

HH searches in CMS

Agni Bethani for the CMS collaboration

EPS 2021
27th July

Higgs pair production at the LHC

- Higgs field potential:

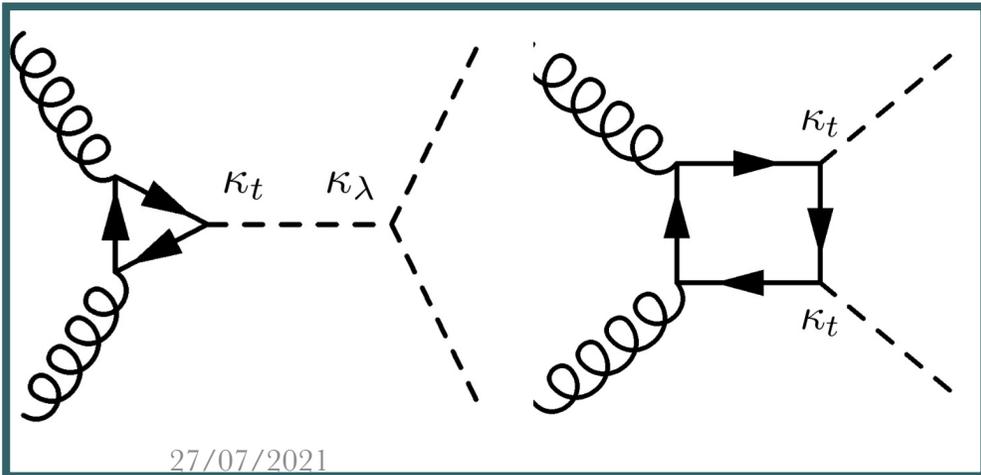
$$V(h) = V_0 + \frac{1}{2} m_h^2 h^2 + \frac{m_h^2}{2v^2} v h^3 + \frac{1}{4} \frac{m_h^2}{2v^2} h^4 + \dots$$

Mass term

Higgs trilinear self-coupling ($\kappa\lambda$)
Higgs pair production

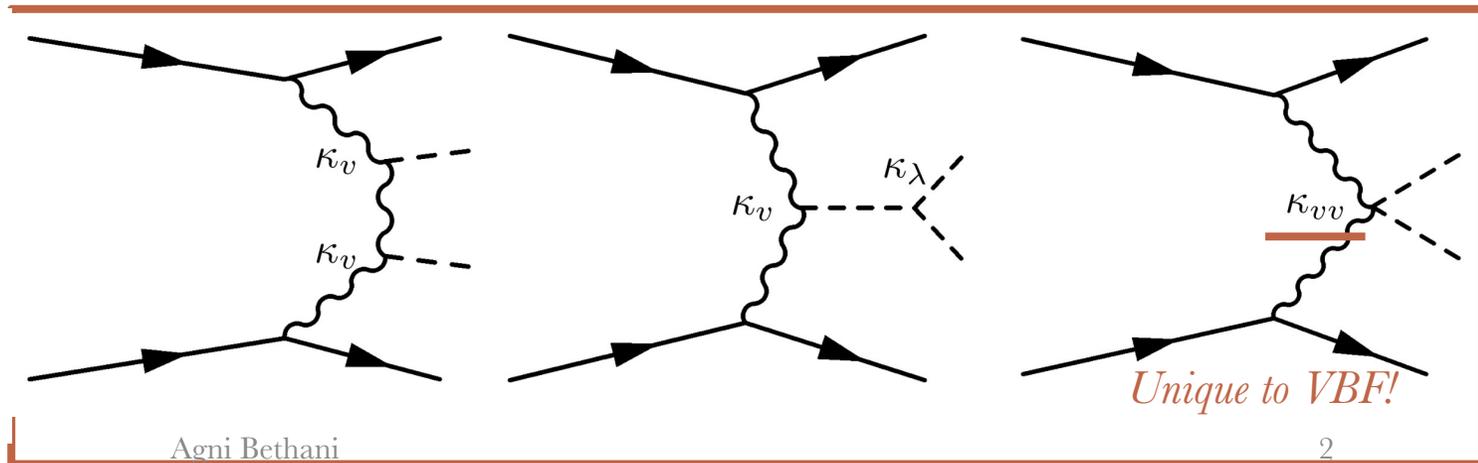
Higgs quadratic self-coupling

Gluon Gluon Fusion (GGF)



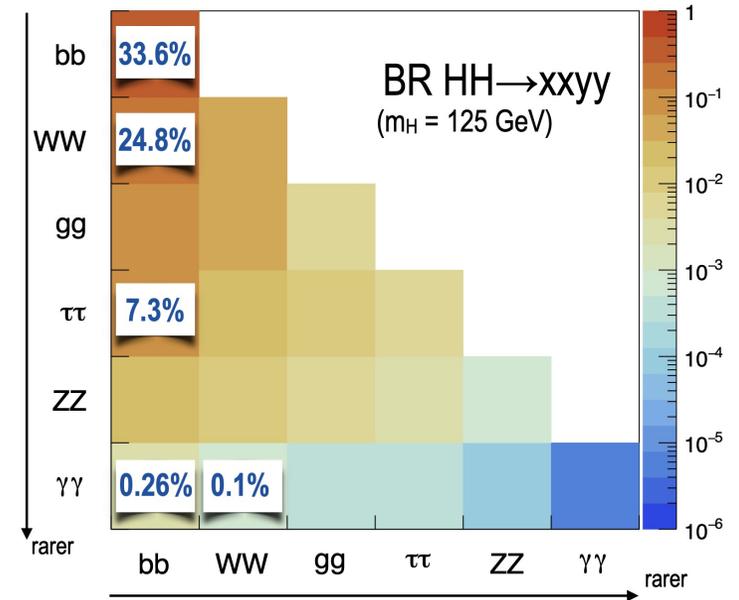
27/07/2021

Vector Boson Fusion



Agni Bethani

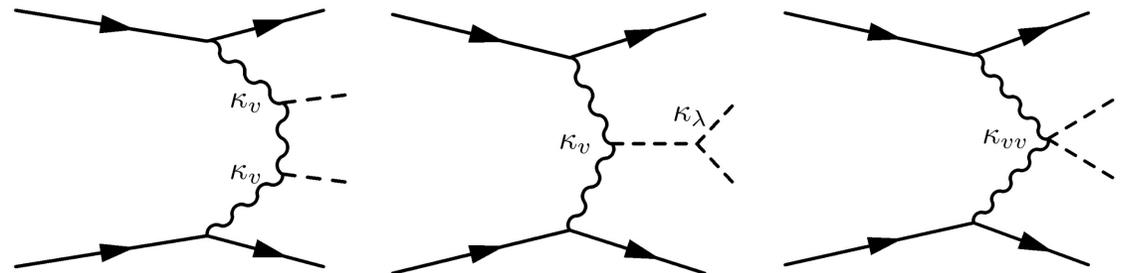
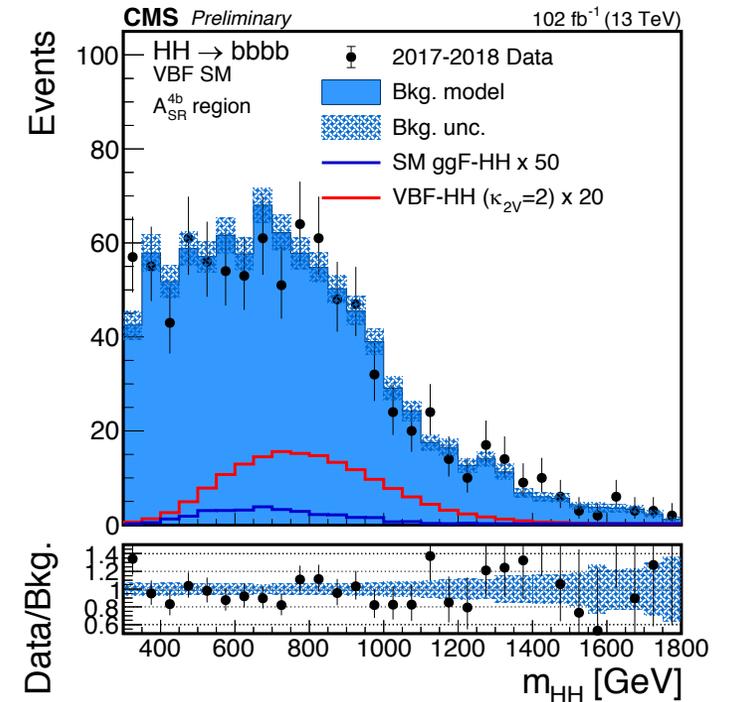
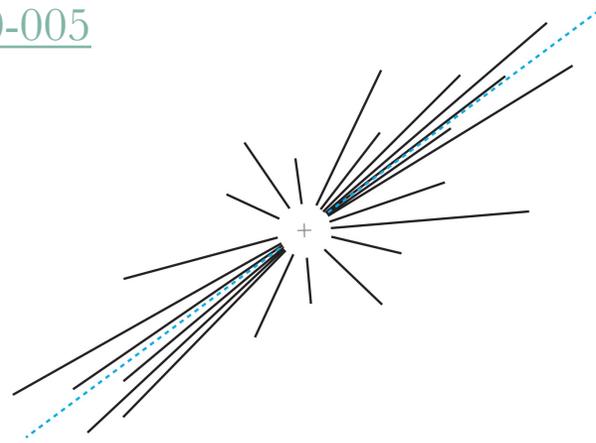
2



Non-resonant and SM searches

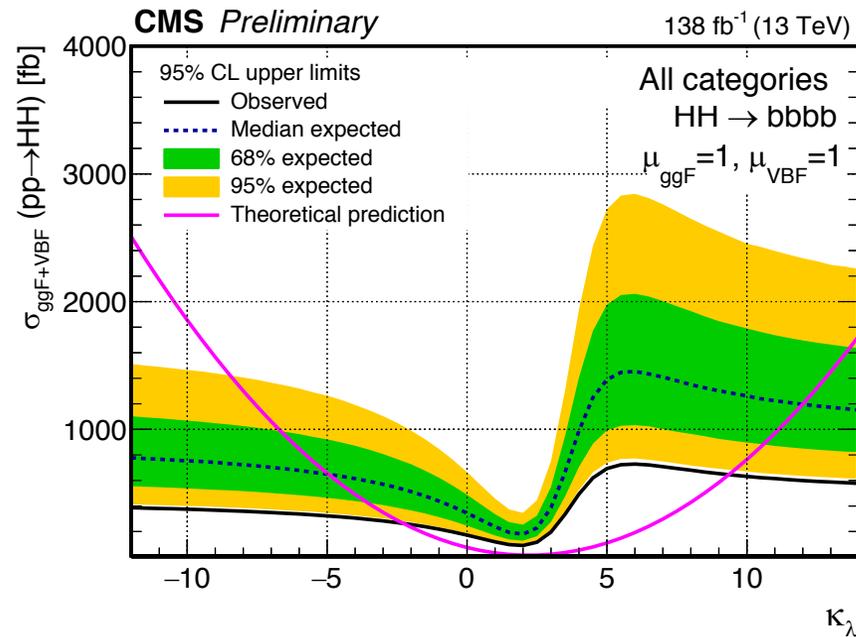
bbbb (resolved) [HIG-20-005](#)

- 4 distinct b-jets in the final state
 - large combinatoric background
- Large QCD multijets background
 - datadriven!
- Study both GGF and VBF
- GGF strategy
 - BDT to discriminate GGF HH vs background
 - GGF high mass
 - GGF low mass
 - GGF categories: fit on BDT discriminator
- VBF strategy (requiring 2 extra jets)
 - BDT to discriminate GGF and VBF (GGFKiller)
 - Categories based on GGF killer
 - VBF SM
 - VBF anomalous couplings
 - VBF categories fit on m_{HH}

