Analysis improved with latest CMS Run 2 calibrations → ~40% reduction of leading lepton RECO/selection efficiency systs
- (Double-)Differential: sensitive to H production and decay to 4l → comprehensive characterization of final states and fiducial phase space
  - Include H, Z and associated jet kinematics; H + jets system (ie $T_C^{max} = \max\left(\frac{\sqrt{E_j^2 - p_{Z,j}^2}}{2\cosh(y_j - y_H)}\right)$): probing dynamic evolution of renormalization/factorization effects and resummation effects

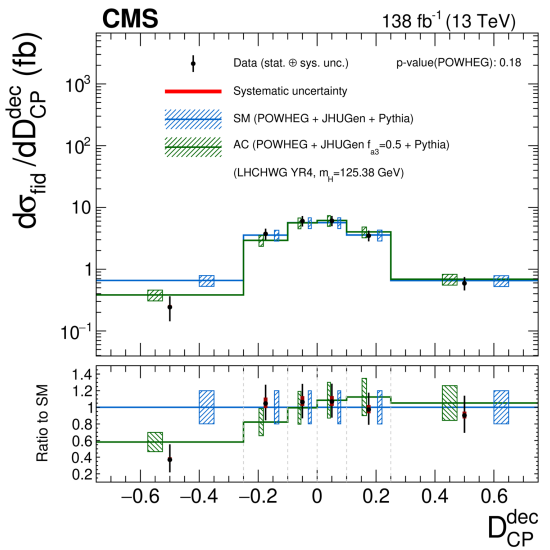
$\mathcal{D}_{\text{alt}}$ $\mathcal{D}_{\text{int}}$

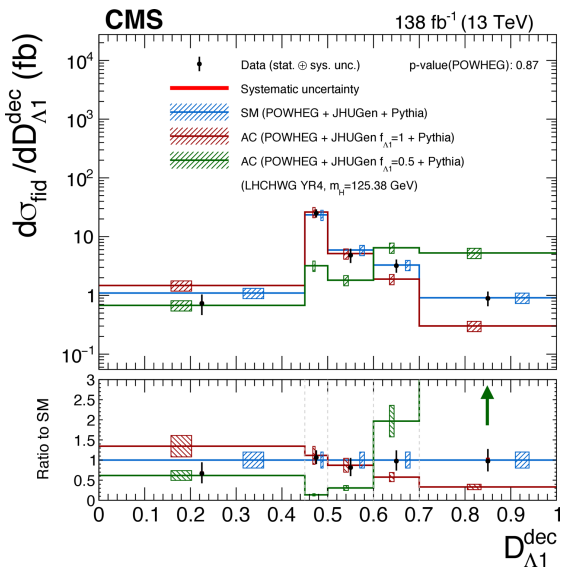
	Coupling					
	a_3	a_2	Λ_1	$\Lambda_1^{Z\gamma}$	a_3	a_2
Discriminant	$\mathcal{D}_{0-}^{\text{dec}}$	$\mathcal{D}_{0h+}^{\text{dec}}$	$\mathcal{D}_{\Lambda 1}^{\text{dec}}$	$\mathcal{D}_{\Lambda 1}^{Z\gamma,\text{dec}}$	$\mathcal{D}_{\text{CP}}^{\text{dec}}$	$\mathcal{D}_{\text{int}}^{\text{dec}}$

Matrix elements: Sensitive to anomalous HVV couplings, valuable test of SM/BSM!



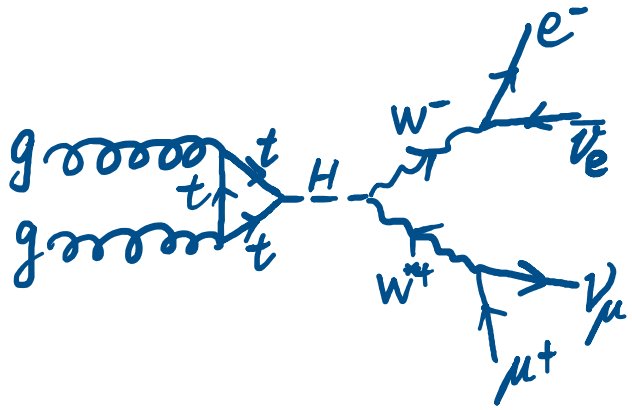






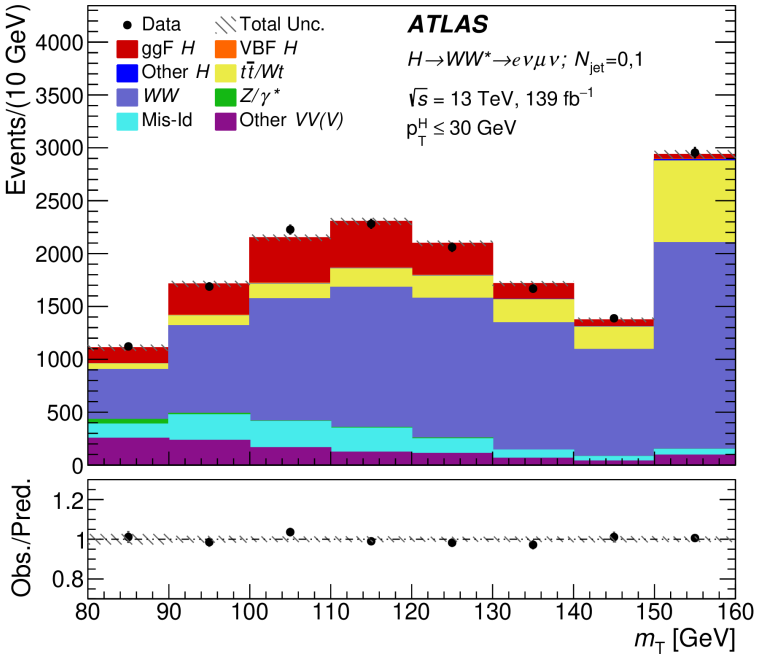
Run 2 ggF $H \to WW^* \to e\nu\mu\nu$ differential XS at ATLAS [Eur. Phys. J. C 83 (2023) 774]

