GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN

Searches for non-resonant Higgs pair-production at ATLAS and CMS

Jason Veatch

University of Göttingen (AG Lai)

Bundesministerium für Bildung und Forschung

BMBF-Forschungsschwerpunkt ATLAS-EXPERIMENT

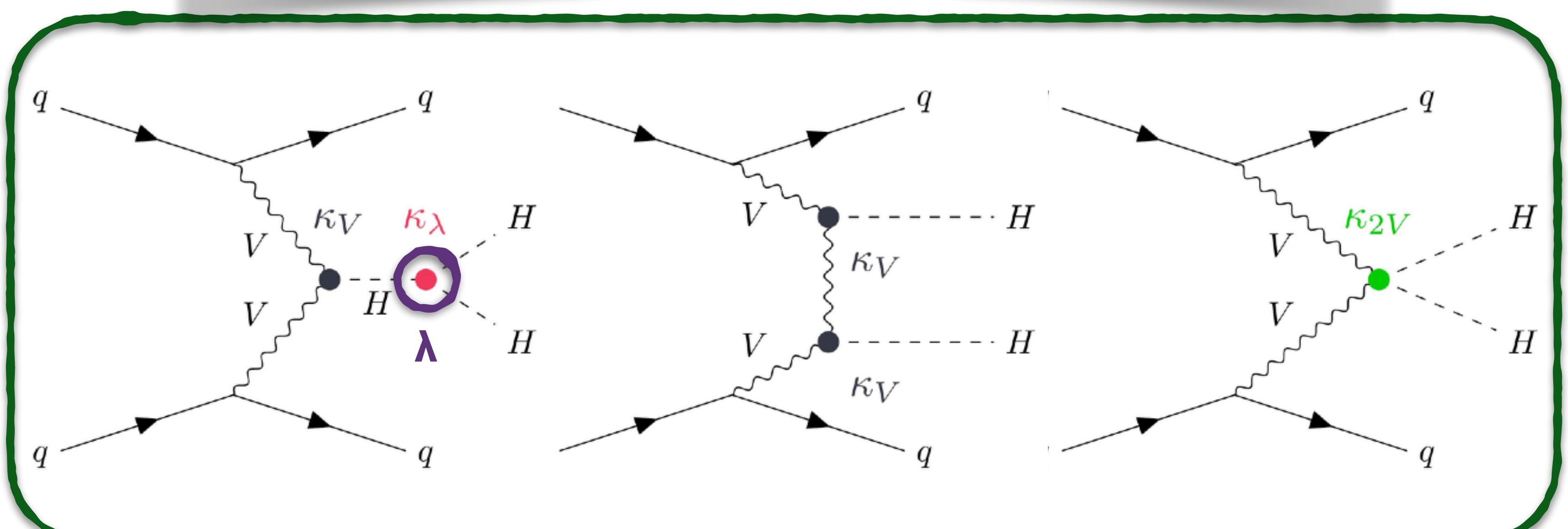
Physik bei höchsten Energien mit dem ATLAS-Experiment am LHC

FSP 103

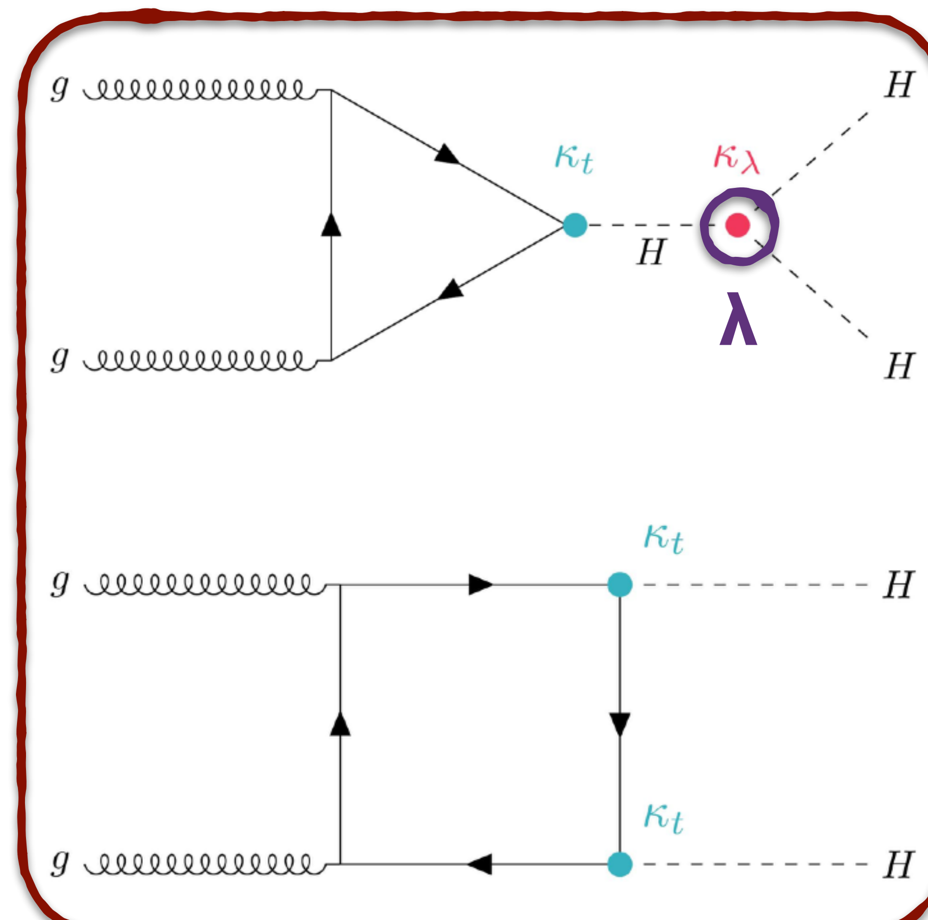
Non-resonant HH production

- Observation of HH pair production is a top (HL-)LHC priority
- Standard Model production: directly measure Higgs potential
- SM predicts trilinear Higgs self-coupling **λ**
- Low cross sections due to interference
  - $\sigma_{ggF} \approx 31$ fb @ $\sqrt{s} = 13$ TeV
  - $\sigma_{VBF} \approx 1.73$ fb @ $\sqrt{s} = 13$ TeV

$$V(h) \simeq \frac{1}{2} m_H^2 h^2 + \lambda v h^3 + \frac{1}{4} \lambda h^4 + \ldots$$



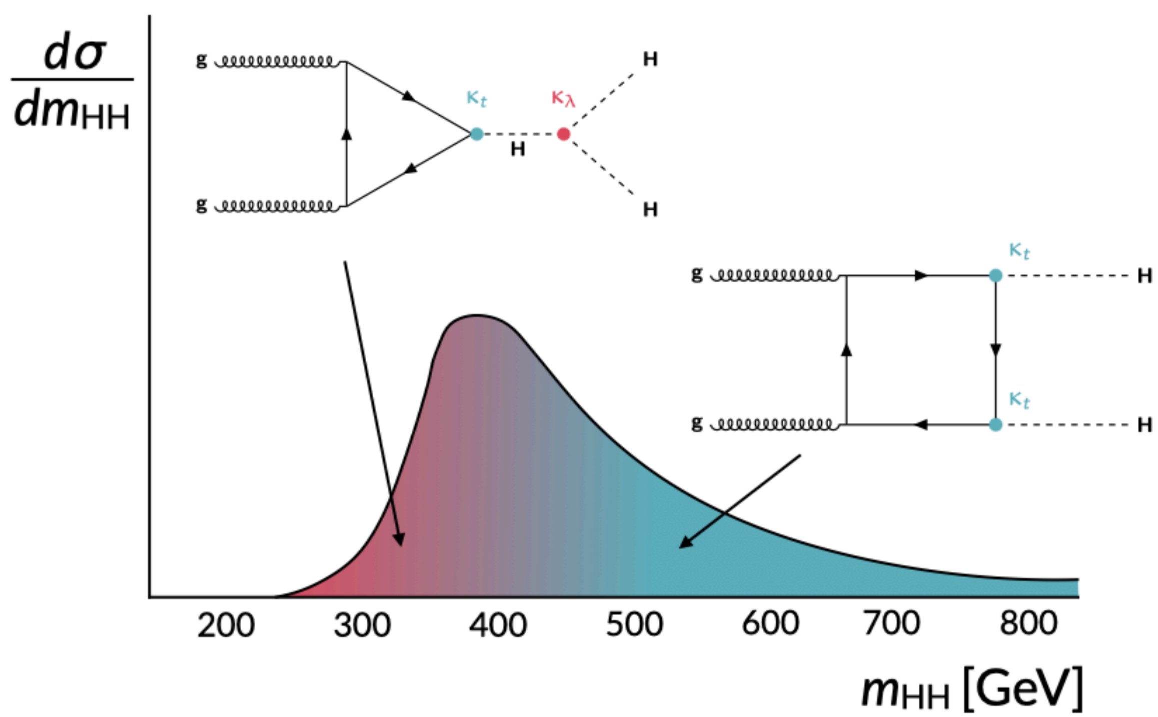
VBF



ggF

Non-resonant HH production

- Observation of HH pair production is a top (HL-)LHC priority
- Standard Model production
- <u>Anomalous couplings</u>
- Deviations from SM couplings could indicate BSM physics
  - $\kappa_\lambda = \lambda / \lambda^{SM}$
  - $\kappa_{2V} = c_{HHVV} / c_{HHVV}^{SM}$ (HHVV quartic coupling strength)
- κ_λ and κ_{2V} modify cross-section and kinematics



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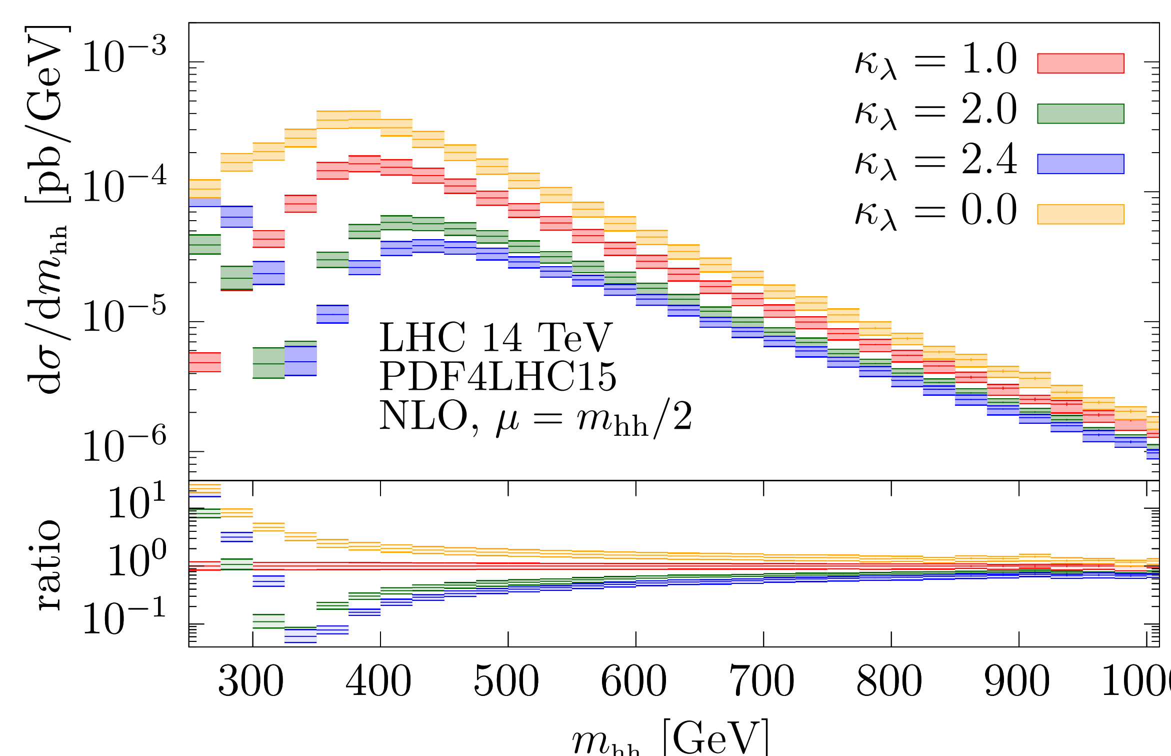