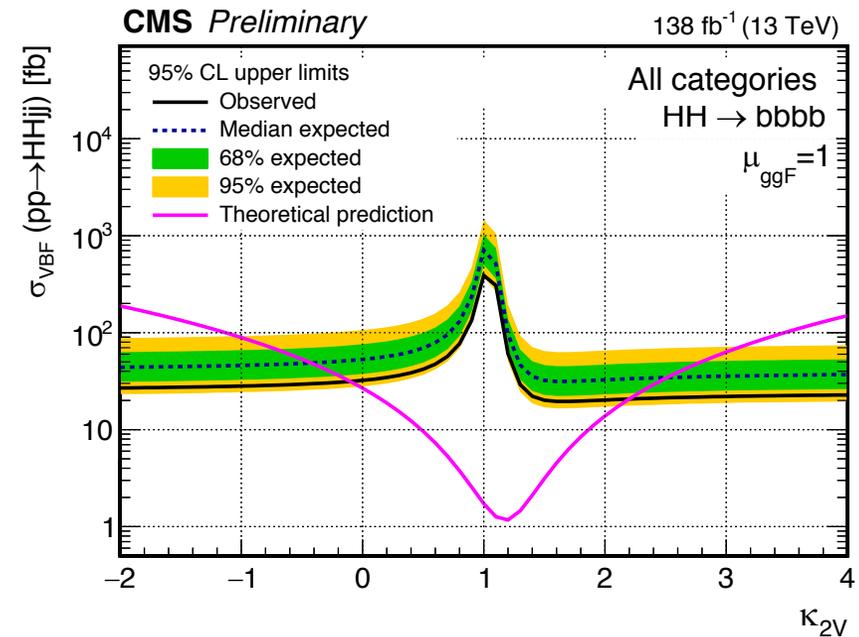


bbbb (resolved)

Observed (expected) $\sigma/\sigma_{\text{SM}} < 3.7(7.3)$ at 95% CL



Observed: $-2.5 < \kappa_\lambda < 9.5$
Expected: $-5.0 < \kappa_\lambda < 12.0$

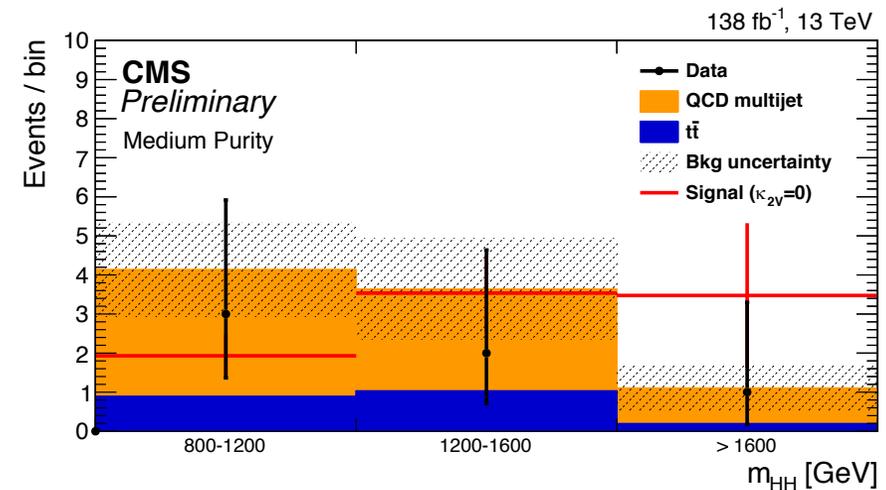
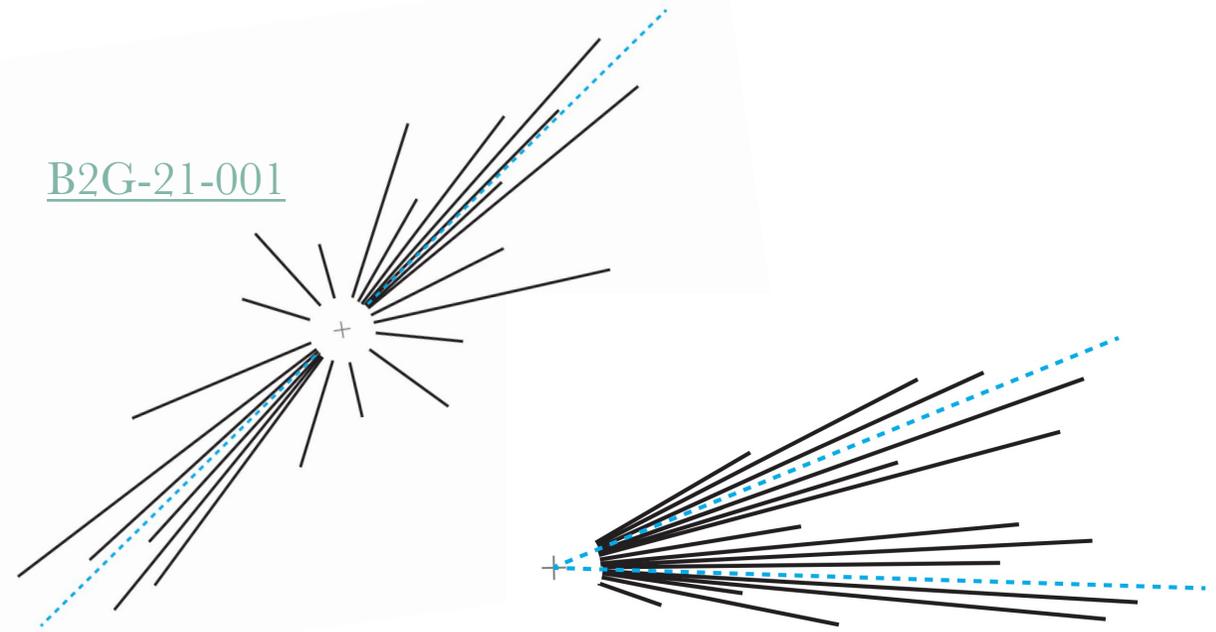


Observed: $-0.1 < \kappa_{\text{vV}} < 2.2$
Expected: $-0.4 < \kappa_{\text{vV}} < 2.5$

bbbb(VBF boosted) New!

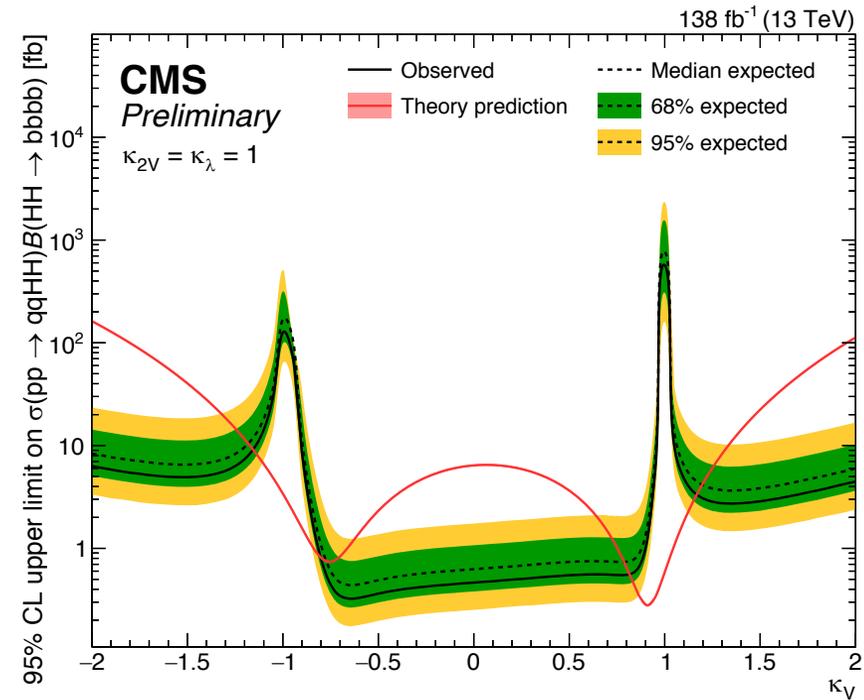
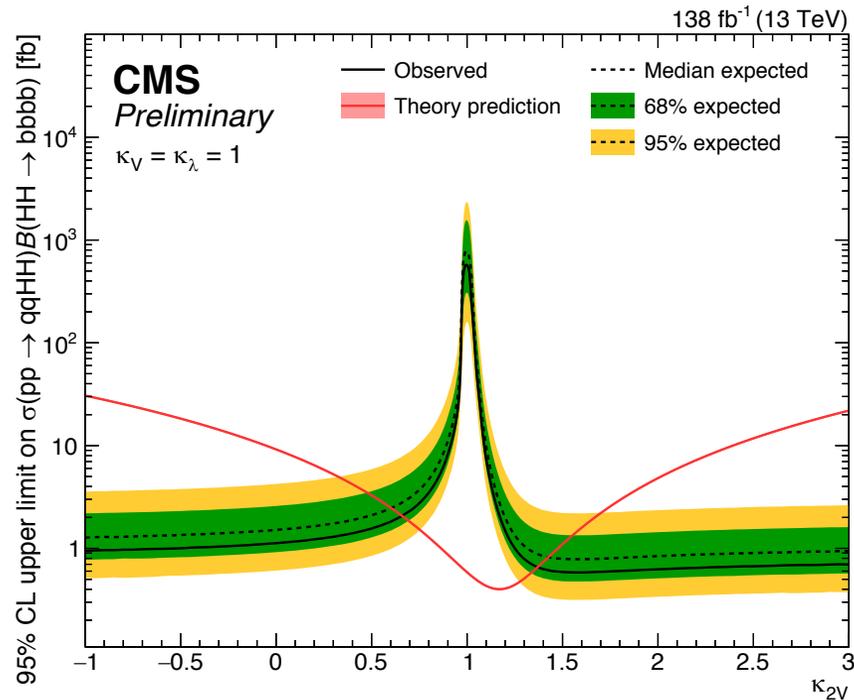
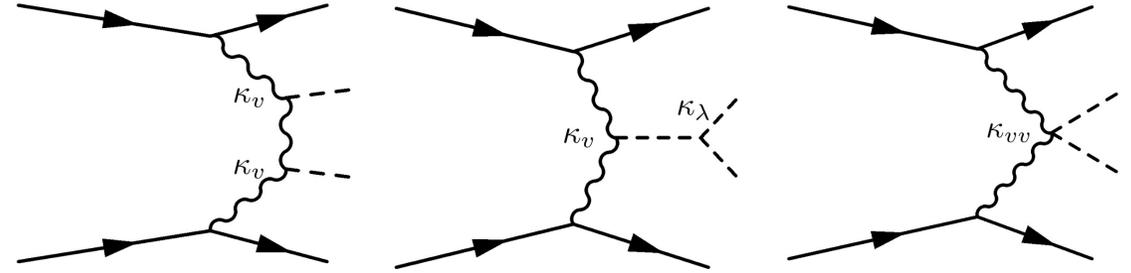
B2G-21-001

- Modified couplings can lead to boosted topologies!
- Less combinatorics than resolved search
 - 2 defined large R jets, 1 per Higgs decay.
- H→bb identified using novel neural network (NN) algorithm, ParticleNet
 - graph convolutional NNs, multi-classifier
 - 3 event categories according the ParticleNet score (high, medium and low purity)
- ParticleNet also used for jet mass regression
- QCD multijet background estimated using sidebands in data
- Fit is performed on m_{HH}

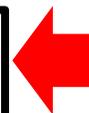


$\kappa_{VV}=0$ is shown in red
Very sensitive search!

bbbb(VBF boosted) New!