- $H \to WW$: one of the most sensitive channel to fully characterize H properties
  - Second largest BR (21%, LHCHXS) ;-)
  - ν in W decay → impossible to fully reconstruct final states ;-(
  - ggF $H \to WW$: good sensitivity in full p_T^H → more comprehensive than boosted $H \to bb$
  - Lower bkg than $H \to bb$ in lepton final states → competitive with cleaner $\gamma\gamma/ZZ$!
  - $e\nu\mu\nu$ final states: avoid large Drell-Yan bkg (SF)



Fiducial phase space: $N_j \leq 1$ → avoid large top bkg;

Category	$N_{\text{jet},(p_T>30\ \text{GeV})} = 0$	$N_{\text{jet},(p_T>30\ \text{GeV})} = 1$
Pre-Selection	Exactly two isolated leptons ($\ell = e, \mu$) with opposite charge $p_T^{\text{lead}} > 22\,GeV$, $p_T^{\text{sublead}} > 15\,GeV$ $\lvert\eta_e\rvert < 2.5$, $\lvert\eta_\mu\rvert < 2.5$, $p_T^{\text{jet}} > 30\,GeV$ $m_{\ell\ell} > 10\,GeV$ $E_T^{\text{miss, track}} > 20\,GeV$	
Background rejection	$N_{b\text{-jet},(p_T>20\ \text{GeV})} = 0$ $\Delta\phi_{\ell\ell,E_T^{\text{miss}}} > \pi/2$ | $\max(m_T^\ell) > 50\,GeV$ $p_T^{\ell\ell} > 30\,GeV$ | $m_{\tau\tau} < m_Z - 25\,GeV$ $m_T > 80\,GeV$	
$H \to WW^* \to \ell\nu\ell\nu$ topology	$m_{\ell\ell} < 55\,GeV$ $\Delta\phi_{\ell\ell} < 1.8$	

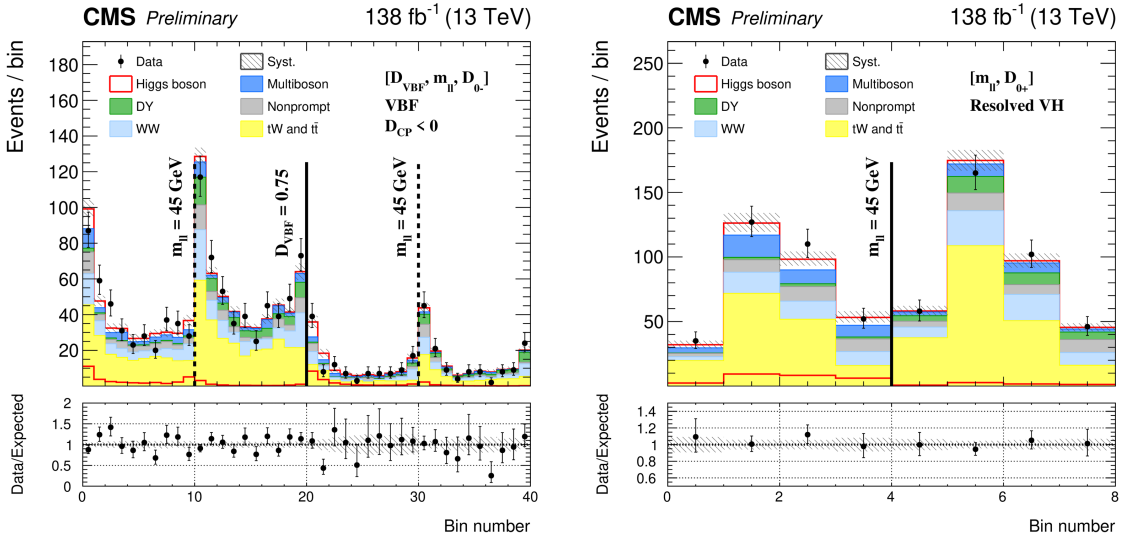


Run 2 ggF $H \to WW^* \to e\nu\mu\nu$ differential XS at ATLAS [Eur. Phys. J. C 83 (2023) 774]

- $H \to WW$: important decay states to fully characterize H properties
  - Though ν in W decay → impossible to fully reconstruct final states; While large BR → competitive with cleaner $\gamma\gamma/ZZ$!
  - ggF $H \to WW$: good sensitivity for detailed study in full p_T^H → more comprehensive than boosted $H \to bb$
  - $e\nu\mu\nu$ final states: avoid large Drell-Yan bkg
- Fiducial phase space: $N_j \leq 1$ → avoid top bkg; VBF, VH fixed to SM
- (Double-)differential variable: H, jet kinematic sensitive to production; Leptonic kinematic sensitive to WW decay
  - p_T^H: balanced by soft quark/gluon emission → test non-perturbative effects, soft-gluon emission modelling, loop effects sensitive to H-b/c Yukawa couplings in low p_T^H regions; High p_T^H sensitive to perturbative QCD effects, BSM contributions
  - N_j; $|y_{j0}|$: Hard gluon/quark emission modelling, probe higher order QCD contributions
  - Leptonic kinematic: Sensitive to WW decay; y_{ll}: sensitive to PDF; $\cos\theta^*$: longitudinally boost-invariant, sensitive to spin structure of diparticle pairs

