Rare Higgs decays, Higgs BSM and di-Higgs

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on behalf of the ATLAS and CMS Collaborations

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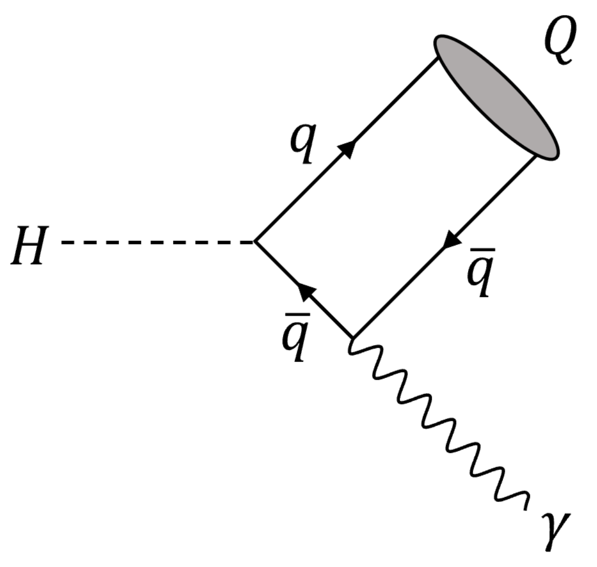
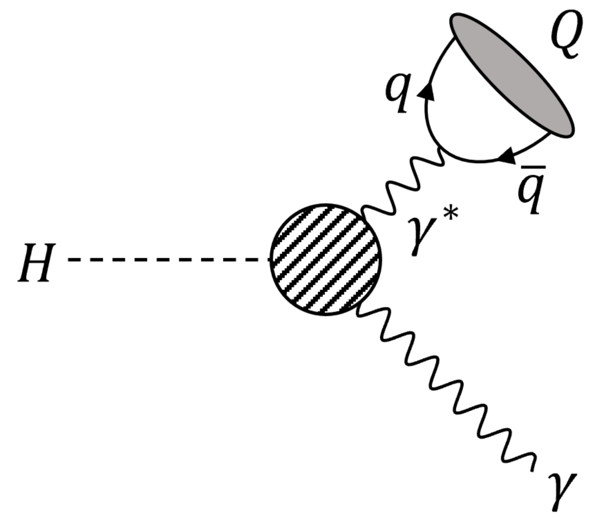
Rare Higgs decays

ATLAS search for Higgs decays to $\omega\gamma$ and $K^*\gamma$, and Quarkonium

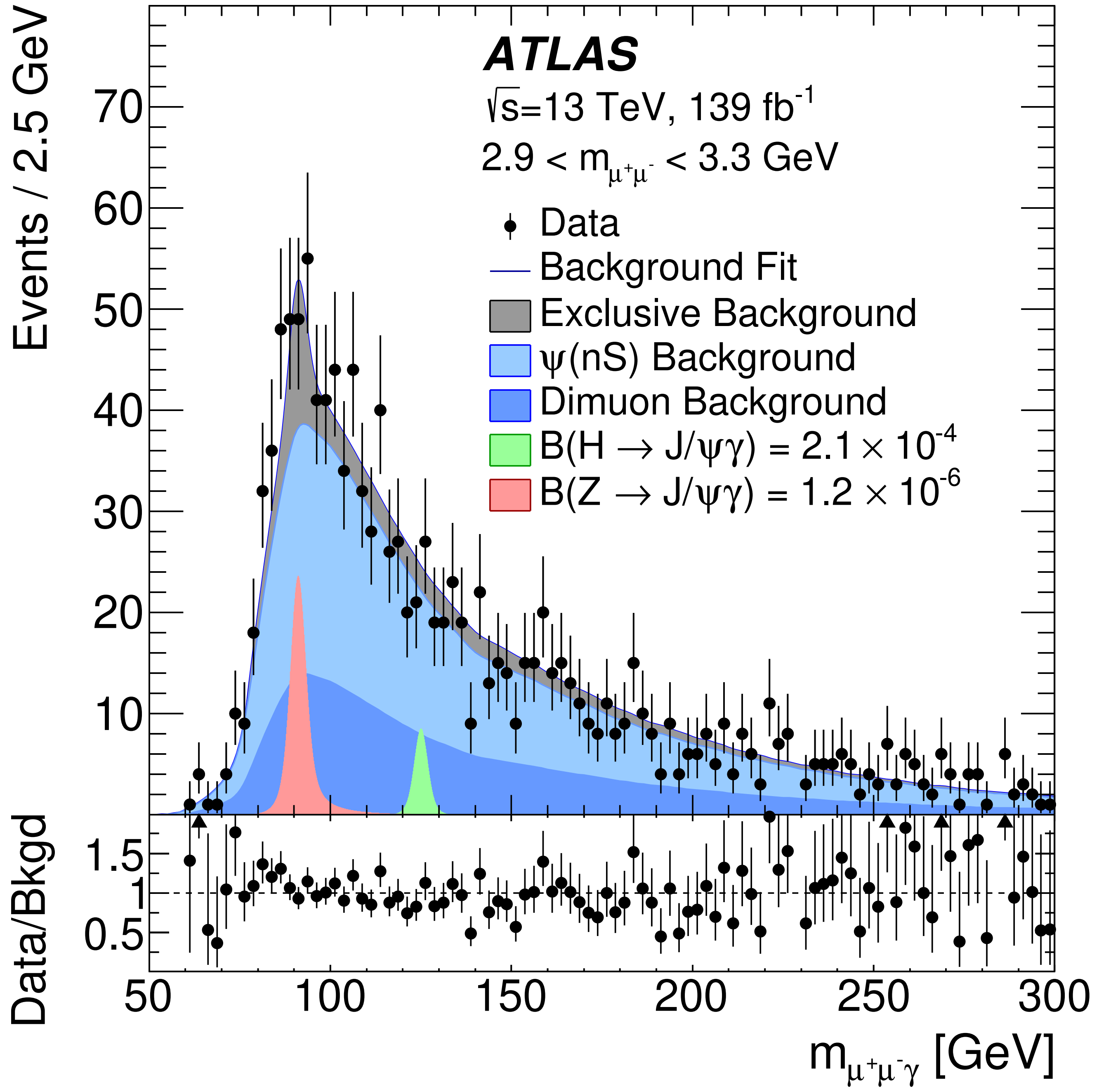
HDBS-2018-53 arXiv:2208.03122



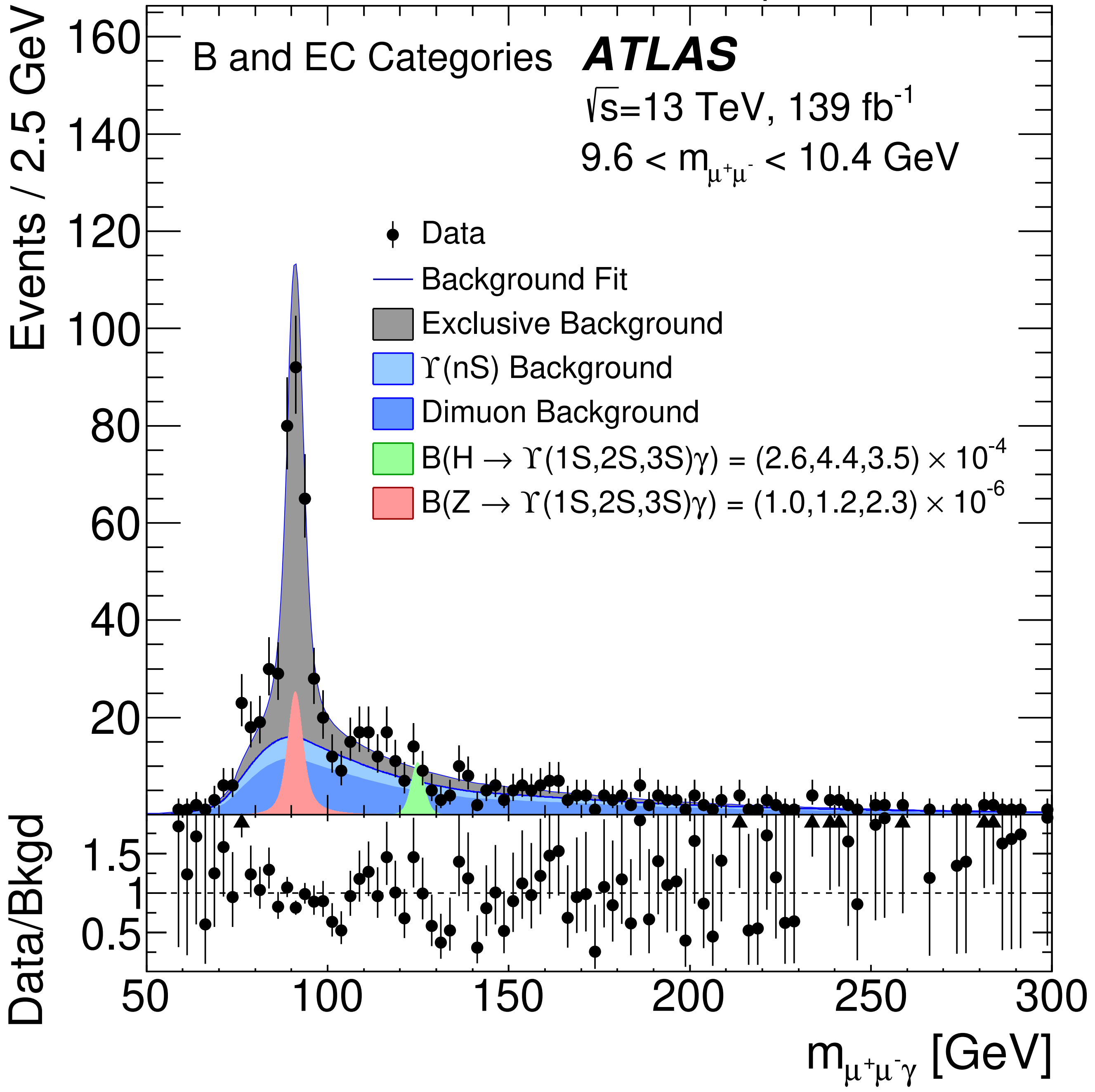


Higgs decays to Quarkonium + photon

- Allows for exploration of the Higgs couplings to *c* and *b* quarks
- Reconstruction of the event is performed via the muons from the Quarkonium decay and the photon



B: barrel, EC: endcap



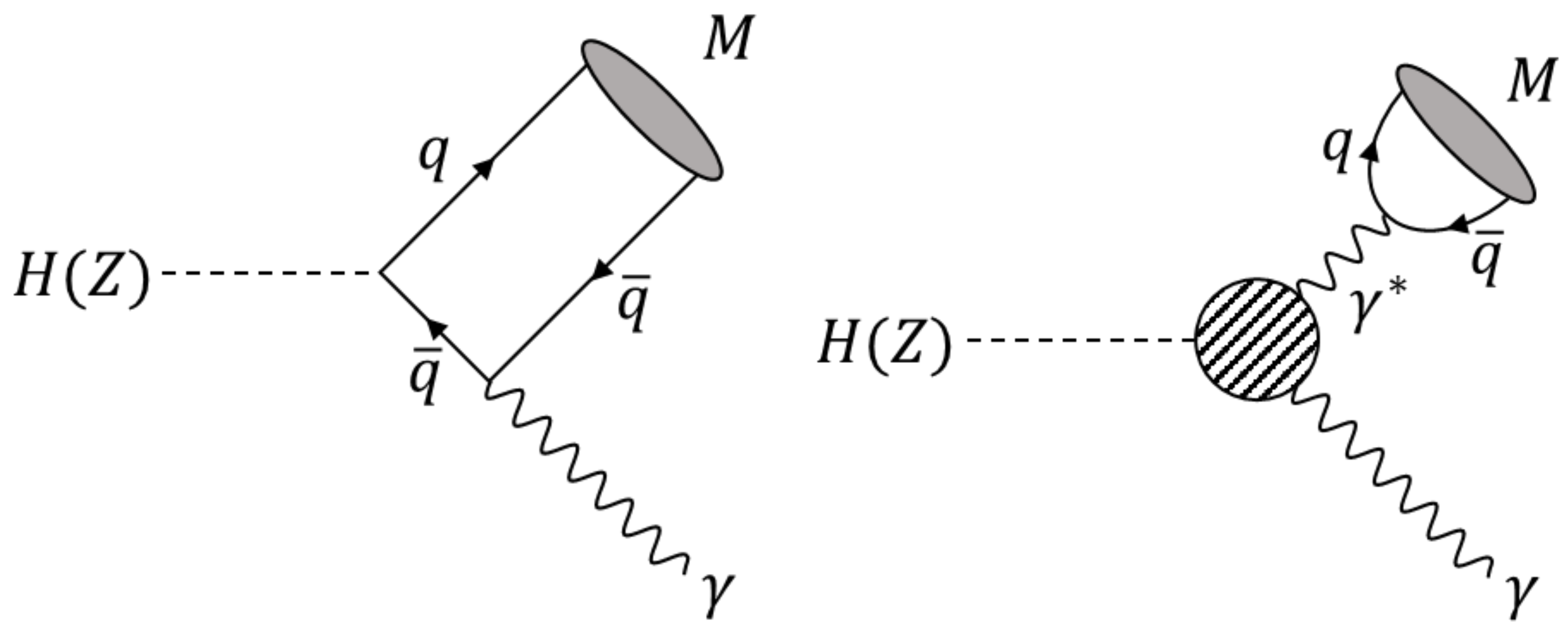
	95% CL upper limits					
	Branching fraction				$\sigma \times \mathcal{B}$	
Decay	Higgs boson [10^{-4}]		Z boson [10^{-6}]		Higgs boson [fb]	Z boson [fb]
channel	Expected	Observed	Expected	Observed	Observed	Observed
$J/\psi\,\gamma$	$1.9^{+0.8}_{-0.5}$	2.1	$0.6^{+0.3}_{-0.2}$	1.2	12	71
$\psi(2S)\,\gamma$	$8.5^{+3.8}_{-2.4}$	10.9	$2.9^{+1.3}_{-0.8}$	2.3	61	135
$\Upsilon(1S)\,\gamma$	$2.8^{+1.3}_{-0.8}$	2.6	$1.5^{+0.6}_{-0.4}$	1.0	14	59
$\Upsilon(2S)\,\gamma$	$3.5^{+1.6}_{-1.0}$	4.4	$2.0^{+0.8}_{-0.6}$	1.2	24	71
$\Upsilon(3S)\,\gamma$	$3.1^{+1.4}_{-0.9}$	3.5	$1.9^{+0.8}_{-0.5}$	2.3	19	135

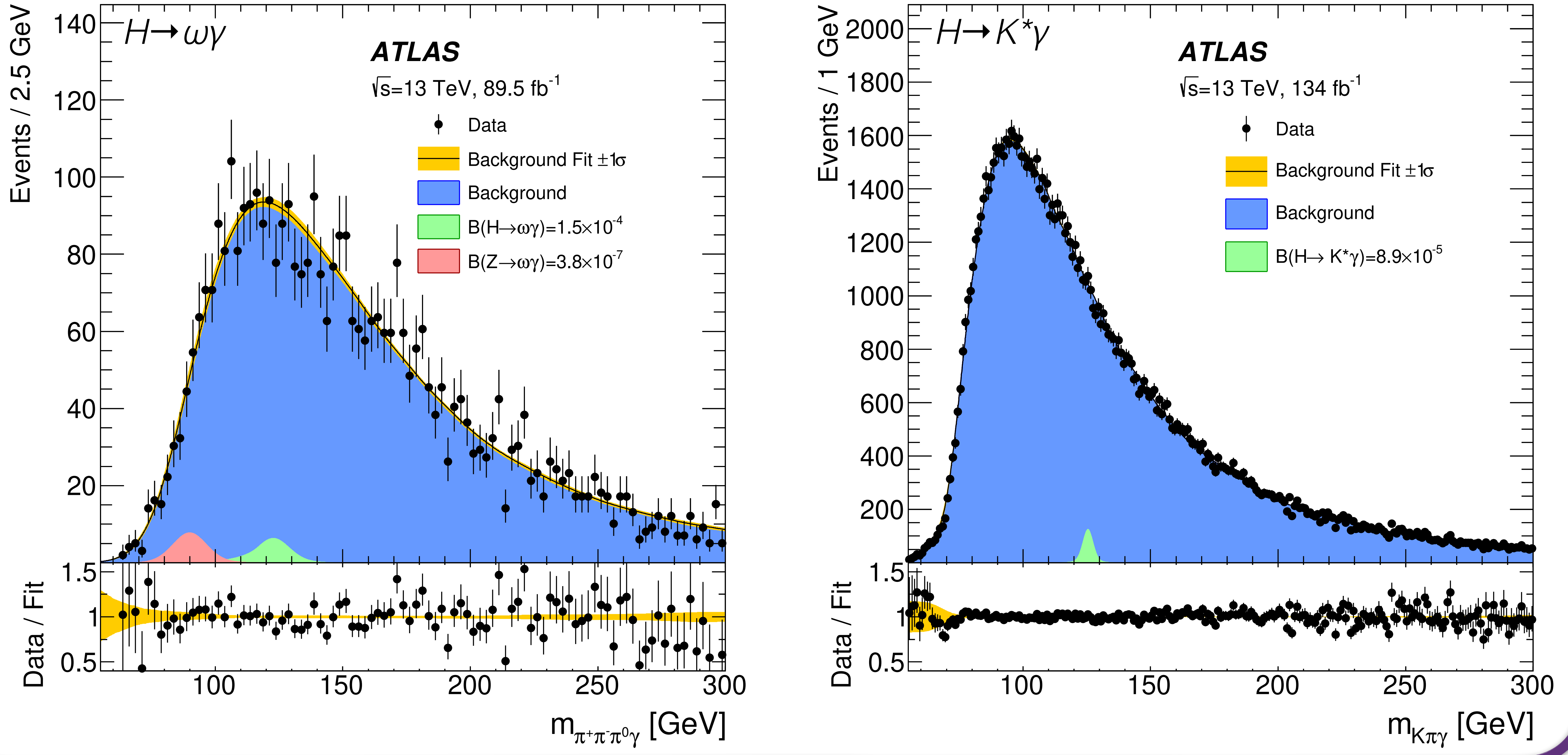
ATLAS search for Higgs decays to $\omega\gamma$ and $K^*\gamma$, and Quarkonium

HDBS-2019-33 arXiv:2301.09938

Higgs decays to ωγ and K*γ

- Rare decays allow for exploration of Higgs couplings to light quarks
- Exclusive decay analysis targeting flavor-changing interactions
- Events are reconstructed via their predominant $\pi^+\pi^-\pi^0$ and $K^\pm\pi^\pm$ final states





BR limits

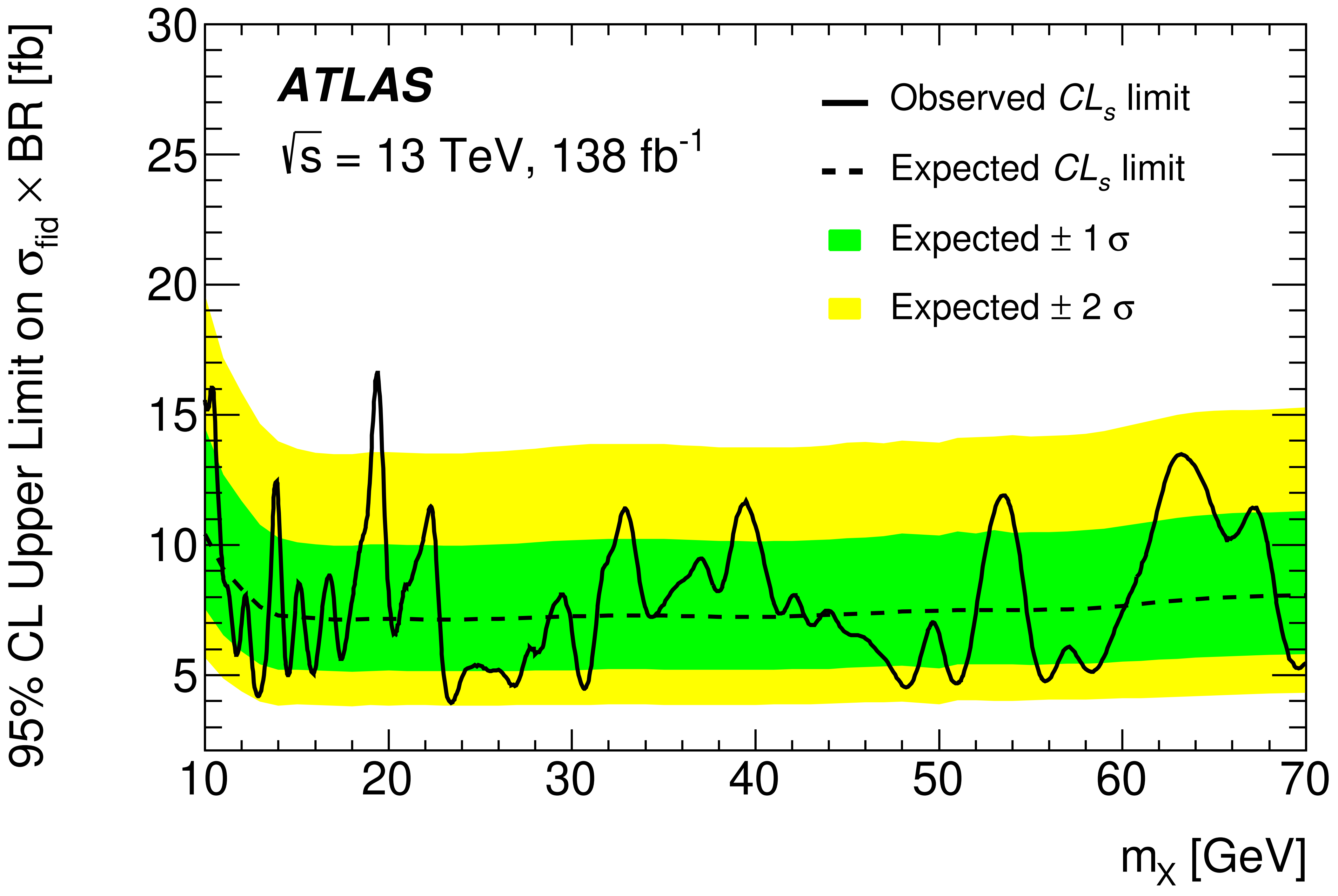
Channel	95% CL upper limit Expected	95% CL upper limit Observed
$H \to \omega\gamma\ [10^{-4}]$	$3.0^{+1.2}_{-0.8}$	1.5
$H \to K^*\gamma\ [10^{-5}]$	$12.2^{+4.9}_{-3.4}$	8.9

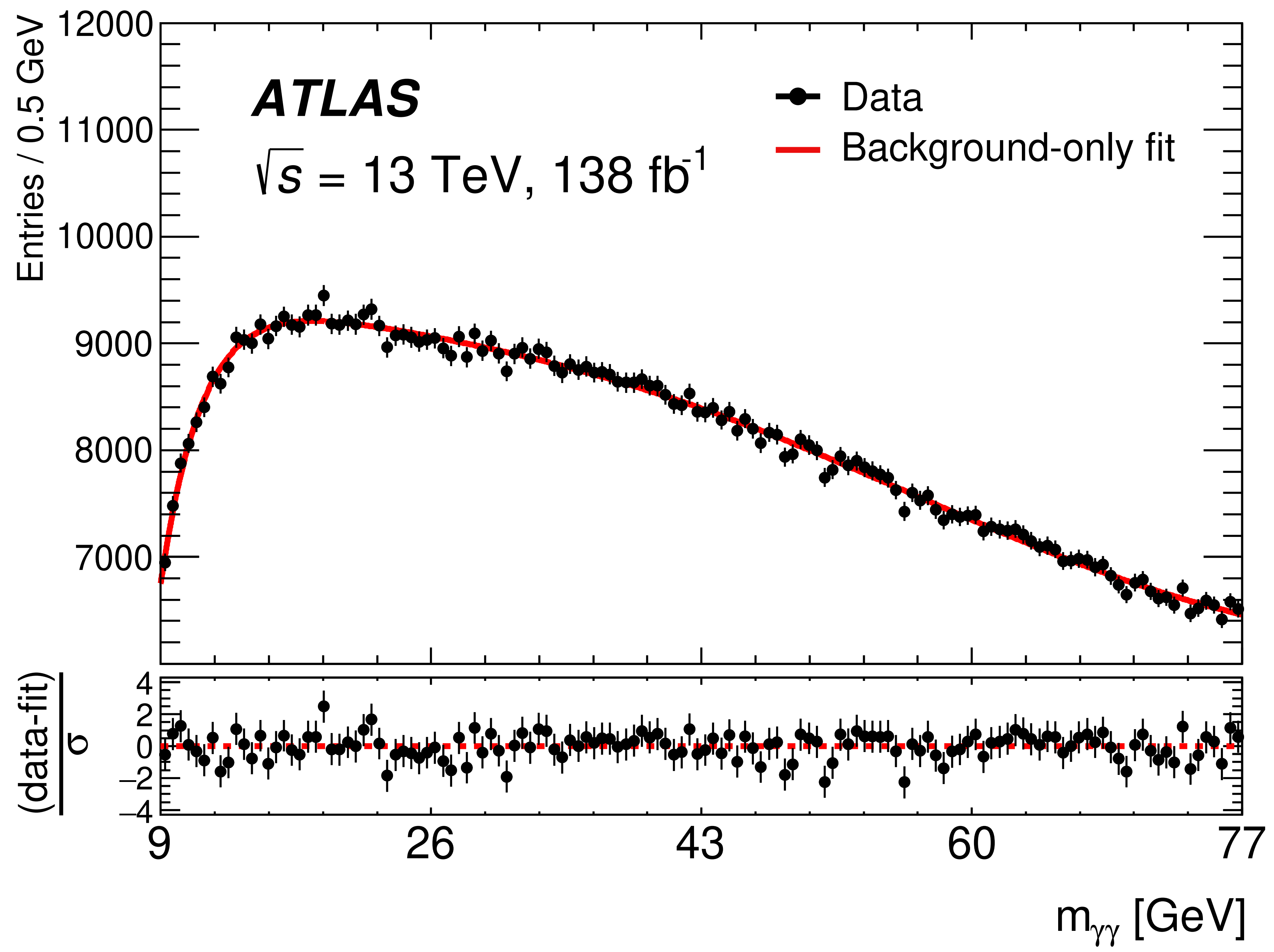
Higgs BSM

Di-photon resonances

HIGG-2019-23 arXiv:2211.04172

- Narrow resonances of mass 10-70 GeV are explored
- Events with pairs of closely spaced photons with large $p_T^{\gamma\gamma}$ are selected
- Analysis also recasted in a so-far uncovered phase-space of axion-like particles by di-γ searches