Observed: 0.6 < κ_{vν} < 1.4
Expected: 0.6 < κ_{vν} < 1.4



Best to date!
Assuming κ_t=κ_v=1,
κ_{vν}=0 is excluded at a
CL higher than 99.99%.
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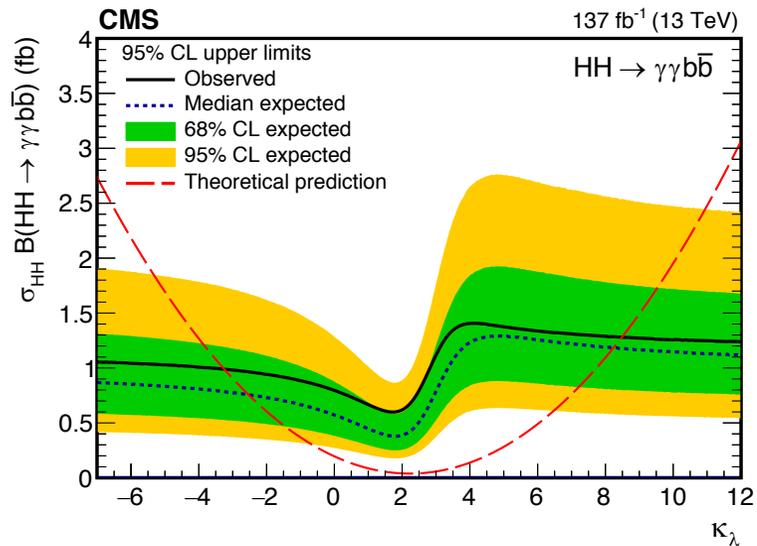
κ_v compatible with SM

bbγγ HIG-19-018

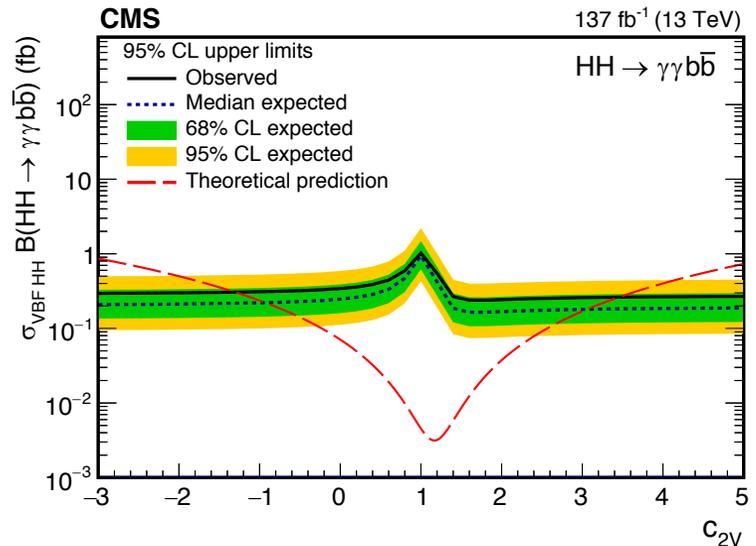
- Final state: 2 γ and 2 b-jets
- Both GGF and VBF production studied
- SpecificMVA discriminator against ttH background

Observed (expected) $\sigma/\sigma_{SM} < 7.7(5.2)$ at 95% CL

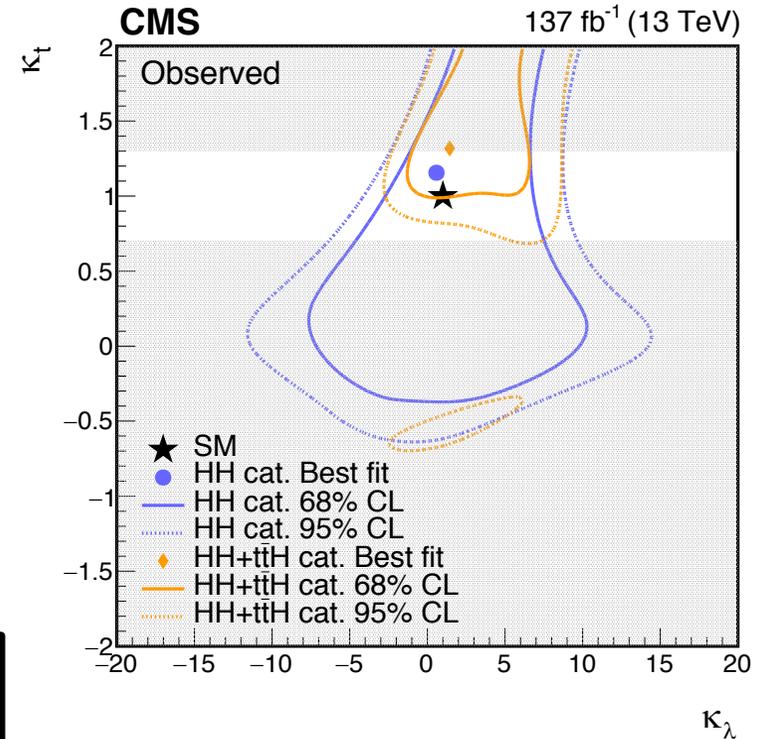
**combination with
ttH category,
improved
constraints on κ_t**



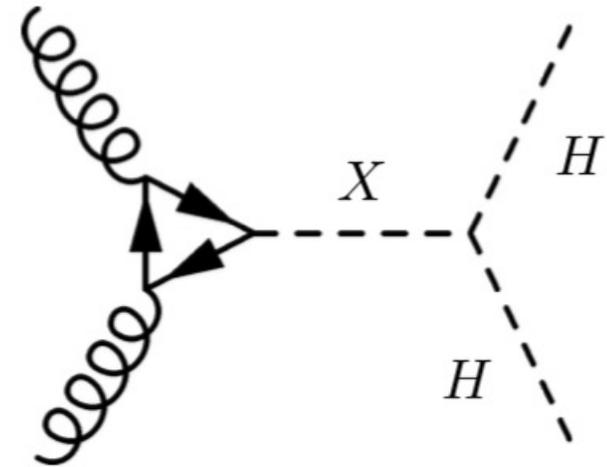
**Observed: $-3.3 < \kappa_\lambda < 8.5$
Expected: $-2.5 < \kappa_\lambda < 8.2$**



**Observed: $-1.3 < \kappa_{VV} < 3.5$
Expected: $-0.9 < \kappa_{VV} < 3.0$**



Resonant searches



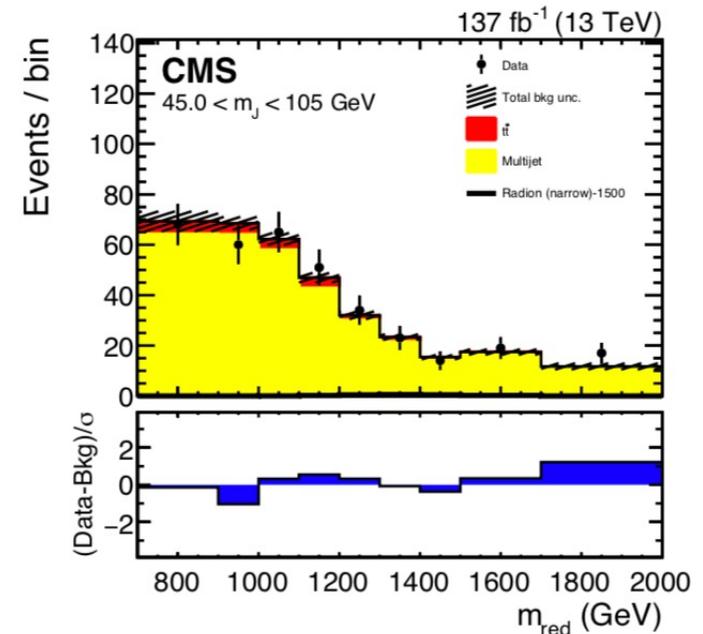
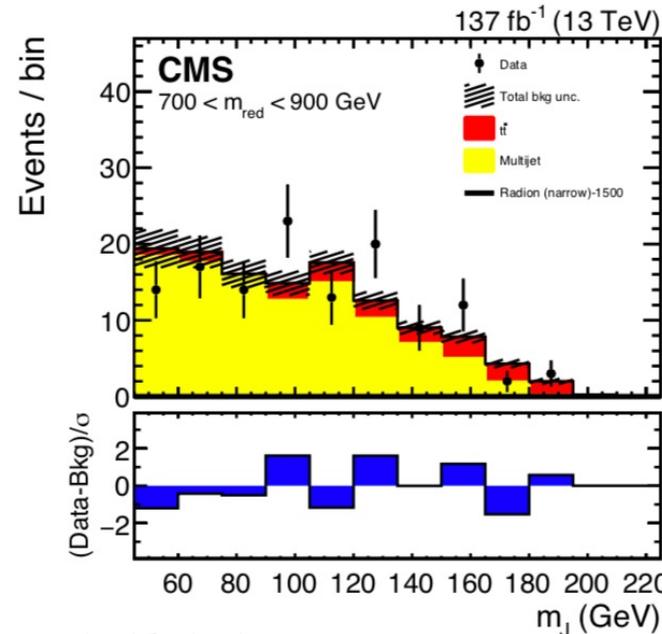
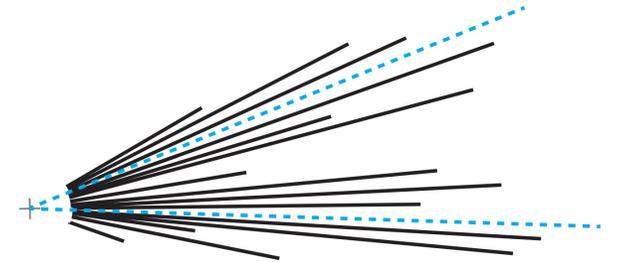
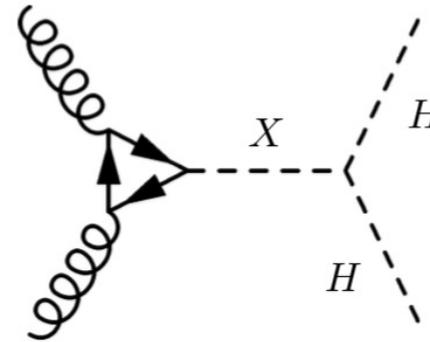
bbbb (boosted and semi-boosted)

New!