HH final states

	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

Covered in this talk

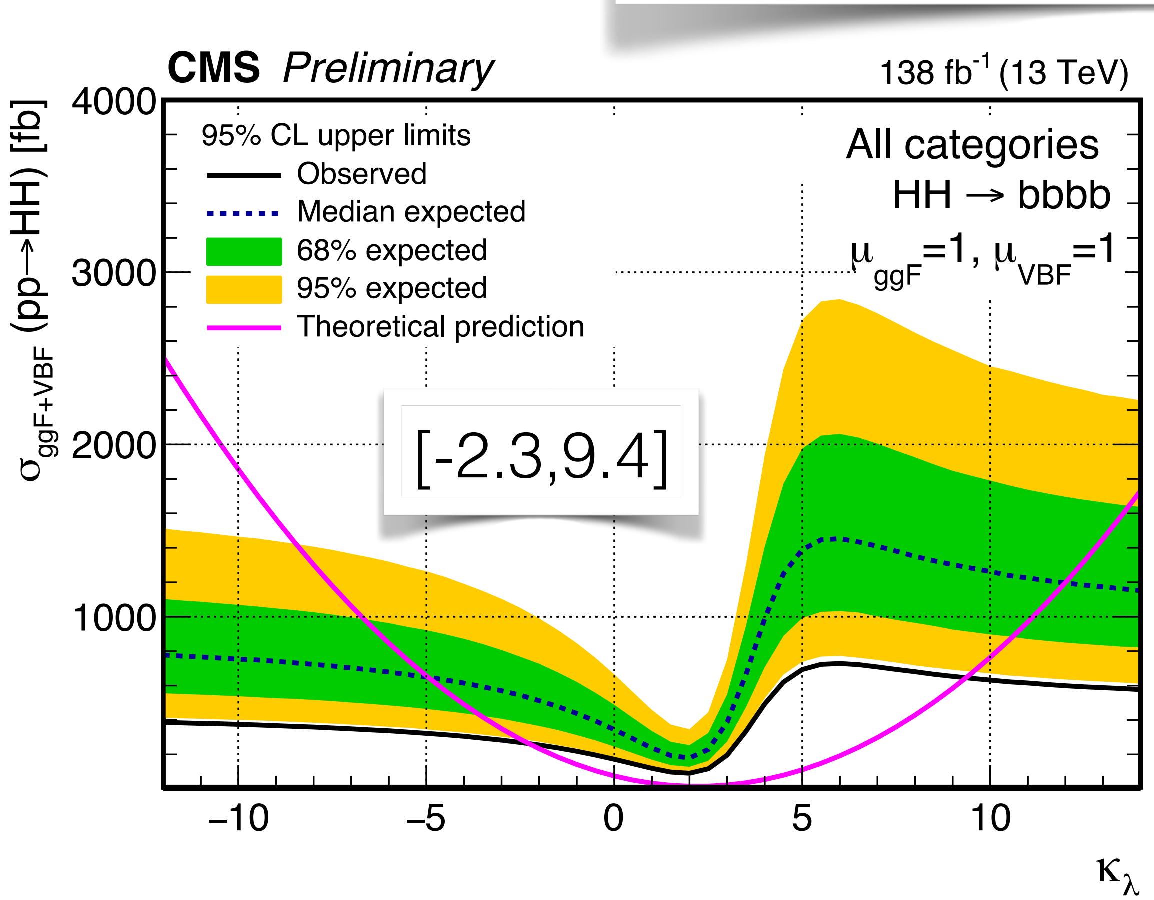
- Numerous final states
- No single “golden” channel
  - Branching ratios
  - Background suppression
  - Kinematic regime sensitivity
- Combination of multiple channels necessary for observation

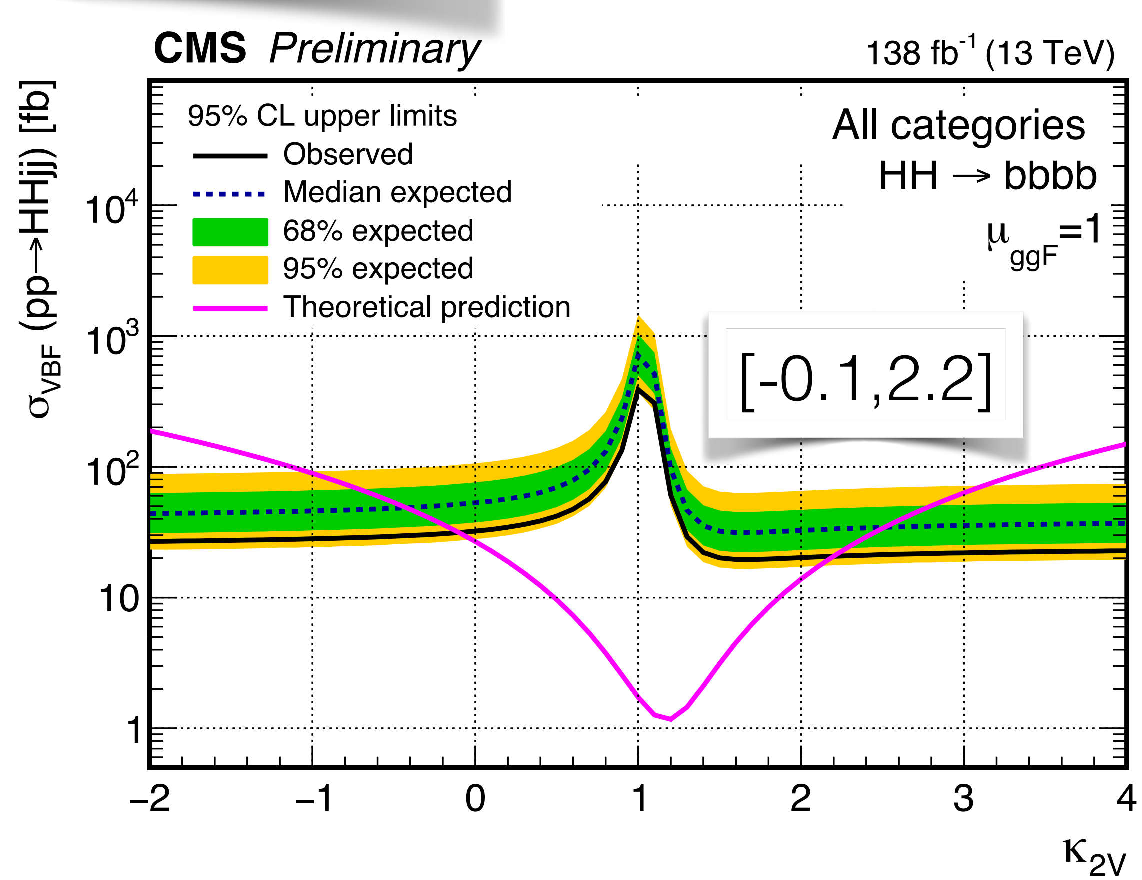
CMS resolved 4b

- Excellent BR from two H→bb decays
- Distinct 4 b-tagged jet final state
    - Additional 2 forward jets required for VBF selection
- BDT used to identify signal and classify ggF vs VBF topologies
- Huge QCD background estimated using data-driven techniques

Obs. (exp.) limit: $\mu_{SM} < 3.7\ (7.3)$

CMS-PAS-HIG-20-005

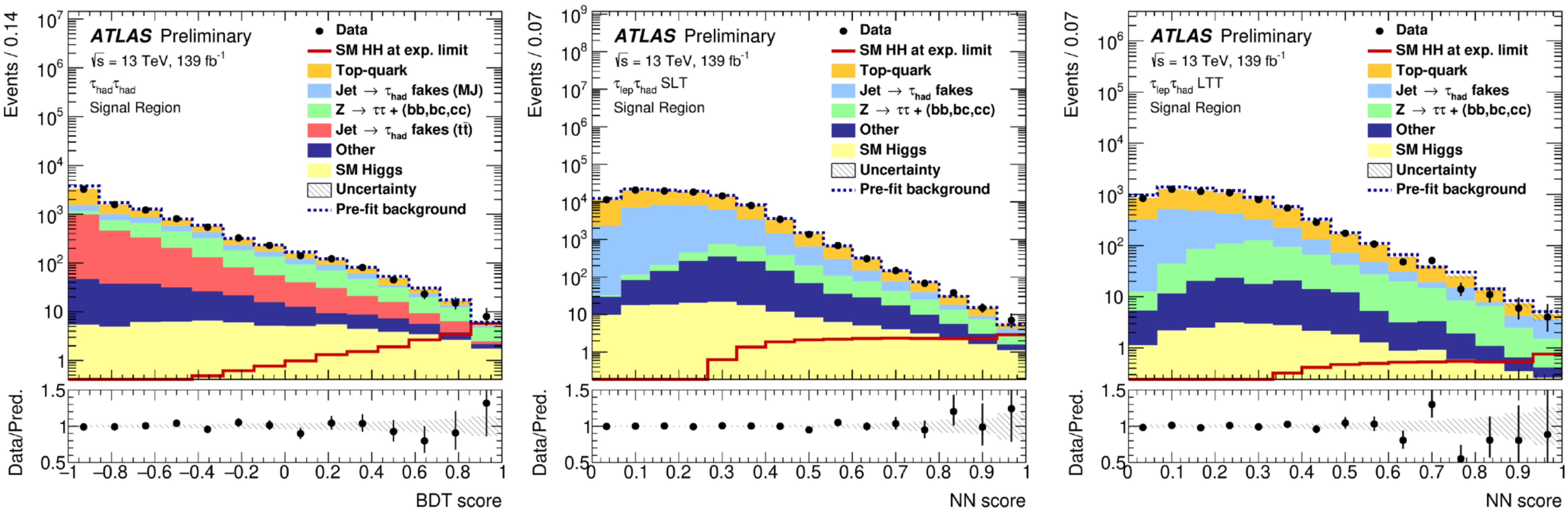




ATLAS bbττ

- Good BR from H→bb and low background from H→ττ
- Two final states used $\tau_{had}\tau_{had}$ and $\tau_{lep}\tau_{had}$
    - $\tau_{lep}\tau_{had}$ channel further split by trigger selection (SLT and LTT)
- BDT- and NN-based discrimination
- Data-driven methods to estimate fake τ background
- More details in Chris' talk

ATLAS-CONF-2021-030

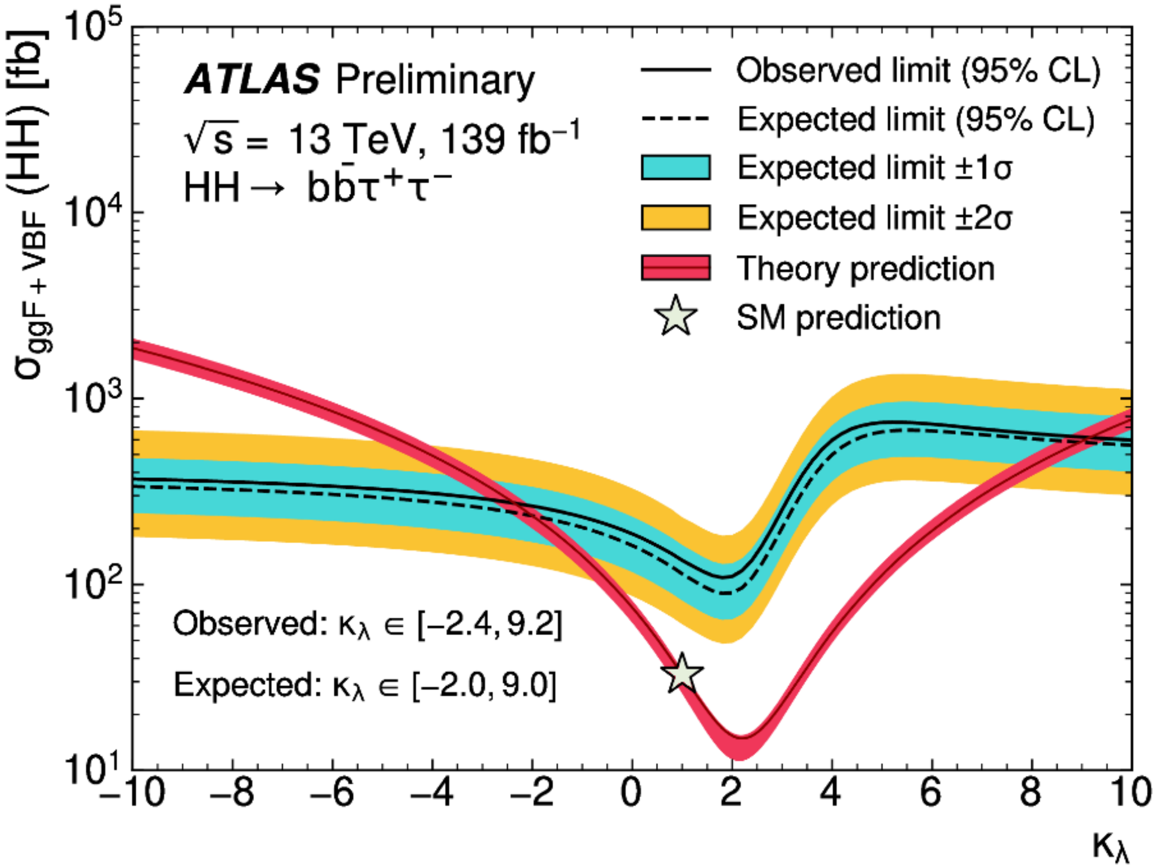


ATLAS bbττ

- MVA score used as the final discriminant in the fit
- Limits set on μ_{SM} and κ_λ

Channel	Observed	-1σ	Expected	+1σ
$\tau_{had}\tau_{had}$	4.95	3.19	4.43	6.17
$\tau_{lep}\tau_{had}$	9.16	5.66	7.86	10.9
Combined	4.65	2.79	3.87	5.39