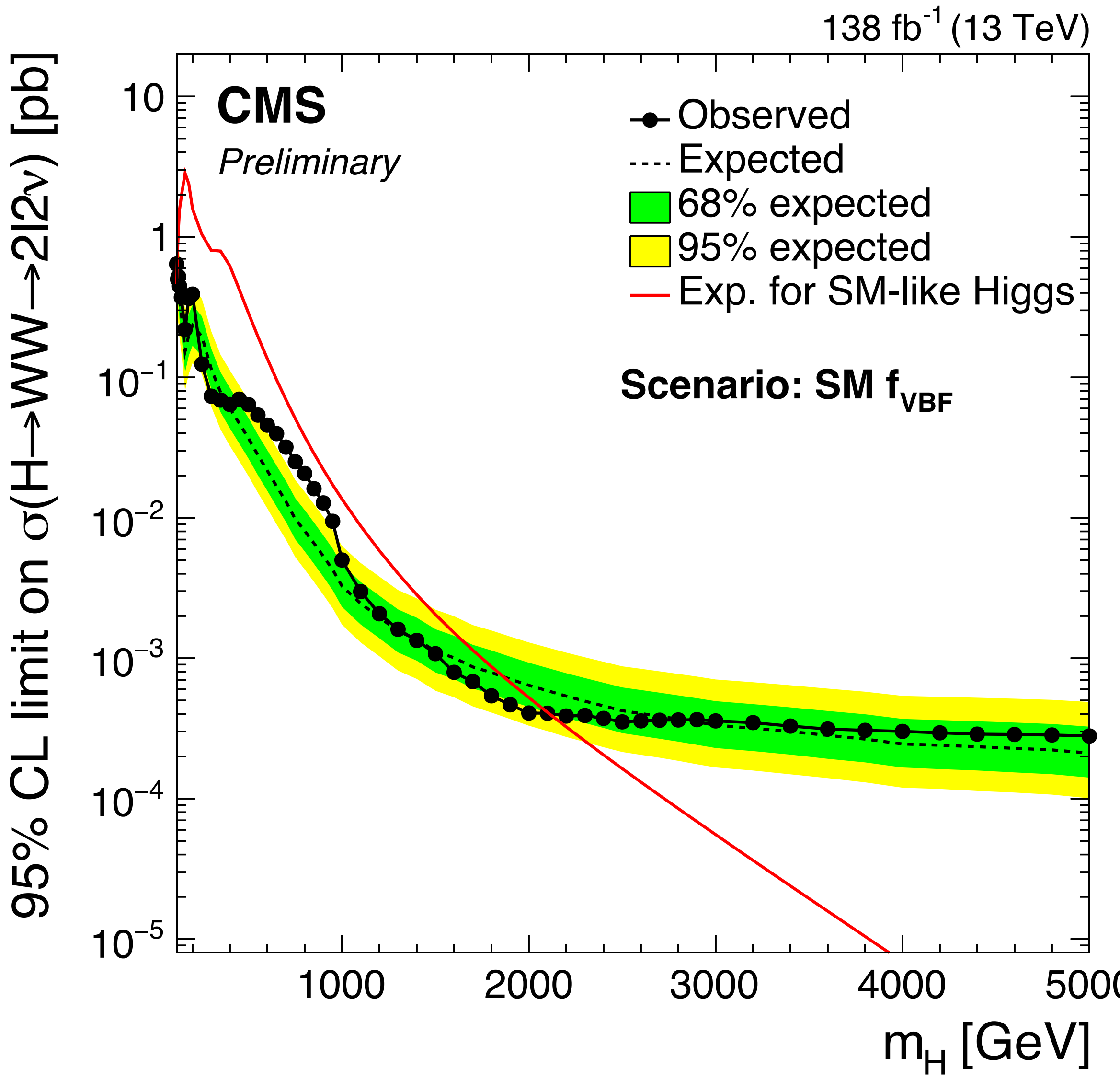
- Deviation at m_X=19.4 GeV with local significance 3.1σ and global significance 1.5σ

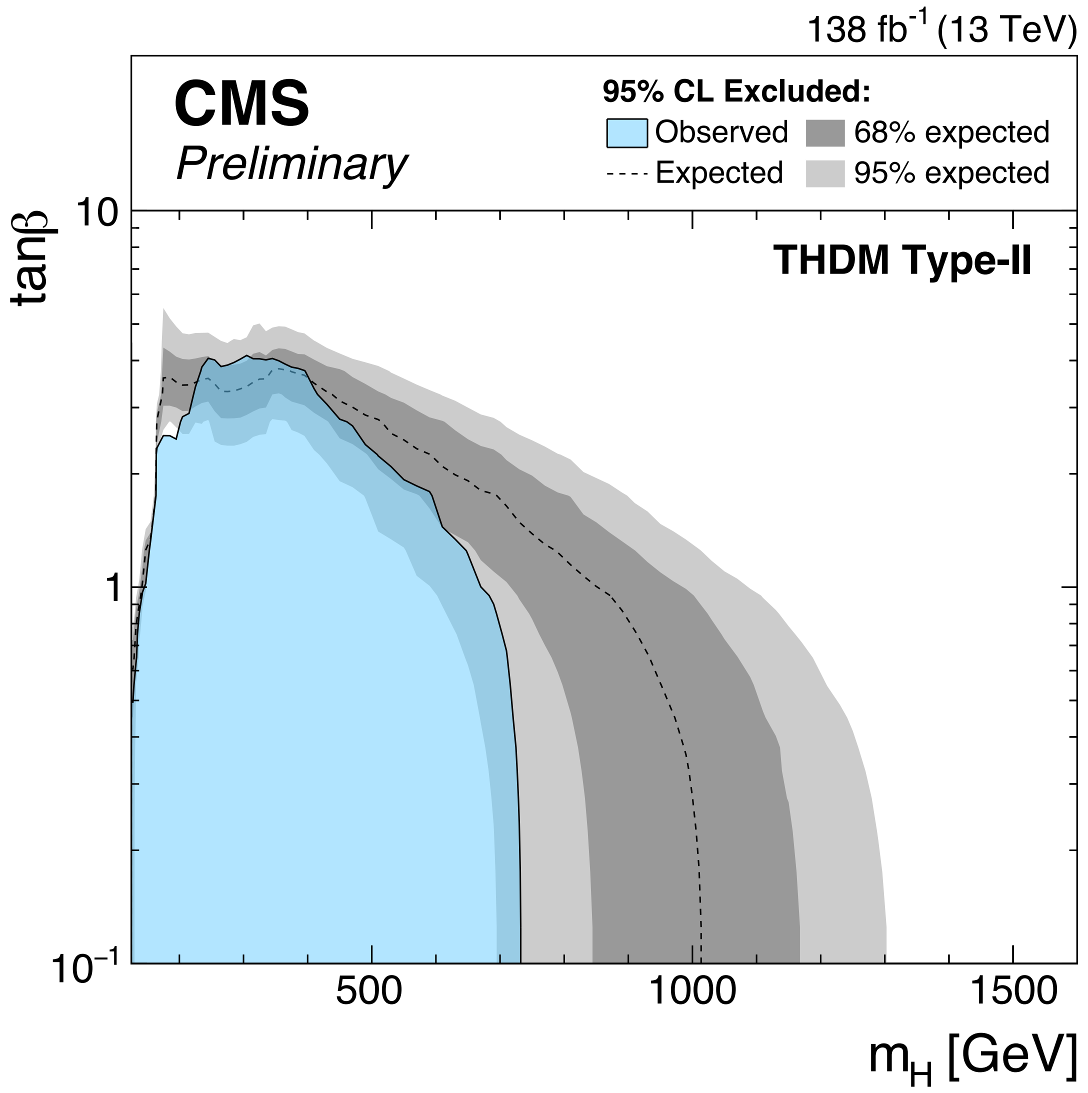
ATLAS and CMS resonances to W^+W^-

CMS-PAS-HIG-20-016

$H \to W^+W^- \to e\nu\mu\nu, \mu\nu\mu\nu, e\nu e\nu$

- In addition to a narrow width, various relative widths up to 10% have been considered
- The fraction of VBF production (f_{VBF}) has been studied in the rage $0 < f_{VBF} < 1$
  - Non-negligible interference effects are accounted for





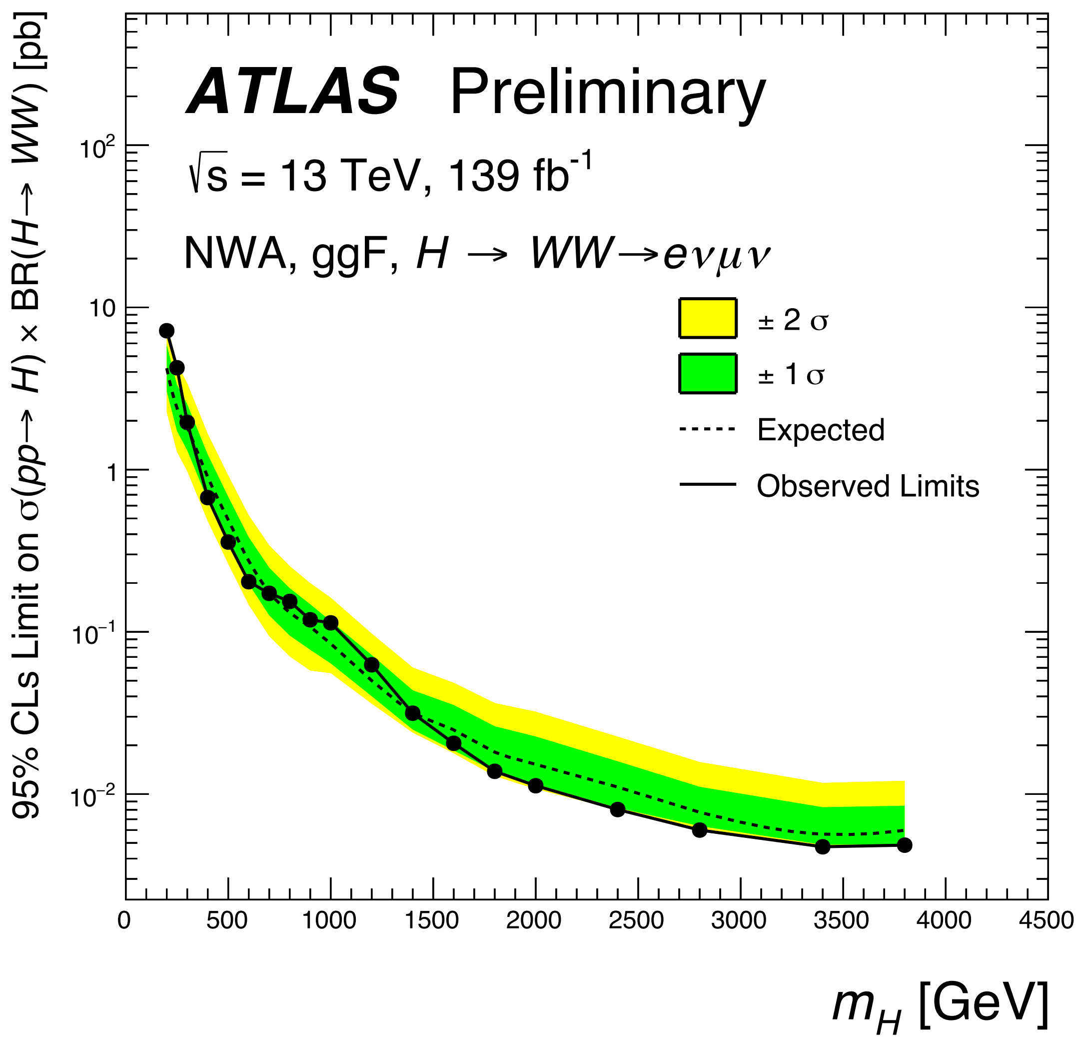
- Interpretation in the framework of NMSSM and 2HDM also performed
- Small excess of data is observed in a *DNN* m_T range

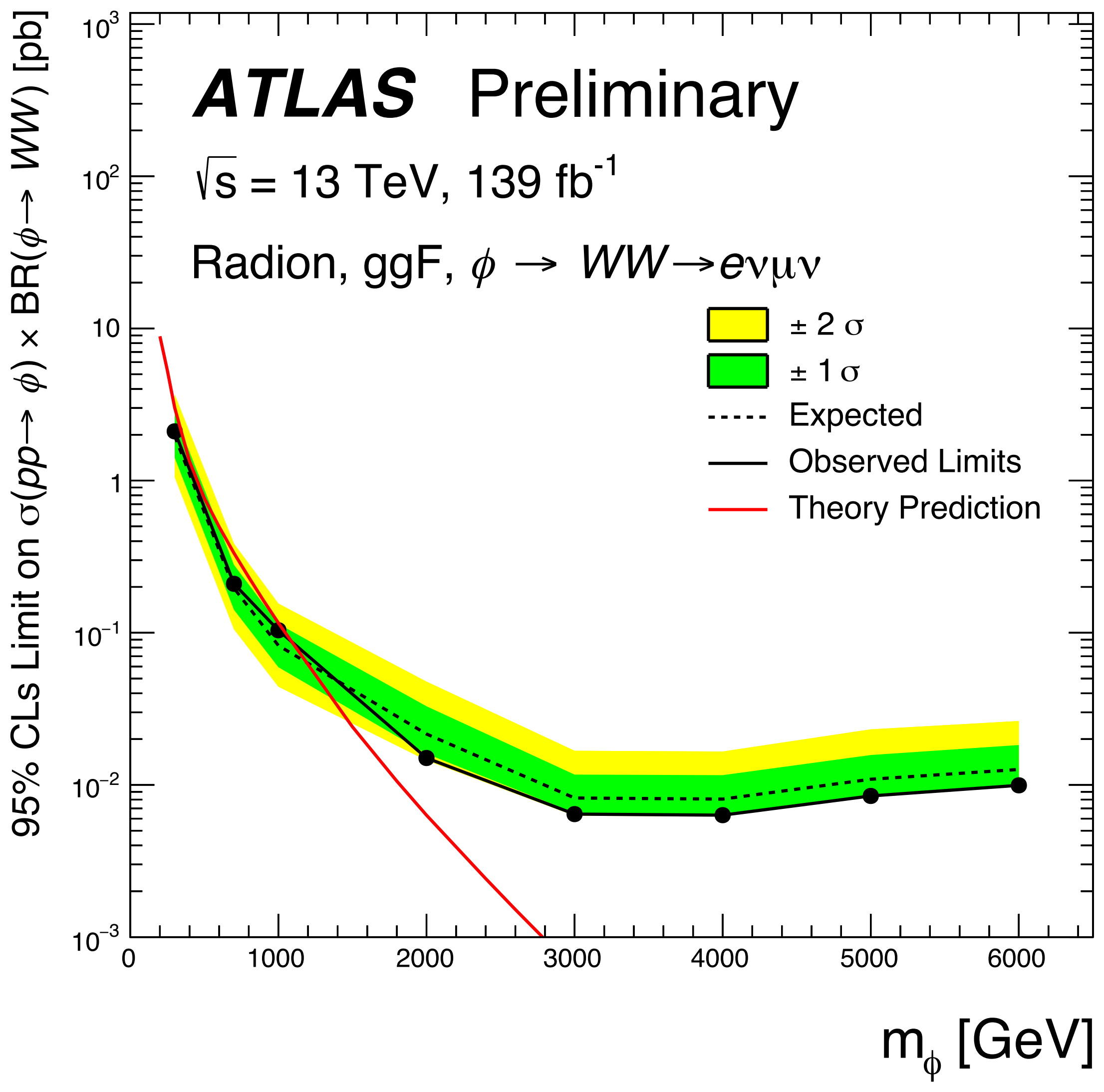
Scenario	Mass [GeV]	ggF cross sec. [pb]	VBF cross sec. [pb]	Local signi. [σ]	Global signi. [σ]
SM f_{VBF}	800	0.16	0.057	3.2	1.7 ± 0.2
$f_{VBF} = 1$	650	0.0	0.16	3.8	2.6 ± 0.2
$f_{VBF} = 0$	950	0.19	0.0	2.6	0.4 ± 0.6
floating f_{VBF}	650	2.9×10^{-6}	0.16	3.8	2.4 ± 0.2

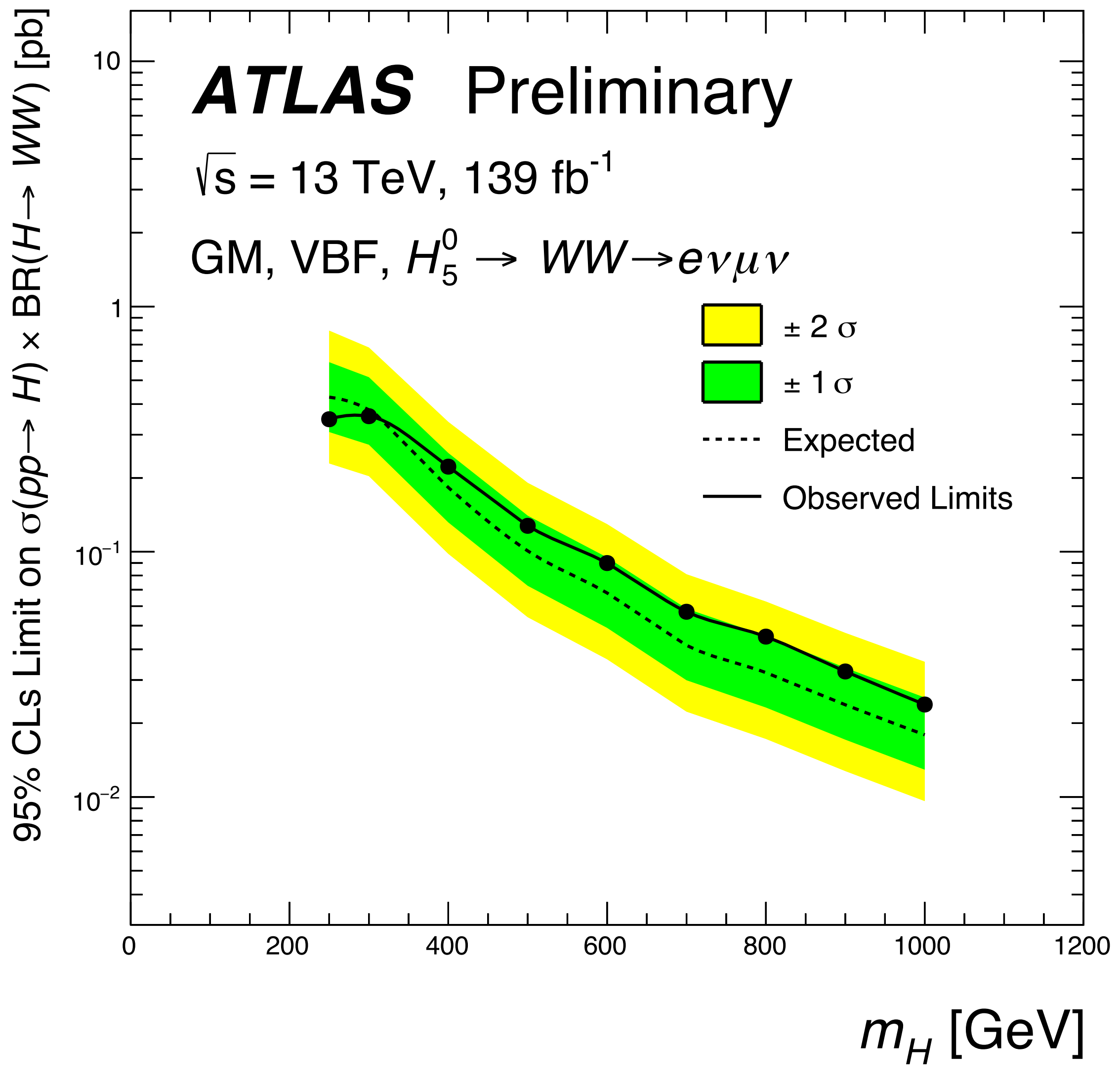
ATLAS-CONF-2022-066

$H \to W^+W^- \to e\nu\mu\nu$

- Production via *ggF* and *VBF* mechanisms treated separately
- Considers three scalars: NWA, Radion and GM scalar (VBF production only)
- Radions of mass lower than 1090 GeV are excluded







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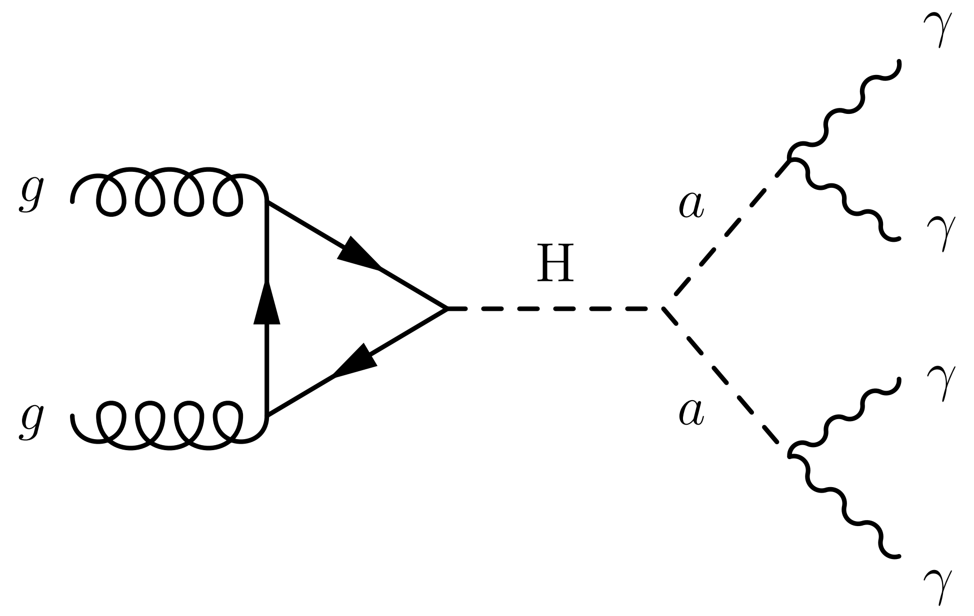
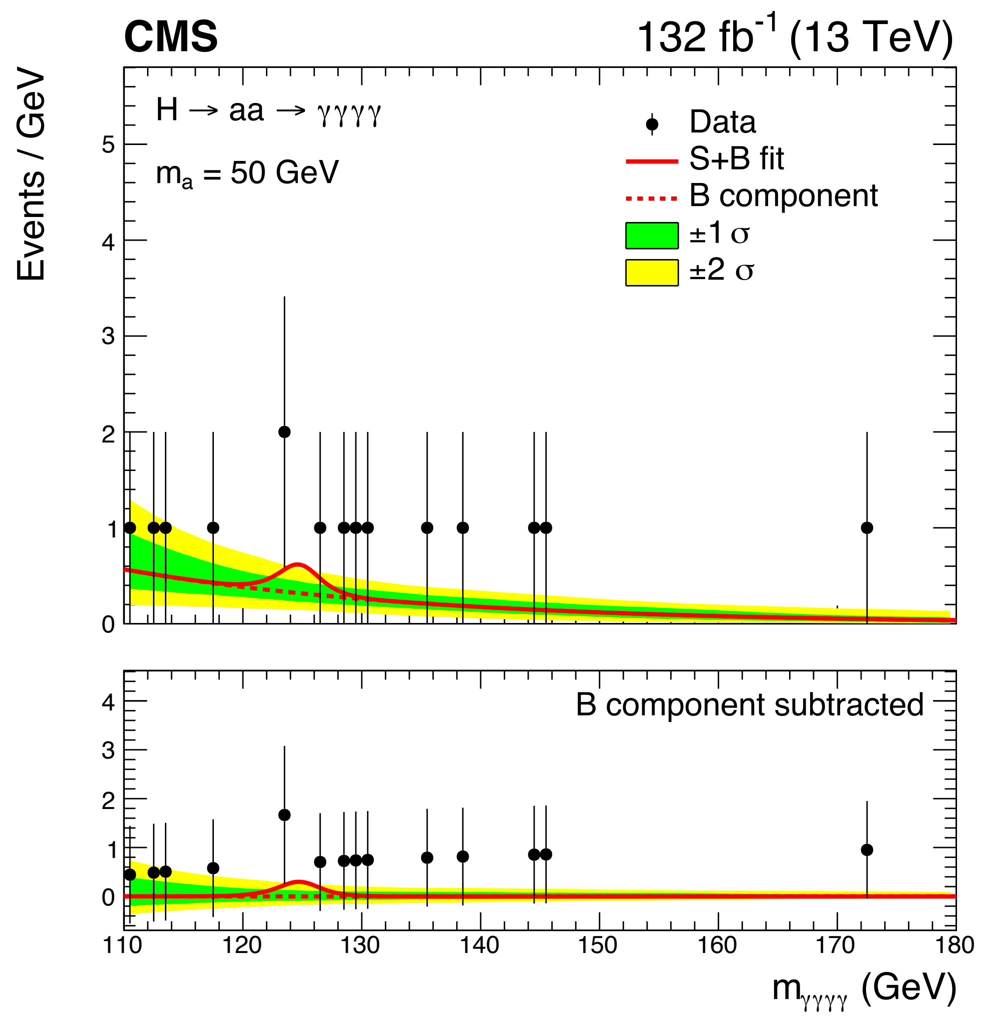
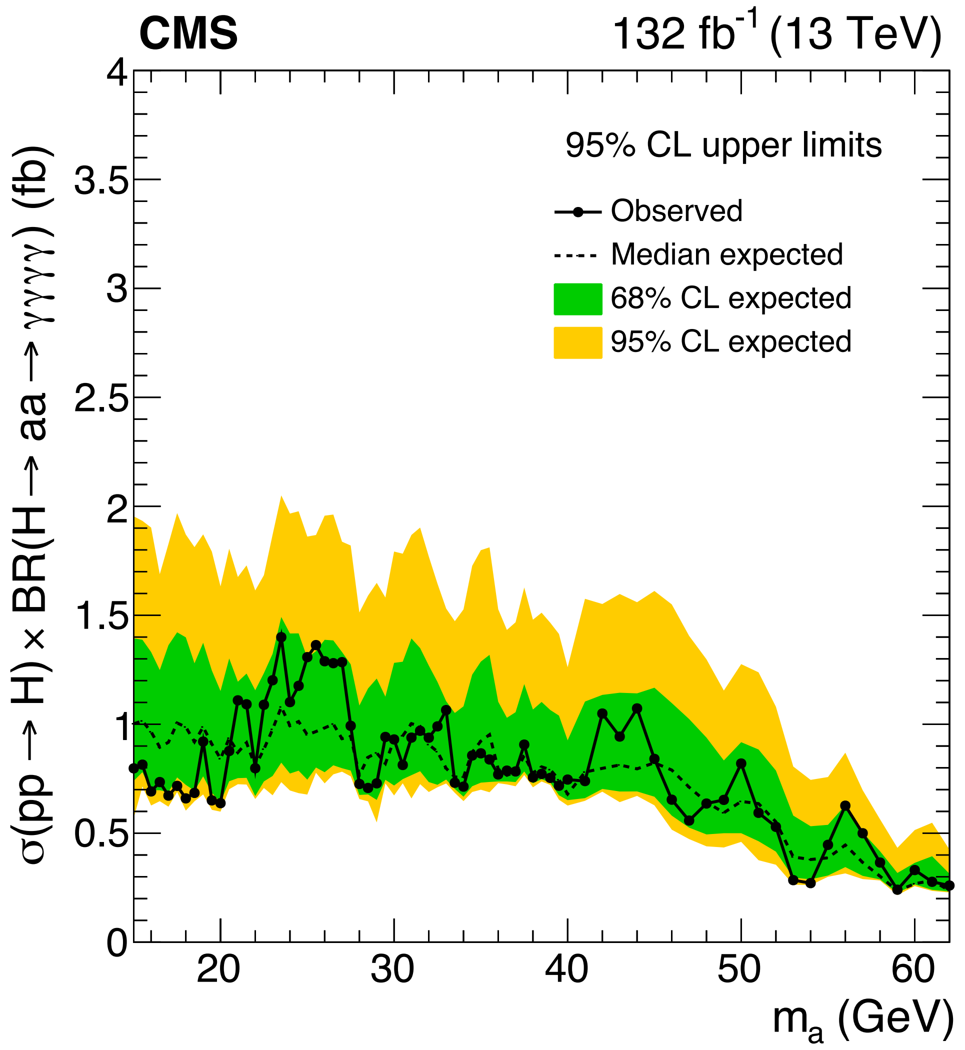
CMS $H \to AA \to \gamma\gamma\gamma\gamma$