B2G-20-004

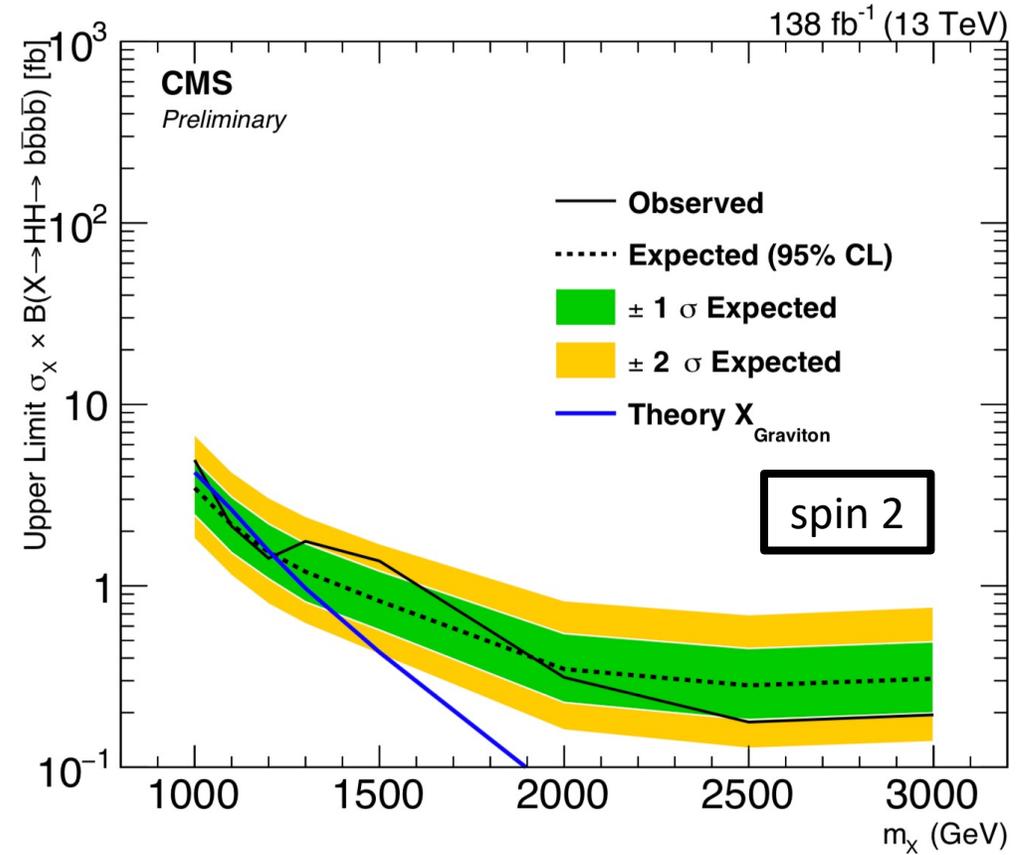
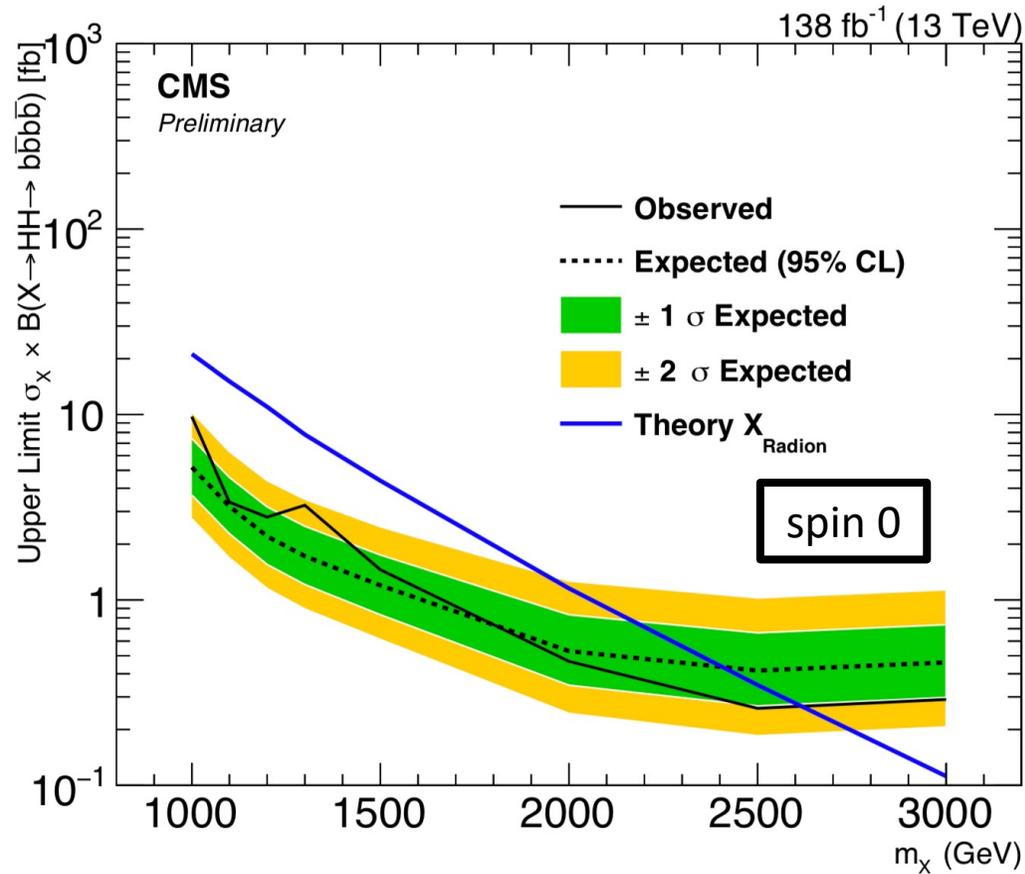
- Search for resonances
 $1\text{ TeV} < m_X < 3\text{ TeV}$
spin 0 (Radion) and spin 2 (Graviton)
- Large R jets identified by DeepAk8
- 3 event categories
 - 2 large R jets both pass tight selection
 - 2 large R jets both pass loose selection
 - 1 large R jet and 2 resolved jets
- QCD multijets background: datadriven
- Fit is performed on 2D m_{J1} vs m_{jjred}

$$m_{jjred} \equiv m_{JJ} - (m_{J1} - m_H) - (m_{J2} - m_H)$$



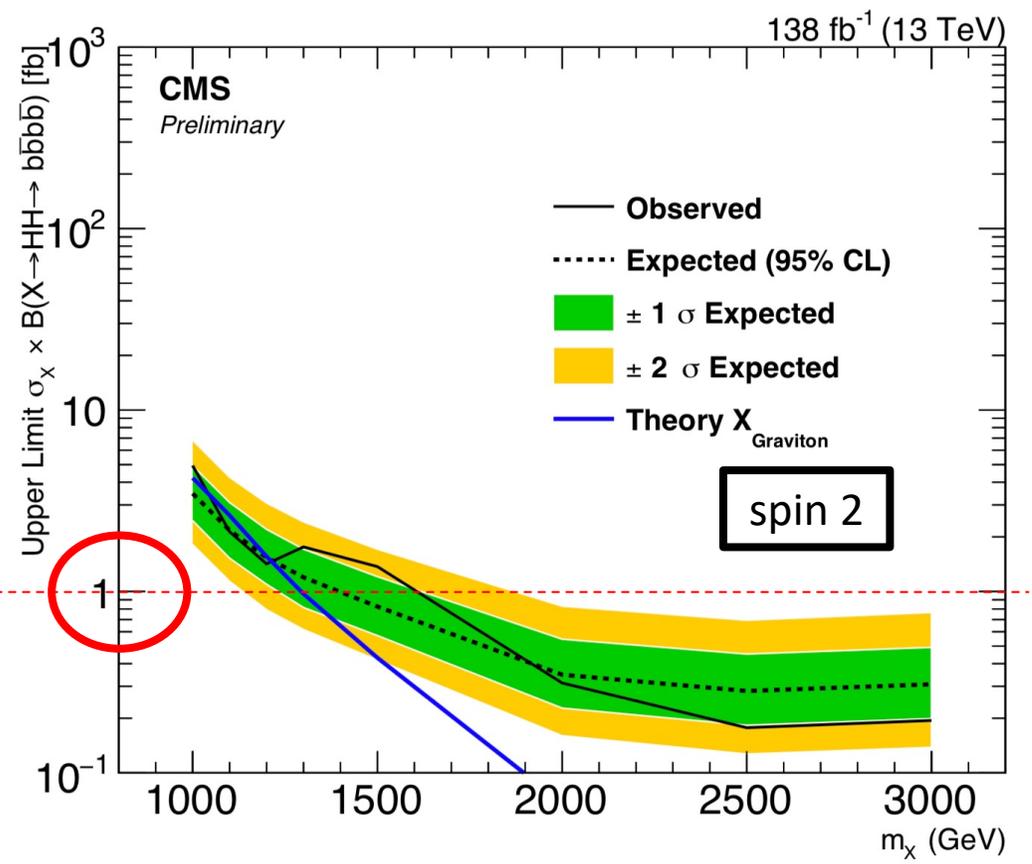
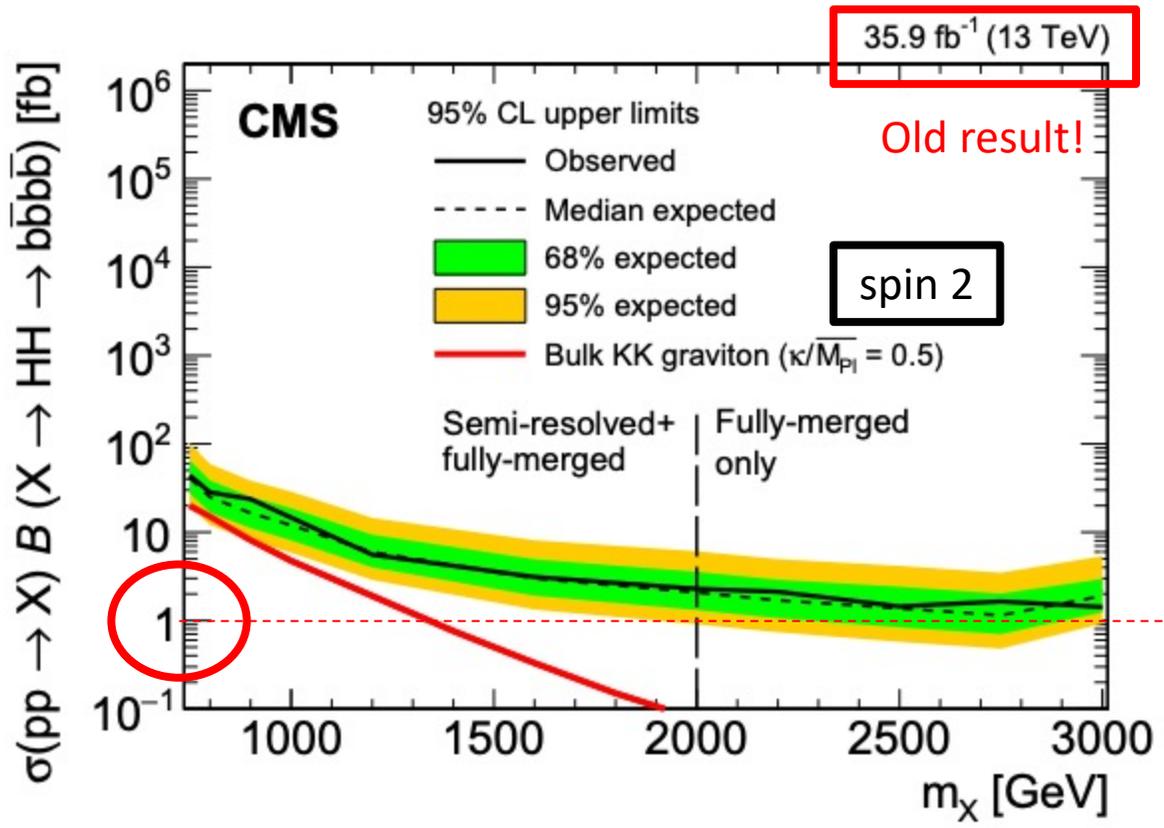
bbbb (boosted and semi-boosted)

New!



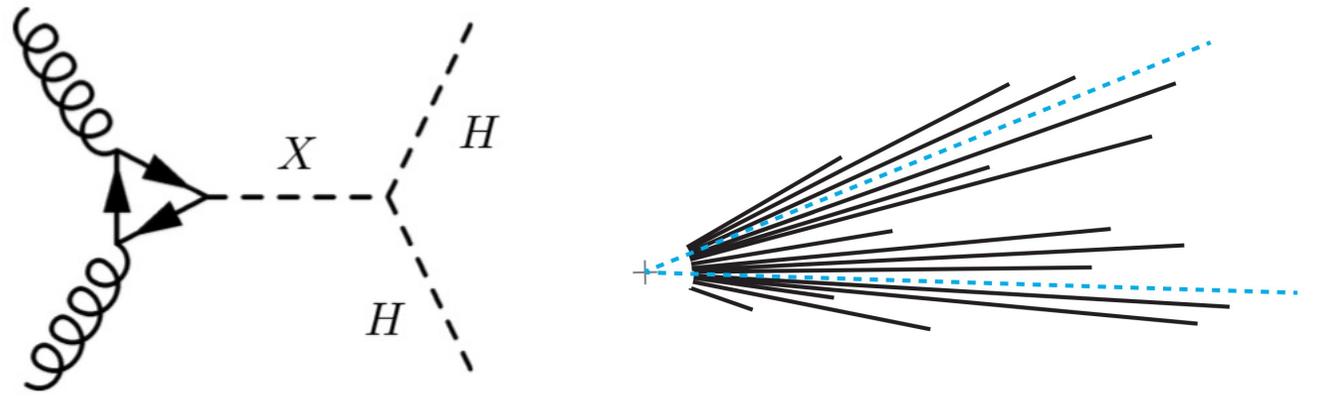
bbbb (boosted and semi-boosted)

New!