ATLAS-CONF-2021-030

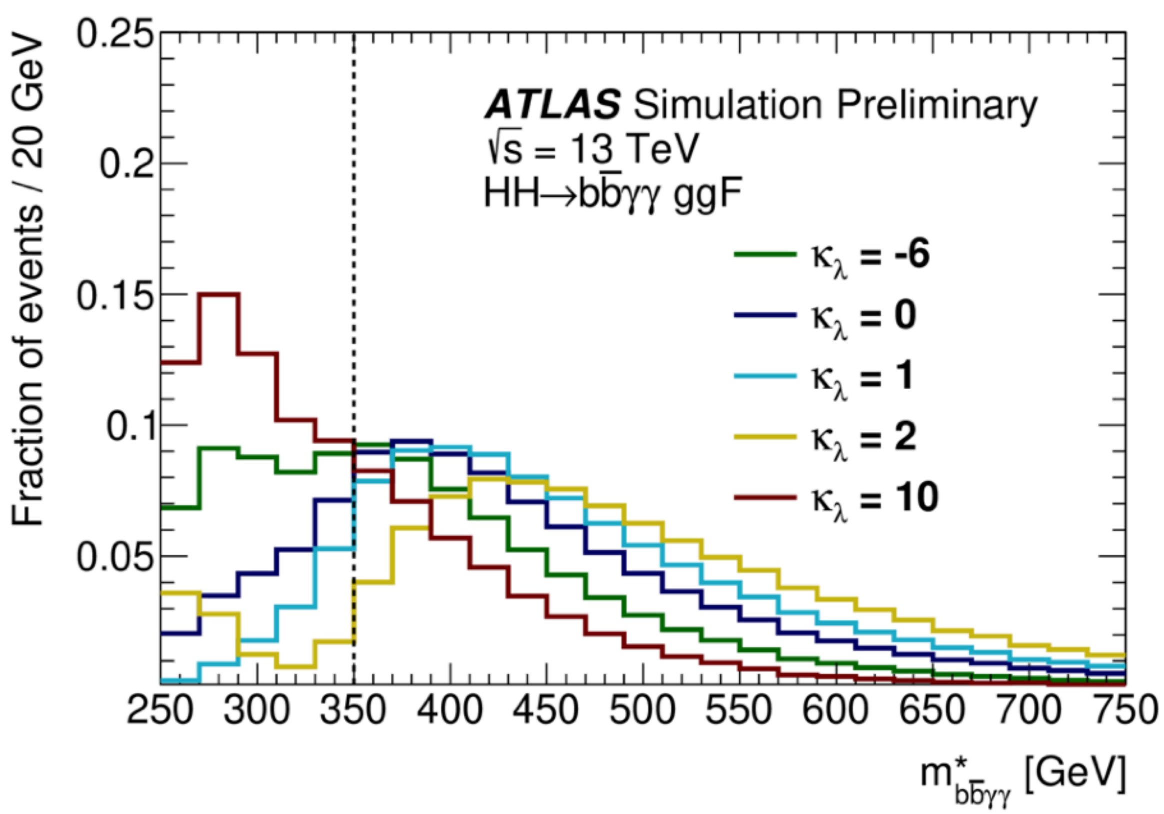


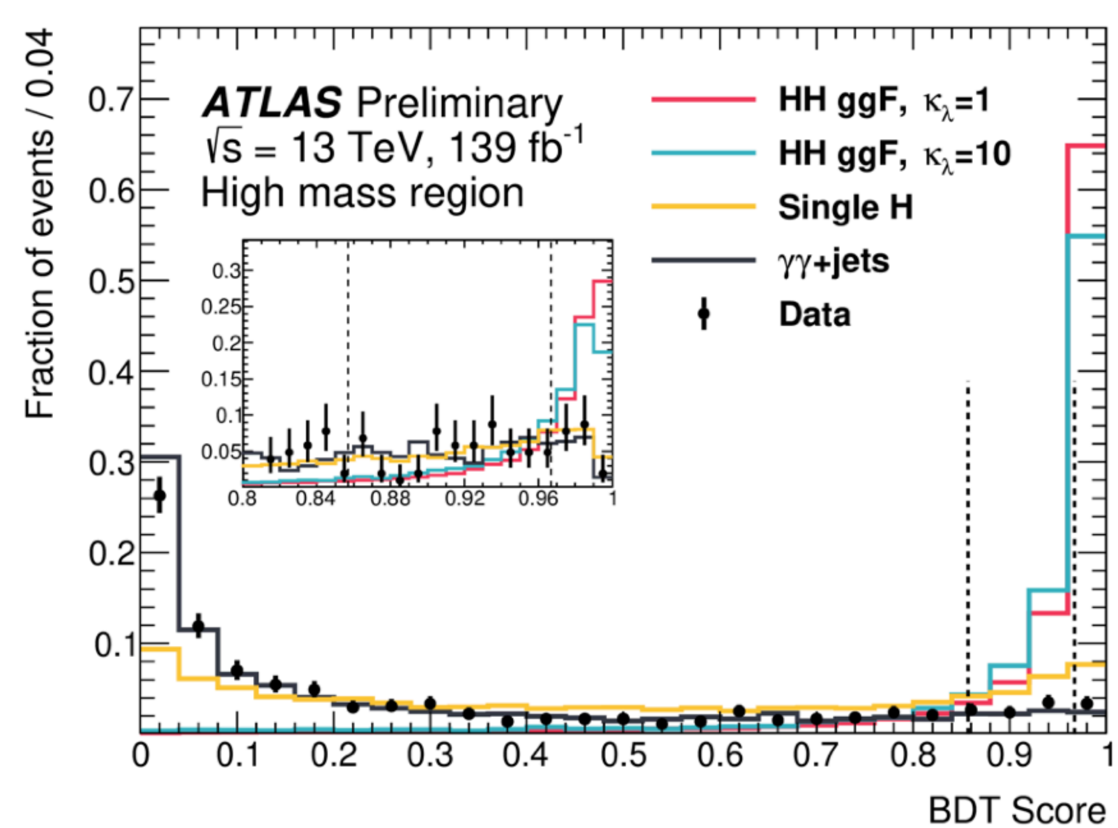
ATLAS-CONF-2021-052

ATLAS bbγγ

- Good BR from H→bb and very low background from H→γγ
- Require di-photon triggers, two photons, and 2 b-tagged jets
- Events split into high- and low-mass regions
  - Targeting SM and BSM signals
- BDT used to separate signal from background
  - Loose and tight BDT regions defined

ATLAS-CONF-2021-016

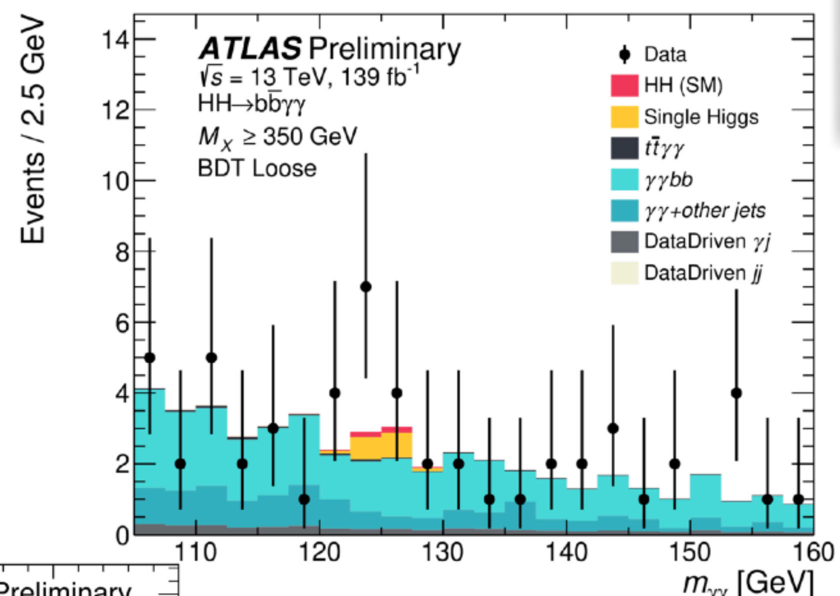


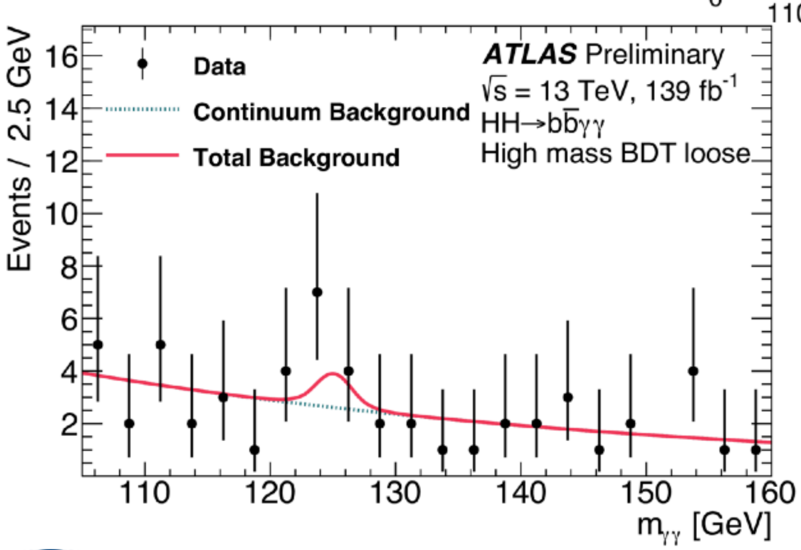


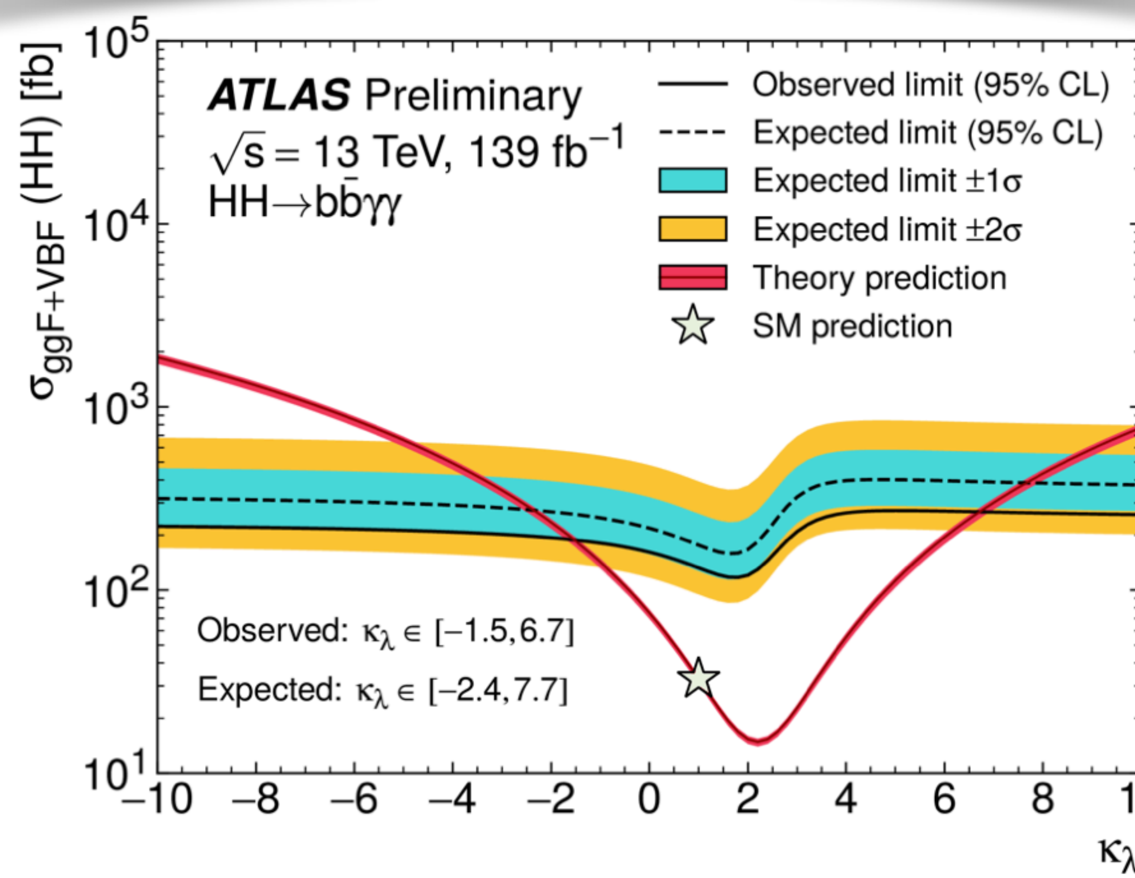
ATLAS bbγγ

- Signal extracted from a mγγ distribution fit
    - Continuum background - exponential function from sidebands
    - Signal and single-Higgs bkg - DSCB function from MC
- Limits set on μ_{SM} and κ_λ

Obs. (exp.) limit: μ_{SM} < 4.65 (3.87)







ATLAS-CONF-2021-016

CMS bbγγ

- Require two photons and 2 b-tagged jets
- BDTs designed to distinguish ggF and VBF signals
- Categories defined based on invariant mass and BDT score
- Simultaneous 2D fit in $m_{\gamma\gamma}$ and m_{jj}