Resolved arXiv:2208.01469 CMS-HIG-21-003

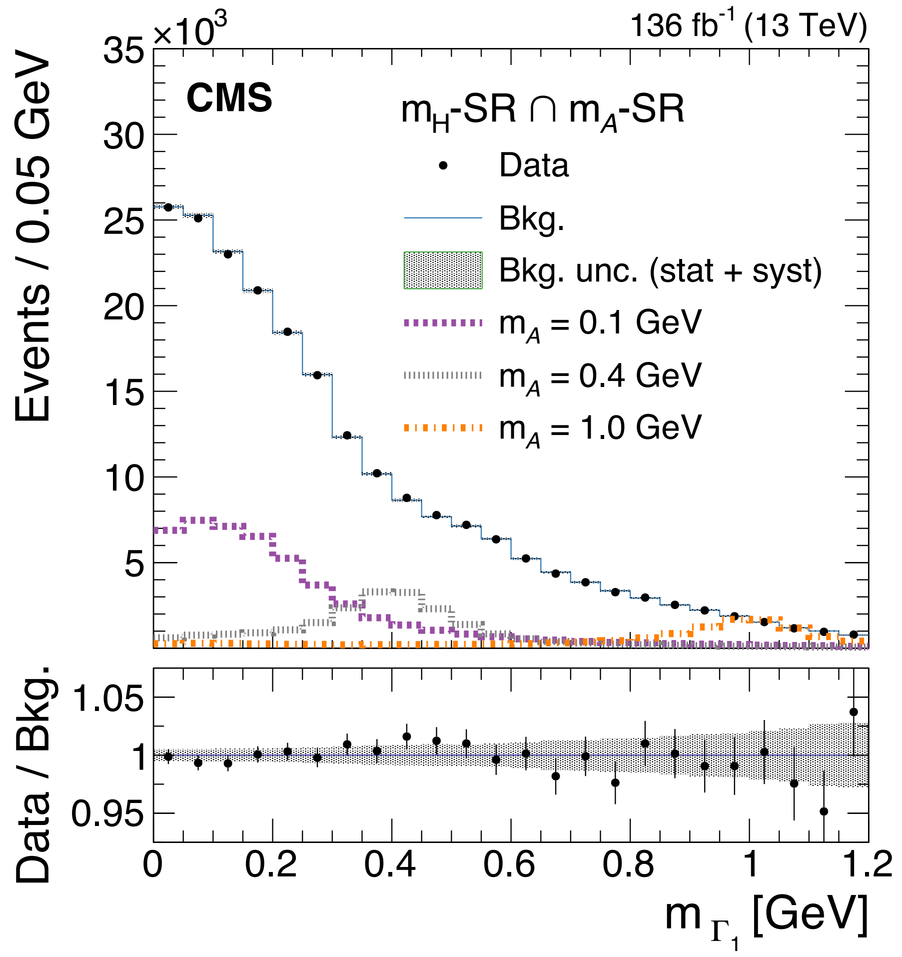
- Probes pseudoscalars with mass 15-62 GeV
- Well isolated photons in final state
- A parametrized signal model is built for each m_a hypothesis



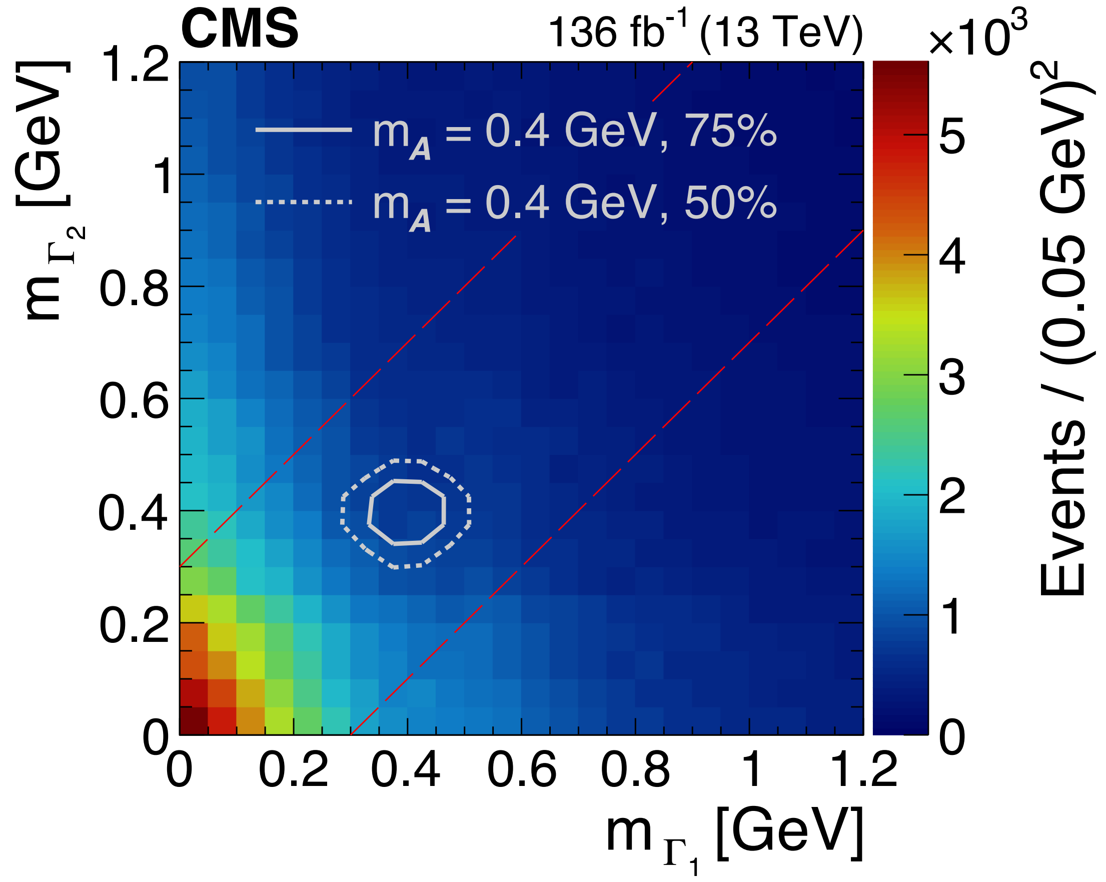


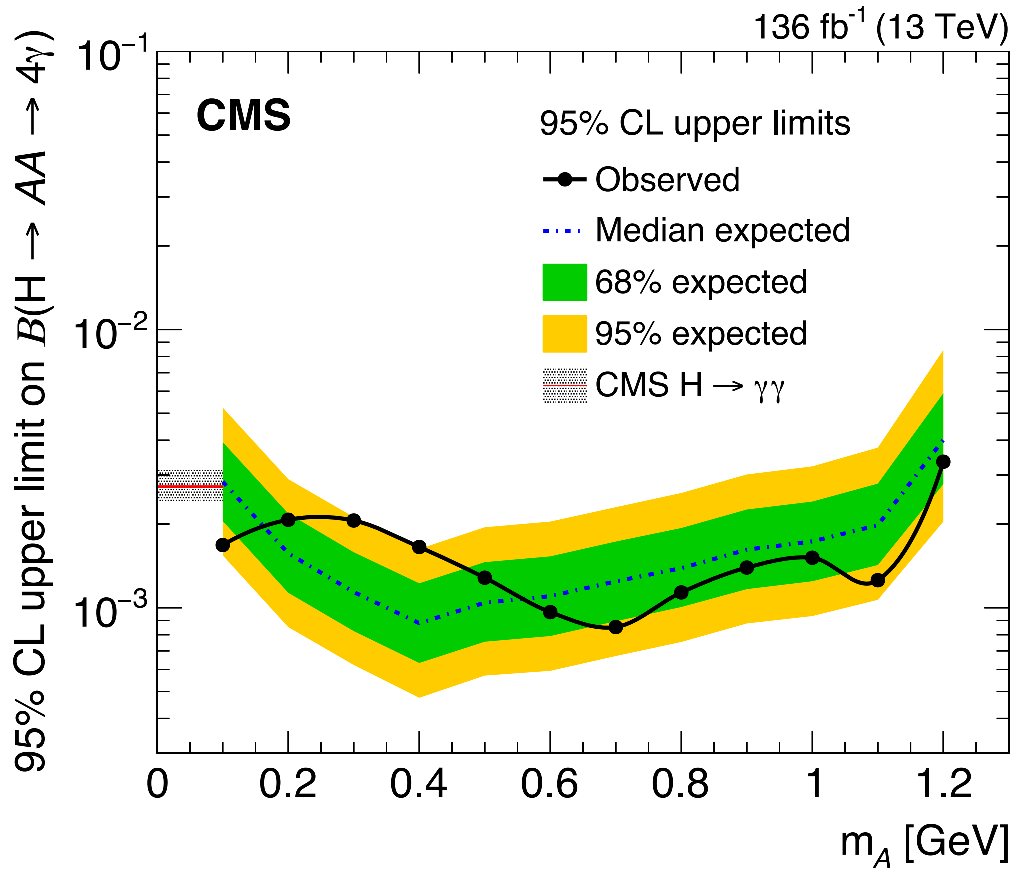


Merged arXiv:2209.06197 CMS-HIG-21-016



- $A \to \gamma\gamma$ relevant for $m_A < 1$ GeV
- Distance between photons lower than Moliere radius of ECAL material
  - The two photons are reconstructed as a single photon-like object
- Best constraints for this decay mode in studied m_A range

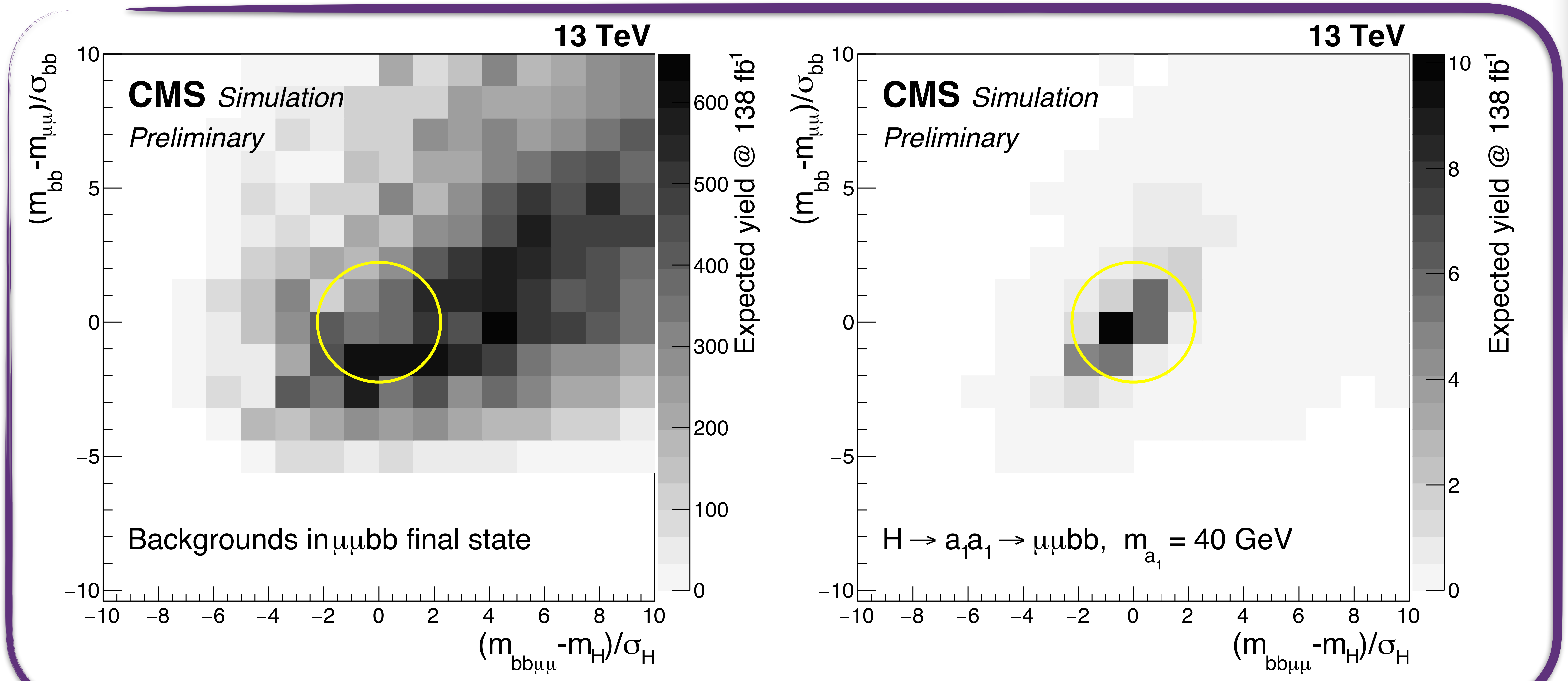


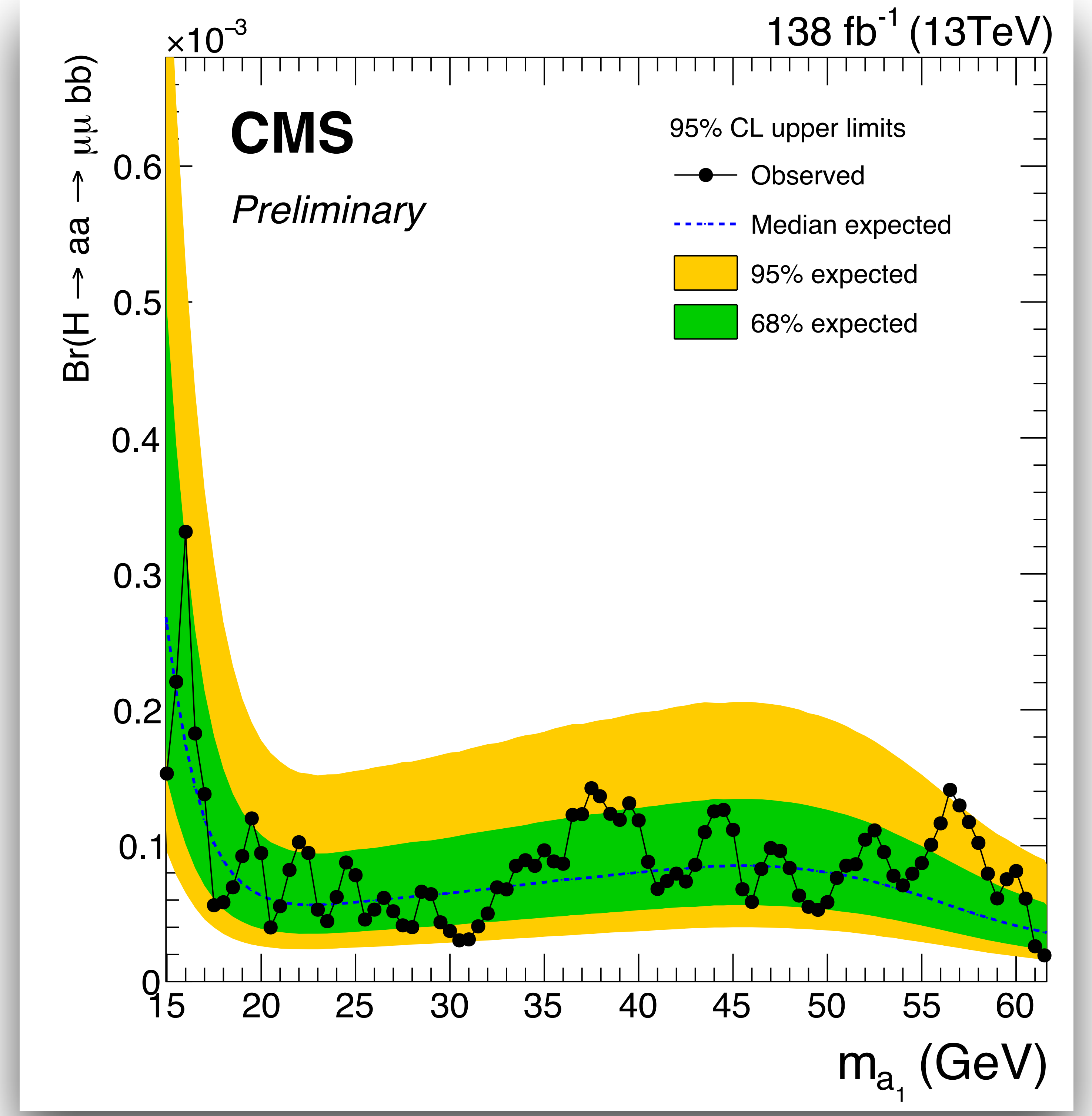


CMS $H \to aa \to \mu\mu bb$

CMS-HIG-21-021

- Covers range $15 < m_a < 62.5$ GeV
- Considers both *ggF* and *VBF* production mechanisms
- The compatibility of the *bb* and *μμ* systems with *a*, and of the *bbμμ* system with *H* is used to select the signal
- Events are categorized in terms of b-jet p_T, production mechanism and b-jet classification score

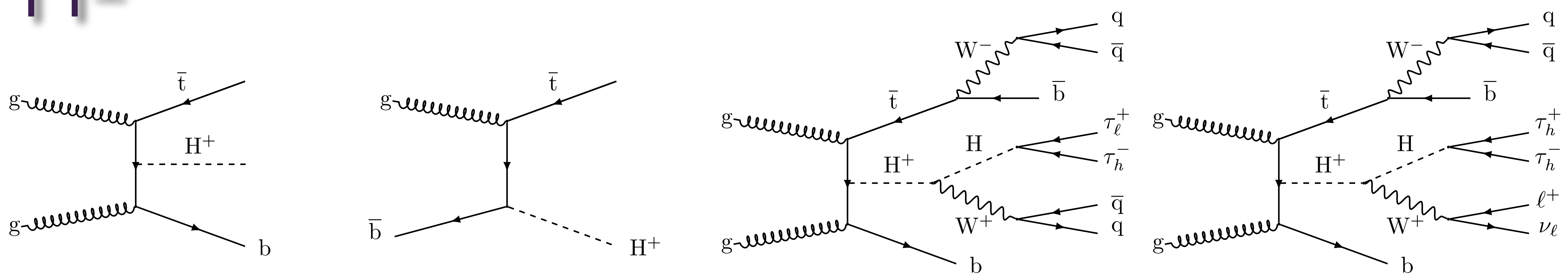




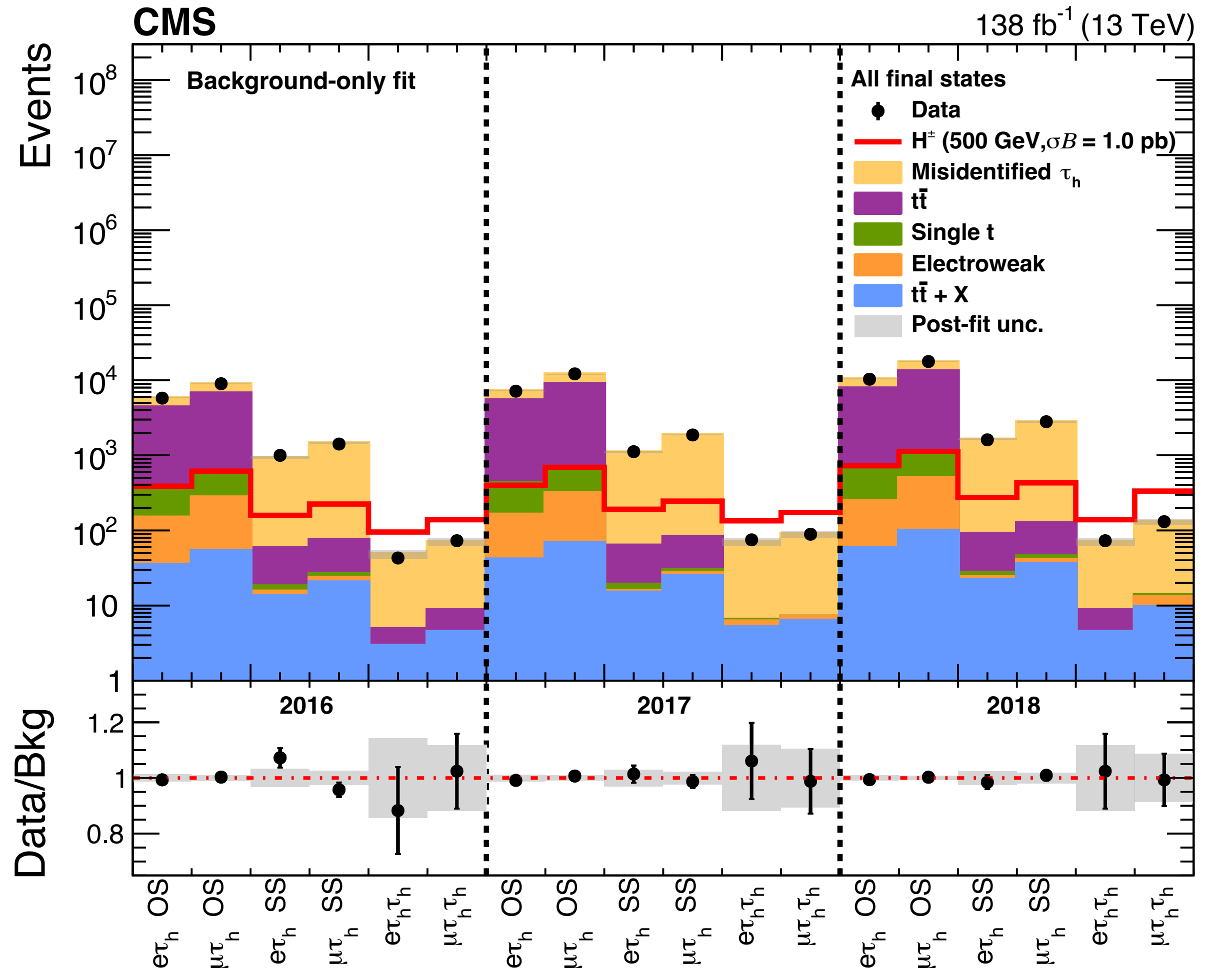
ATLAS and CMS charged Higgs

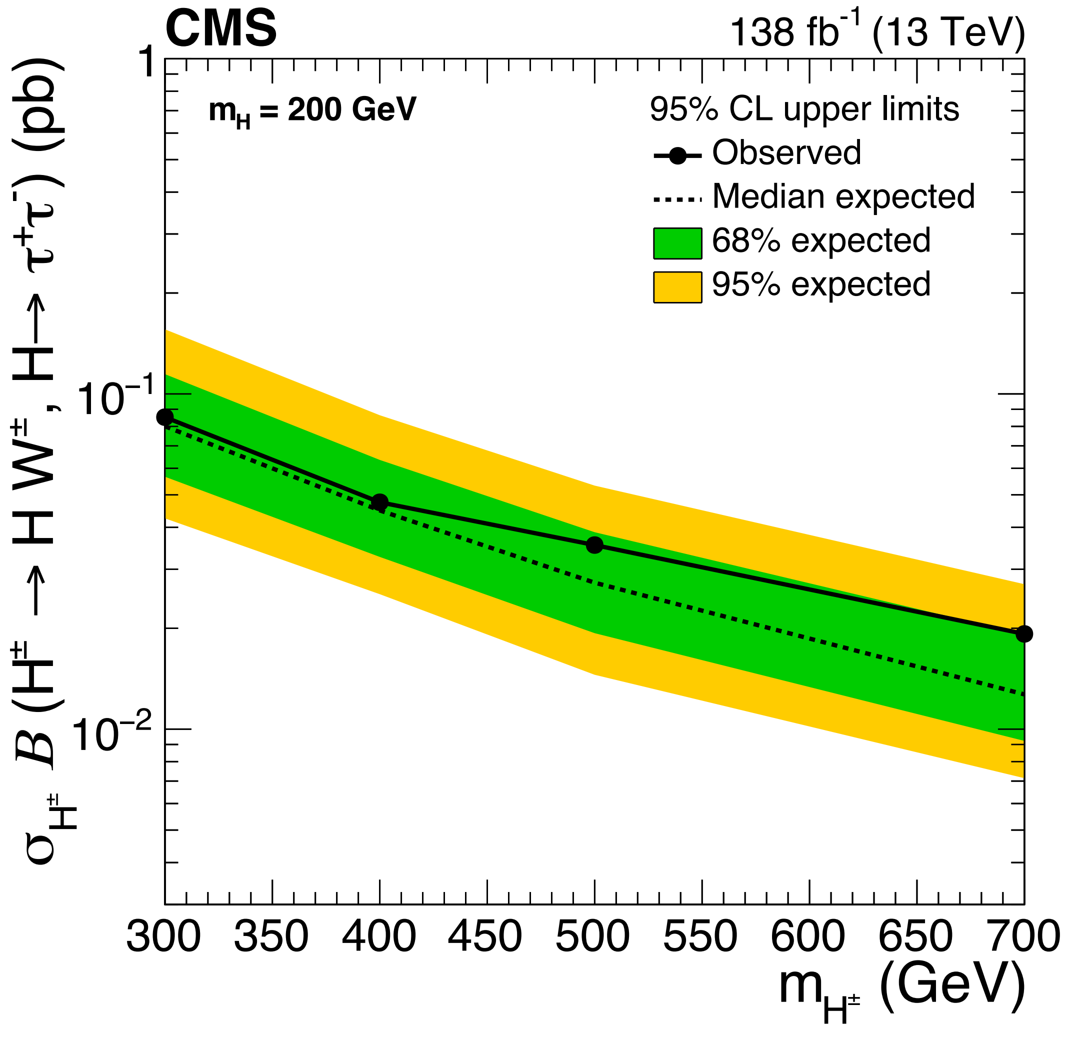
$H^{\pm}$

arXiv:2207.01046 CMS-HIG-21-010



- Focus on $H^{\pm}$ production in association with a Top quark that decays hadronically and m_H=200 GeV
- The mutually exclusive $e\tau_h$, $\mu\tau_h$, $e\tau_h\tau_h$ and $\mu\tau_h\tau_h$ final states are considered and the selection is optimized for each
- $l\tau_h\tau_h$ final states provide the largest sensitivity, and addition of $l\tau_h$ improves the result by 20-35%