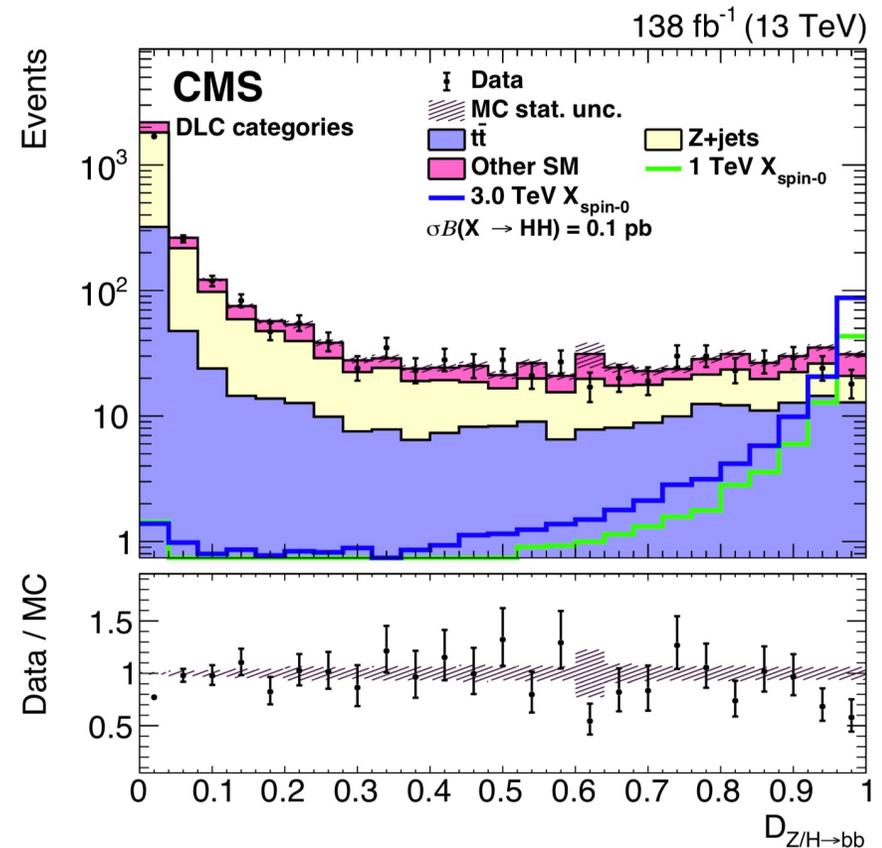


bbWW

New! B2G-20-007

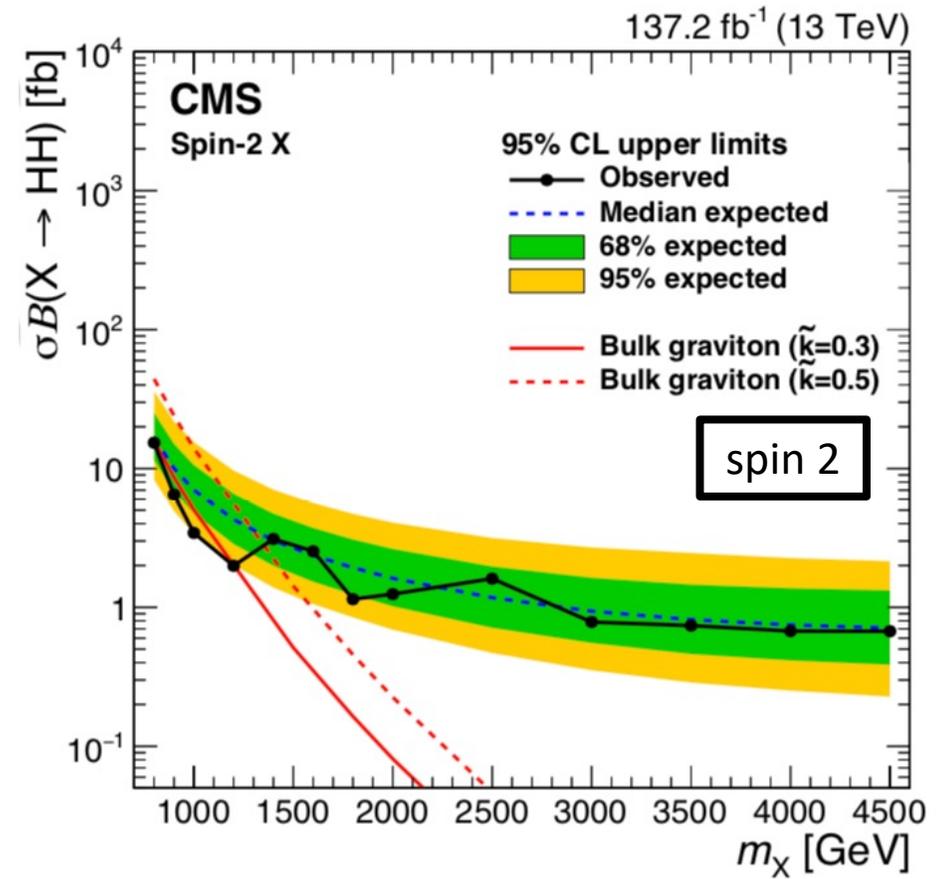
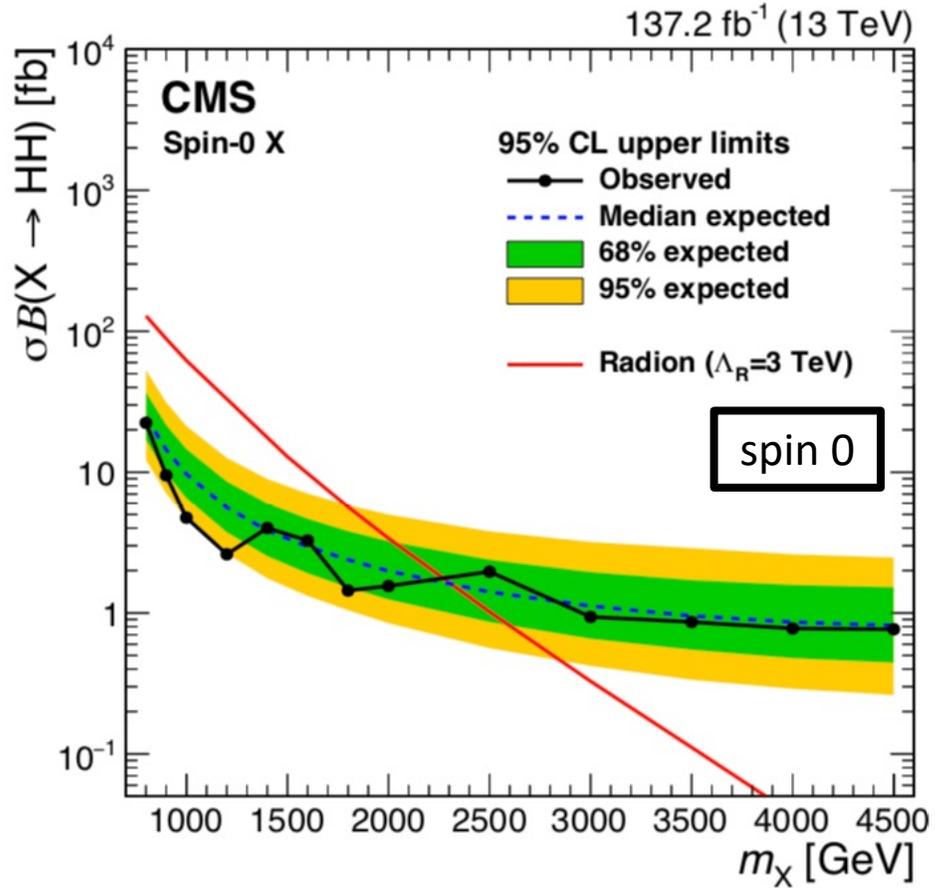


- Search for resonances
 $1\text{ TeV} < m_X < 4.5\text{ TeV}$
spin 0 (Radion) and spin 2 (Graviton)
- $H \rightarrow bb$
 - Large R jet identified by $H \rightarrow bb$ tagger ($D_{Z/H \rightarrow bb}$)
- $H \rightarrow WW$ (or $H \rightarrow \tau\tau$)
 - Single-lepton (11) channel
 - Dilepton (21) channel
- 8 categories in 11, 4 categories in 21
 - according the lepton flavour and $D_{Z/H \rightarrow bb}$ and signal purity (11)
- Simultaneous fit in 2D m_{bb} - m_{HH} plane



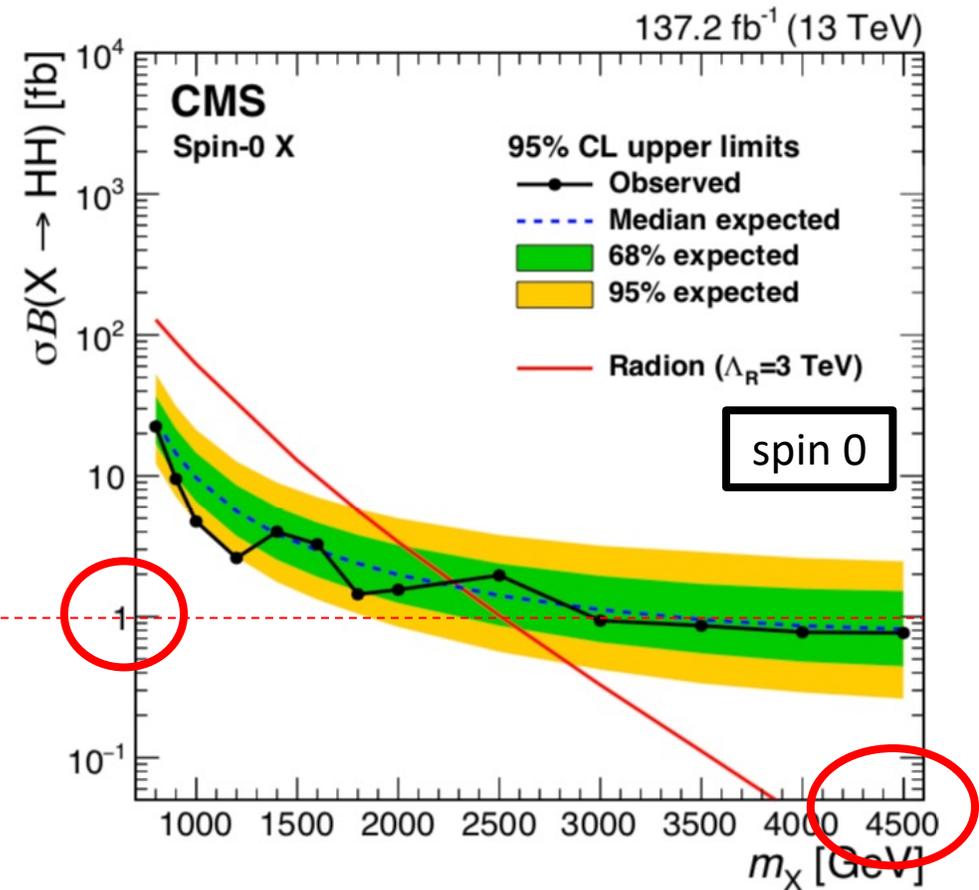
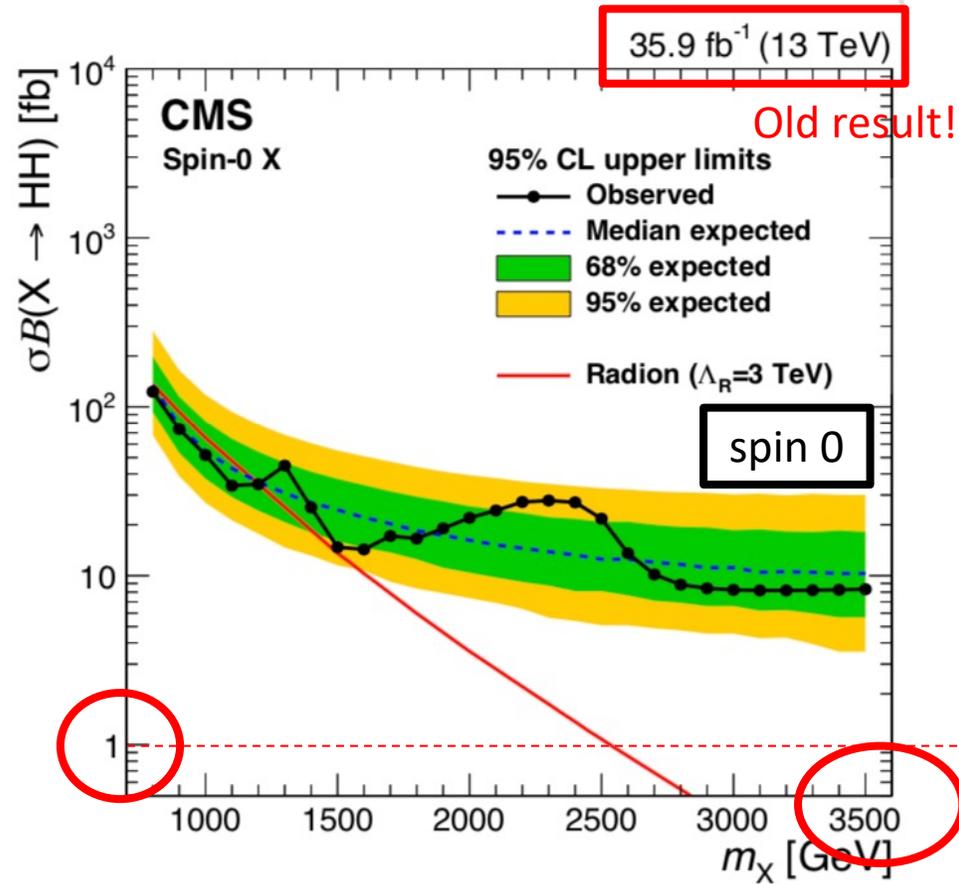
bbWW