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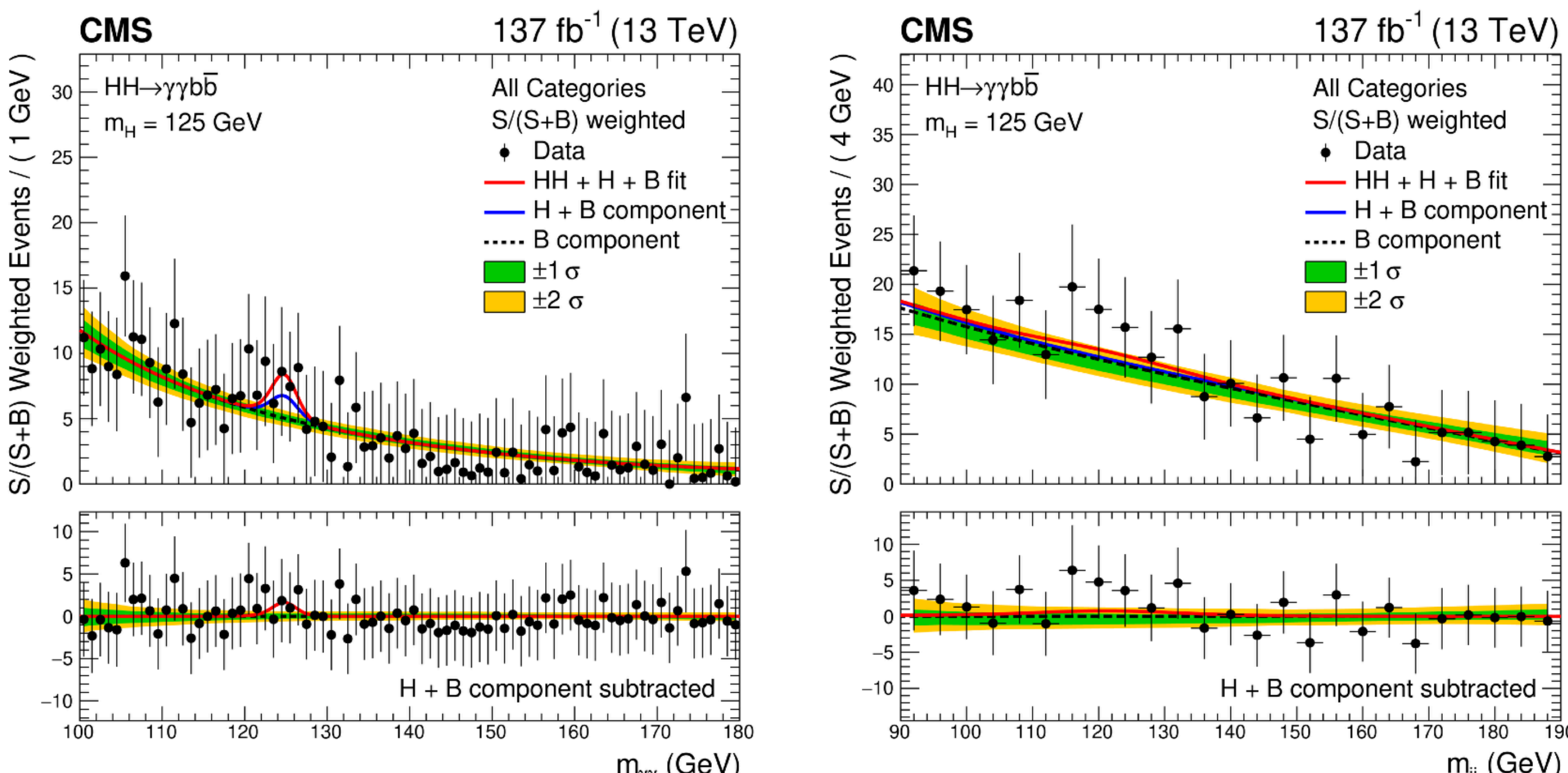
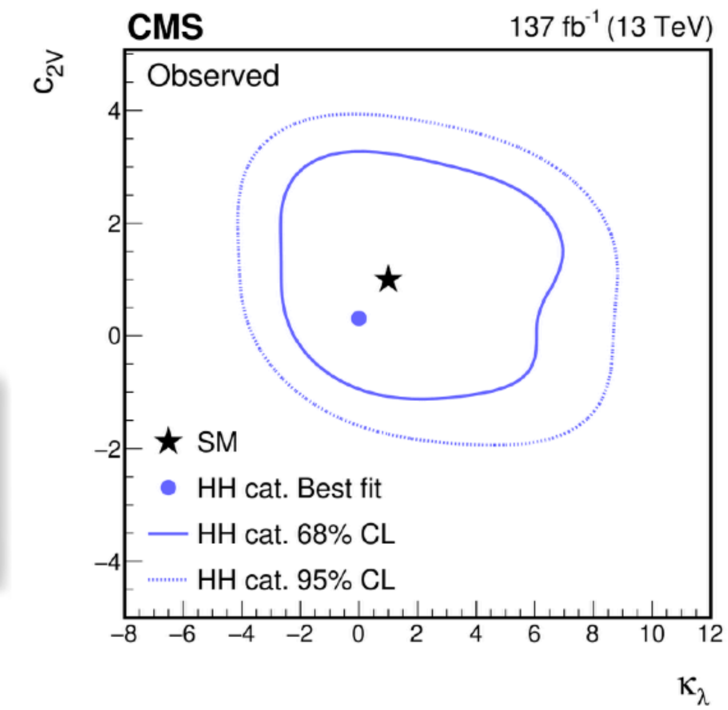
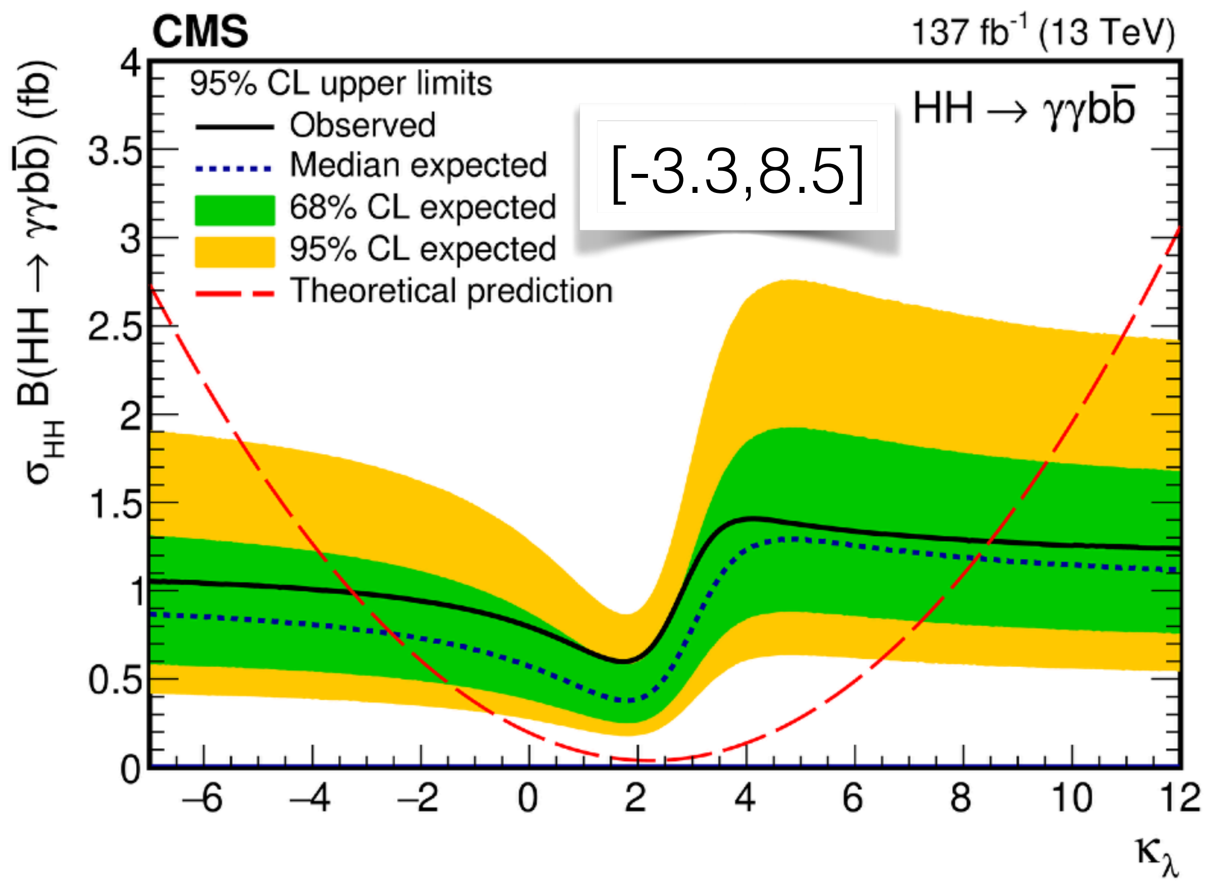


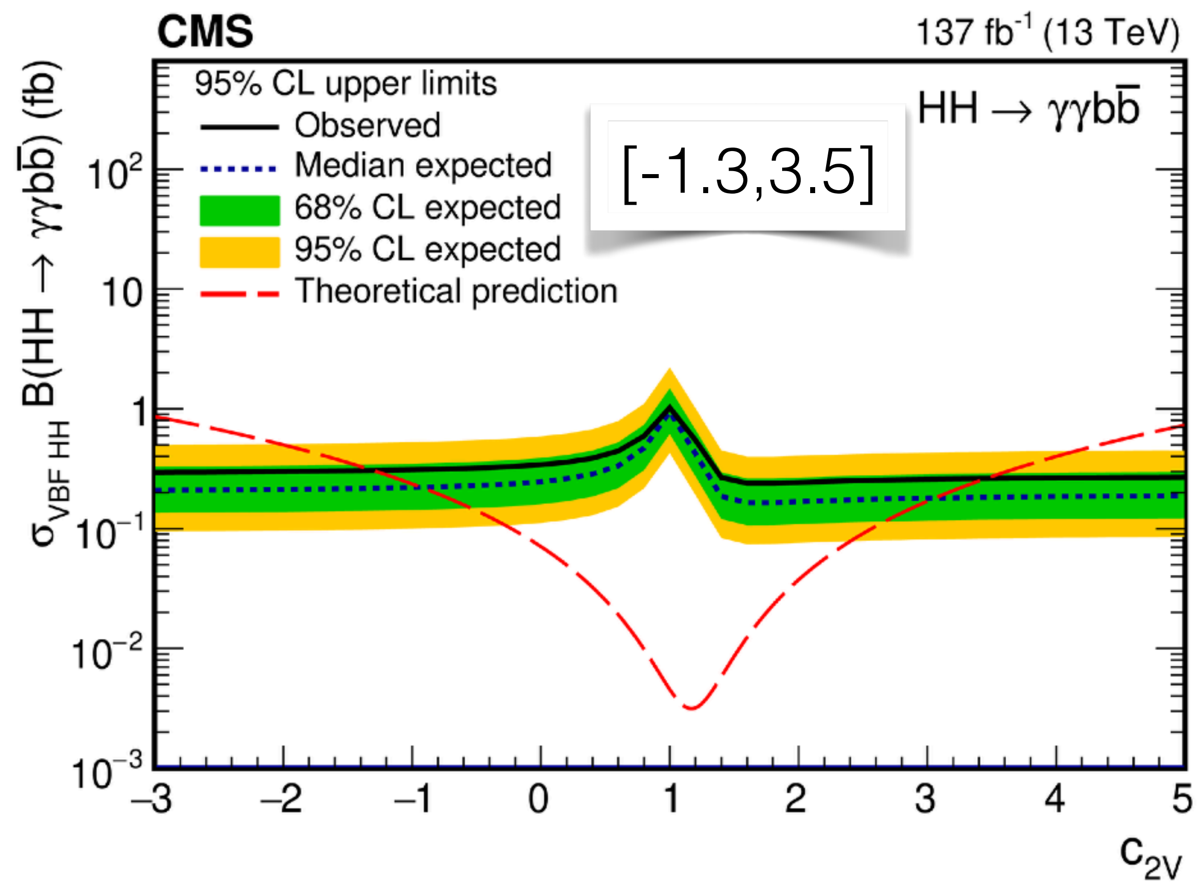
CMS bbγγ

- Limits set on μ_{SM}, κ_λ, and κ_{2V}

Obs. (exp.) limit: μ_{SM} < 7.7 (5.2)