Run 2 anomalous H couplings constraints in $H \to WW$ at CMS [CMS-PAS-HIG-22-008]

- H quantum numbers consistent with SM: $J^{PC} = 0^{++}$; While small anomalous couplings not ruled out
- ➢ New analysis: study tensor structure of Hgg/HVV coupling in BSM, search for anomalous effects
  - ➢ $A(HV^1V^2) \sim \left[a_1^{VV} + \frac{\kappa_1^{VV} q_{V1}^2 + \kappa_2^{VV} q_{V2}^2}{(\Lambda_1^{VV})^2}\right] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^* + \frac{1}{v} a_2^{VV} f^{*(1)}_{\mu\nu} f^{*(2),\mu\nu} + \frac{1}{v} a_3^{VV} f^{*(1)}_{\mu\nu} \tilde{f}^{*(2),\mu\nu}$
  - ➢ Fractional contribution of anomalous couplings: $f_{ai} = \frac{|a_i|^2 \sigma_i}{\sum_j |a_j|^2 \sigma_j} \text{sign}\left(\frac{a_i}{a_1}\right)$
- Target: ggF, VBF, VH with DF lepton final states
- Jet kinematic information combined using ME techniques → increase sensitivity to anomalous effects

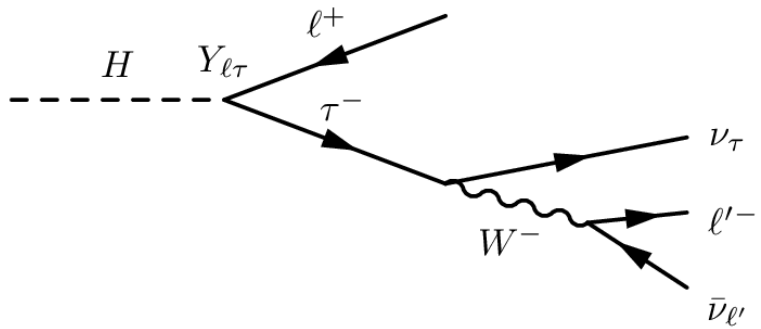


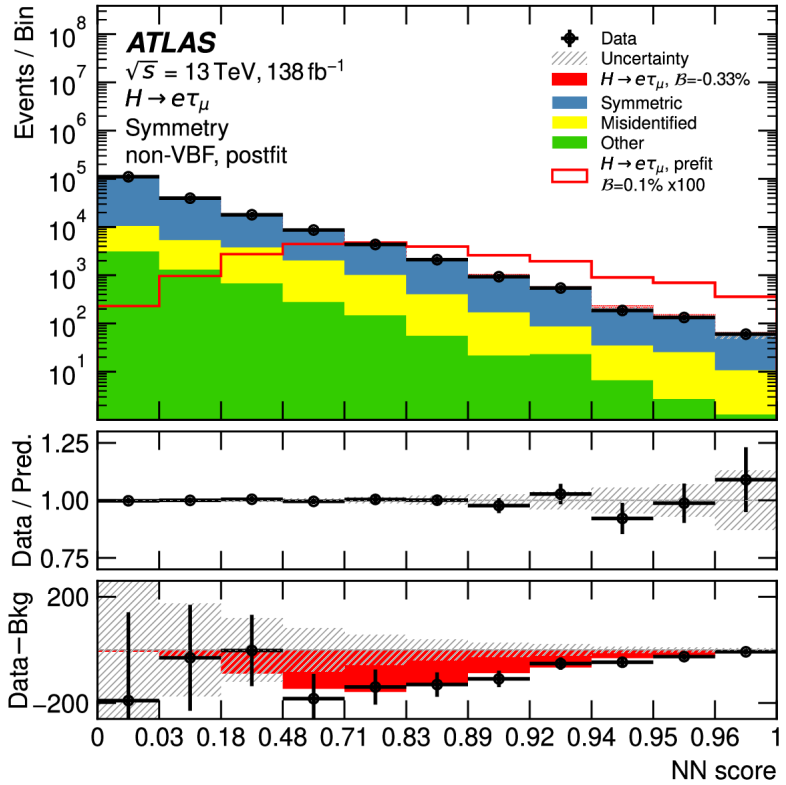
Analysis	f_{ai}	Observed ($\times 10^{-3}$)		Expected ($\times 10^{-3}$)	
		Best-fit with 68% CL	95% CL	Best-fit with 68% CL	95% CL
HVV Approach 1	f_{a3}	0.9 [-2.7, 4.1]	[-553, 561]	0.0 [-0.7, 0.7]	[-2.8, 2.9]
	f_{a2}	0.5 [-0.8, 3.5]	[-5.7, 12]	0.0 [-1.4, 1.3]	[-5.2, 6.1]
	$f_{\Lambda 1}$	-0.2 [-0.5, 0.0]	[-1.4, 0.7]	0.0 [-0.2, 0.5]	[-0.6,1.4]
	$f_{\Lambda 1}^{Z\gamma}$	3.0 [-11, 9.1]	[-55, 42]	0.0 [-5.0, 3.8]	[-14, 11]
HVV Approach 2 (fixed others)	f_{a3}	0.84 [-0.83, 3.5]	[-7.6, 58.8]	0.0 [-0.8,1.1]	[-3.4,4.3]
	f_{a2}	38 [-112.2, 129.3]	[-376.6, 430.0] ∪[-989.2, -826.3]	0.0 [-30.9,37.5]	[-126.1,136.8]
	$f_{\Lambda 1}$	-0.15 [-1.21, 0.16]	[-19.5, 118.5] ∪[909.9, 964.1]	0.0 [-0.4,0.4]	[-1.7,18.9]
HVV Approach 2 (float others)	f_{a3}	0.34 [-0.69, 3.4]	[-8.0, 361.5]	0.0 [-1.0,1.2]	[-4.3,5.3]
	f_{a2}	-1.0 [-104.1, 139.9]	[-986.4, 981.2]	0.0 [-31.1,39.8]	[-127.5,148.7]
	$f_{\Lambda 1}$	-0.1 [-1.08, 3.78] ∪[7.2, 20.7]	[-994.8, 993.9]	0.0 [-0.4,0.90]	[-1.9,21.4]
Hgg	f_{a3}^{ggH}	-34 [-721, 383]	—	0.0 —	—