New!



bbWW

New!



Summary

- Results using all data collected 2016-2018 (137-138fb⁻¹)
 - Non-resonant:
 - bbbb resolved (GGF and VBF) [HIG-20-005](#)
 - bb $\gamma\gamma$ resolved (GGF and VBF) [HIG-19-018](#)
 - bbZZ(4l) resolved (GGF) [HIG-20-004](#), (not featured here)
 - bbbb boosted (VBF) [B2G-21-001](#), **New!**
Best constraint in κ_{VV} to date! Assuming SM values for all other couplings ($\kappa_t, \kappa_\nu, \kappa_\lambda$) we can exclude $\kappa_{VV}=0$!
 - Resonant:
 - bbbb boosted B2G-20-004, **New!**
 - bbWW(1 or 2 l) boosted B2G-20-007, **New!**
 - NMSSM HY bb $\tau\tau$ [HIG-20-014](#)
(not featured here, check Mariarosaria's [talk](#) yesterday)
 - SUSY search, associated production with HH, SUS-20-004 New!
(not featured here, check Liam's [talk](#) yesterday)
- New results keep coming! Very promising future for HH 😊

Additional material

Double Higgs production in the Standard Model (SM)

- Higgs complex doublet

- Higgs potential (real part): $V(\varphi) = -\frac{1}{2}\mu^2\varphi^2 + \frac{1}{4}\lambda\varphi^4$

$$v = \frac{\mu}{\sqrt{\lambda}} \text{ and } \mu = \frac{m_h^2}{2}$$

- Expand around the vacuum expectation value: $V(\varphi) \rightarrow V(v + h)$

- $V(h) = V_0 + \lambda v^2 h^2 + \lambda v h^3 + \frac{1}{4}\lambda h^4 + \dots$

In the SM $v=246$ GeV
and $\lambda=0.13$

- $V(h) = V_0 + \frac{1}{2}m_h^2 h^2 + \frac{m_h^2}{2v^2} v h^3 + \frac{1}{4} \frac{m_h^2}{2v^2} h^4 + \dots$

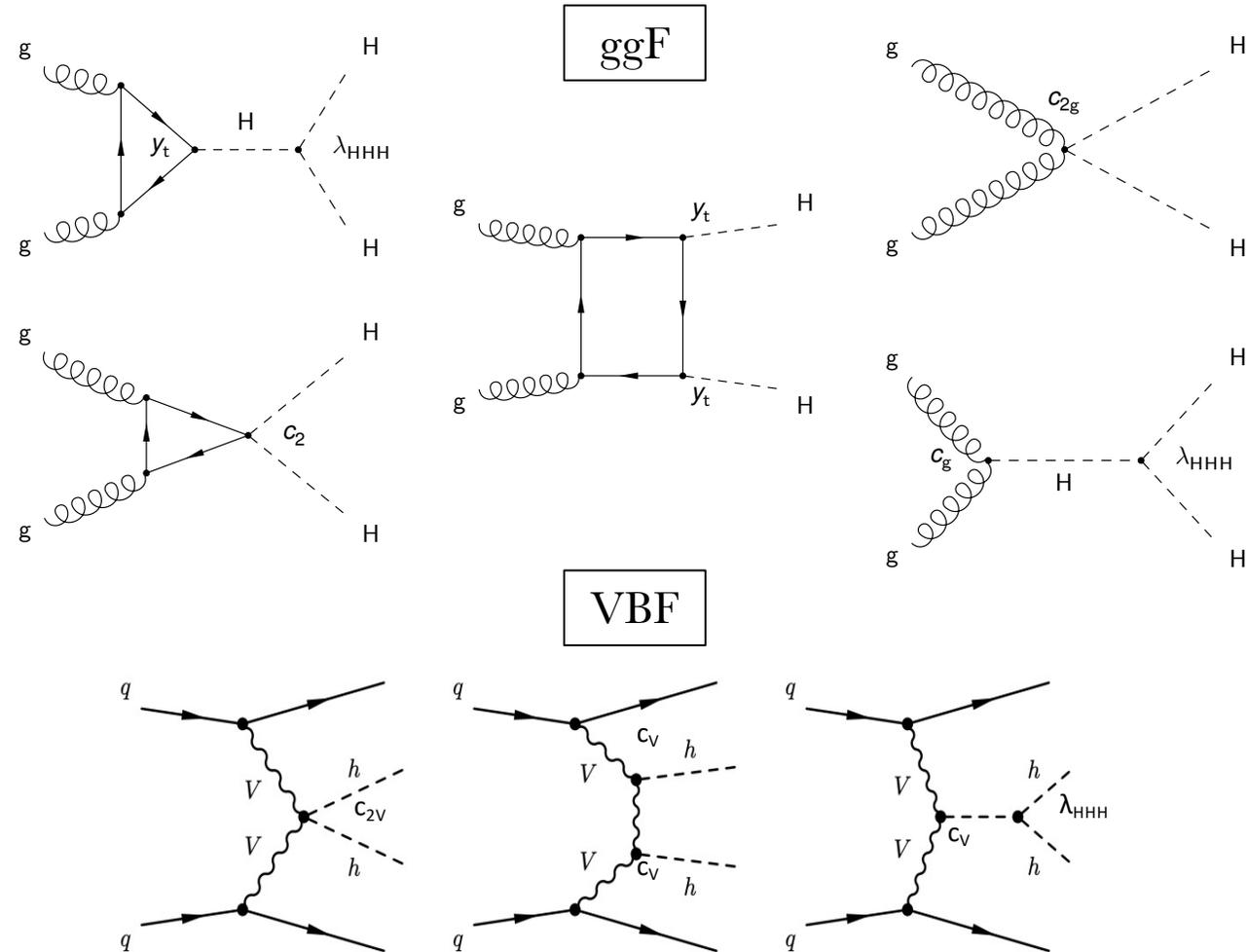
Mass term

Higgs trilinear self-coupling
Double Higgs production

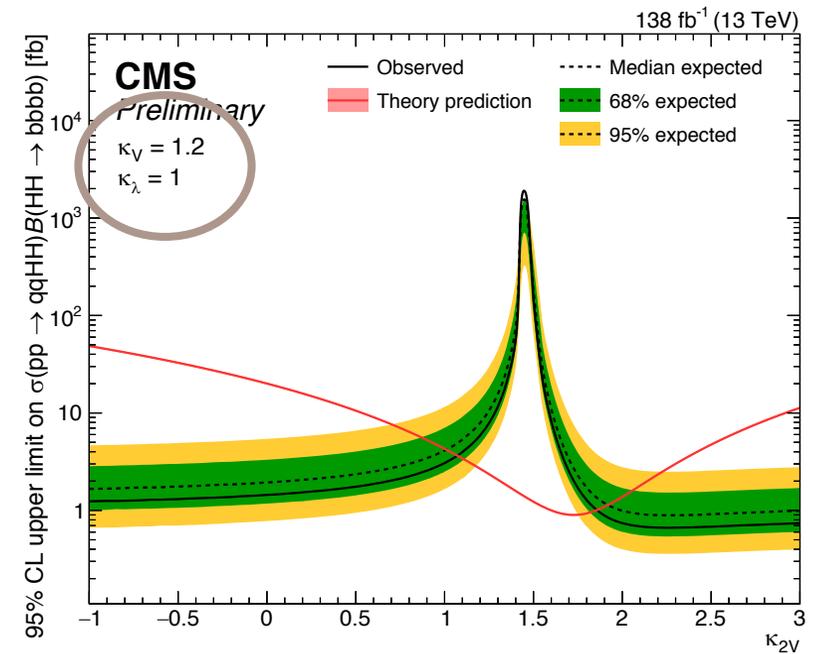
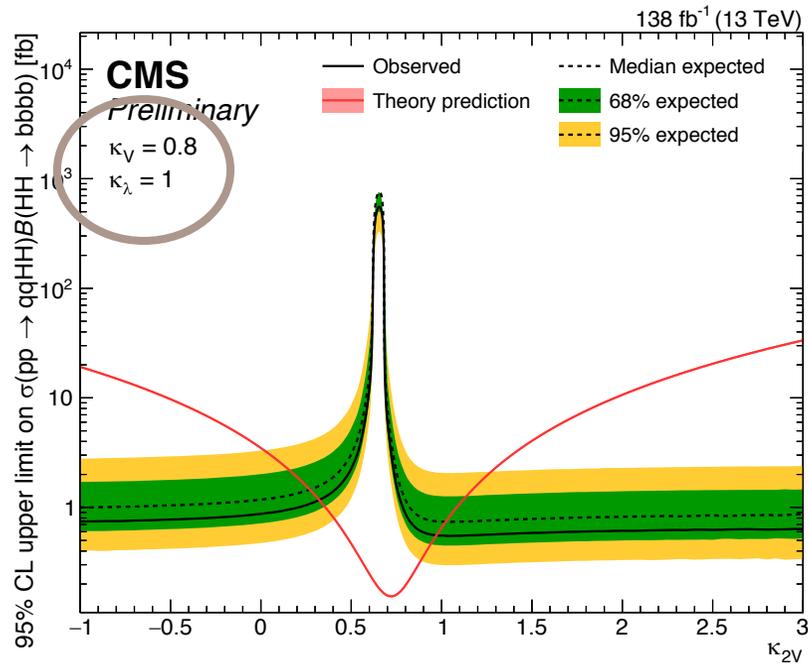
Higgs quadratic self-coupling

Double Higgs production at the LHC (BSM)