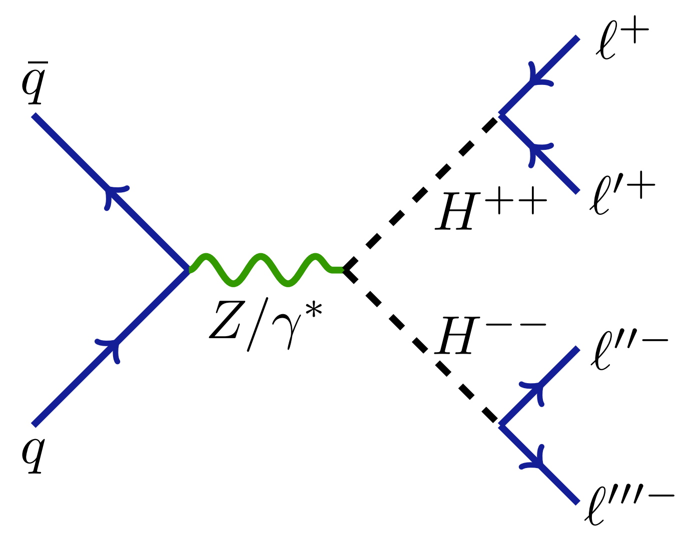


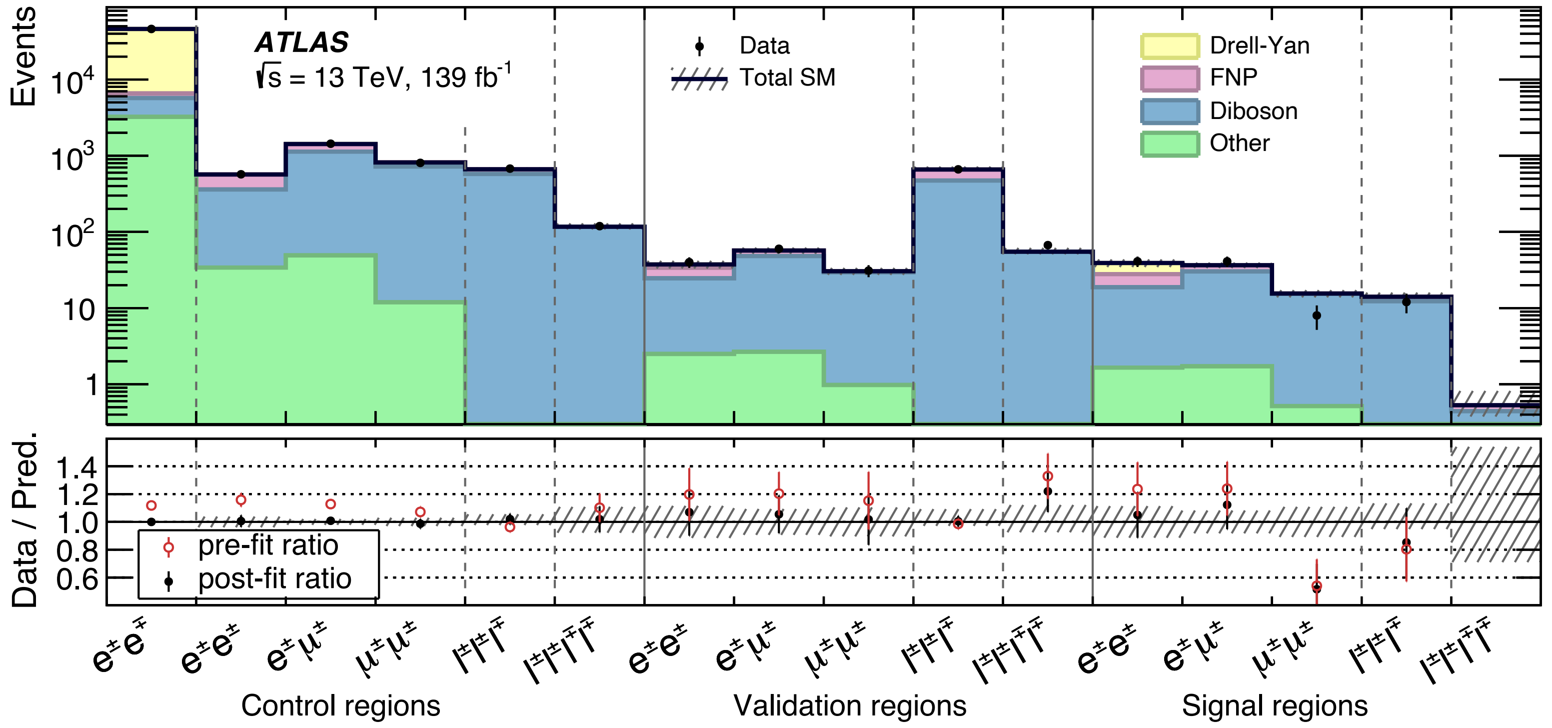


$H^{\pm\pm}$

arXiv:2211.07505 EXOT-2018-34

- Doubly charged Higgs exist in type-II seesaw models, LRSMs, Zee-Babu neutrino mass model, and others.
  - Using DY production, type-II seesaw and Zee-Babu models can be used for



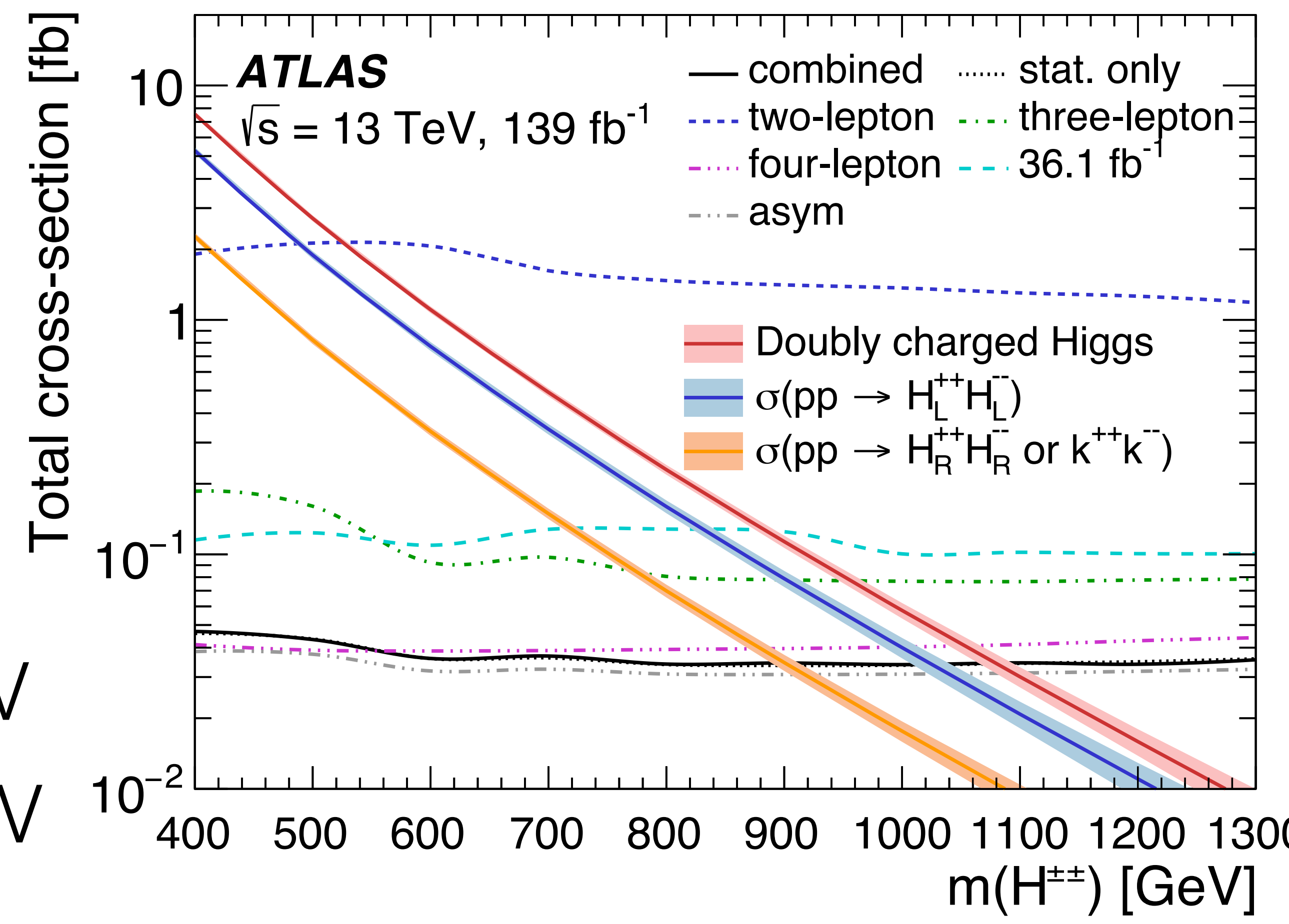


- Analysis focuses on decays to a pair of leptons of the same charge assuming that all leptonic final states are equally possible

- Shape analysis using $m(l^{\pm}, l^{\pm})_{lead}$ is performed for 2- and 3-lepton category
- 4-lepton category as single bin fit

Observed (expected) limits

- LRMSs: 1080 (1065^{+30}_{-50}) GeV
- Zee-Babu: 900 (800^{+30}_{-40}) GeV

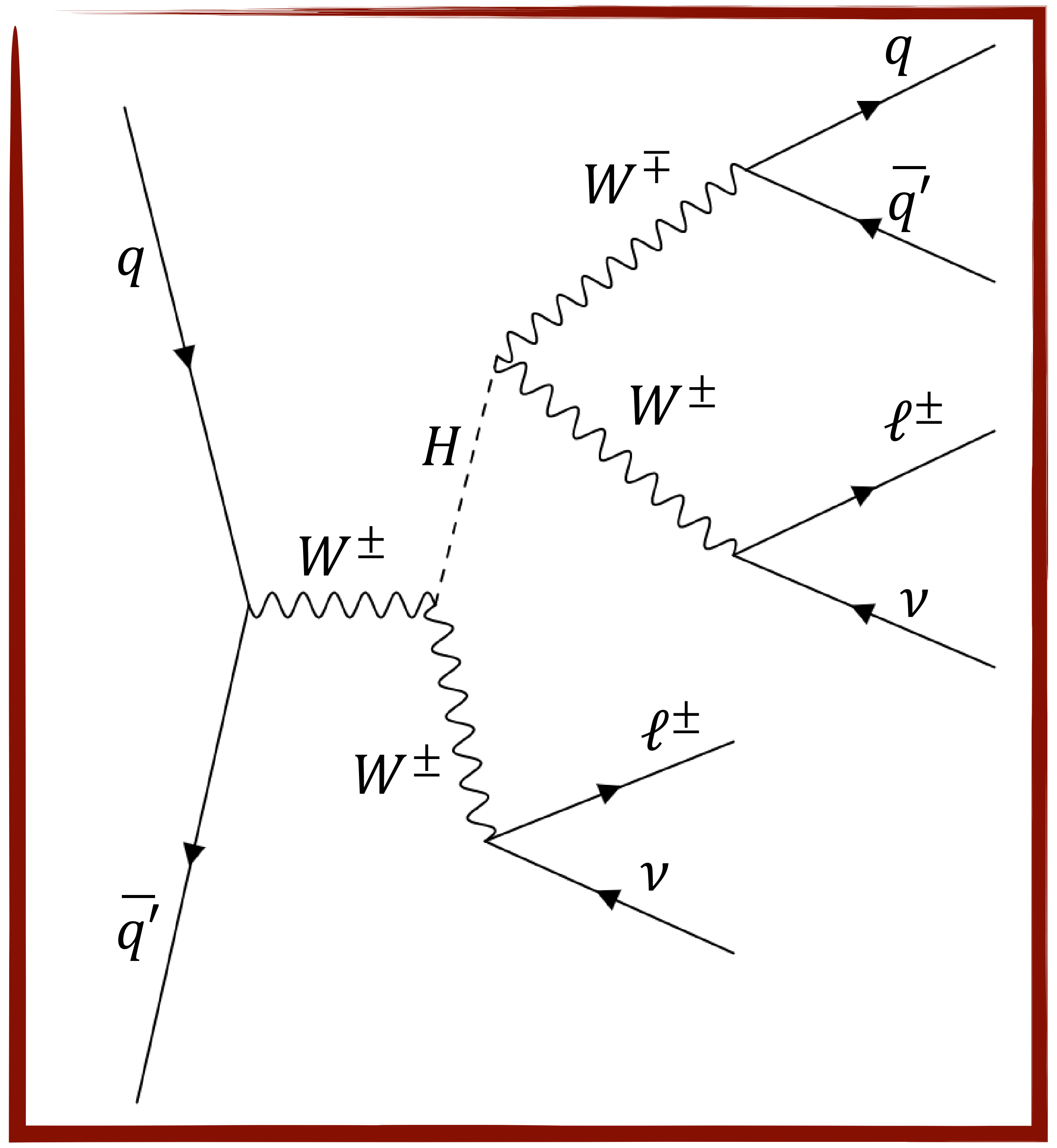


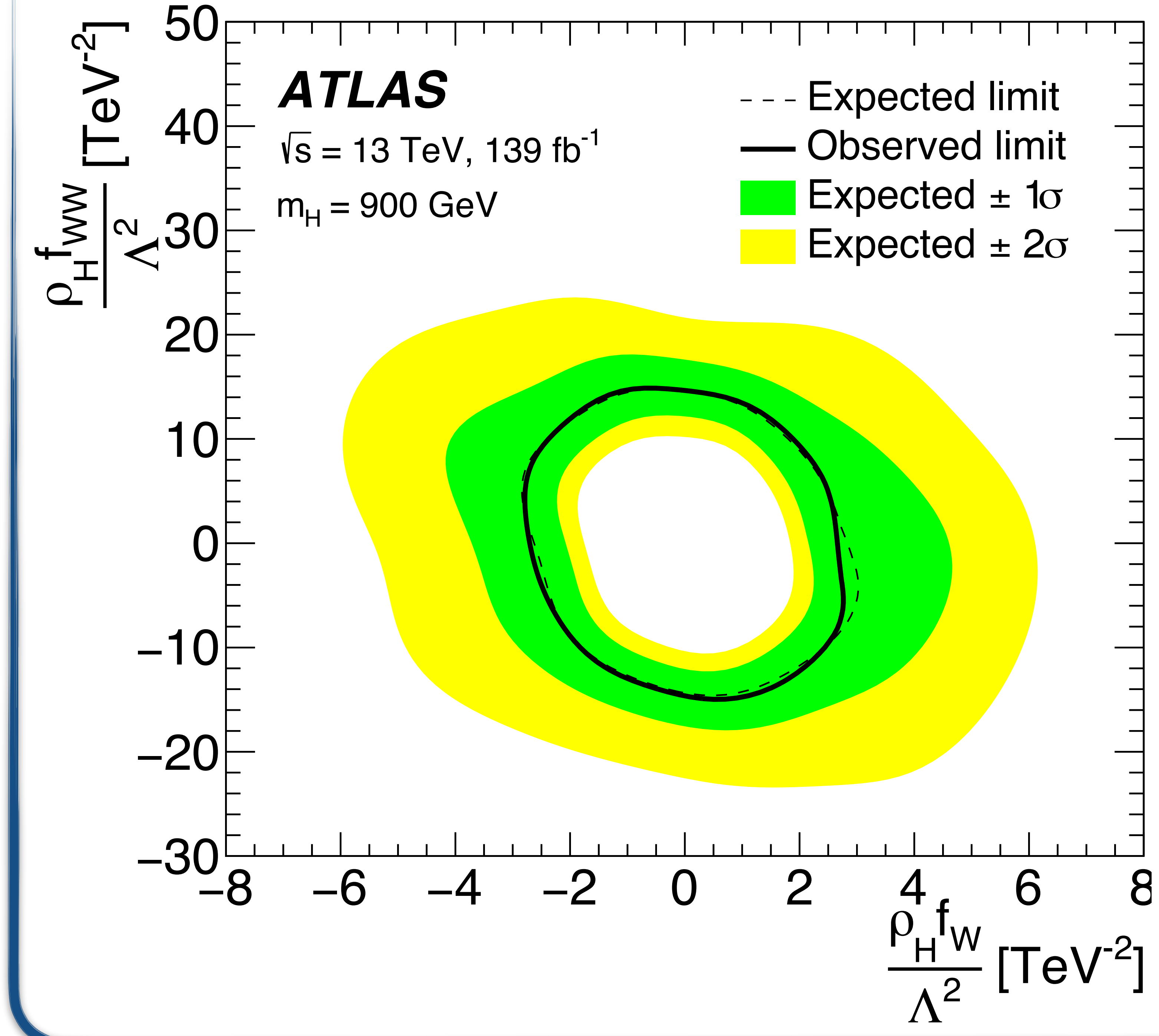
ATLAS heavy Higgs to bosons

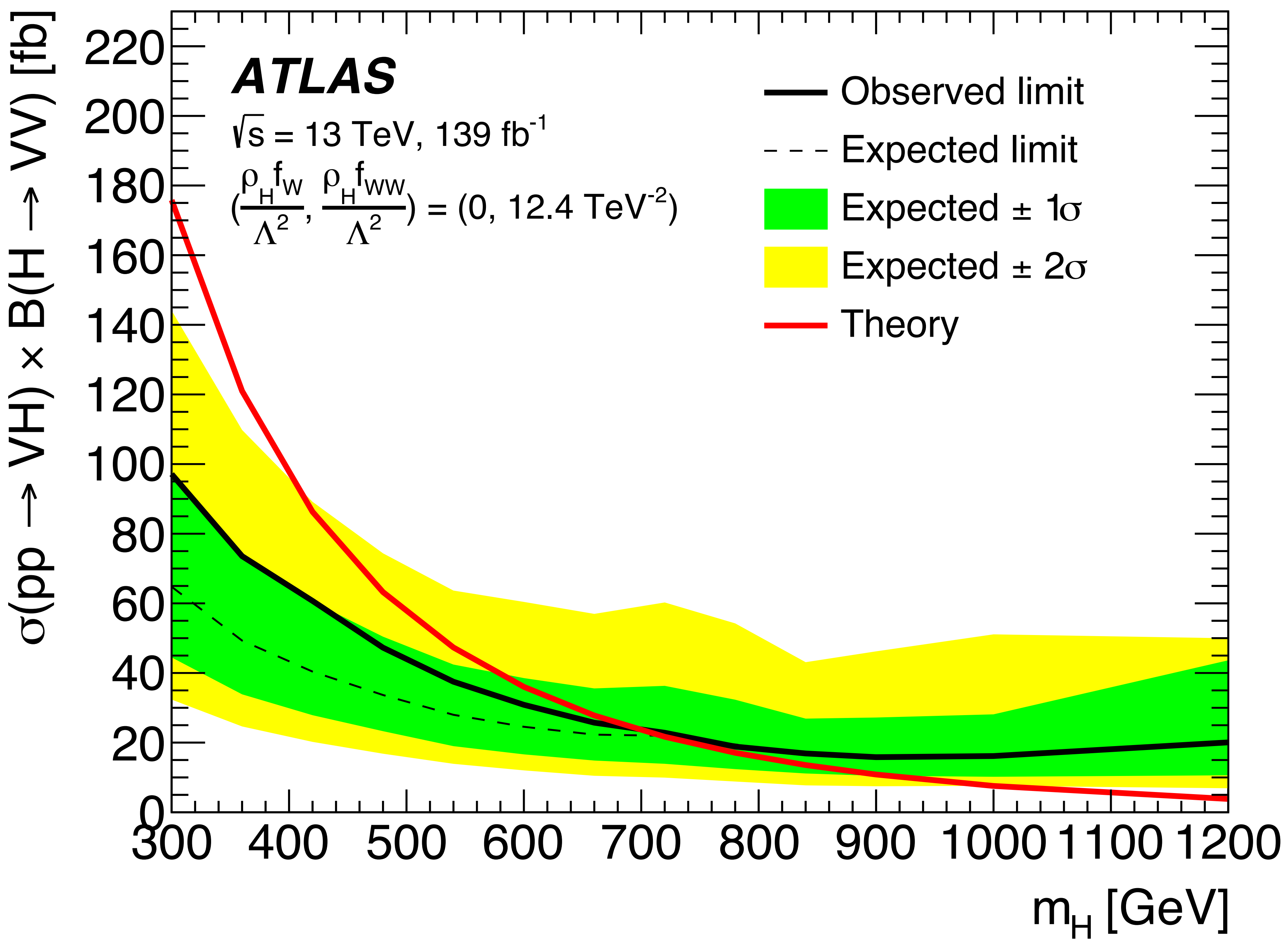
arXiv:2211.02617 HDBS-2019-16

- Generic search in the $W^\pm H \to W^\pm W^\pm W^\mp \to l^\pm \nu l^\pm \nu jj$ final state with hadronic W decaying to resolved jets or a single large-R jet
- Lower SM background compared to other bosonic VH decay channels and sizeable $H \to WW$ BR yields highest sensitivity
- Production is described by an EFT Lagrangian that includes dimension-six operators with negligible $H \to Vh$ production

$$\mathcal{L}^{(4)}_{hWW} = \rho_h g m_W h W^\mu W_\mu,$$
$$\mathcal{L}^{(4)}_{hZZ} = \rho_h \frac{g m_W}{2c_W^2} h Z^\mu Z_\mu,$$
$$\mathcal{L}^{(4)}_{HWW} = \rho_H g m_W H W^\mu W_\mu,$$
$$\mathcal{L}^{(4)}_{HZZ} = \rho_H \frac{g m_W}{2c_W^2} H Z^\mu Z_\mu,$$
$$\mathcal{L}^{(6)}_{HWW} = \rho_H g m_W \frac{f_W}{2\Lambda^2}\left(W^+_{\mu\nu} W^{-\mu}\partial^\nu H + h.c.\right) - \rho_H g m_W \frac{f_{WW}}{\Lambda^2} W^+_{\mu\nu} W^{-\mu\nu} H,$$
$$\mathcal{L}^{(6)}_{HZZ} = \rho_H g m_W \frac{c_W^2 f_W + s_W^2 f_B}{2c_W^2\Lambda^2} Z_{\mu\nu} Z^\mu \partial^\nu H - \rho_H g m_W \frac{c_W^4 f_{WW} + s_W^4 f_{BB}}{2c_W^2\Lambda^2} Z_{\mu\nu} Z^{\mu\nu} H$$



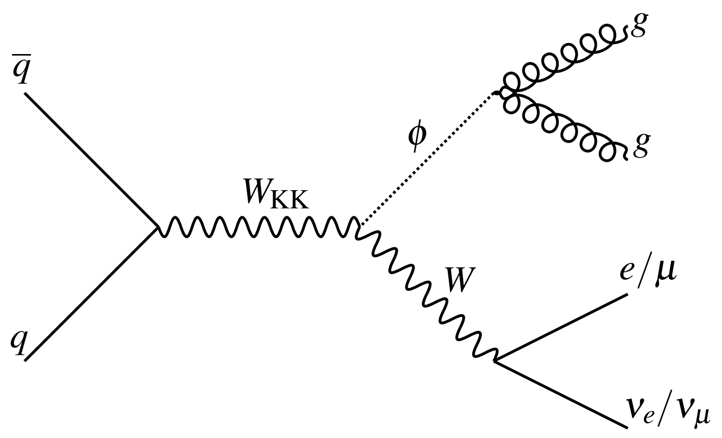




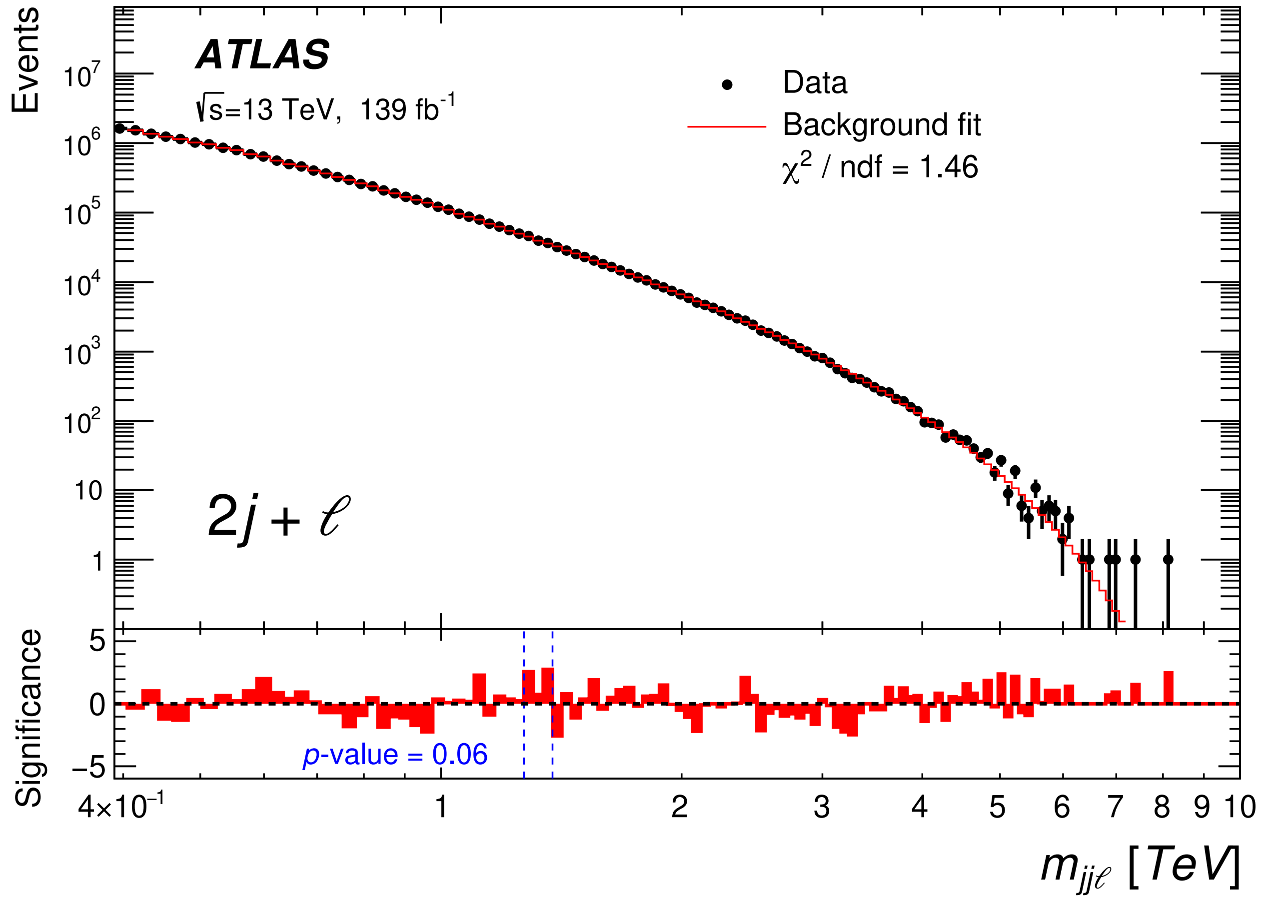
ATLAS searches involving production of vector bosons