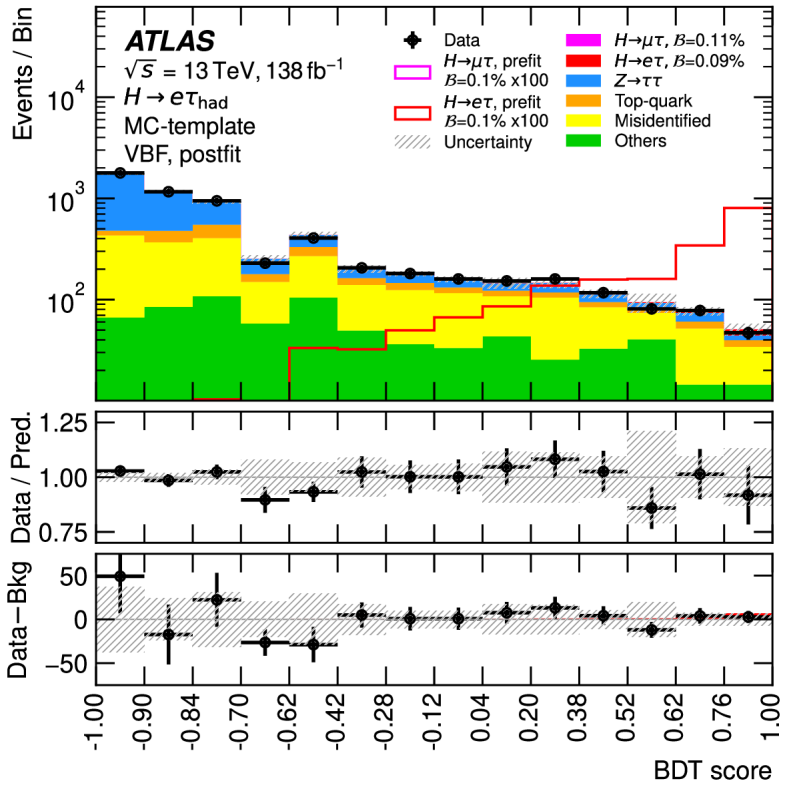
- Interpret HVV couplings in SMEFT, measured simultaneously
- All consistent with SM, significantly surpass the previous analysis [Phys. Lett. B 759 (2016) 672] in precision and coverage

Run 2 LFV search of $H \to e\tau$ or $\mu\tau$ at ATLAS [JHEP 07 (2023) 166]

- Neutrino oscillation observation → LFV realized, lepton flavor not an exact symmetry → BSM contribute to flavor changing dynamics
- Direct search of $H \to e\tau$ or $\mu\tau$: most stringent bounds on LFV
  - Final state: $l\tau_{l'}, l\tau_h$; $l\tau_{l'}$: only DF leptons to avoid large Drell-Yan bkg
- MVA developed to improve sensitivity