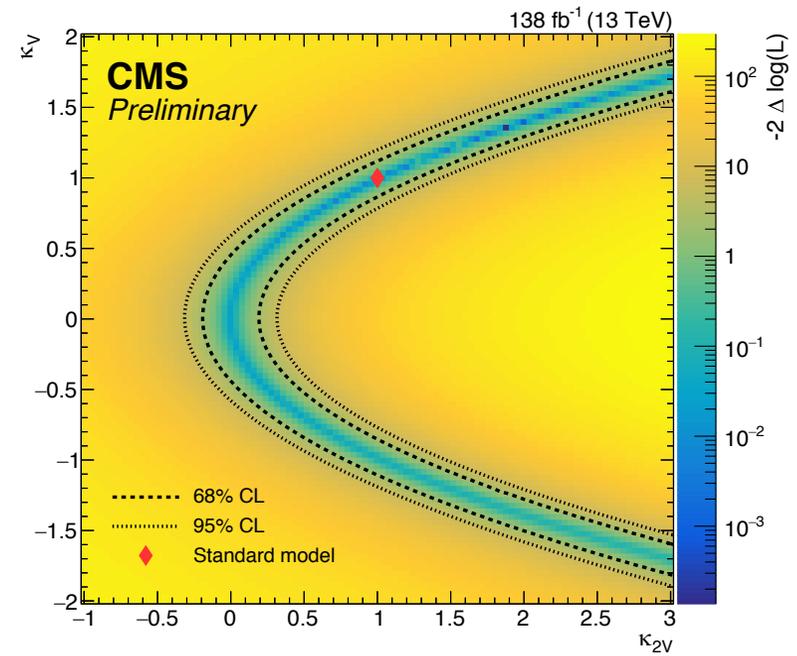
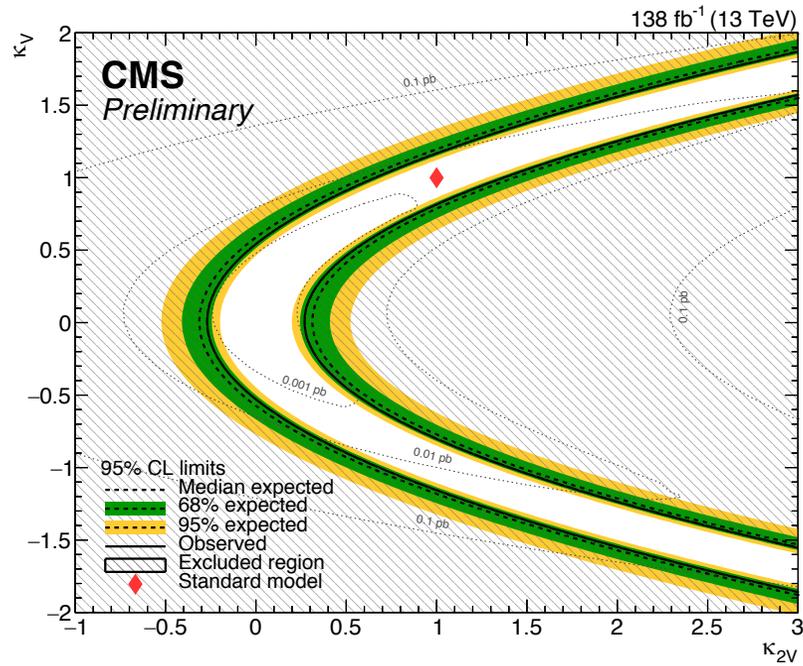
- Beyond the standard model
 - Modified y_t , λ_{HHH} , c_v , c_{2v} couplings
 - c_{2v} only accessible via VBF production!
 - BSM couplings (c_2 , c_{2g} , c_g)
- Effective Field Theory
 - 12 benchmarks with various combinations of values for the coupling modifiers



bbbb(VBF boosted)



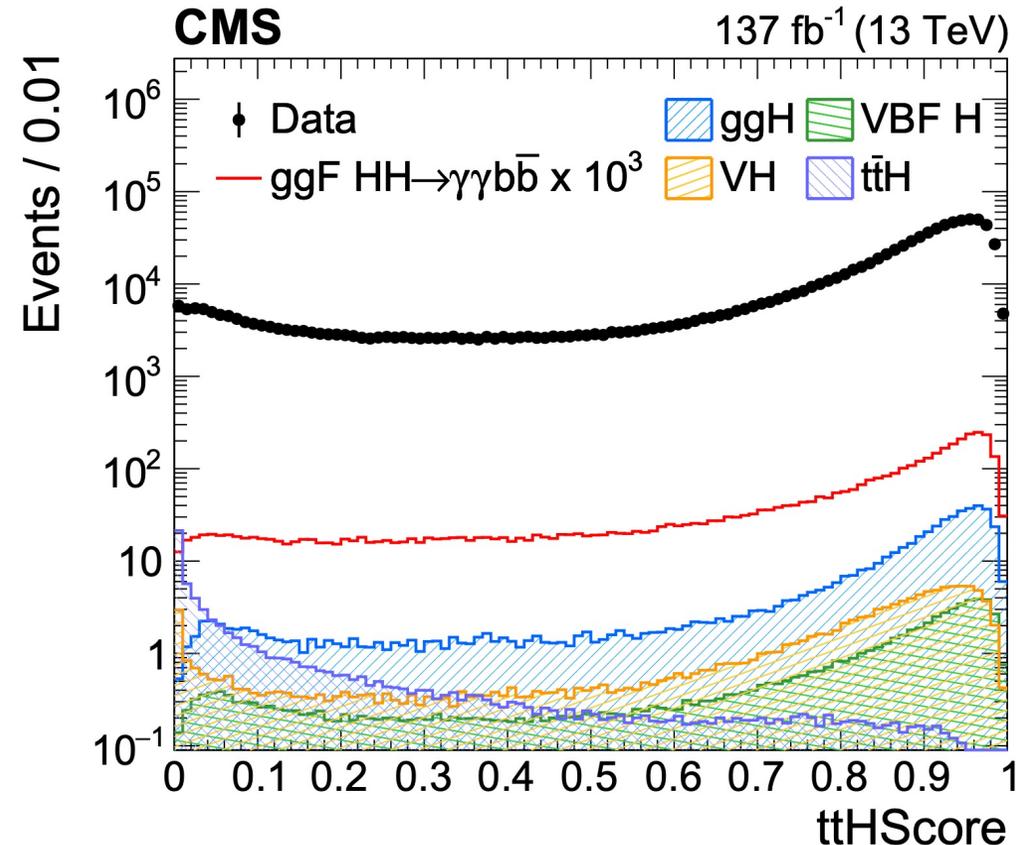
bbbb(VBF boosted)



$bb\gamma\gamma$

CMS PAS HIG-19-018

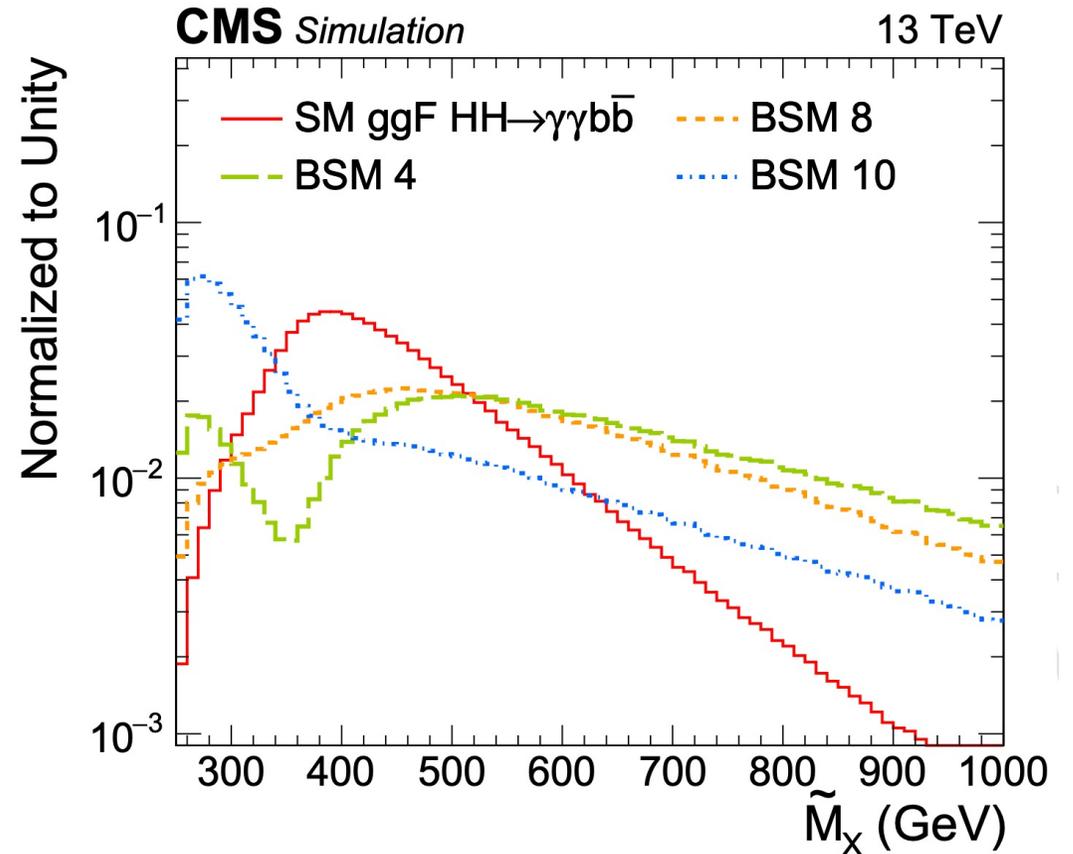
- Final state: 2 γ and 2 b-jets
- Both gluon fusion (ggf) and VBF production studied
- To reduce $t\bar{t}H$ background contamination, a dedicated DNN (ttHScore) was developed.
- Two BDTs were trained, 1 for ggf and 1 for VBF to discriminate the HH signal from the $\gamma\gamma + \text{jets}$ and $\gamma + \text{jets}$ backgrounds



bb $\gamma\gamma$

$$\tilde{M}_X = m_{\gamma\gamma jj} - (m_{jj} - m_H) - (m_{\gamma\gamma} - m_H)$$

- \tilde{M}_X creates signal regions sensitive to multiple theoretical scenarios.
- Several categories are defined for ggF and VBF, depending on the BDT output and \tilde{M}_X



bb $\gamma\gamma$

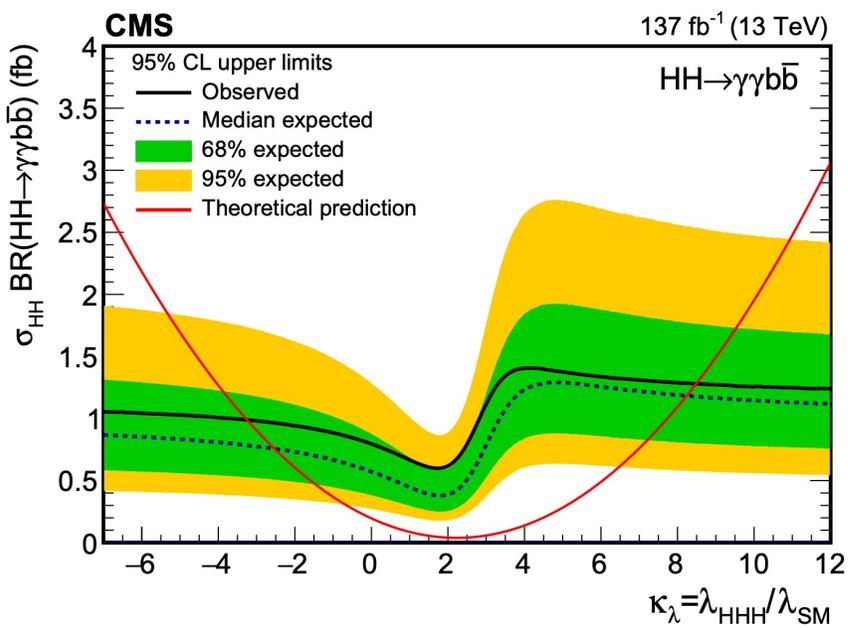
- In the dedicated BDT for the VBF production mode, the ggF HH events are considered as background
- The HH signal is extracted from a 2D fit to the invariant mass of the two Higgs bosons ($m_{\gamma\gamma}$, m_{bb}) in the final state simultaneously in all categories.