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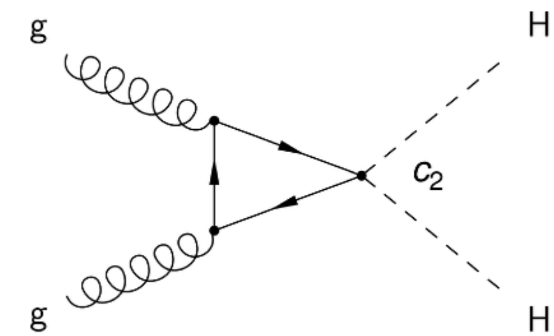
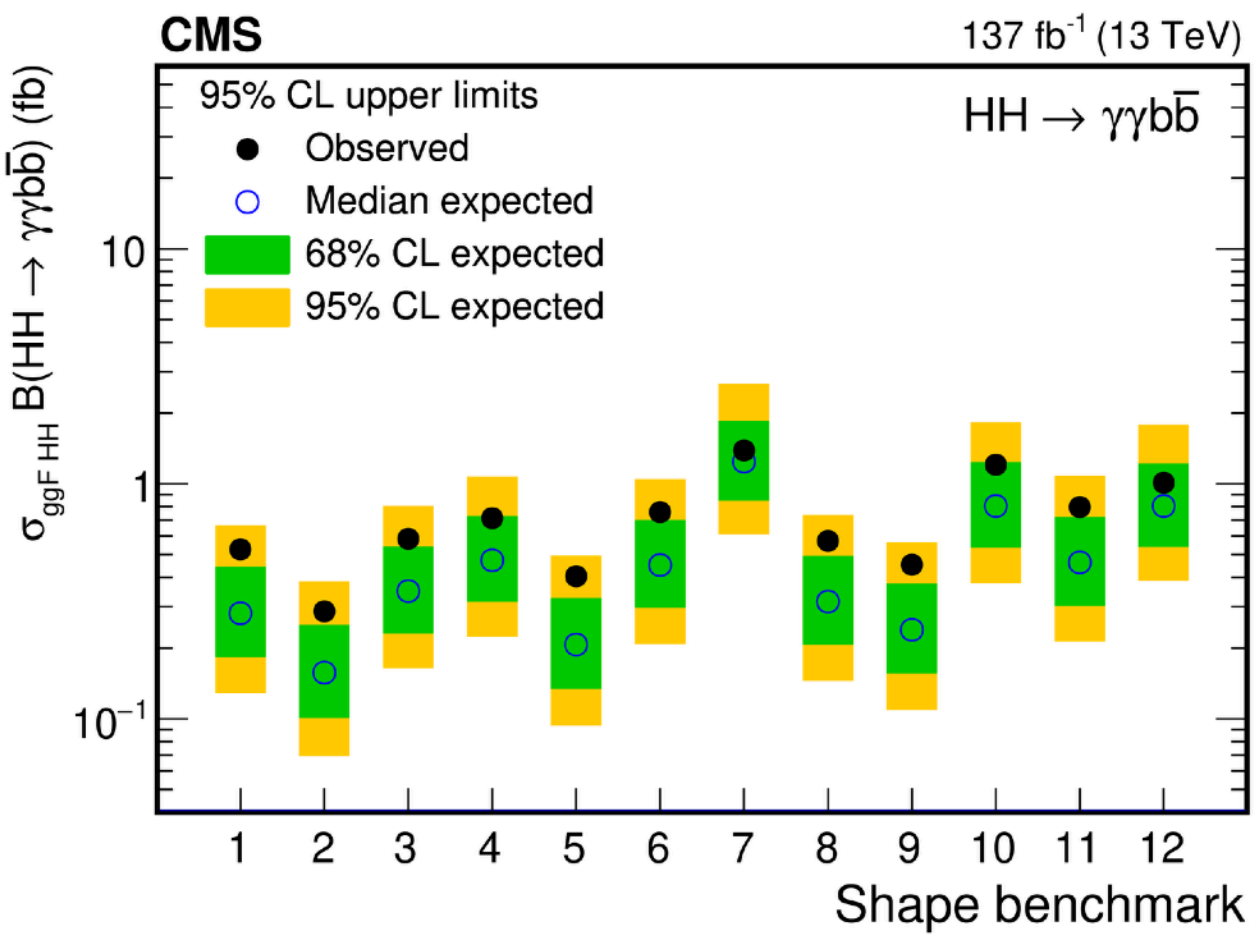
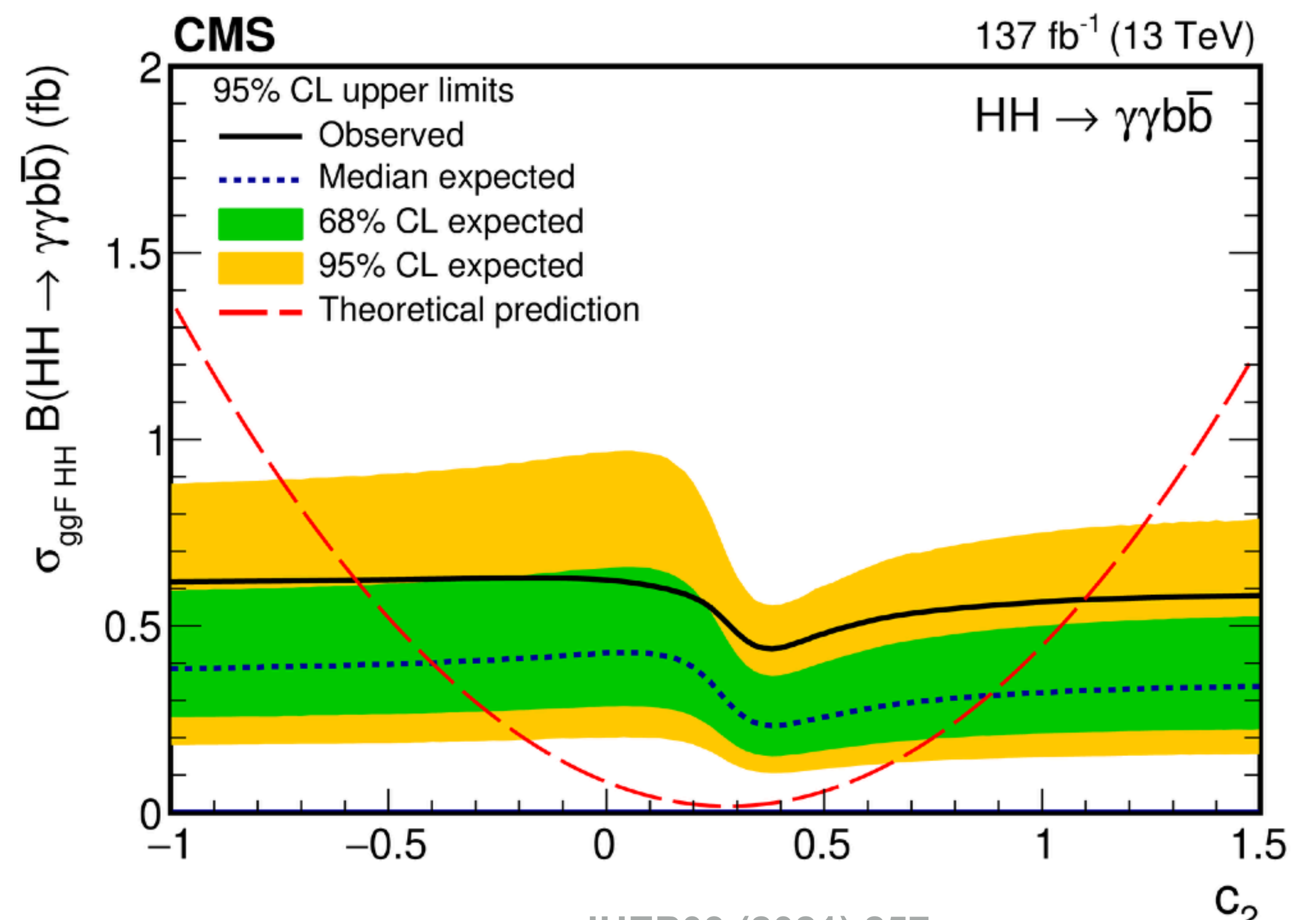
CMS bbγγ

- Limits set on μ_{SM}, κ_λ, and κ_{2V}
- Limits set on 12 EFT benchmarks and on function of C_2 coupling

	1	2	3	4	5	6	7	8	9	10	11	12	SM
κ_λ	7.5	1.0	1.0	−3.5	1.0	2.4	5.0	15.0	1.0	10.0	2.4	15.0	1.0
κ_t	1.0	1.0	1.0	1.5	1.0	1.0	1.0	1.0	1.0	1.5	1.0	1.0	1.0
c_2	−1.0	0.5	−1.5	−3.0	0.0	0.0	0.0	0.0	1.0	−1.0	0.0	1.0	0.0
c_g	0.0	−0.8	0.0	0.0	0.8	0.2	0.2	−1.0	−0.6	0.0	1.0	0.0	0.0
c_{2g}	0.0	0.6	−0.8	0.0	−1.0	−0.2	−0.2	1.0	0.6	0.0	−1.0	0.0	0.0







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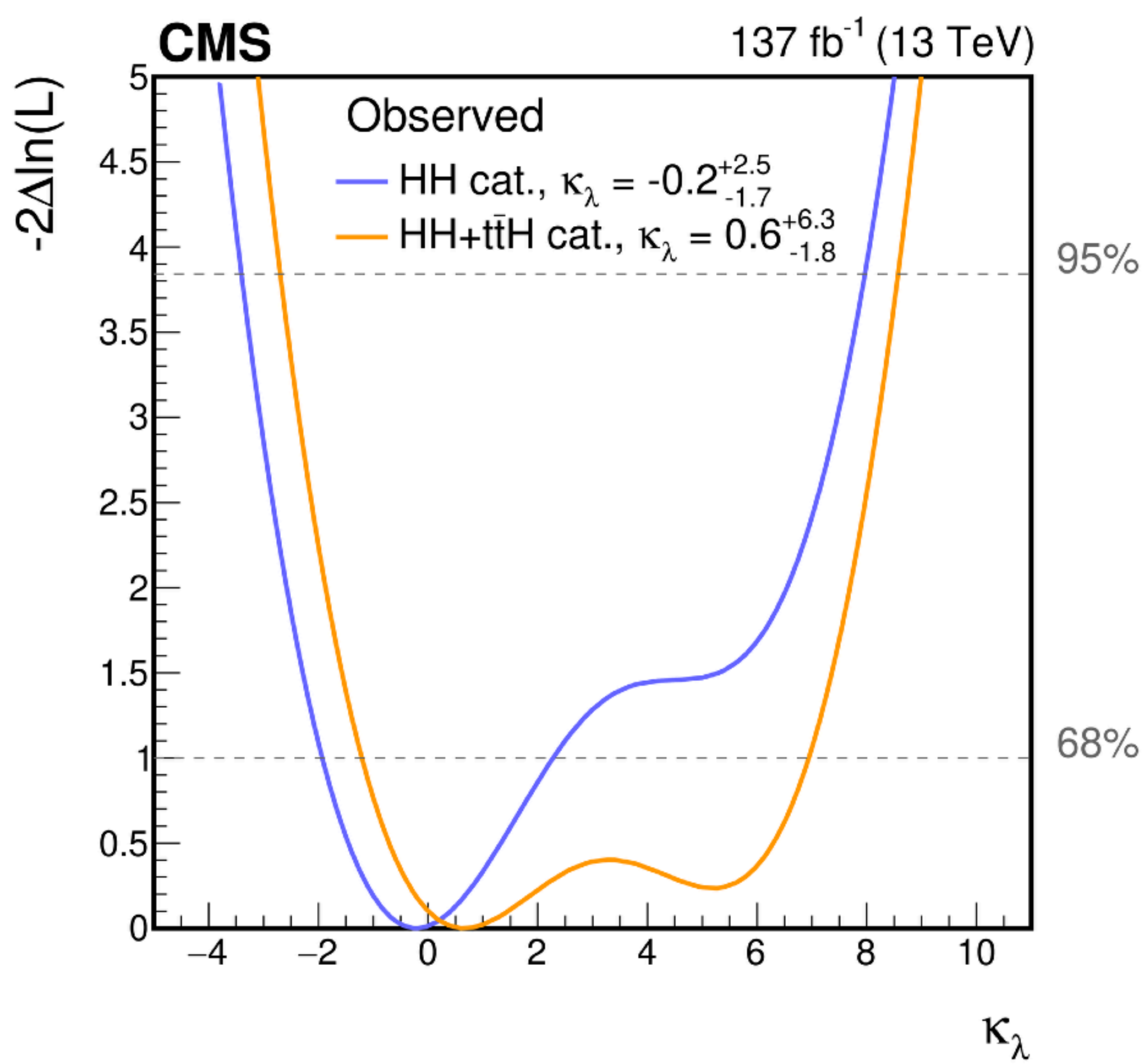
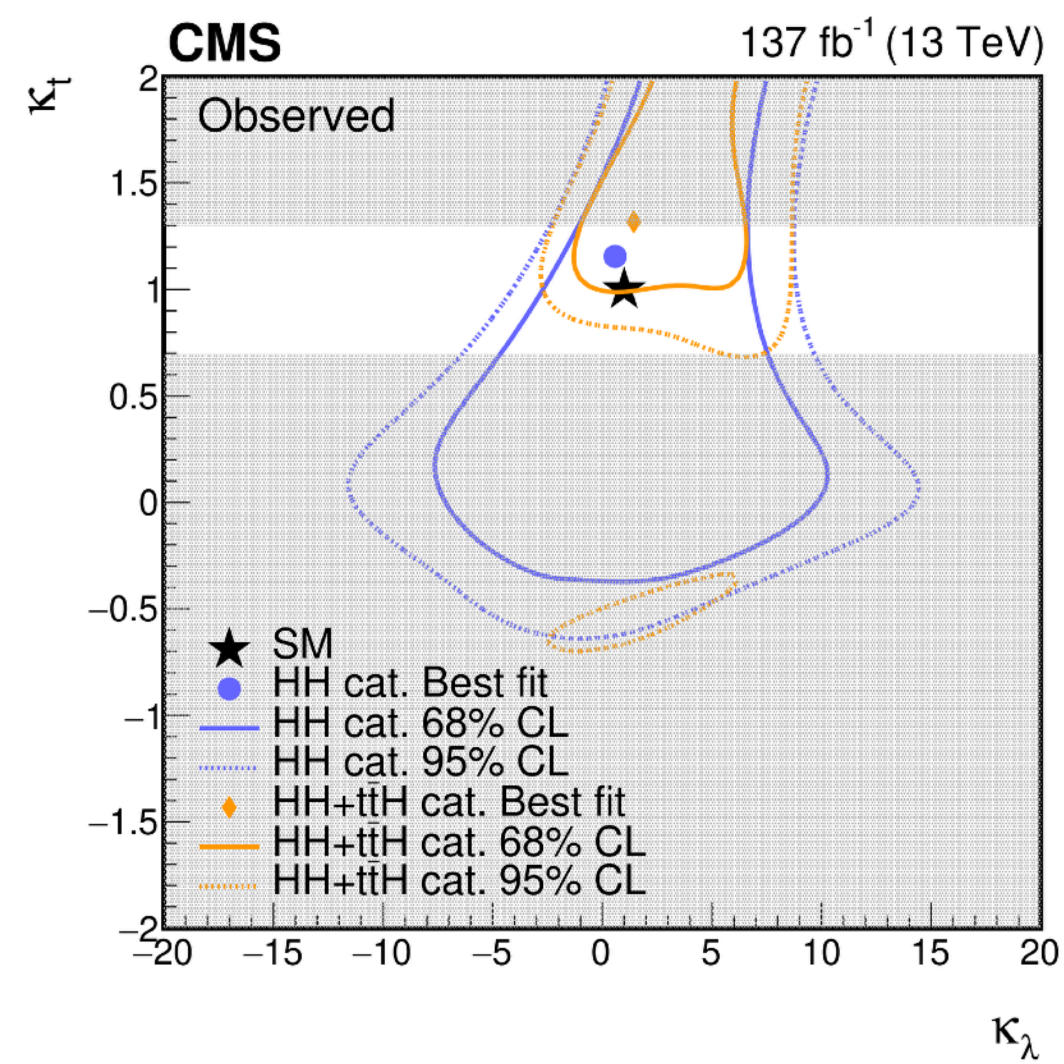
CMS bbγγ