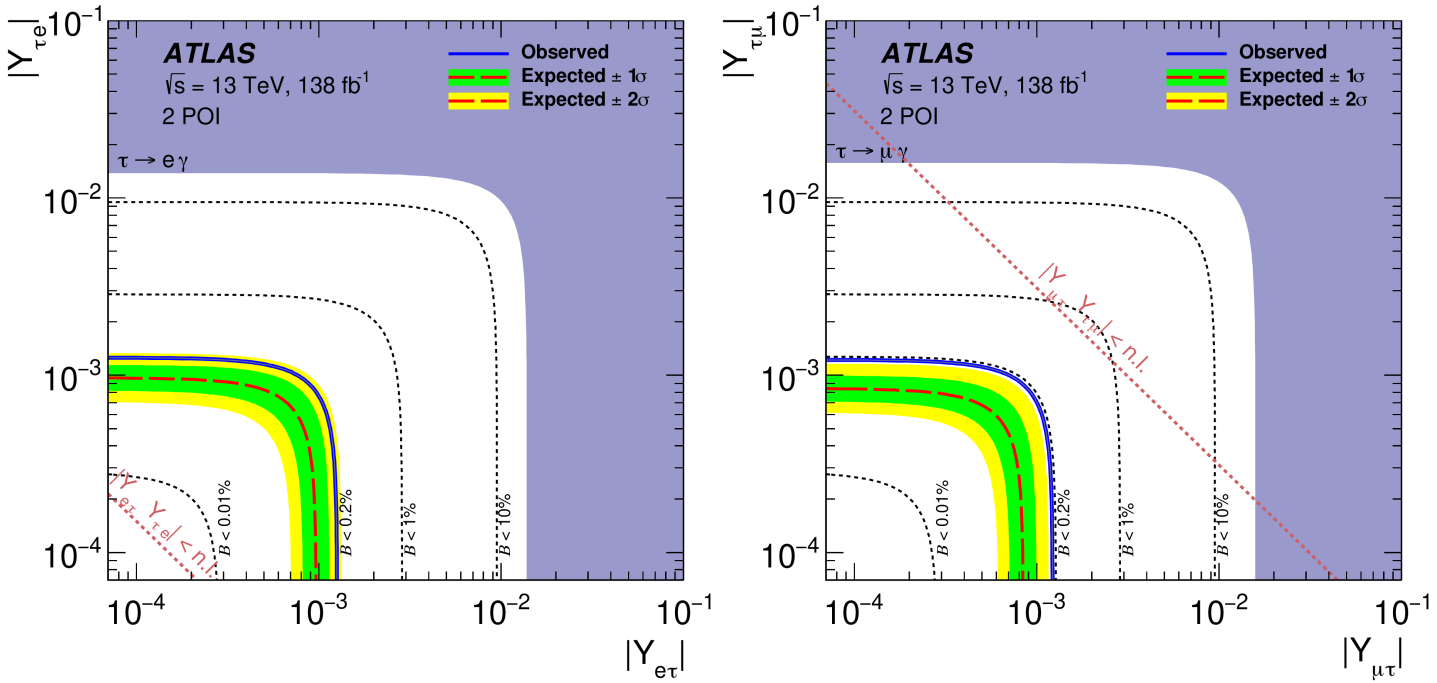


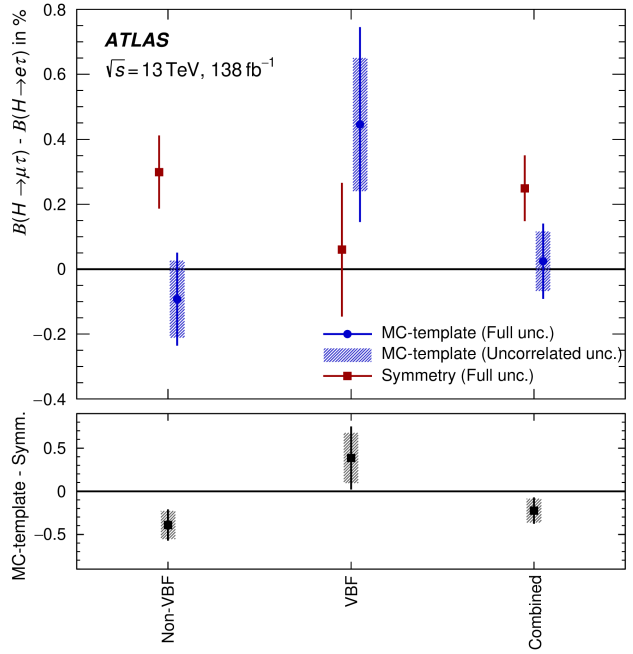




Run 2 LFV search of $H \to e\tau$ or $\mu\tau$ at ATLAS [JHEP 07 (2023) 166]

- $B(H \to e\tau) < 0.20\%\ (0.12\%)$, $B(H \to \mu\tau) < 0.18\%\ (0.09\%)$ at 95% CL with MC template bkg method, consistent with SM within 2.1σ
- $B(H \to \mu\tau) - B(H \to e\tau) = (0.25 \pm 0.10)\%$ in $l\tau_{l'}$ with symmetry bkg method (prompt-lepton bkg are symmetric under exchange of e/μ), compatible with 0 within 2.5σ