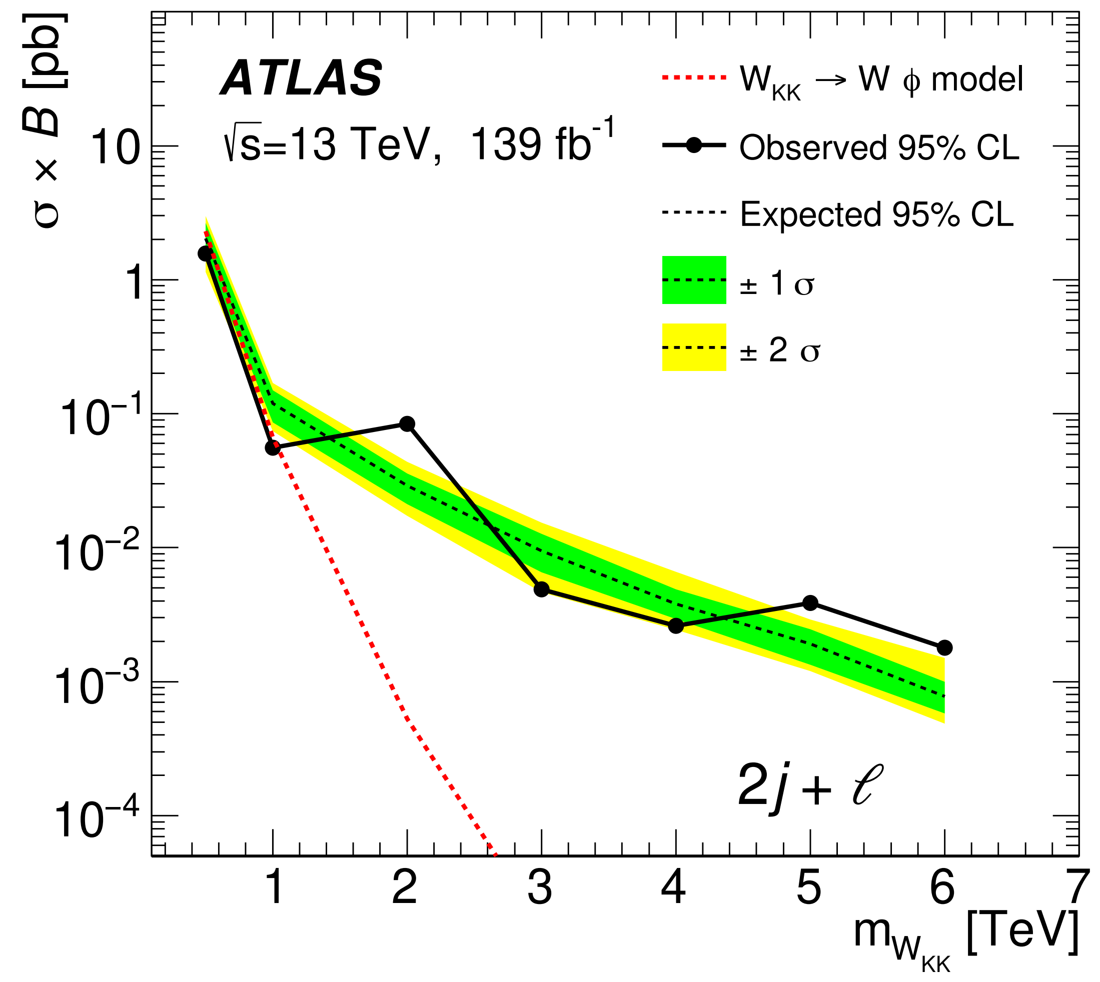
arXiv:2211.08945 EXOT-2020-15

Search for new physics in multi-body invariant masses

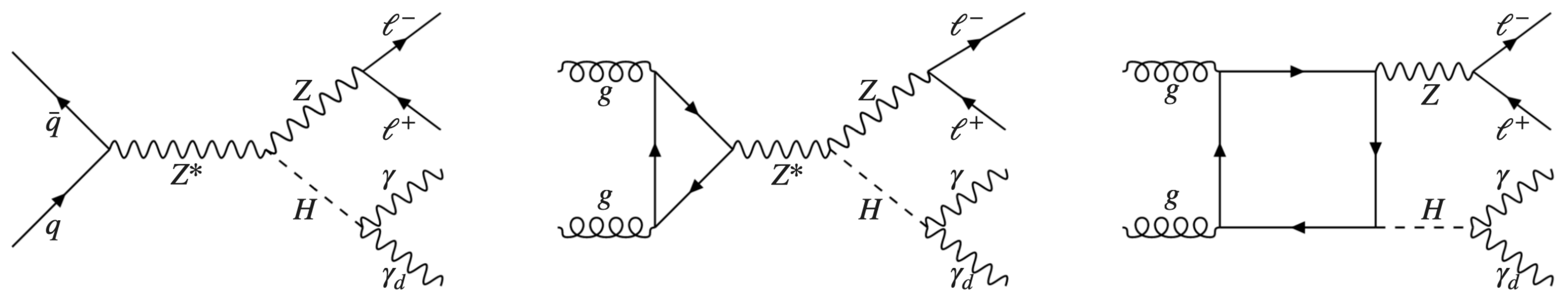


- Production of a Kaluza-Klein excitation of a gauge boson decaying into a radion and a SM W boson
- Assumes m_{Wkk} - m_{ϕ} = 250 GeV to minimize signal peak width
- Larger mass differences result in larger neutrino p_T affecting m_{Wkk} reconstruction
- Three-body invariant mass distribution is tested for deviations in smoothly falling background
- Invariant masses m_{jjl}, m_{jjll}, m_{jbl}, m_{bbl}, tested between 0.4 and 8 TeV
- Largest deviation observed at m_{jjl}=1.3 TeV with local significance 3.5σ and global significance 1.5σ



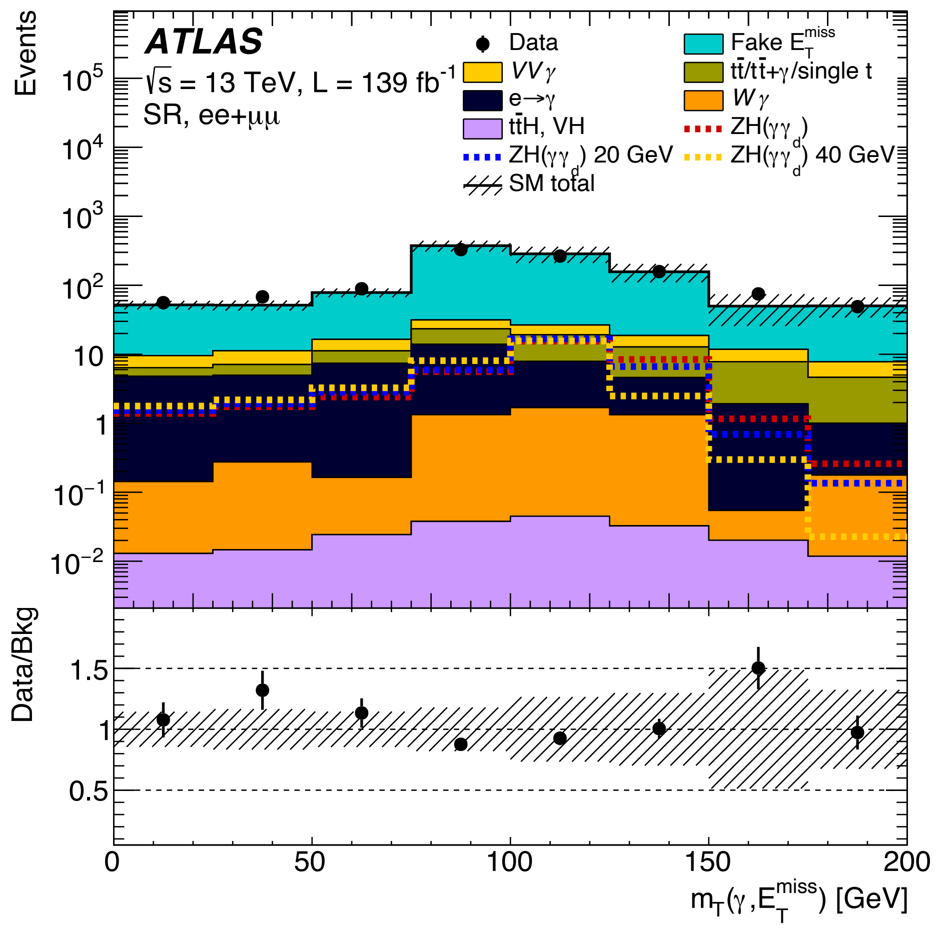


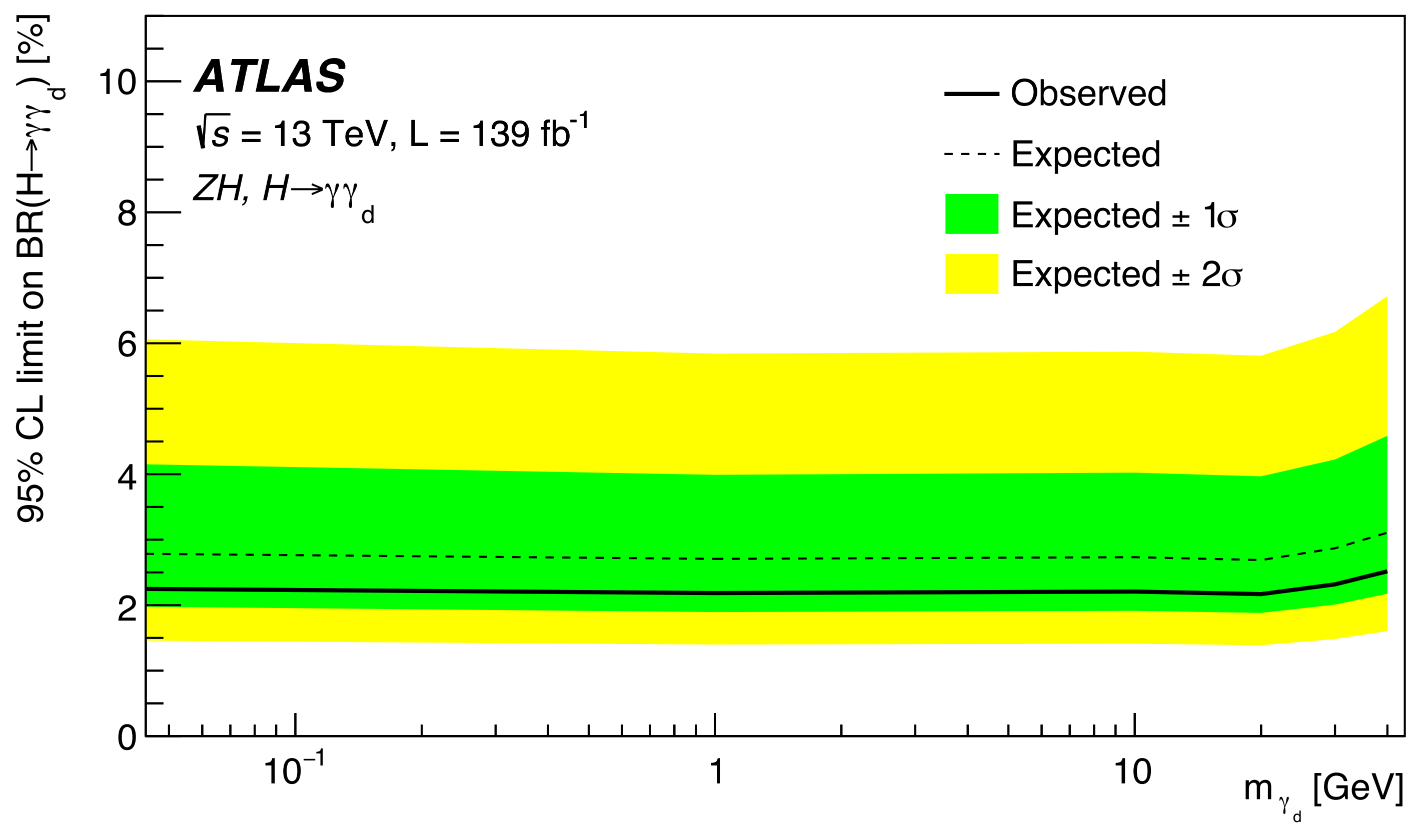
arXiv:2212.09649 HDBS-2019-13



Search for dark photons in ZH production in dilepton final state

- Coupling of m_H=125 GeV Higgs to dark photon with mass in range 0-40 GeV is studied
- Leptons are used as a handle for triggering on the signal events
- Transverse mass of γ-γ_D (γ-E^T_{miss}) system used as a variable of interest in ML-based classification
- Observed upper limits on BR(H→ $\gamma\gamma_D$) range from 2.17% to 2.52%





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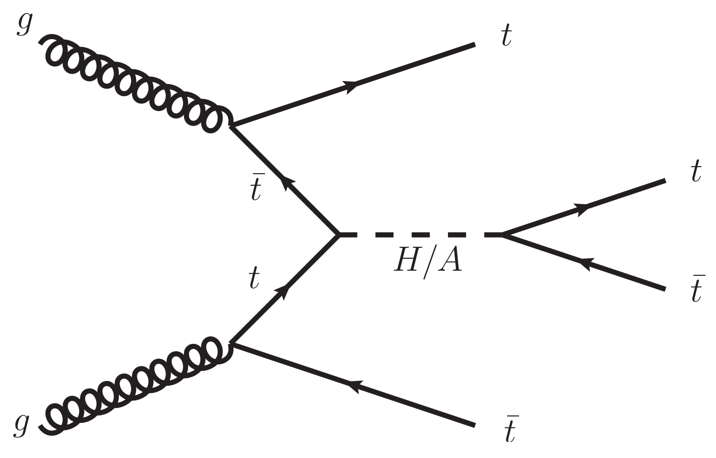
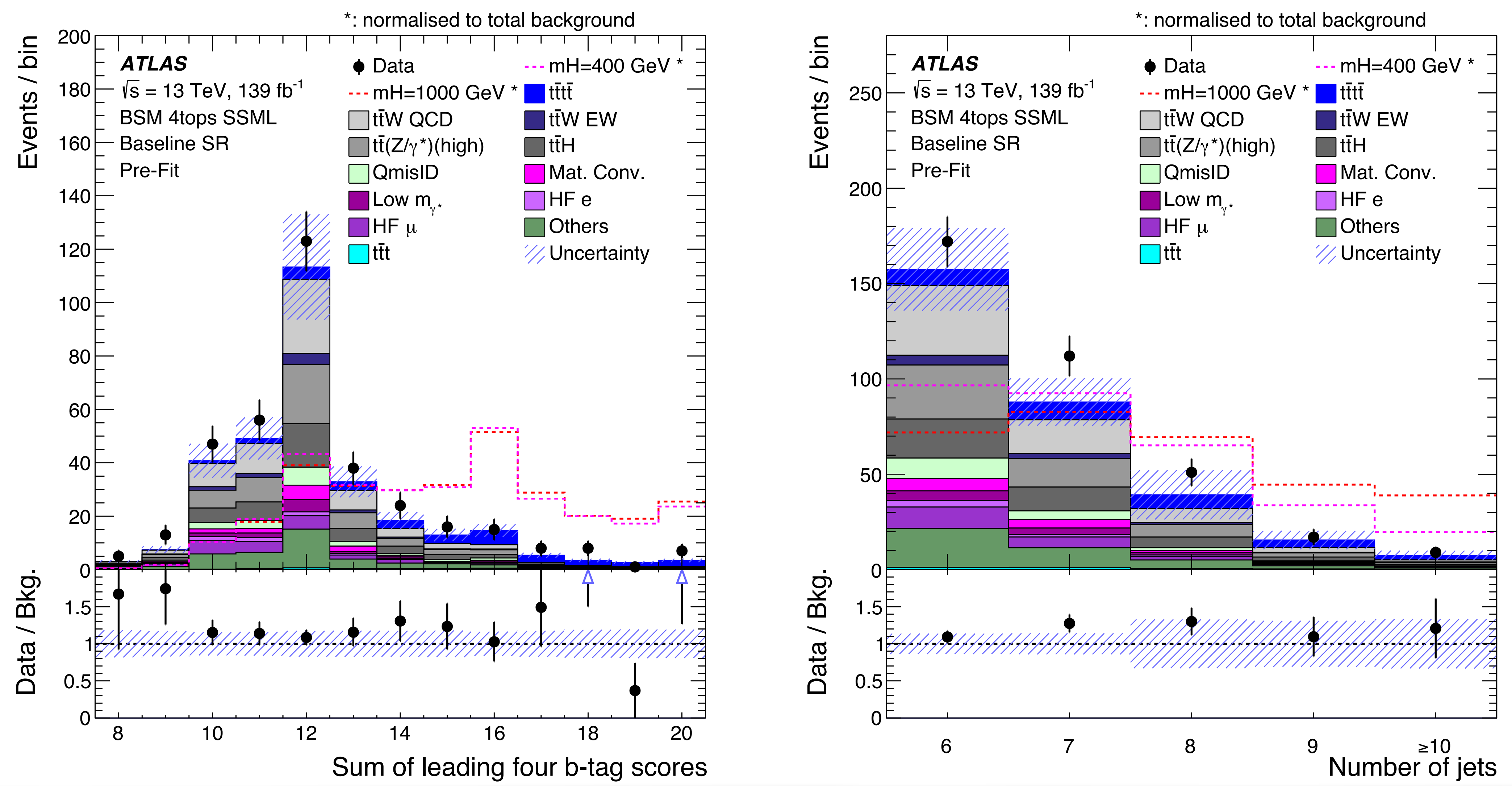
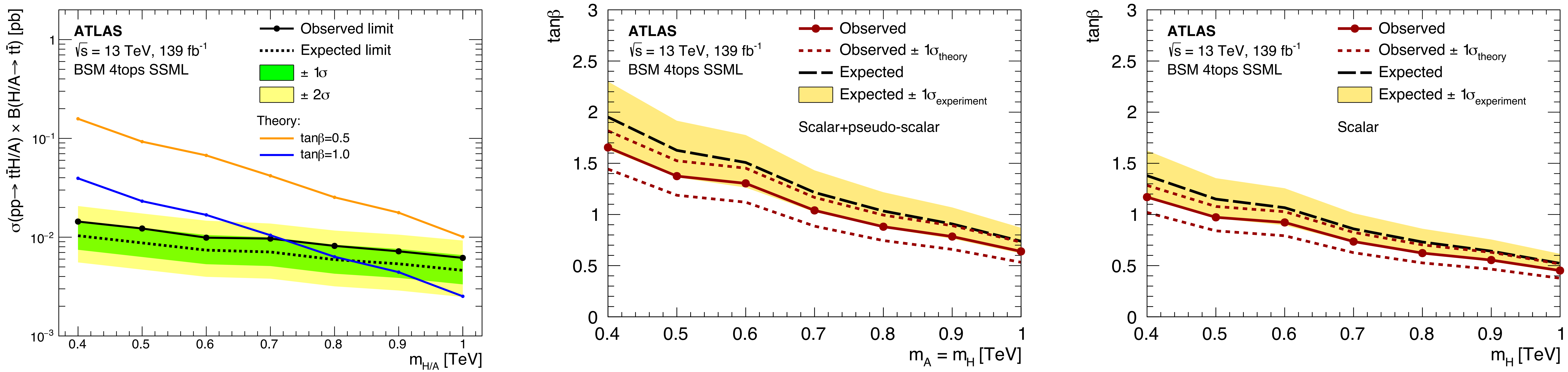
ATLAS search for *ttH/A* to *tttt* in multilepton final state

arXiv:2211.01136 EXOT-2019-26



- Search for heavy *H/A* with $m_{H/A} > 2m_t$
- Destructive interference effect in gg->A/H->ttbar can be avoided by looking at ttH/A production
- Focuses on events with two leptons of same charge or at least three leptons
- b-tagging provides important separation power for the MVA