- Limits set on μ_{SM}, κ_λ, and κ_{2V}
- Limits set on 12 EFT benchmarks and on function of C_2 coupling
- Combined with ttH to set limits on κ_λ and κ_t





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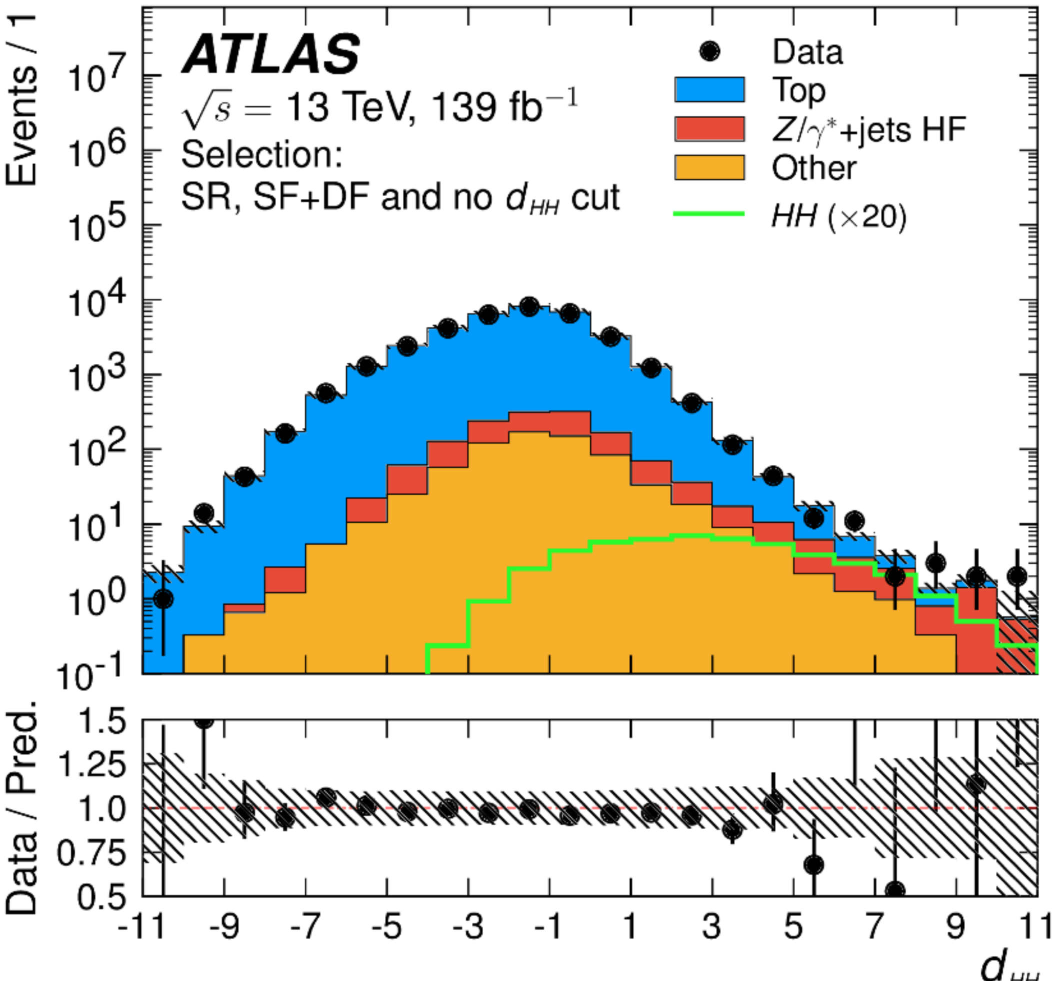
ATLAS bblvlv

- HH→bb+WW*/ZZ*/ττ→bblvlv
- First look at channel
- 2 b-tagged jets and opposite sign 2 e/μ
- Cuts on m_{ll}, m_{bb} and DNN classifier
  - d_{HH} built from kinematic and topology variables

$$d_{HH} = \ln\left[p_{HH} / \left(p_{\text{Top}} + p_{Z\text{-}\ell\ell} + p_{Z\text{-}\tau\tau}\right)\right]$$

- Obs. (exp.) limit: $\mu_{SM} < 40$ (29)



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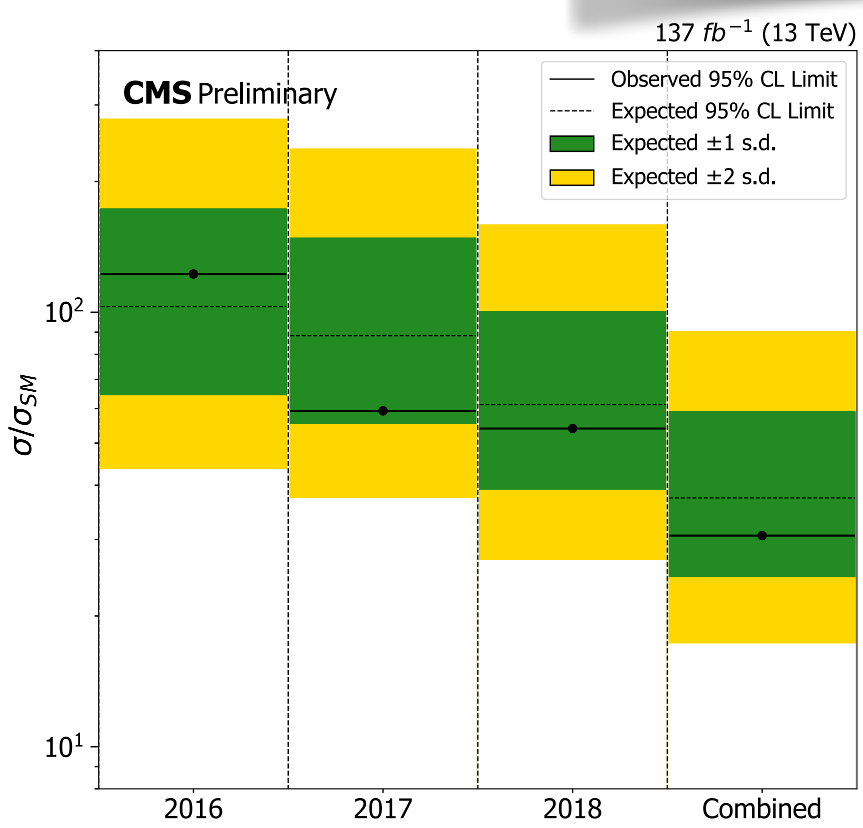
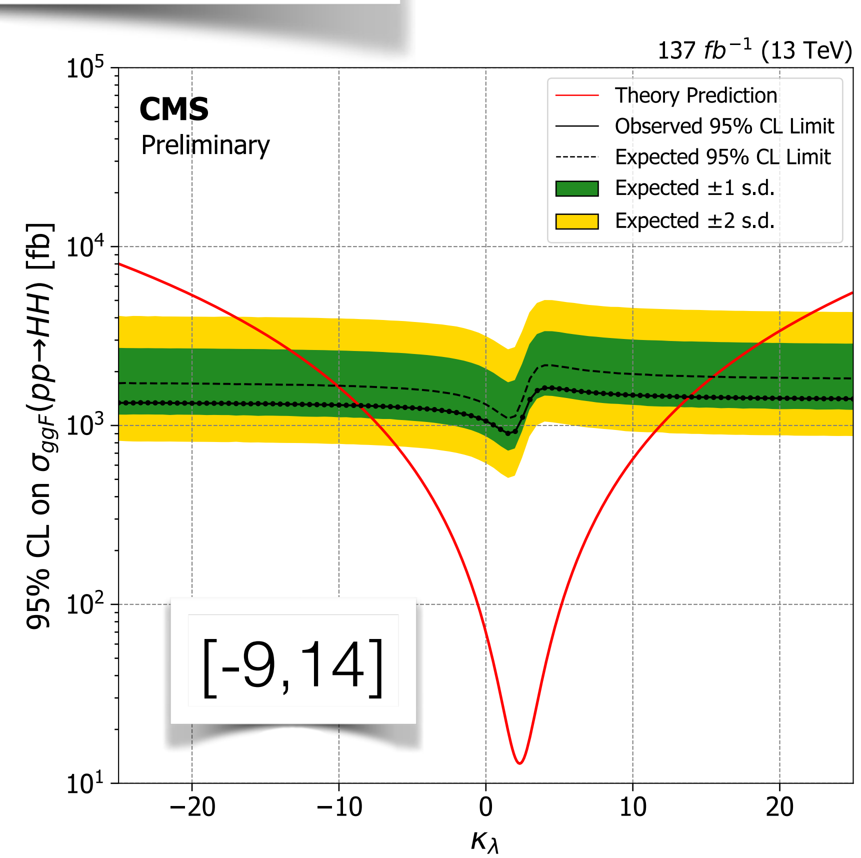
	-2σ	-1σ	**Expected**	$+1\sigma$	$+2\sigma$	**Observed**
$\sigma\,(gg \to HH)$ [pb]	0.5	0.6	0.9	1.3	1.9	1.2
$\sigma\,(gg \to HH)\,/\sigma^{\text{SM}}\,(gg \to HH)$	14	20	29	43	62	40

CMS bbZZ(4l)

- First look at HH→bbZZ*→bbllll
- 2 b-tagged jets and two pairs of same flavor opposite sign e/μ
- Require m4l to be consistent with mH
- BDT used to discriminate against background and in fit

Obs. (exp.) limit: $\mu_{SM} < 30$ (37)