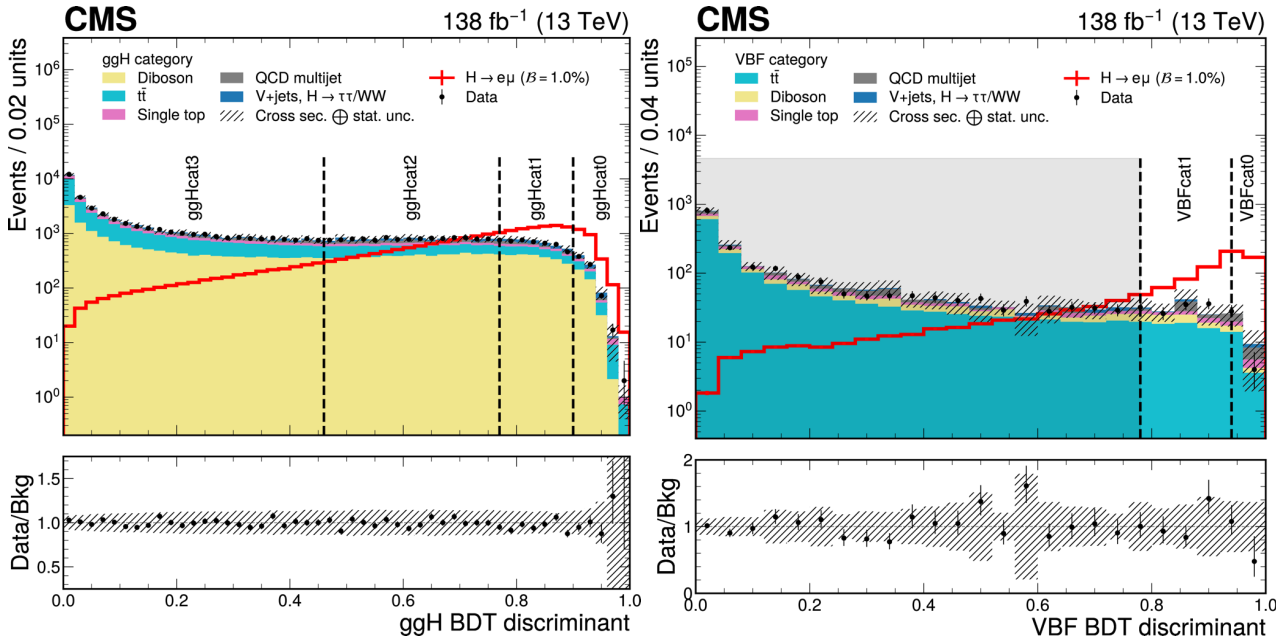


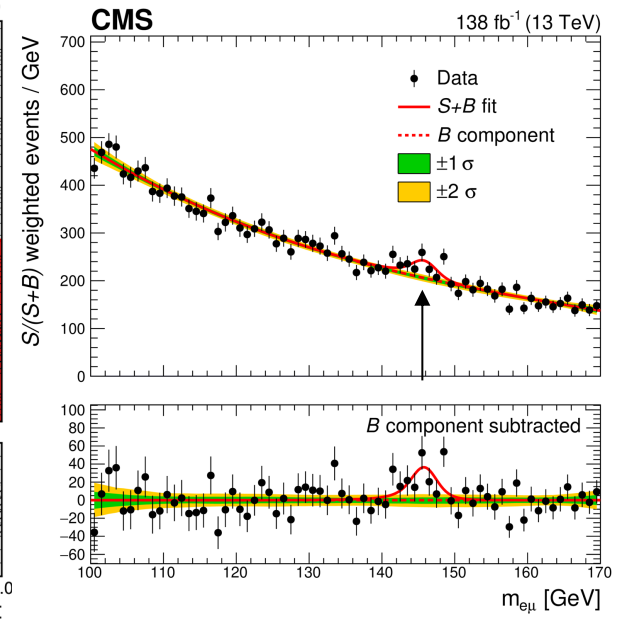


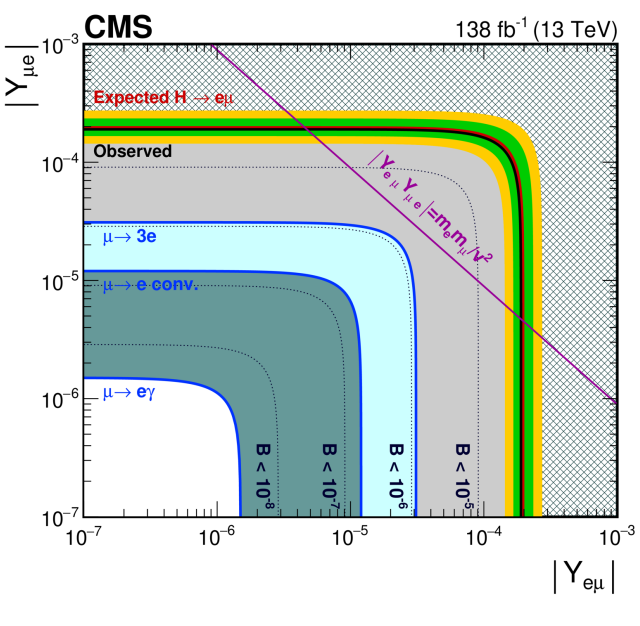
- Observed results more stringent by a factor of 2.5 (1.6) than previous $H \to e\tau$ ($H \to \mu\tau$) analysis, expected results improved by a factor of 3.1 (4.1)
  - Significantly more sophisticated analysis methods besides larger dataset: lepton assignment in the H rest frame of $l\tau_{l'}$ channel, symmetry bkg method, VBF category, more advanced MVA classifiers, improved τ ID

Run 2 LFV search of SM H and additional H in $e\mu$ final states at CMS [Phys. Rev. D 108 (2023) 072004]