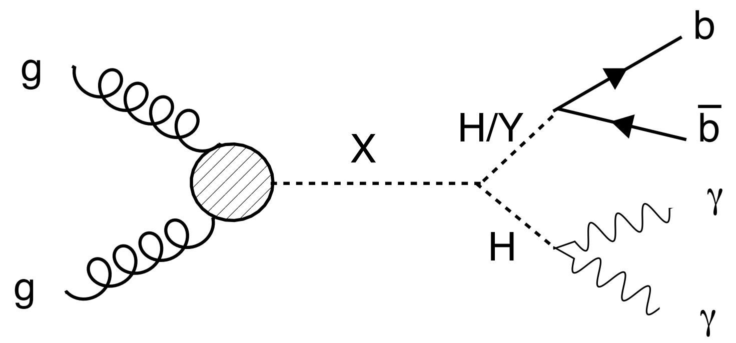


Higgs pair production

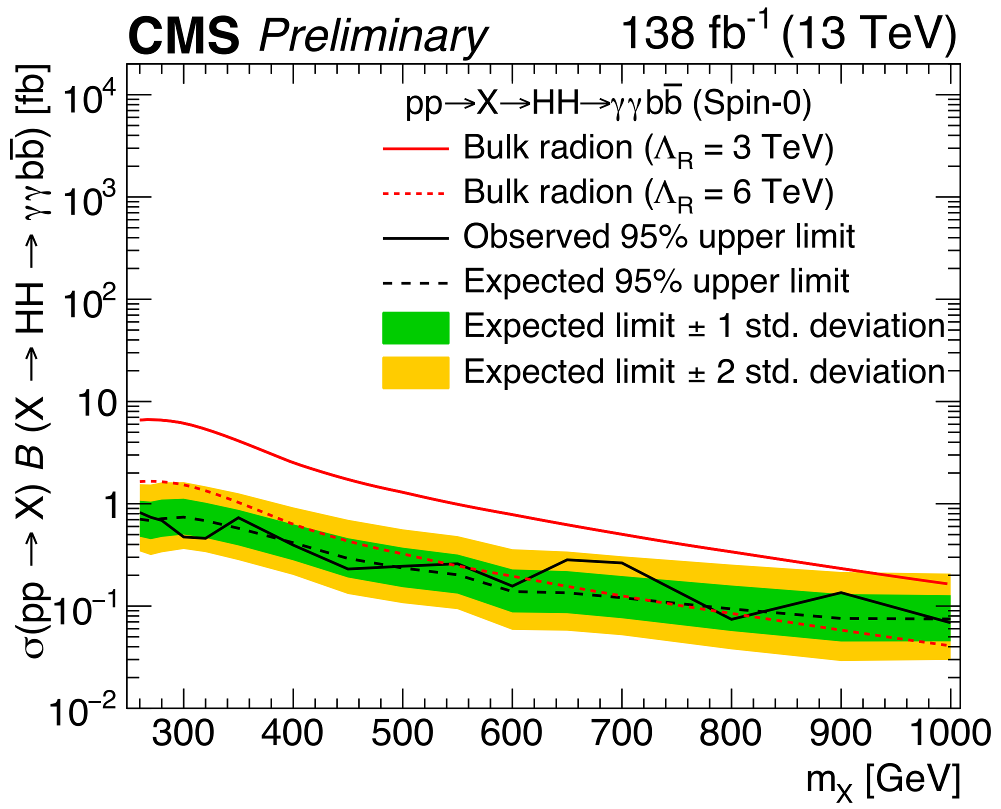
CMS searches for $X \to YH$

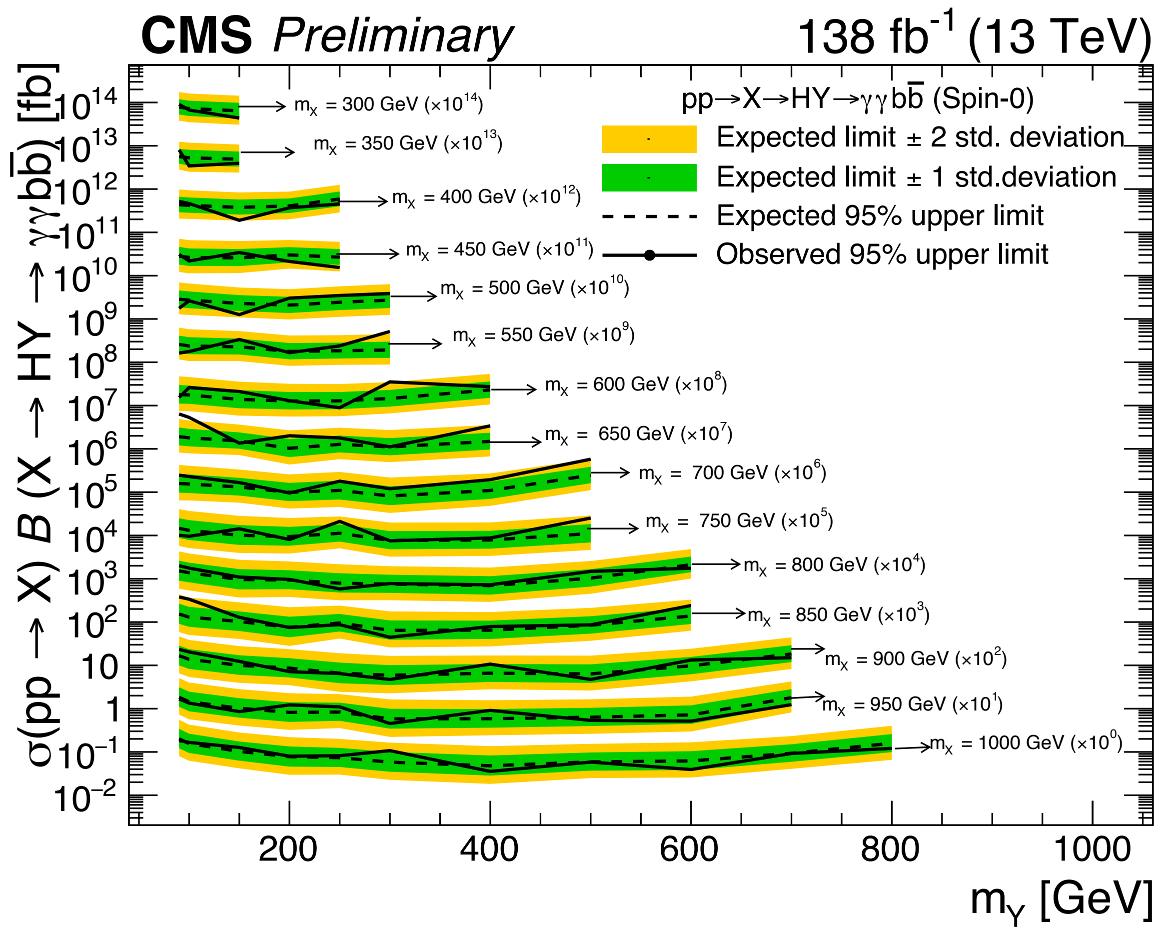
CMS-PAS-HIG-21-011

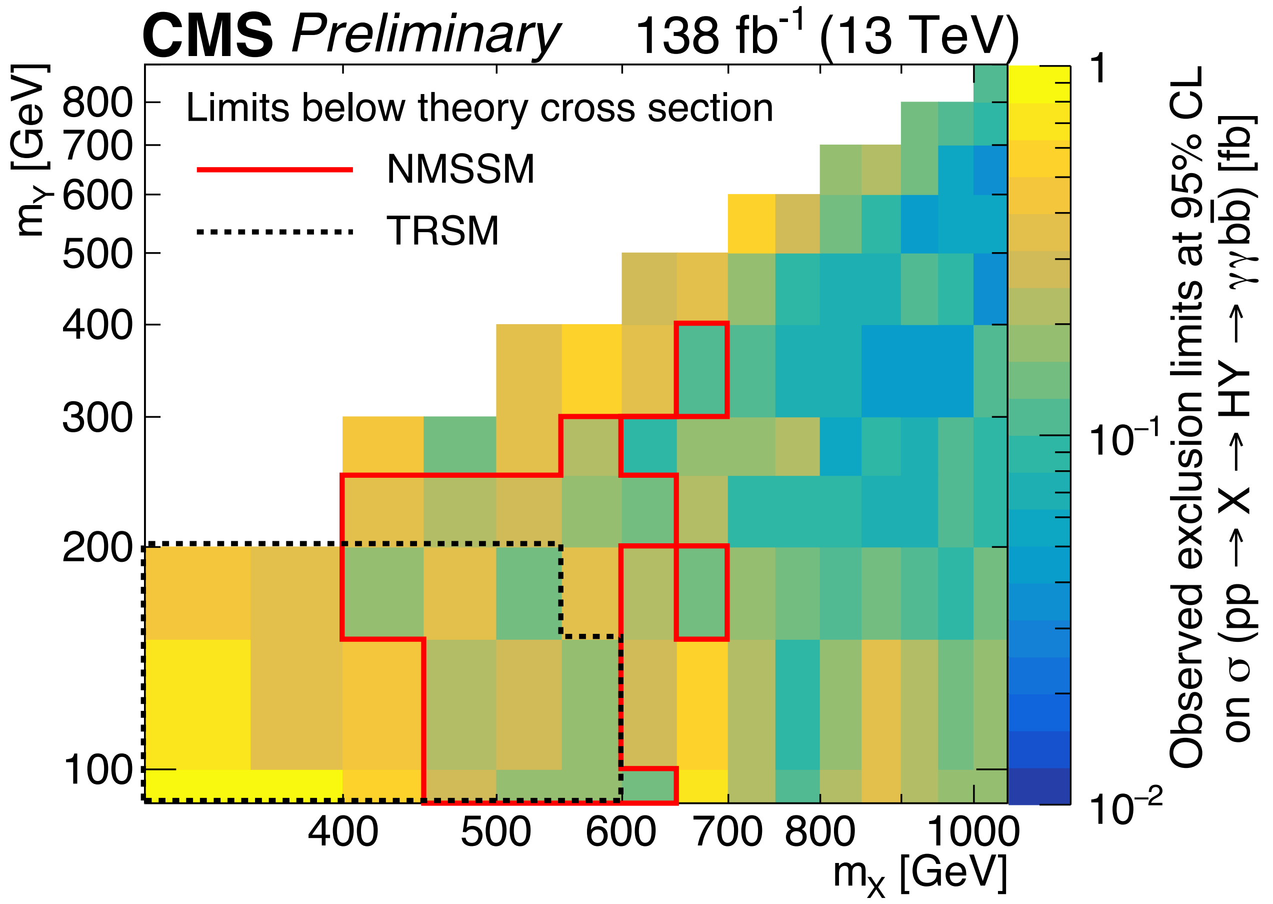
$X \to (H/Y)H \to bb\gamma\gamma$



- Model independent analysis using narrow with approximation for X
  - Interpreted in NMSSM and TRSM
- Resonance reconstructed from invariant mass of the two photons and the two b-jets
- Two-dimensional fit in m_{jj}-$m_{\gamma\gamma}$ plane



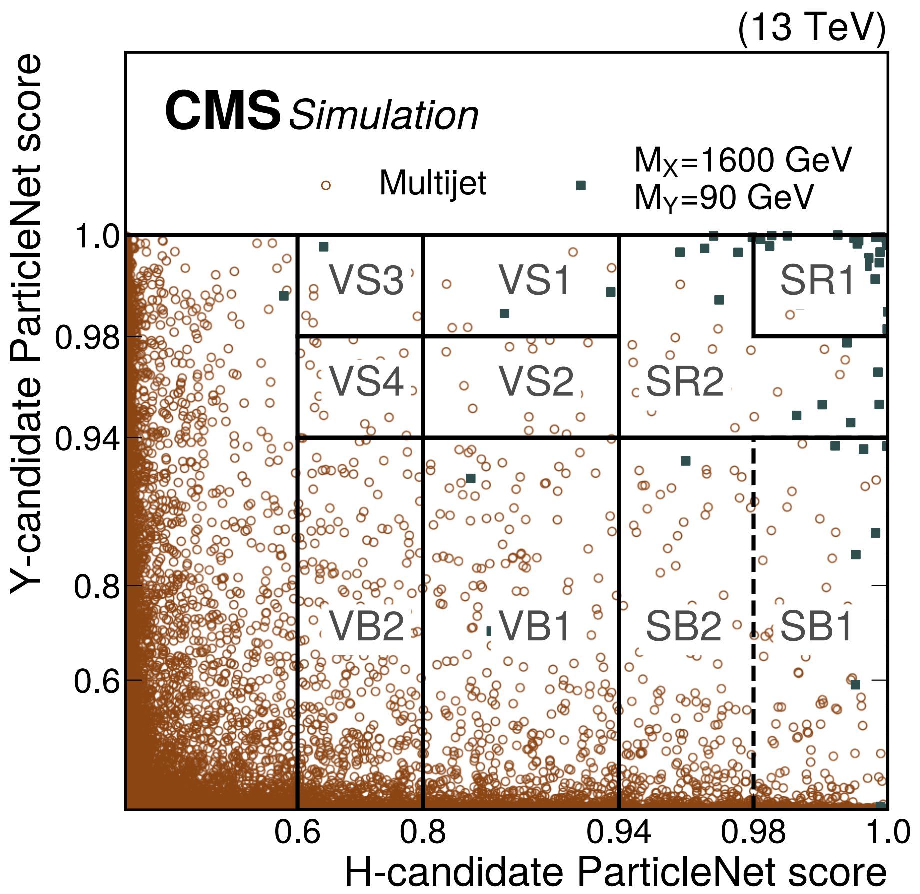


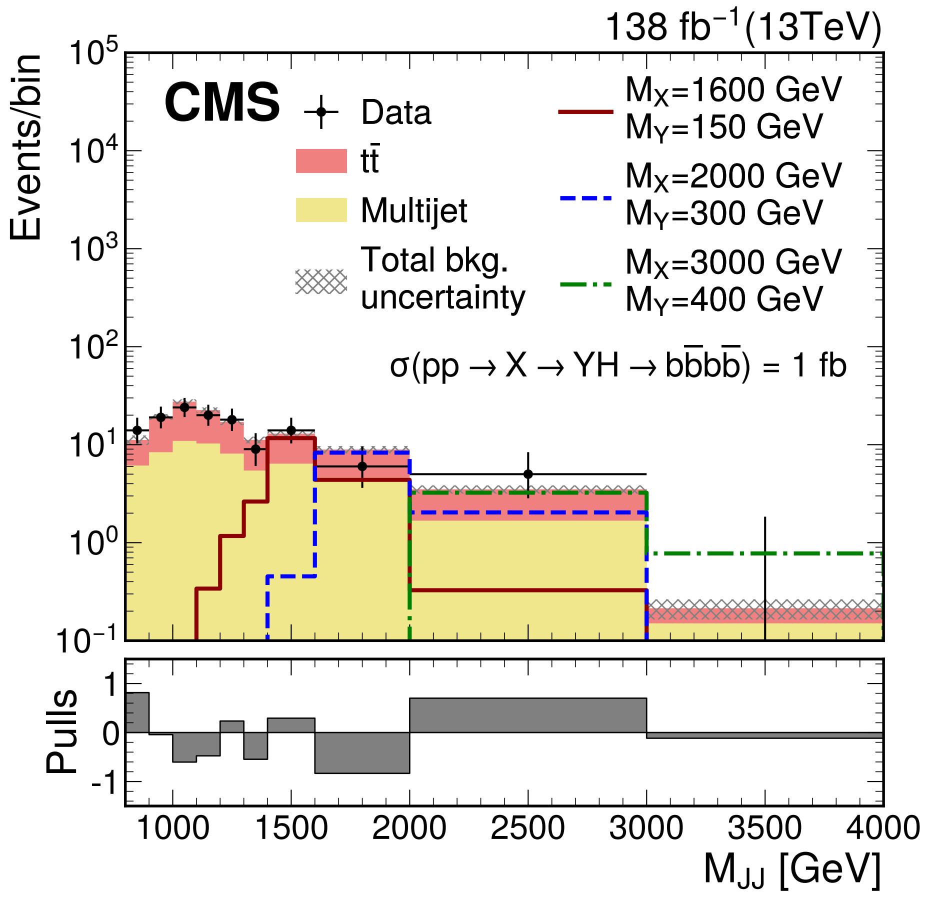


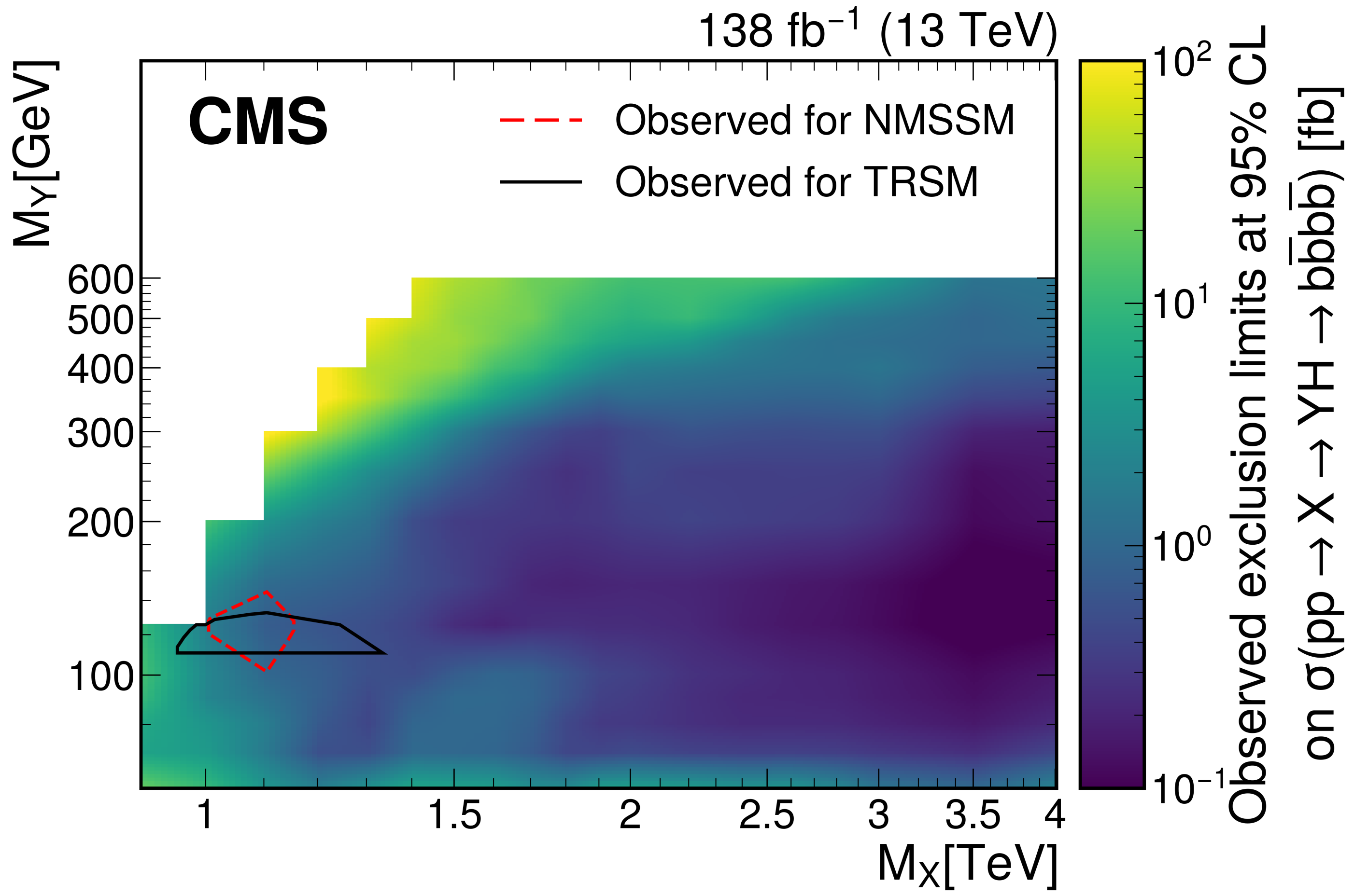
arXiv:2204.12413 CMS-B2G-21-003

$X \to YH \to bbbb$

- NMSSM and TRSM allow for such process
- Studies fully boosted topology with $Y \to bb$ and $H \to bb$ contained in single large-R jet
  - $M_X > M_Y + M_H$
  - $M_X >> M_Y, M_H$
  - $60 < M_Y < 600$ GeV
- Makes use of ML-based *ParticleNet* algorithm to identify boosted decays against background







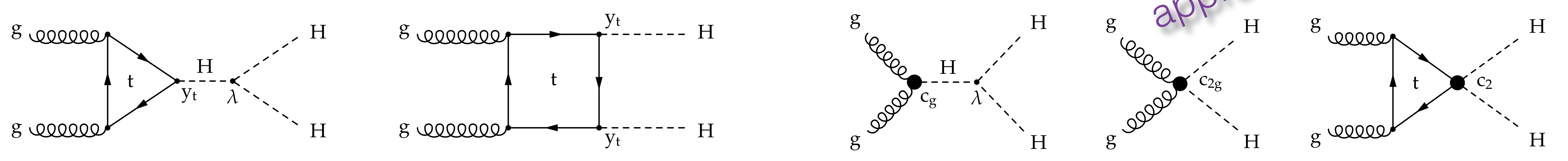
CMS $HH \rightarrow WWWW$, $WW\tau\tau$ and $\tau\tau\tau\tau$

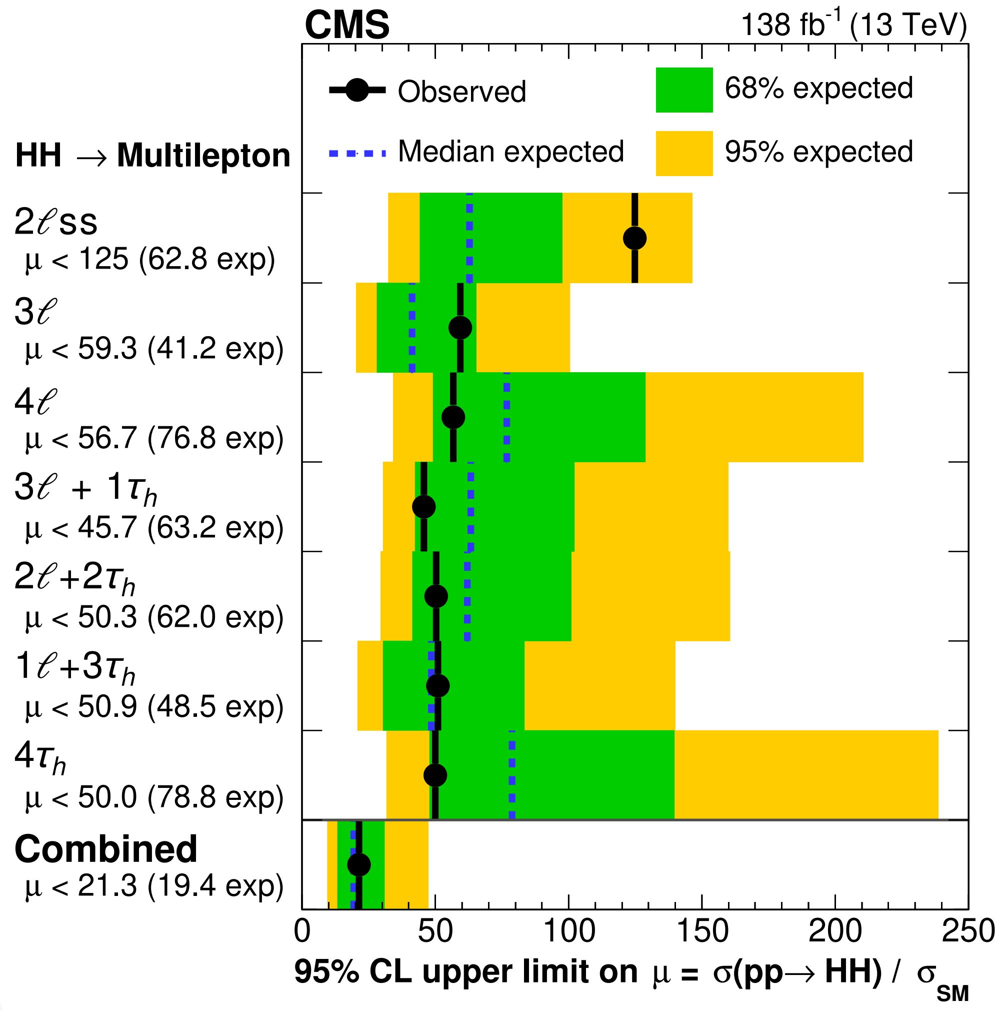
arXiv:2206.10268 CMS-HIG-21-002

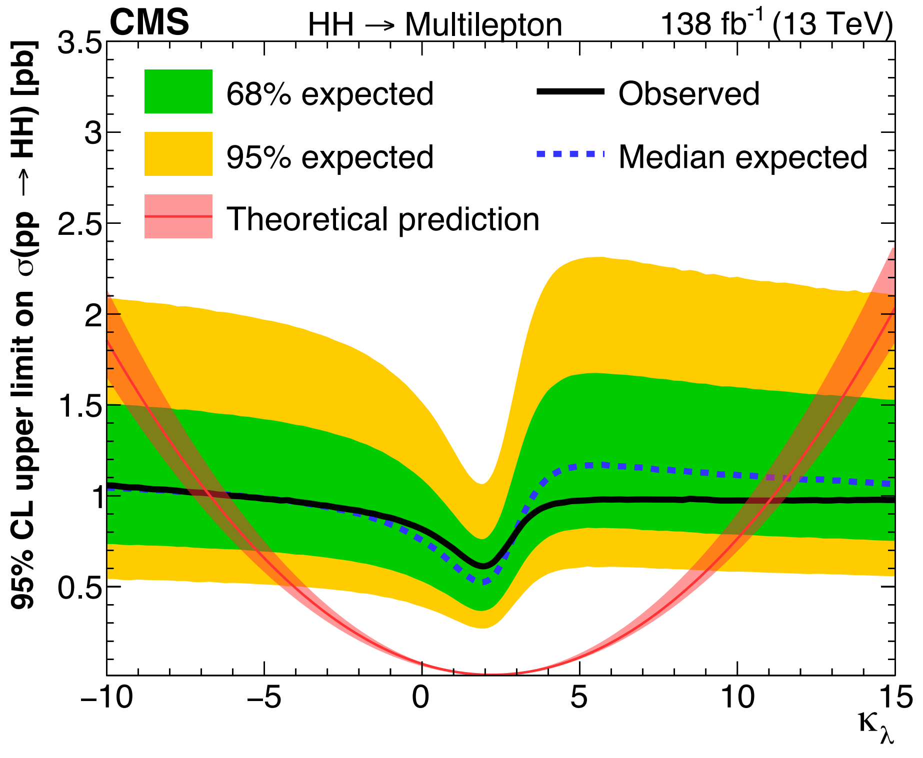
- Explores multi-lepton topology including l=(e, μ) and hadronically decaying τ
  - Covers a total of seven final states: 2l same sign, 3l, 4l, 3l+τ_h, 2l+2τ_h, 1l+3τ_h and 4τ_h
- Investigates non-resonant production as predicted by the SM and in multiple EFT scenarios
- BDTs are trained to classify HH from background for both non-resonant and resonant scenarios and for all seven final states

Non-resonant

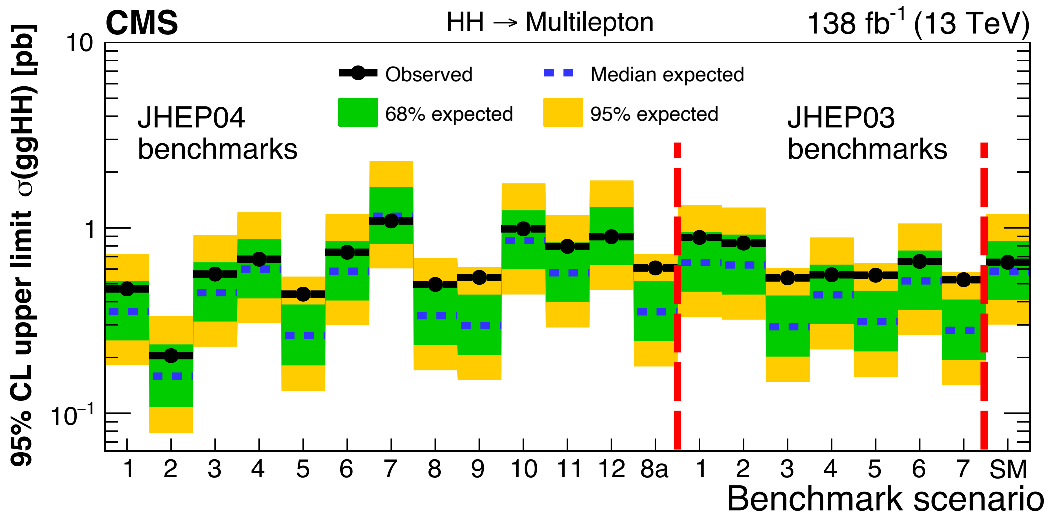
EFT approach





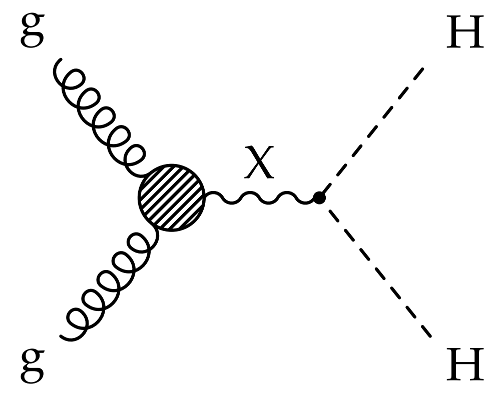


$-6.9 < \kappa_\lambda < 11.1$ ($-6.9 < \kappa_\lambda < 11.7$)