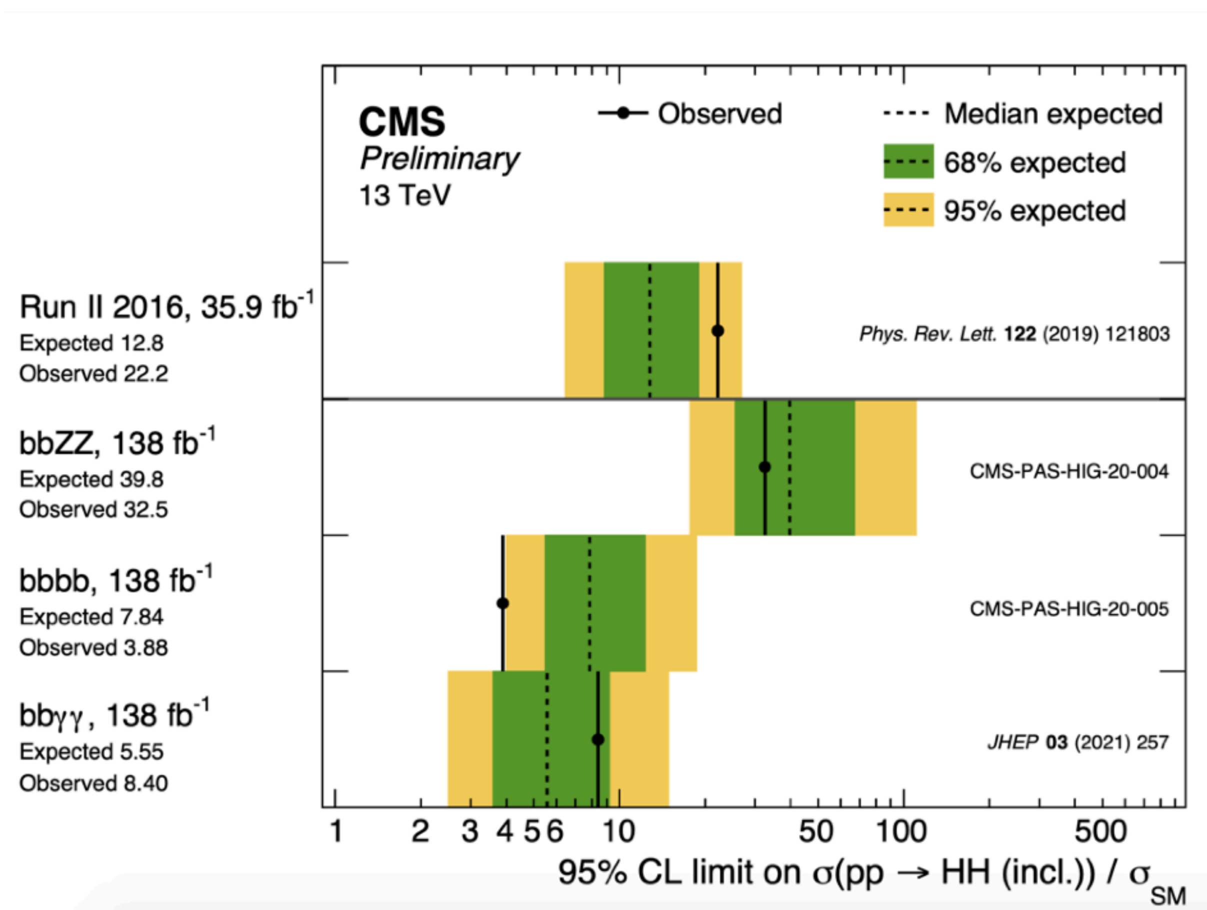


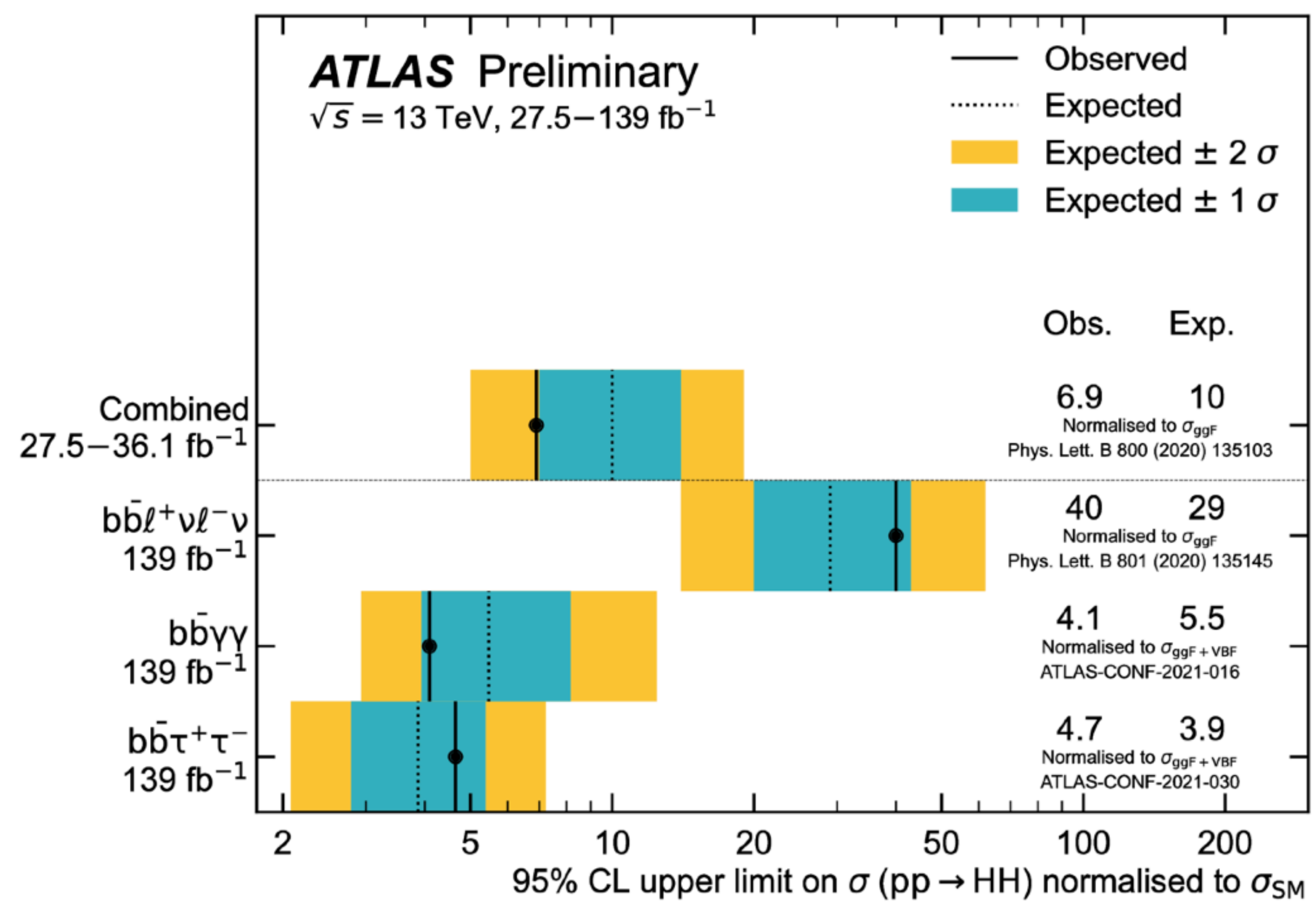


CMS-PAS-HIG-20-004

Summary plots

- Comparison of full Run 2 results to partial Run 2 combination
- Factor of ~2 gain from luminosity
- Additional gains from reconstruction and analysis improvements