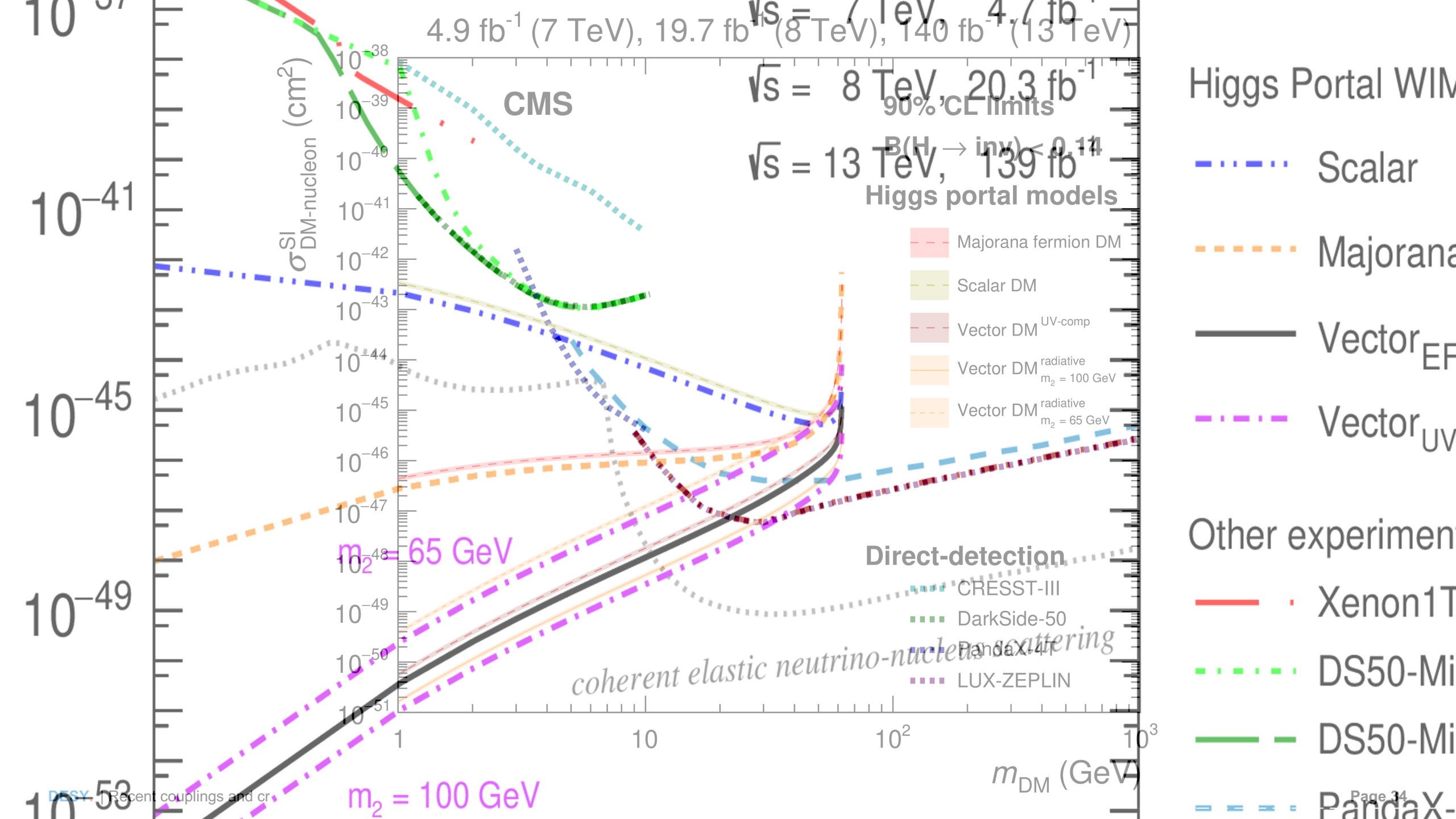
- $B(H \to e\mu)$ can be indirectly obtained from $\mu \to e\gamma$ search, while assume SM $Y_{\mu\mu}$, Y_{ee} and the flavor changing neutral current dominated by H → Direct search is important!
- Analysis optimized for ggF/VBF, $B(H \to e\mu) < 4.4(4.7)\times10^{-5}$ at 95% CL
  - ➢ No excess observed; Most stringent from direct searches!





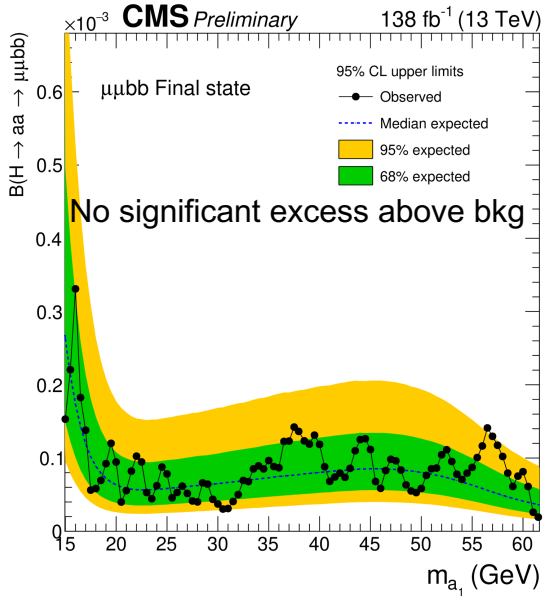


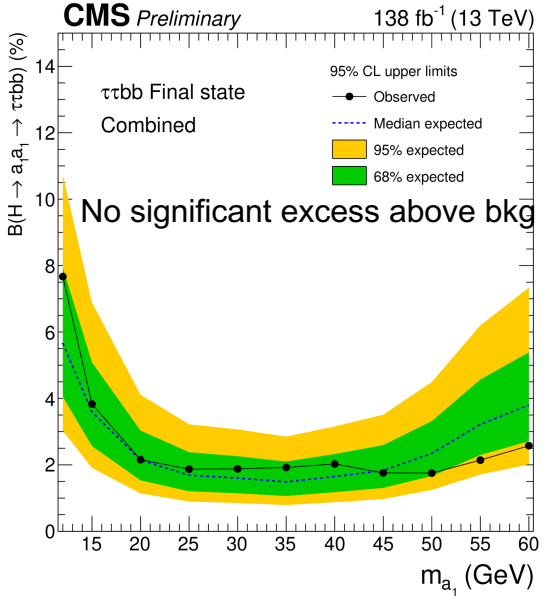
- Search for additional H with $m_X < 2m_W$ in LFV is important to constrain Type III 2HDM → First direct LFV search for m_X in [110, 160] GeV
  - ➢ Largest excess: $m_X = 146$ GeV, 3.8σ (2.8σ) local (global) significance, more data needed to clarify the nature of excess