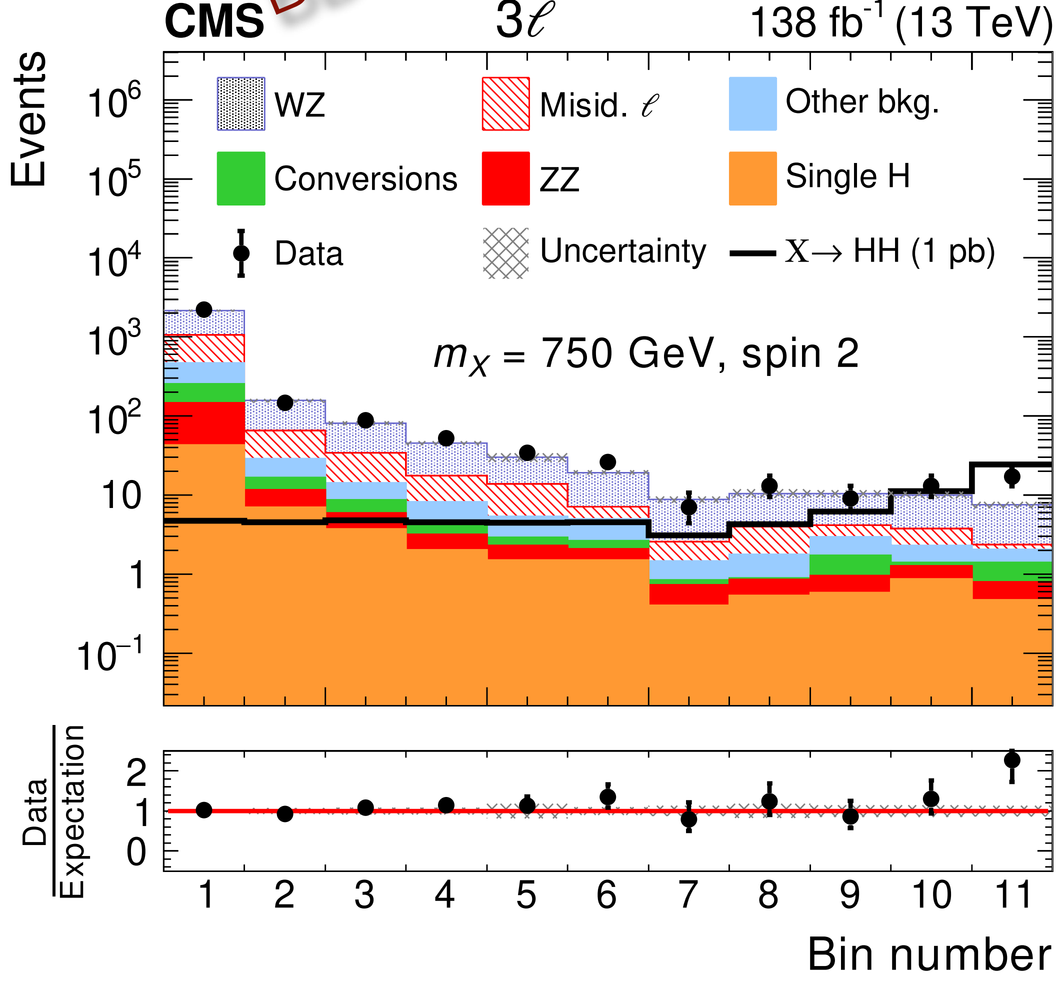
- Twenty EFT benchmark scenarios
- σ_{EFT} in range 0.21 - 1.09 (0.16 - 1.16) pb
- Exclusion regions in κ_λ-c_2 plane also available

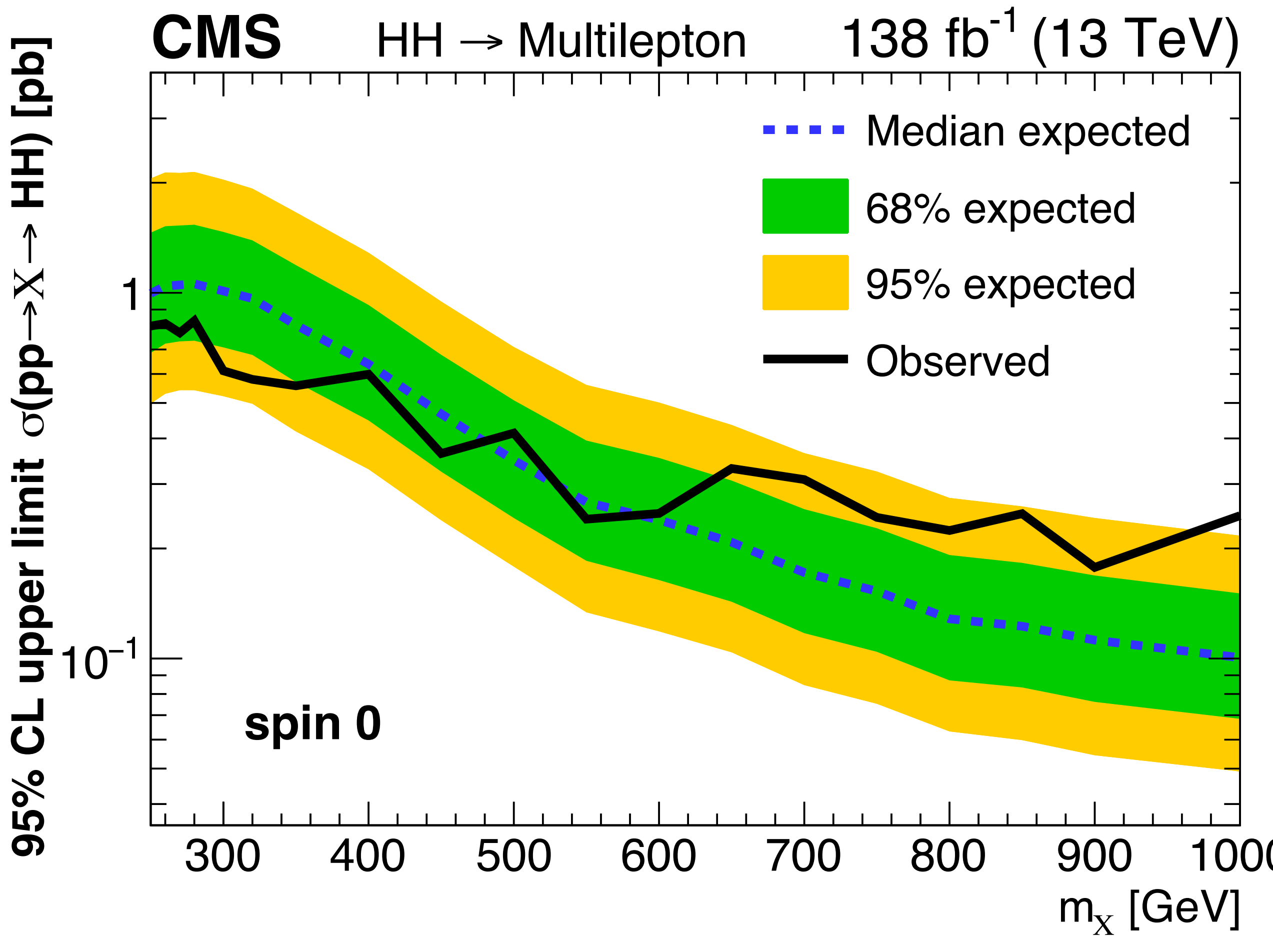
Resonant



Spin-0 and spin-2 resonances included

BDT output



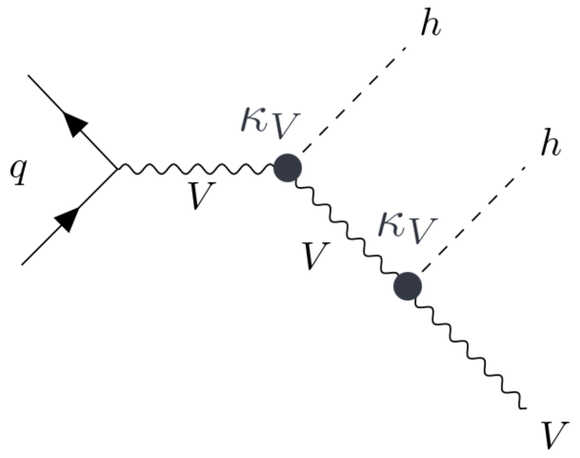


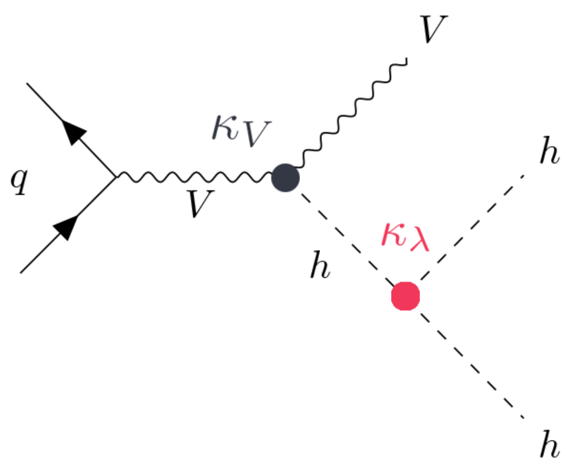
Vhh production in ATLAS

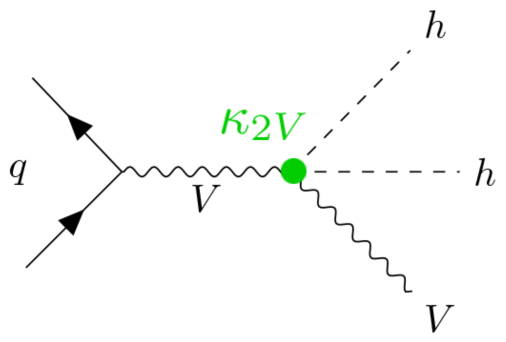
arXiv:2210.05415 HDBS-2019-31

- Targets both non-resonant (SM) and resonant production (BSM)
  - Non-resonant production arises from three different couplings (κ_V, κ_λ and κ_{2V}) and has much smaller cross section than ggF and VBF processes
  - Resonant production includes scenarios such as *Higgsstrahlung* (*VH* → *Vhh*) where *H* is a narrow resonance, and *A*→*ZH*→*Zhh*, where *A* has a width and *H* is a narrow resonance
- Final states cover leptonic decays of vector bosons and *h*→*bb*

Non-resonant

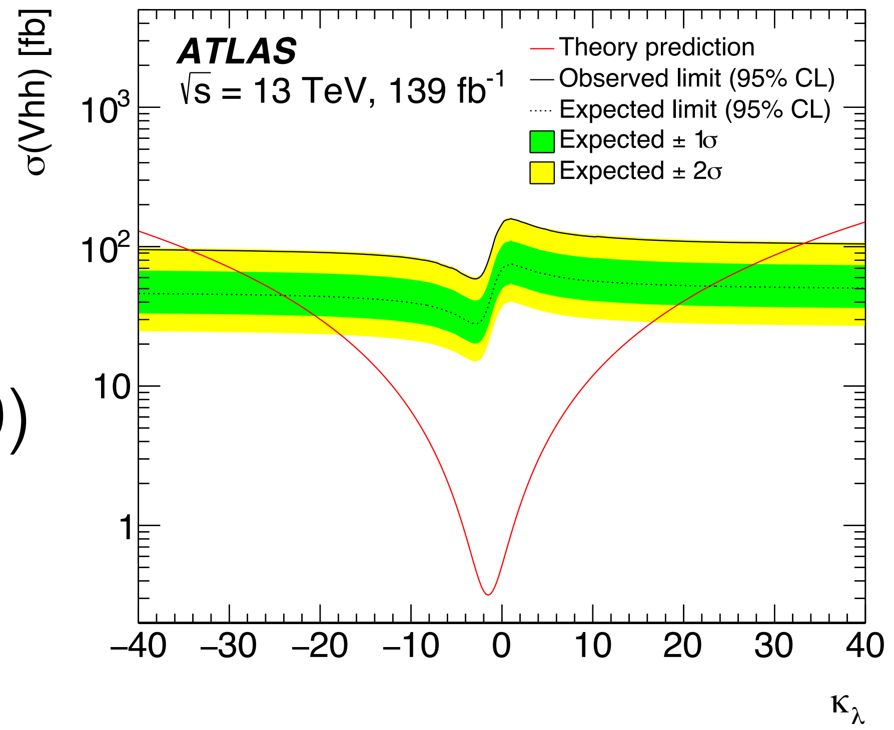


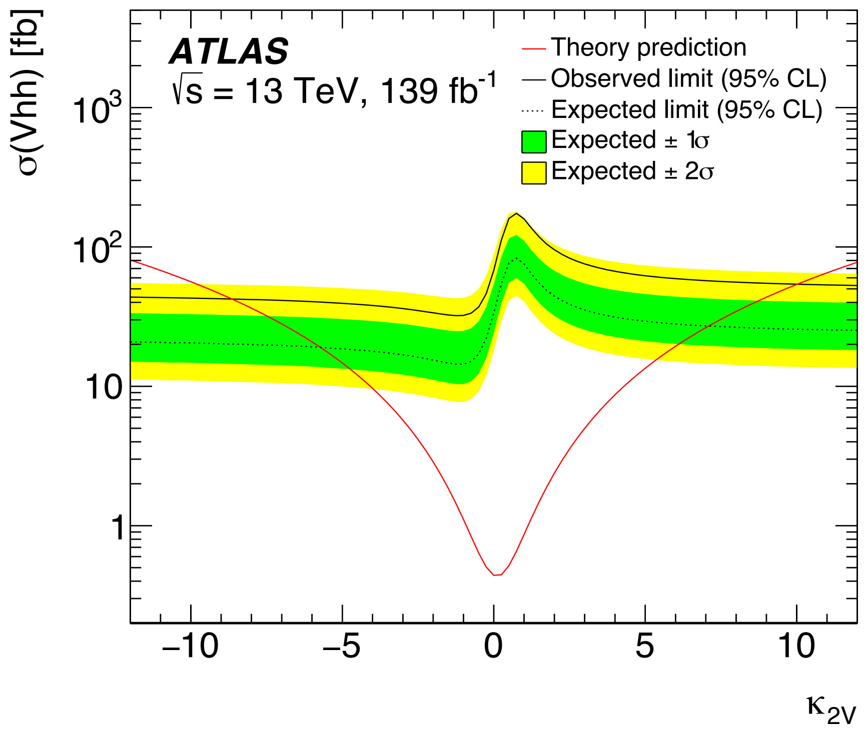




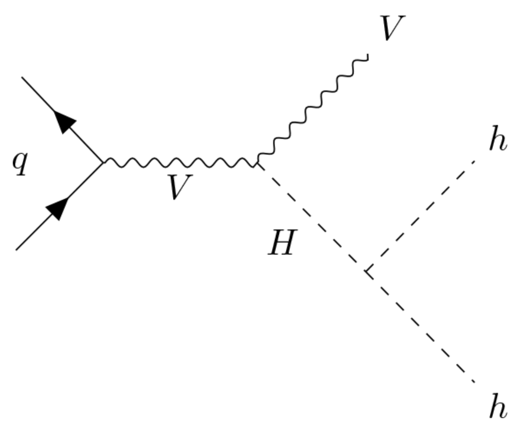
Observed (expected) limits

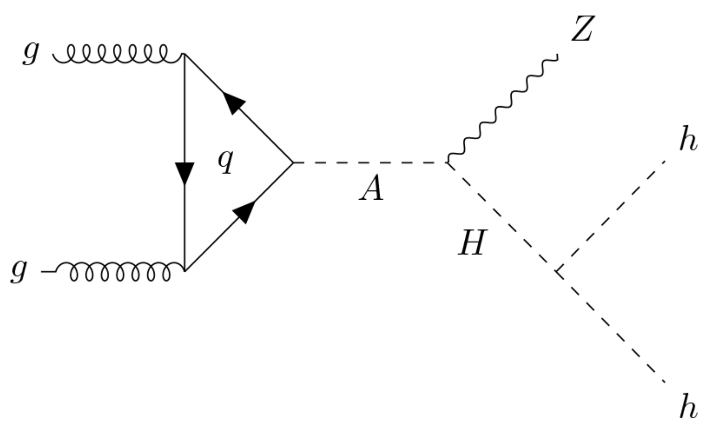
- SM *Vhh*: 183 (87^{+41}_{-24}) x σ_{SM}
- $-34.3 < \kappa_\lambda < 33.3$ ($-24.1 < \kappa_\lambda < 22.9$)
- $-8.6 < \kappa_{2V} < 10.0$ ($-5.7 < \kappa_{2V} < 7.1$)

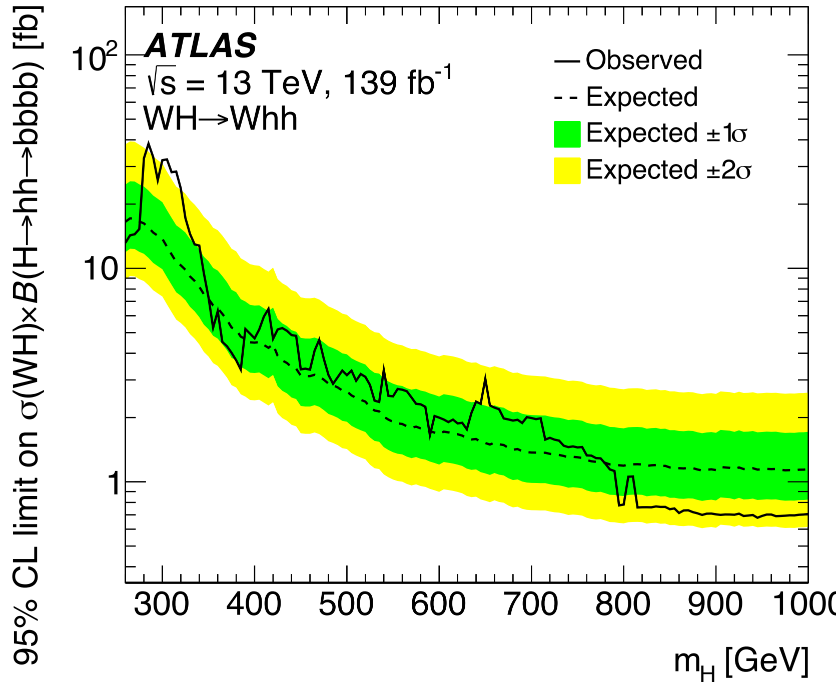


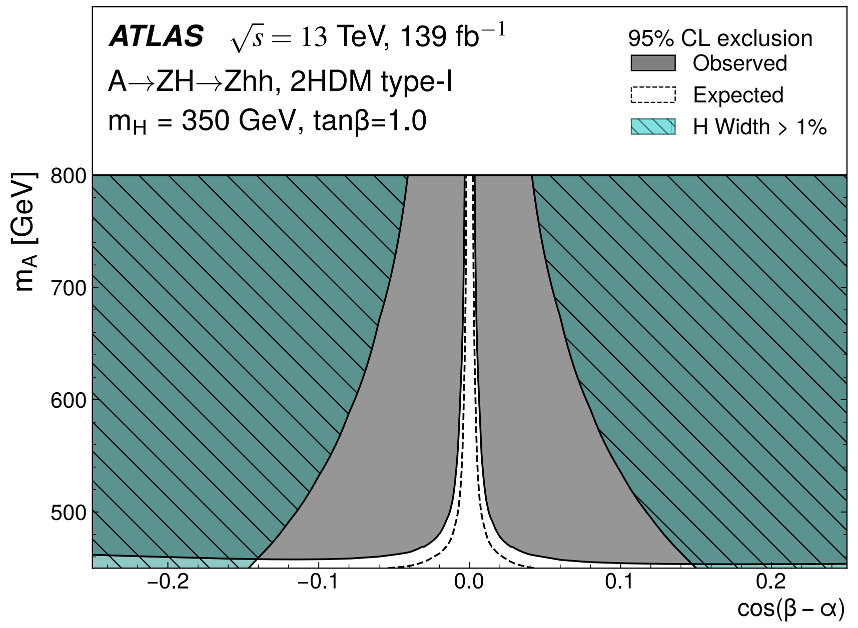


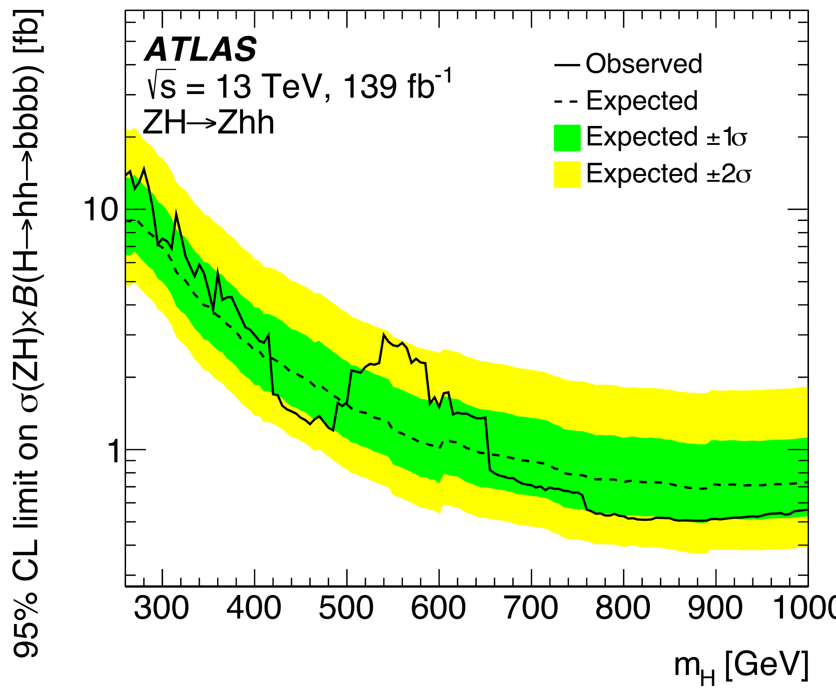
Resonant

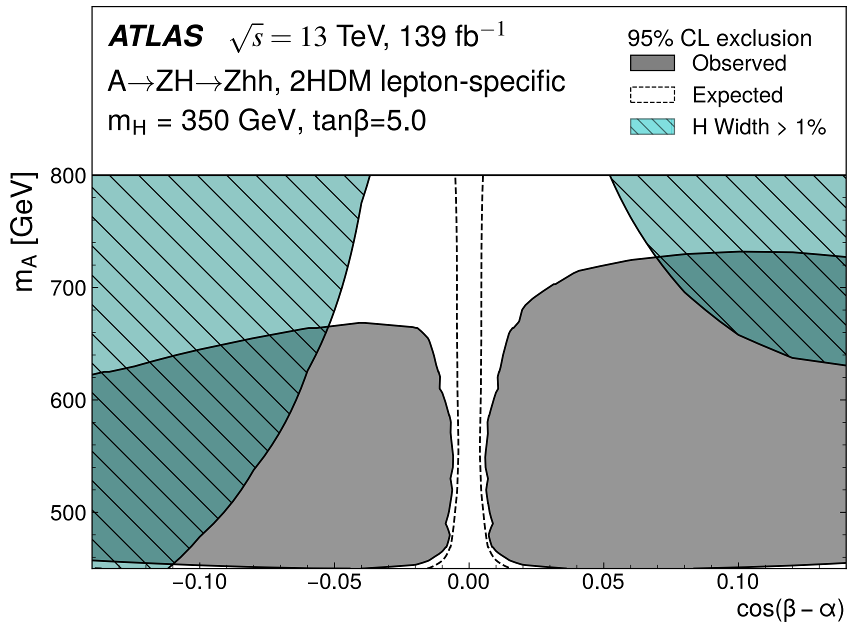










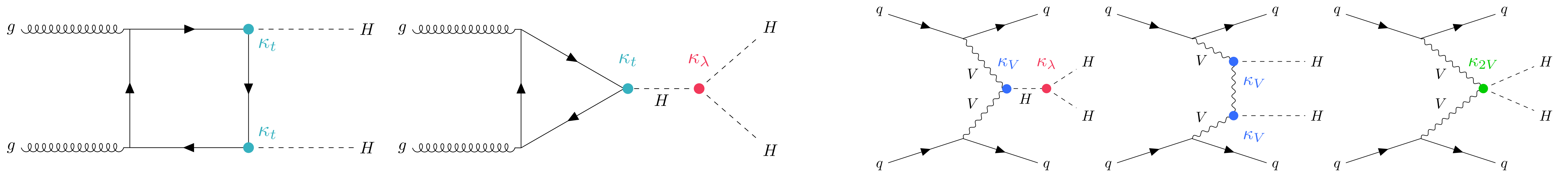


ATLAS combination of $HH + H$

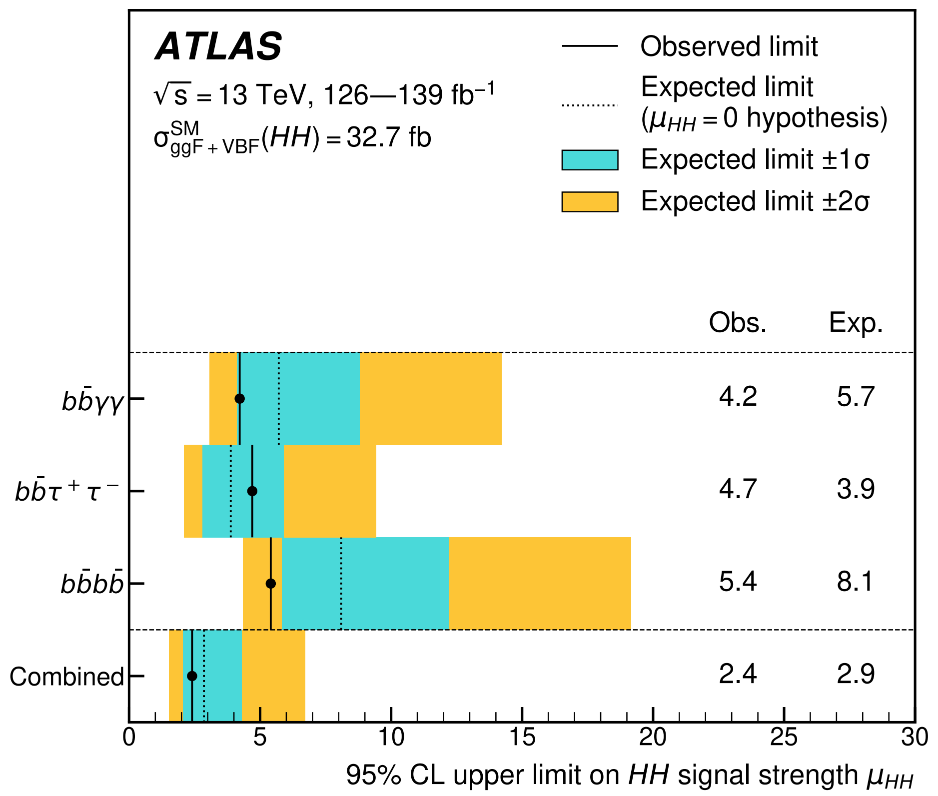
arXiv:2211.01216 HDBS-2022-03

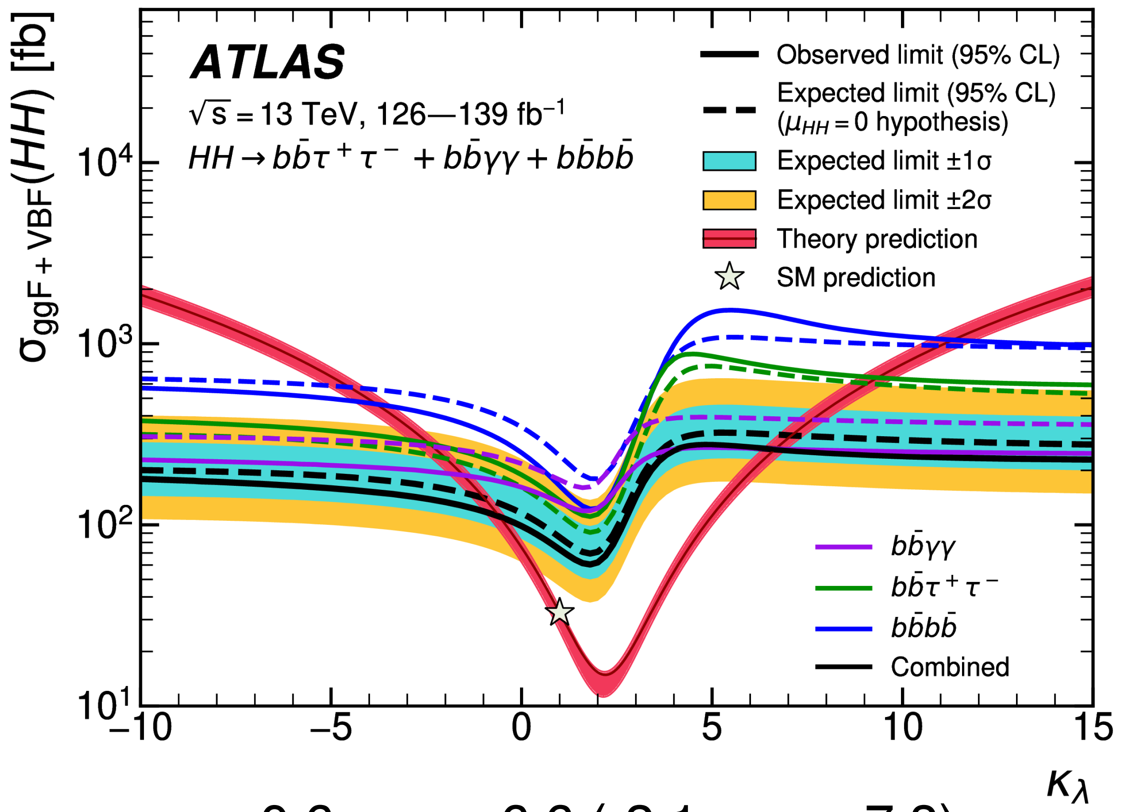
- Constrains the Higgs self coupling via the combination of HH and H analyses
  - HH final states: $bbbb$, $bb\tau\tau$ and $bb\gamma\gamma$
  - H final states: $\gamma\gamma$, ZZ^*, WW^*, $\tau\tau$ and bb
- Combination allows for more stringent or less model dependent constraints to be derived
- Most stringent constraints on λ_{HHH} to date