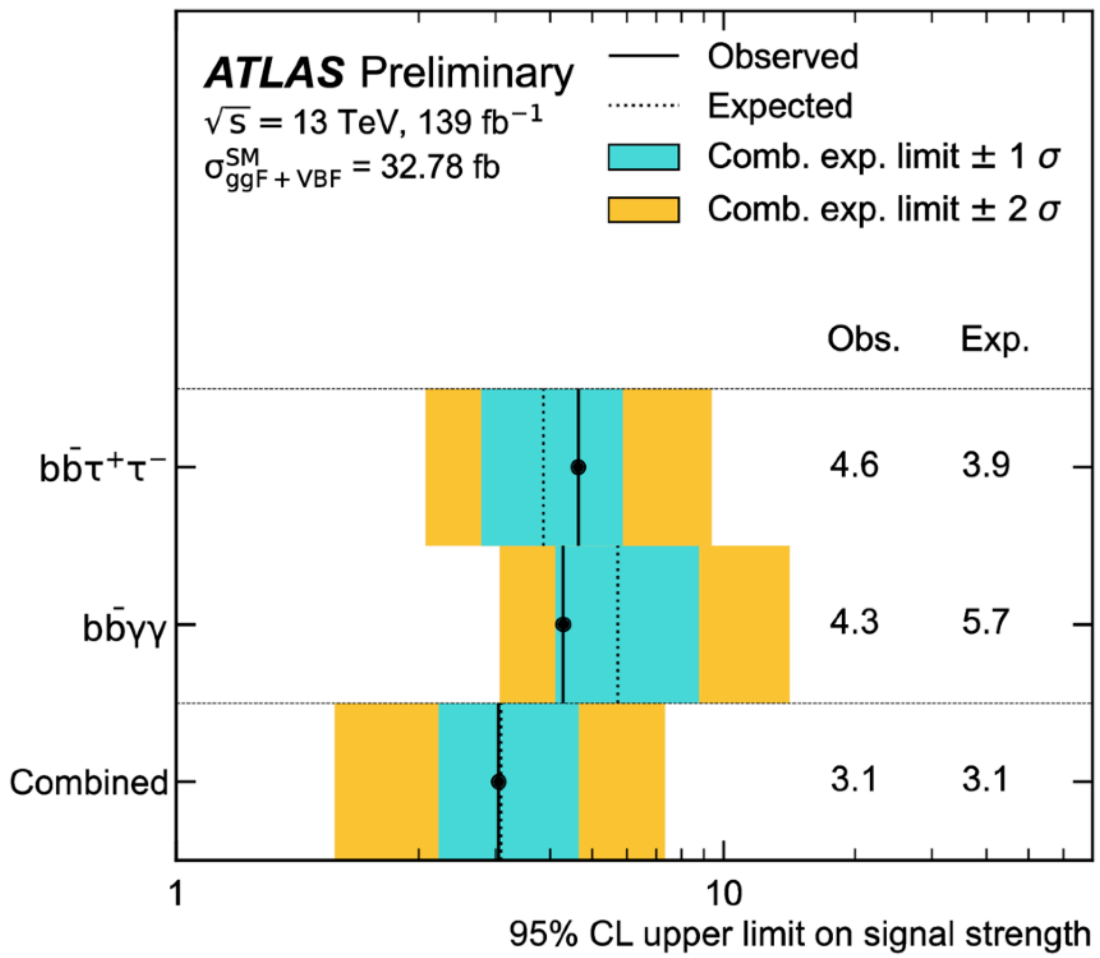


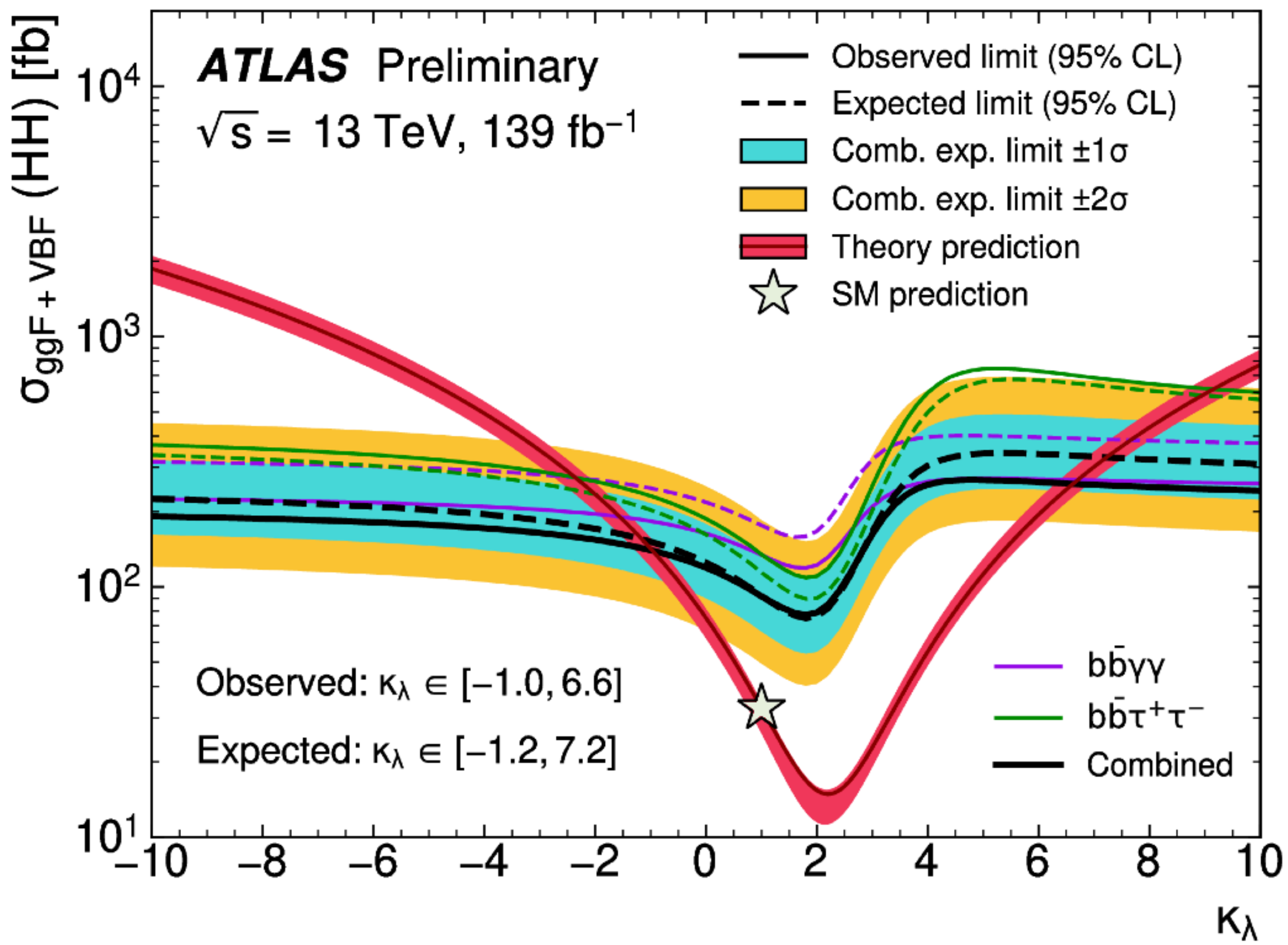
CMS Summary Plots

ATL-PHYS-PUB-2021-031

ATLAS Combination

- Statistical combination of bbττ and bbγγ results

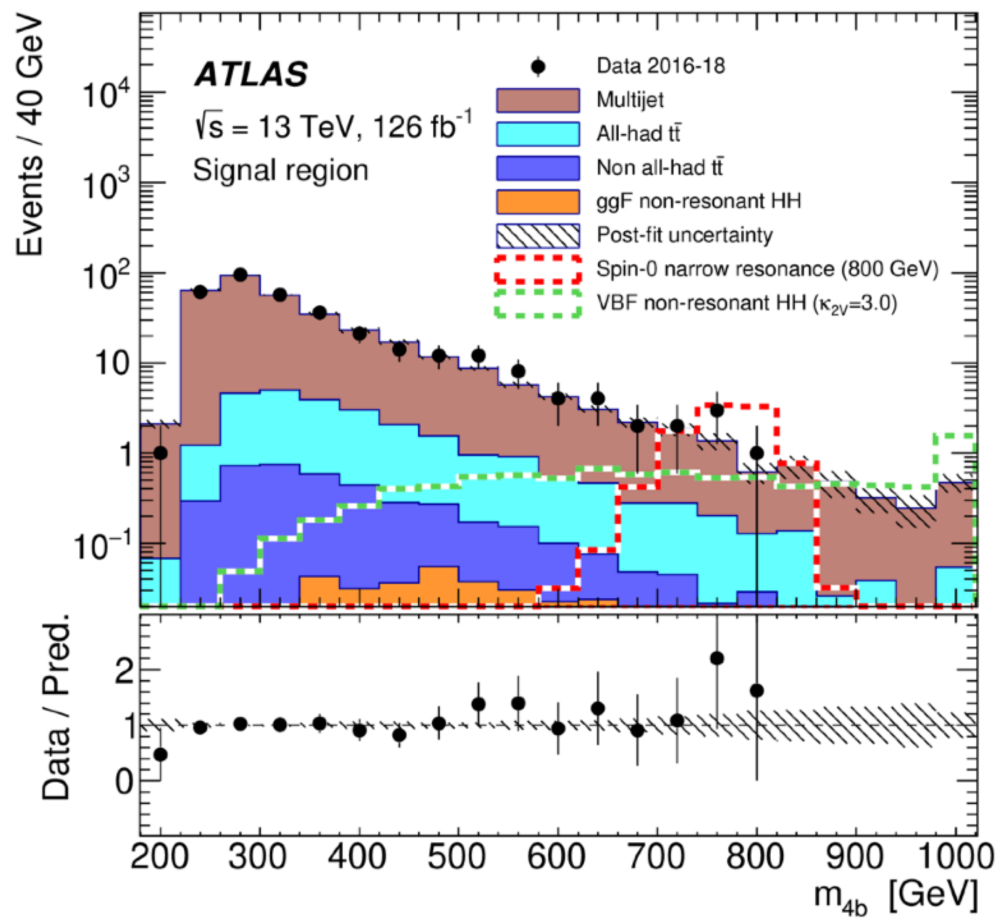


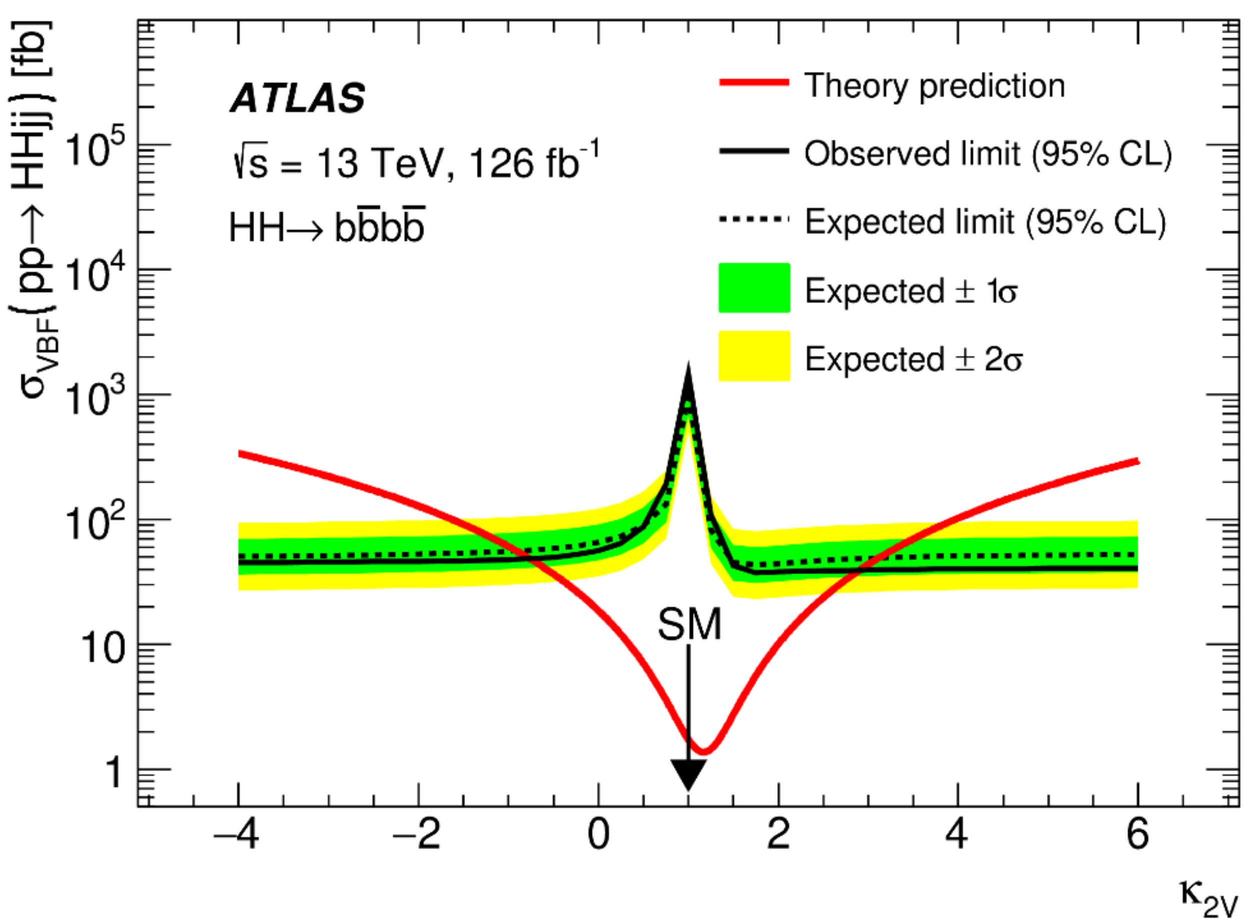


ATLAS-CONF-2021-052

ATLAS 4b VBF

- First VBF HH results
- 4 central b-tagged jets and 2 forward jets
- Data-driven background estimate





Obs. (exp.) limit: μ_{SM} < 840 (550)

-0.56 (-0.91) < κ_{2V} < 2.89 (3.11)

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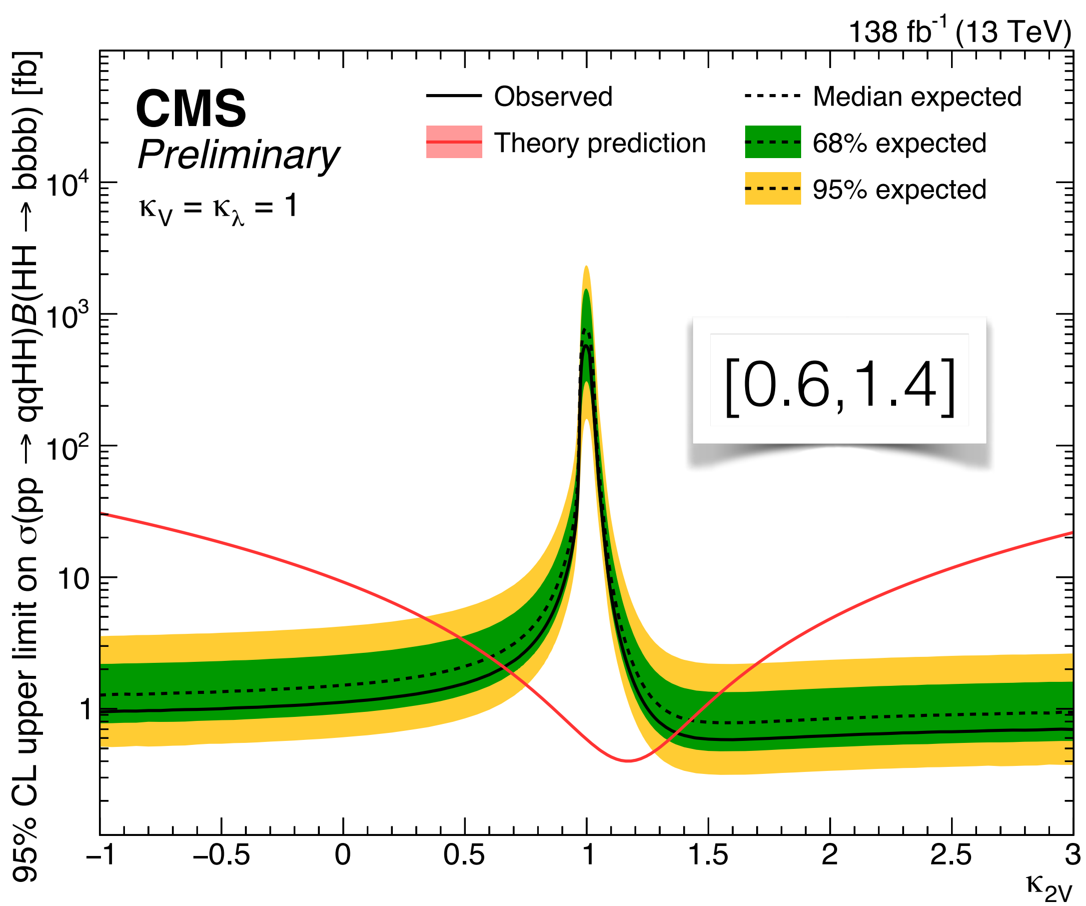
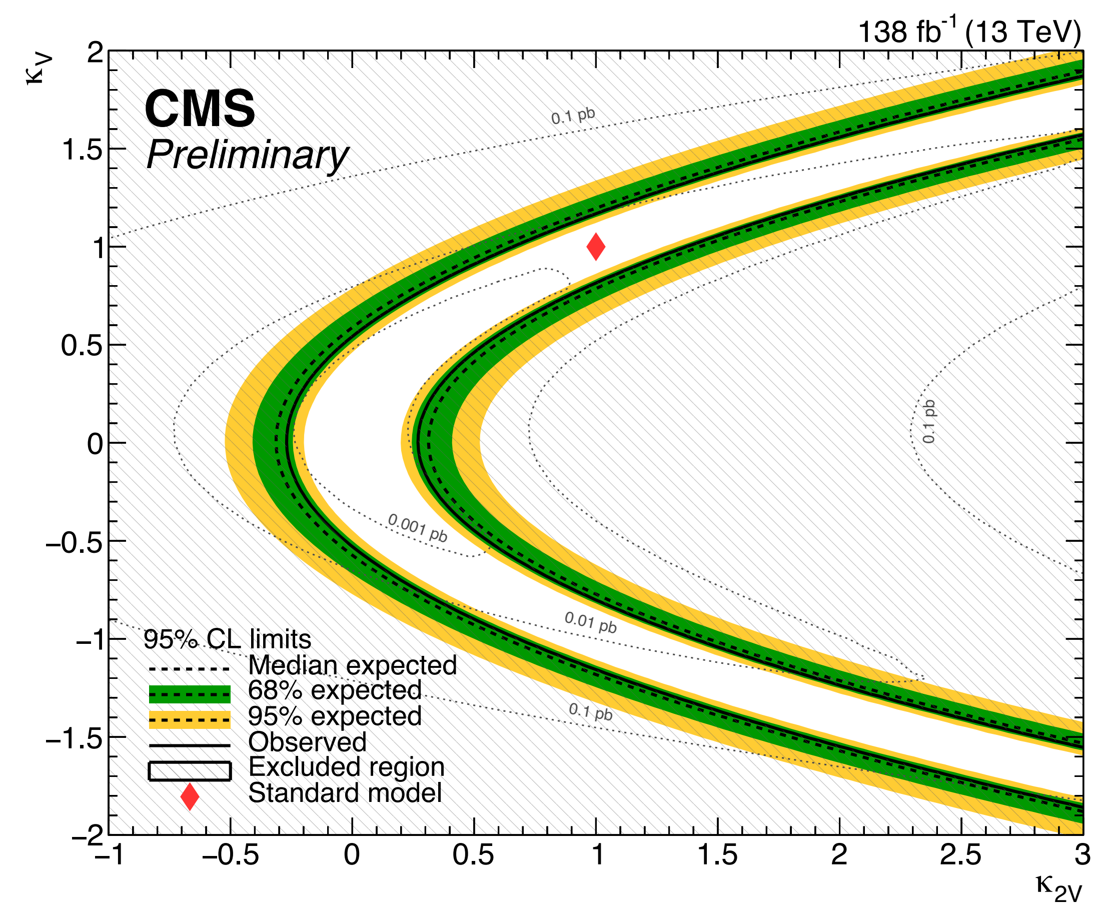
CMS boosted 4b VBF

- First boosted VBF HH results
- Require two forward jets and two large-R jets
- Use ParticleNet NN to identify H→bb and jet mass regression
- Data-driven QCD background estimate
- κ_{2V} = 0 excluded at CL > 99.99%





CMS-PAS-B2G-21-001

Summary

- Search for non-resonant HH production is a key (HL-)LHC goal

- No single golden channel - combination is necessary
  - Full Run 2 combination constrain σ_{HH}, κ_{λ} and κ_{2V}
  - $\kappa_{2V} = 0$ excluded
  - HEFT benchmark exclusions available

- Stay tuned for more full Run 2 results…

Thank you for your attention