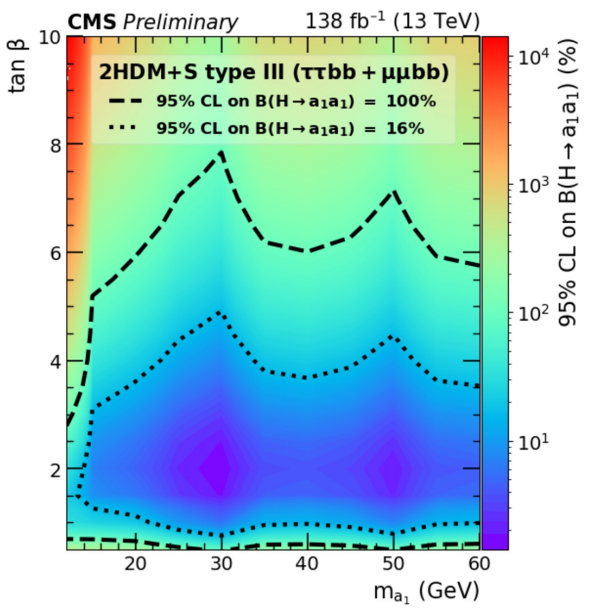

CMS
$\sqrt{s}$ = 7 TeV, 4.7 fb^{-1}
$\sqrt{s}$ = 8 TeV, 20.3 fb^{-1}
$\sqrt{s}$ = 13 TeV, 139 fb^{-1}
4.9 fb^{-1} (7 TeV), 19.7 fb^{-1} (8 TeV), 140 fb^{-1} (13 TeV)
90% CL limits
$\mathcal{B}(H \to inv) < 0.11$
Higgs portal models
Majorana fermion DM
Scalar DM
Vector DM UV-comp
Vector DM radiative m_2 = 100 GeV
Vector DM radiative m_2 = 65 GeV
Direct-detection
CRESST-III
DarkSide-50
PandaX-4T
LUX-ZEPLIN
coherent elastic neutrino-nucleus scattering
m_2 = 65 GeV
m_2 = 100 GeV
$\sigma^{SI}_{DM\text{-}nucleon}$ (cm^2)
m_{DM} (GeV)
Higgs Portal WIM
Scalar
Majorana
Vector$_{EF}$
Vector$_{UV}$
Other experimen
Xenon1T
DS50-Mi
DS50-Mi
PandaX-

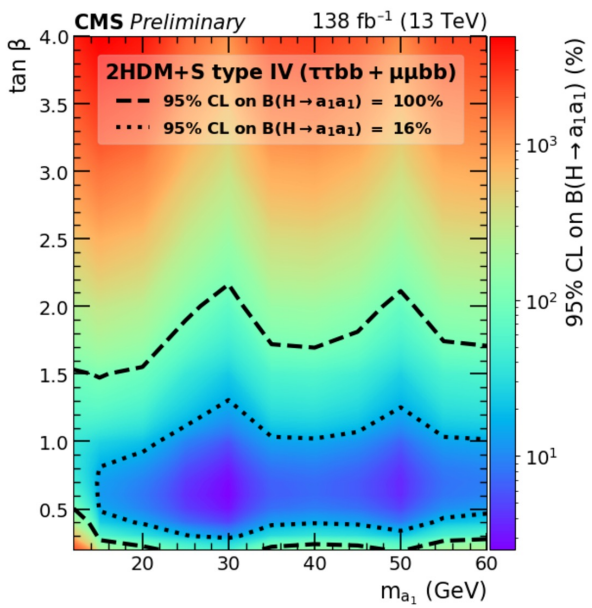
Run 2 $H \to a_1 a_1 \to \mu\mu bb/\tau\tau bb$ at CMS [CMS-PAS-HIG-22-007]

- H to BSM particles not ruled out → leeway for new physics, crucial to examine SM extensions (ie. 2HDM + S)
- Phase space: ggF, VBF, $H \to a_1 a_1 \to \mu\mu bb/\tau\tau bb$, pseudoscalar a_1 in [12, 60] GeV
  - $\tau\tau bb$: large BR; Final state: $\tau_l \tau_h$ or $\tau_l \tau_l$ with DF leptons
  - $\mu\mu bb$: smaller BR, while excellent muon RECO efficiency and $m_{\mu\mu}$ resolution → competitive to $\tau\tau bb$
- $B(H \to a_1 a_1)$: dependent to types of 2HDM + S, m_{a1}, $\tan\beta$
- Most stringent limits to date! Significant improvements wrt earlier measurements
  - $\mu\mu bb$: more thorough studies of sig properties; $\tau\tau bb$: benefit from DNN based categorization









Run 2 $H \to Za$ search at CMS [arXiv:2311.00130]

- ALPs: Axion-like particles, used to address strong CP problem, can also explain observed anomaly in μ magnetic moment
- $H \to Z(\to ll)a(\to \gamma\gamma)$, m_a in [1, 30] GeV: complementary and first search of this channel for ALPs at LHC
- Upper limits set on $\sigma(pp \to H)B(H \to Za \to 2l + 2\gamma)$
  - Excess above bkg observed at $m_a = 3$ GeV with 2.6σ (1.3σ) local (global) significance
  - Interpreted into EFT parameter of ALPs: C_{ZH}^{eff}/Λ