HH combination



- SM ggF production yields σ_{SM}=31.0 fb at 13 TeV
- SM VBF production yields σ_{SM}=1.72 fb at 13 TeV

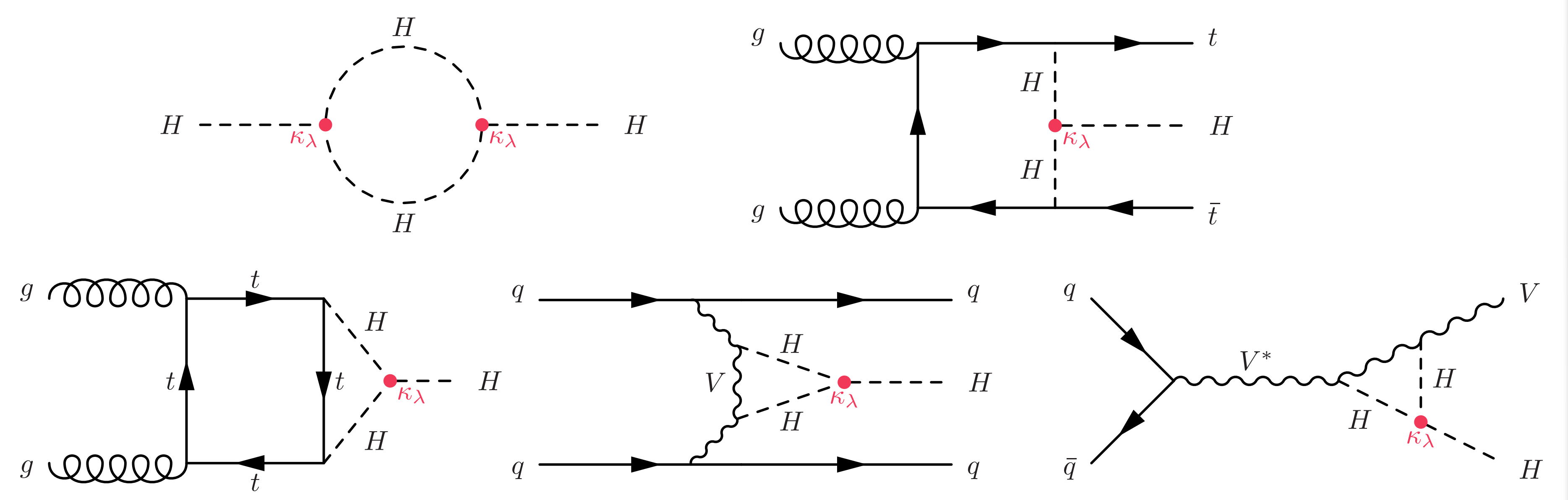


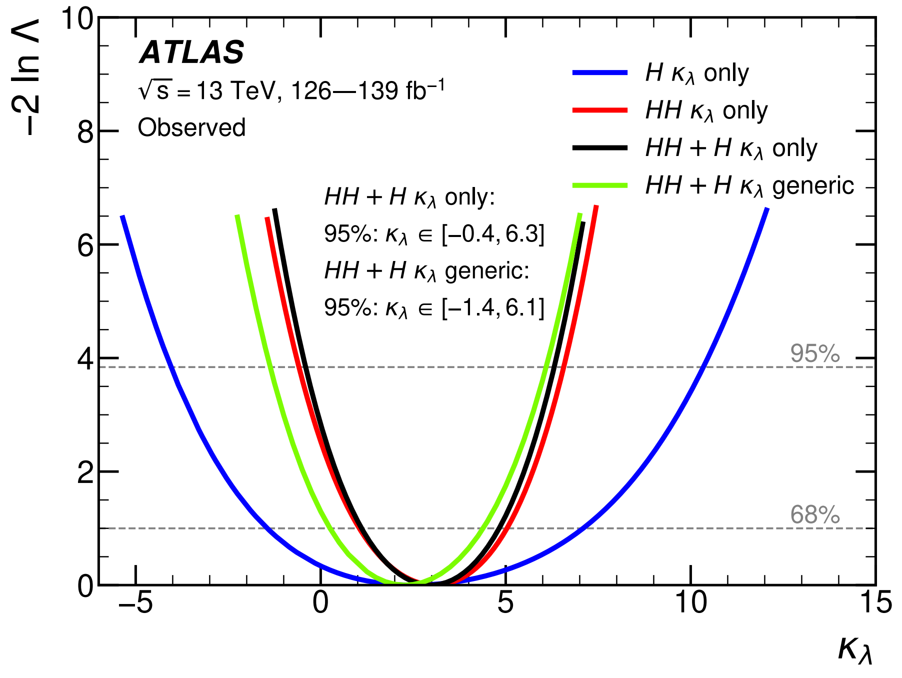


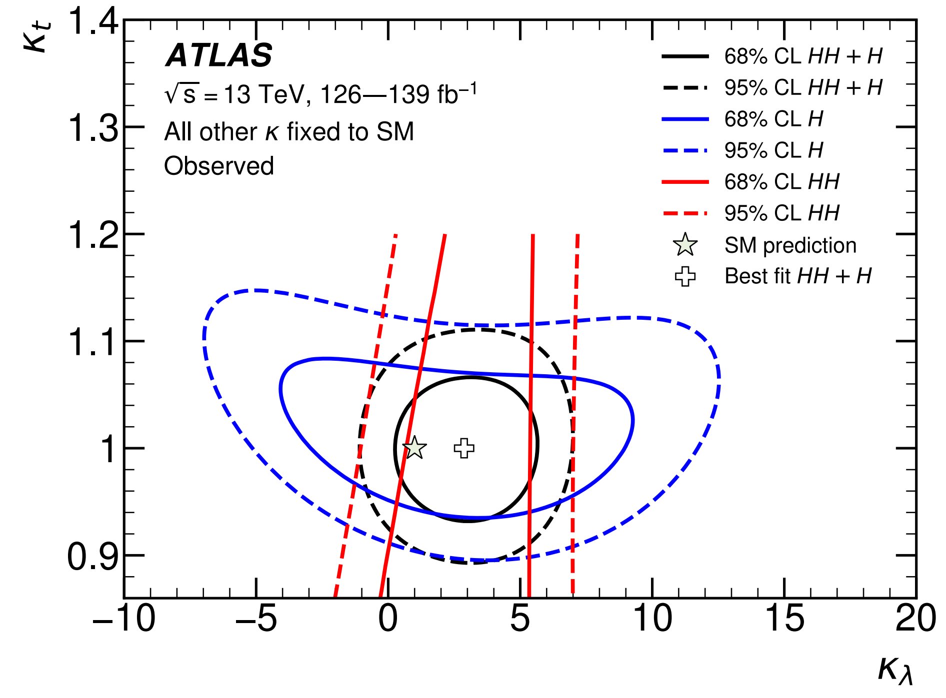
$-0.6 < \kappa_\lambda < 6.6$ ($-2.1 < \kappa_\lambda < 7.8$)

Also sensitive to $HHVV$: $0.1 < \kappa_{2V} < 2.0$ ($0.0 < \kappa_{2V} < 2.1$)

H+HH combination







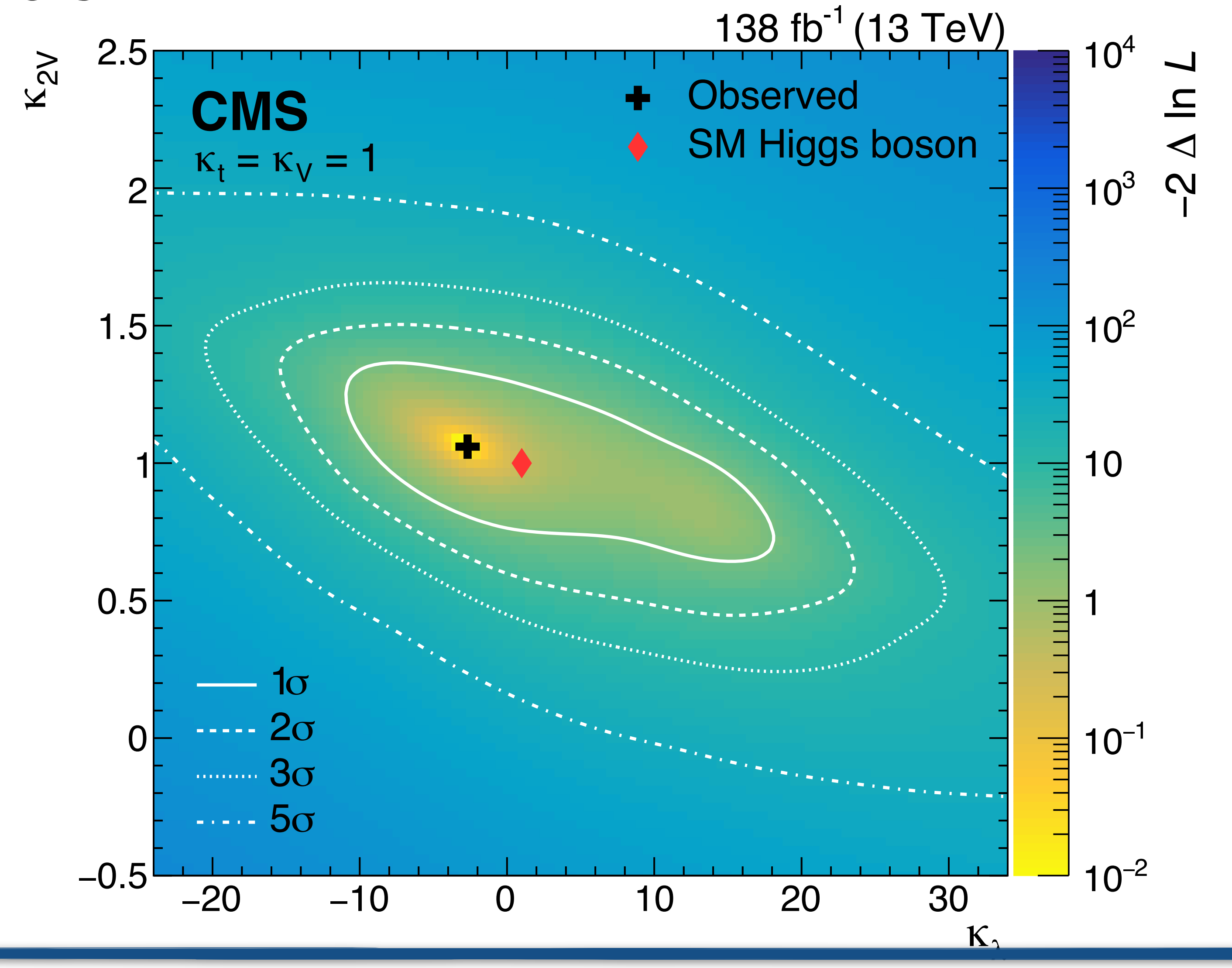
Combination assumption	Obs. 95% CL	Exp. 95% CL	Obs. value$^{+1\sigma}_{-1\sigma}$
HH combination	$-0.6 < \kappa_\lambda < 6.6$	$-2.1 < \kappa_\lambda < 7.8$	$\kappa_\lambda = 3.1^{+1.9}_{-2.0}$
Single-H combination	$-4.0 < \kappa_\lambda < 10.3$	$-5.2 < \kappa_\lambda < 11.5$	$\kappa_\lambda = 2.5^{+4.6}_{-3.9}$
HH+H combination	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
HH+H combination, κ_t floating	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
HH+H combination, κ_t, κ_V, κ_b, κ_τ floating	$-1.4 < \kappa_\lambda < 6.1$	$-2.2 < \kappa_\lambda < 7.7$	$\kappa_\lambda = 2.3^{+2.1}_{-2.0}$

CMS non-resonant *HH*→*4b* and combination of *HH*

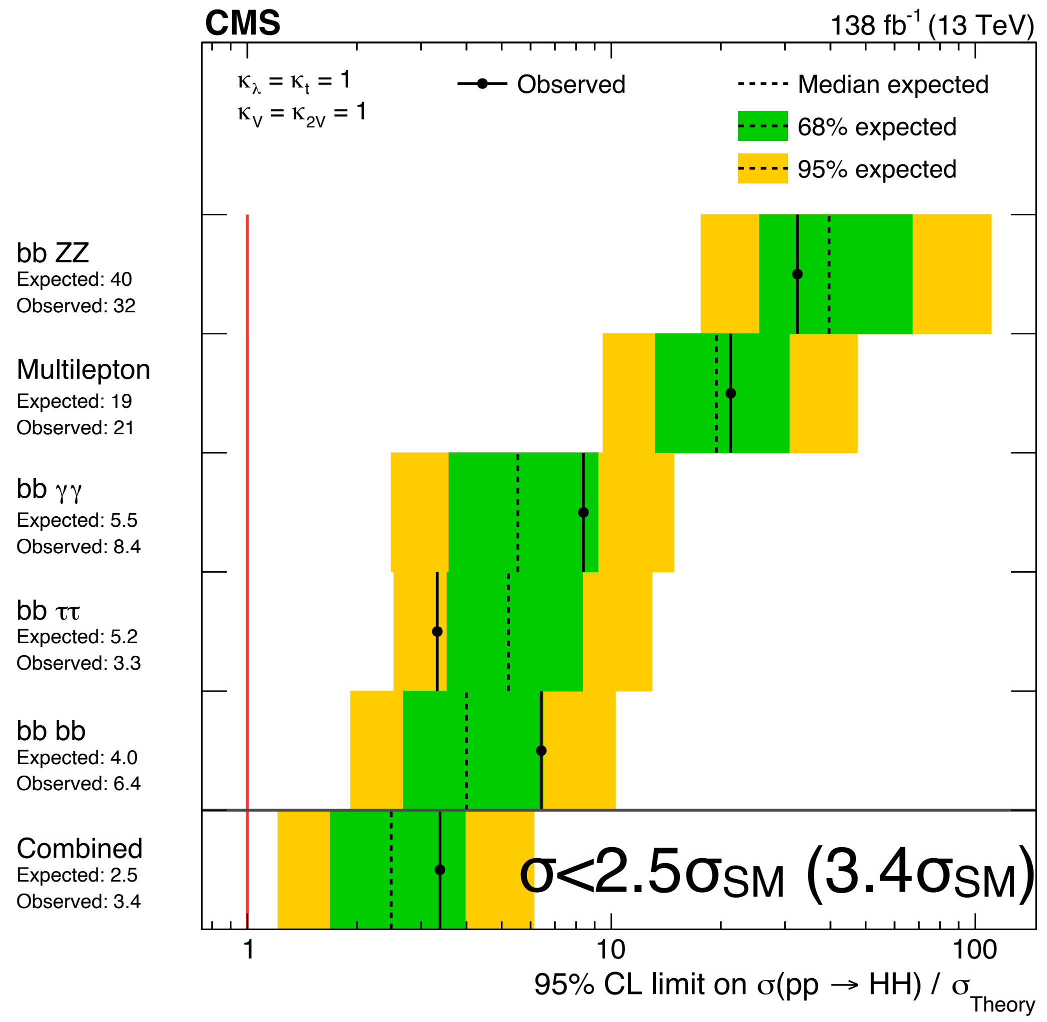
arXiv:2205.06667 (CMS-B2G-22-003) Nature 607 (2022) 60-68 (CMS-HIG-22-001)

Non-resonant *HH*→*bbbb*

- Search for pairs of boosted *H* produced via *ggF* and *VBF*
- Benefits from advances in boosted *H*→*bb* reconstruction and identification
- Exclusion limits
  - SM: $\sigma < 9.9\sigma_{SM}$ ($5.1\sigma_{SM}$)
  - $-9.9 \leq \kappa_\lambda \leq 16.9$ ($-5.1 \leq \kappa_\lambda \leq 12.2$)
  - $0.62 \leq \kappa_{2V} \leq 1.41$ ($0.66 \leq \kappa_{2V} \leq 1.37$)
- **κ_{2V}=0 excluded for the first time** with significance of σ=6.3

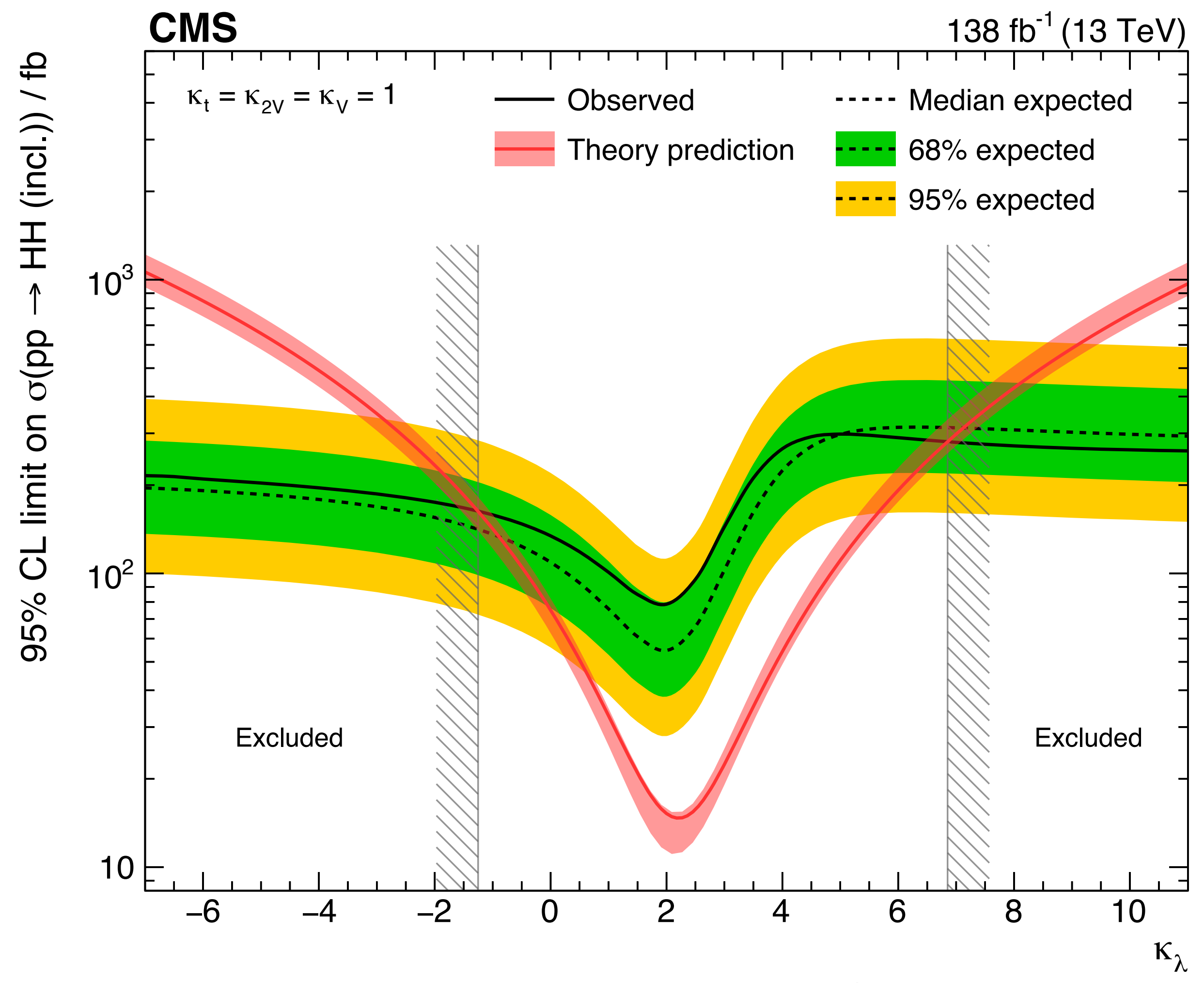


Combination of *HH*

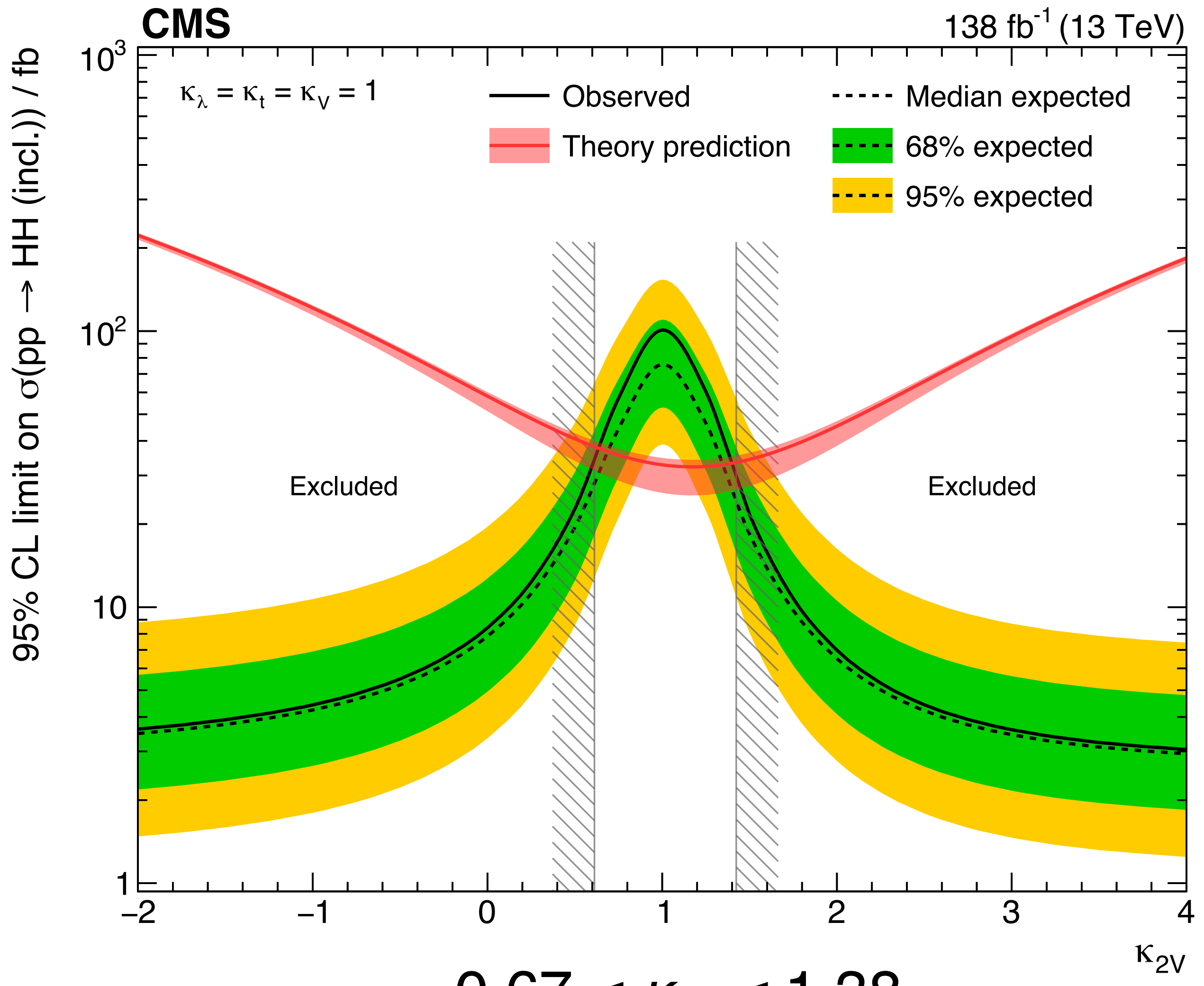


$\sigma<2.5\sigma_{SM}$ ($3.4\sigma_{SM}$)

- Constrains Higgs self coupling and HHVV coupling by combining *HH* analyses
  - *HH* final states: *bbbb*, *bbττ*, *bbγγ, multilepton* and *bbZZ*
- κ_{2V}=0 excluded with significance of σ=6.6
- Non-resonant *HH*→*bbbb* main contributor to κ_{2V} exclusion and helps make *HH*→*bbbb* the most sensitive channel



$-1.24 \leq \kappa_\lambda \leq 6.49$



$0.67 \leq \kappa_{2V} \leq 1.38$

Closing remarks

The ATLAS and CMS collaborations continue to scrutinize every corner of physics available to the LHC through sophisticated and creative approaches