Category	MVA	\tilde{M}_X (GeV)
VBF CAT 0	0.52-1.00	>500
VBF CAT 1	0.86-1.00	250-500
ggF CAT 0	0.78-1.00	>600
ggF CAT 1		510-600
ggF CAT 2		385-510
ggF CAT 3		250-385
ggF CAT 4	0.62-0.78	>540
ggF CAT 5		360-540
ggF CAT 6		330-360
ggF CAT 7		250-315
ggF CAT 8	0.37-0.62	>585
ggF CAT 9		375-585
ggF CAT 10		330-375
ggF CAT 11		250-330

bb $\gamma\gamma$

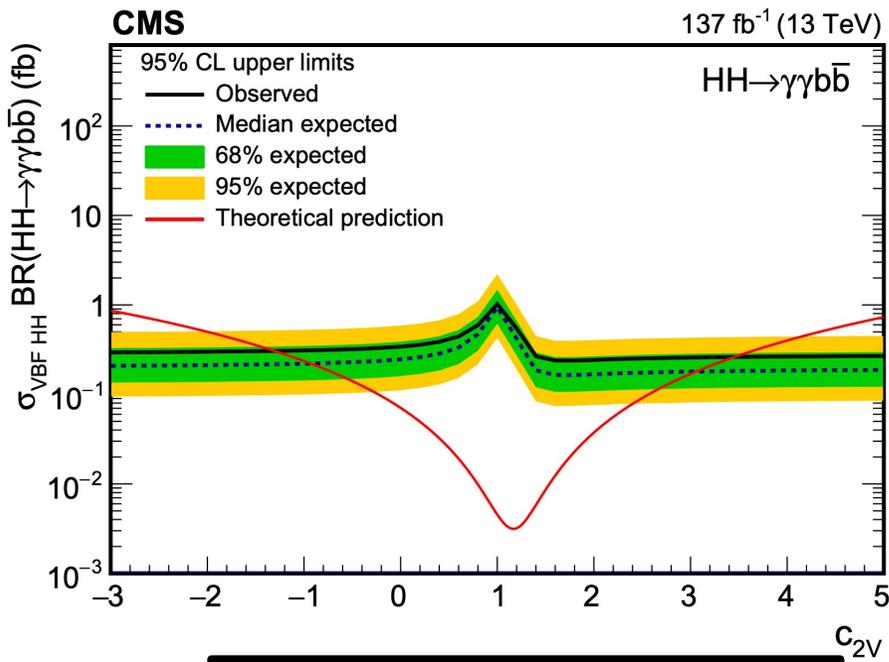
See also talk by [Soumya](#)

Observed (expected) $\sigma/\sigma_{SM} < 7.7(5.2)$ at 95% CL ← **Best to date!**

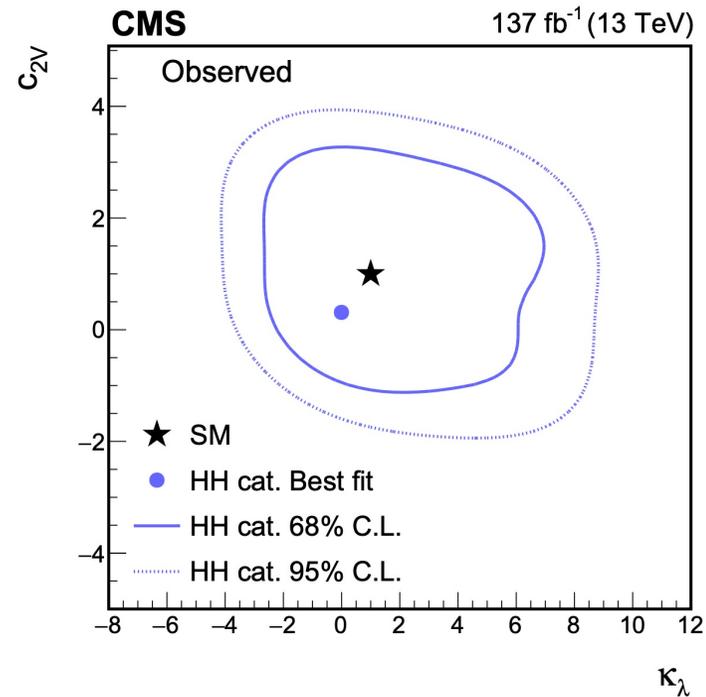


Observed: $-3.3 < \kappa_\lambda < 8.5$
Expected: $-2.5 < \kappa_\lambda < 8.2$

Best to date!



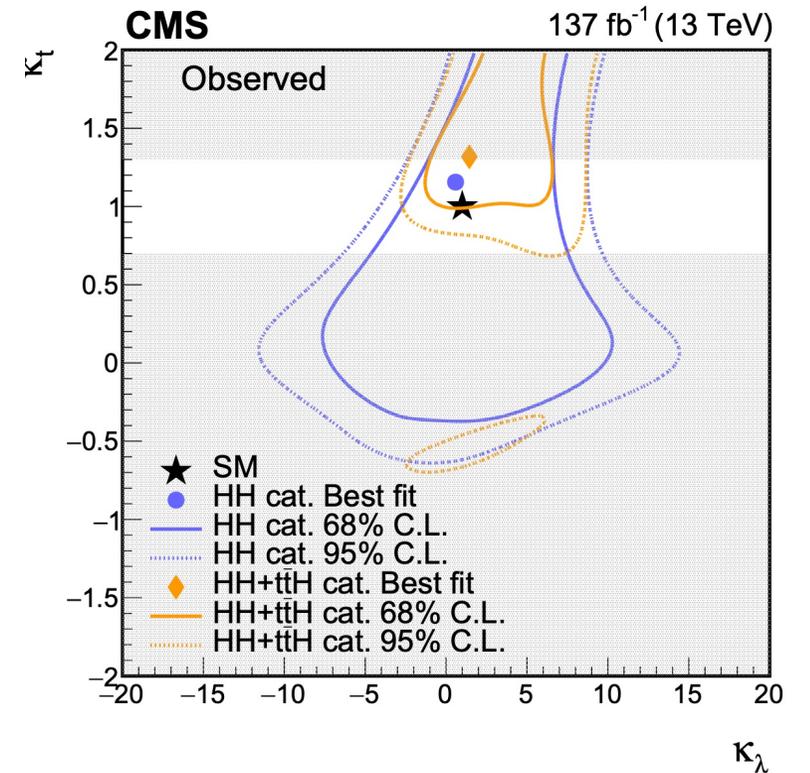
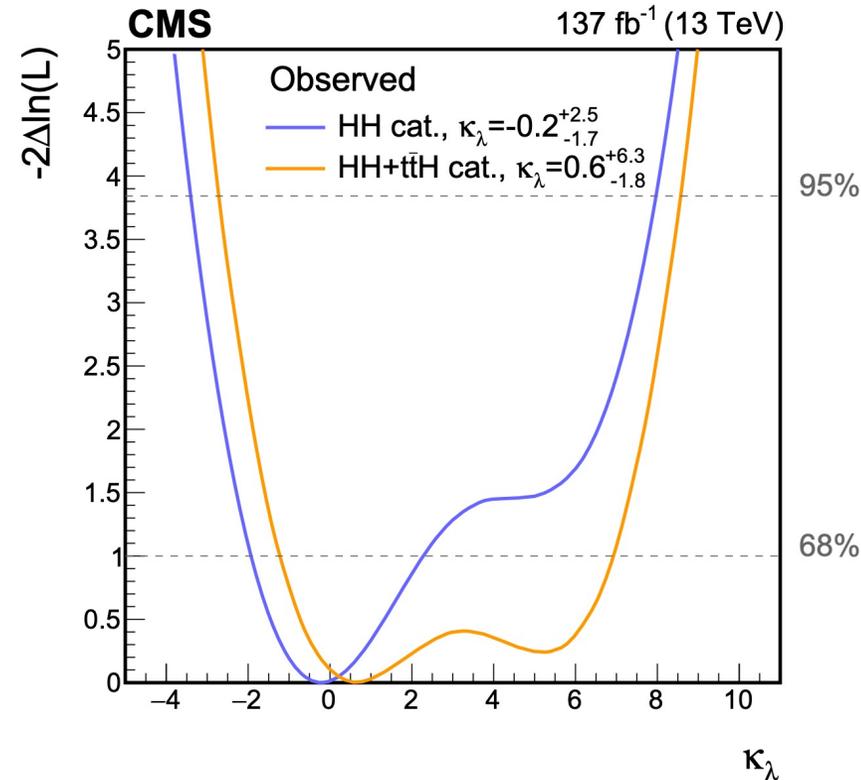
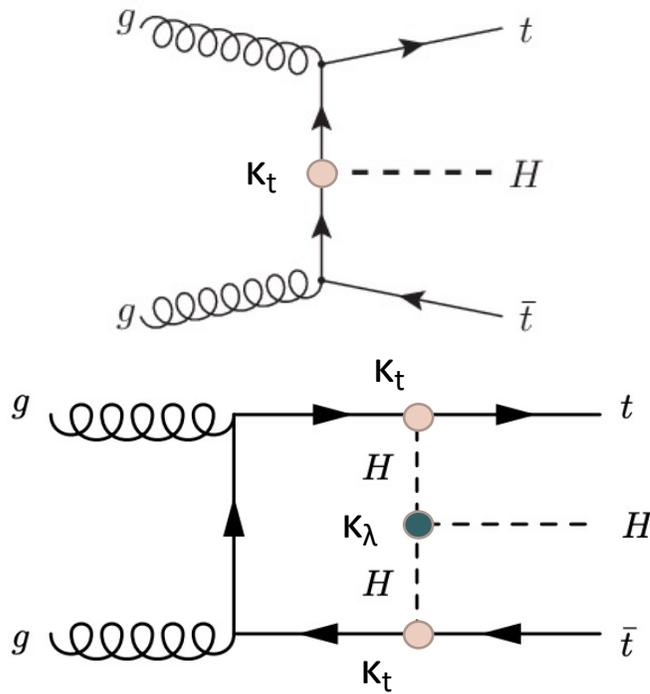
Observed: $-1.3 < c_{2V} < 3.5$
Expected: $-0.9 < c_{2V} < 3.0$



bb $\gamma\gamma$: combined with ttH

See also talk by [Soumya](#)

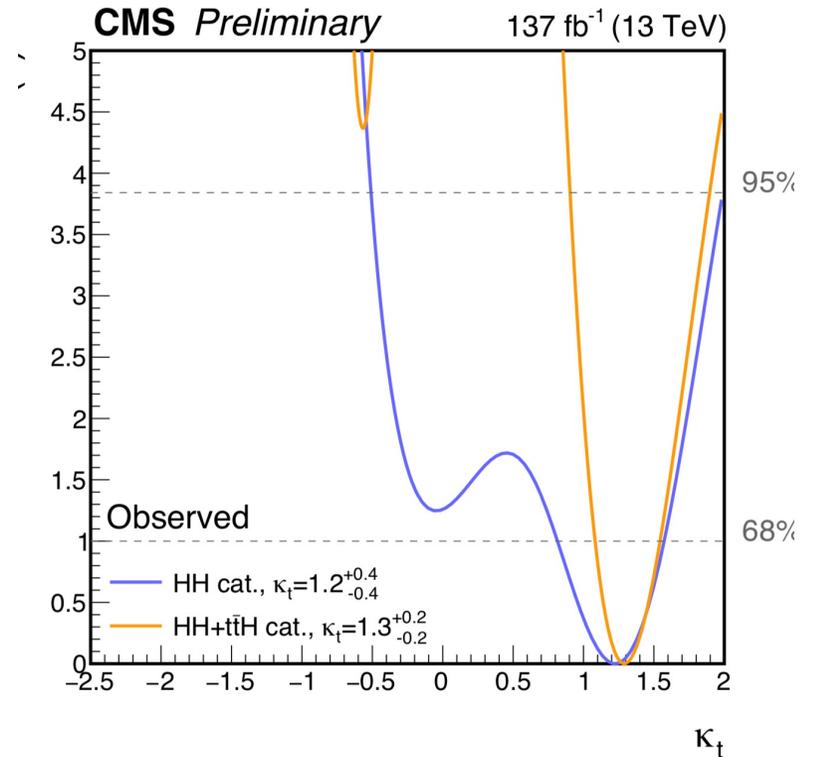
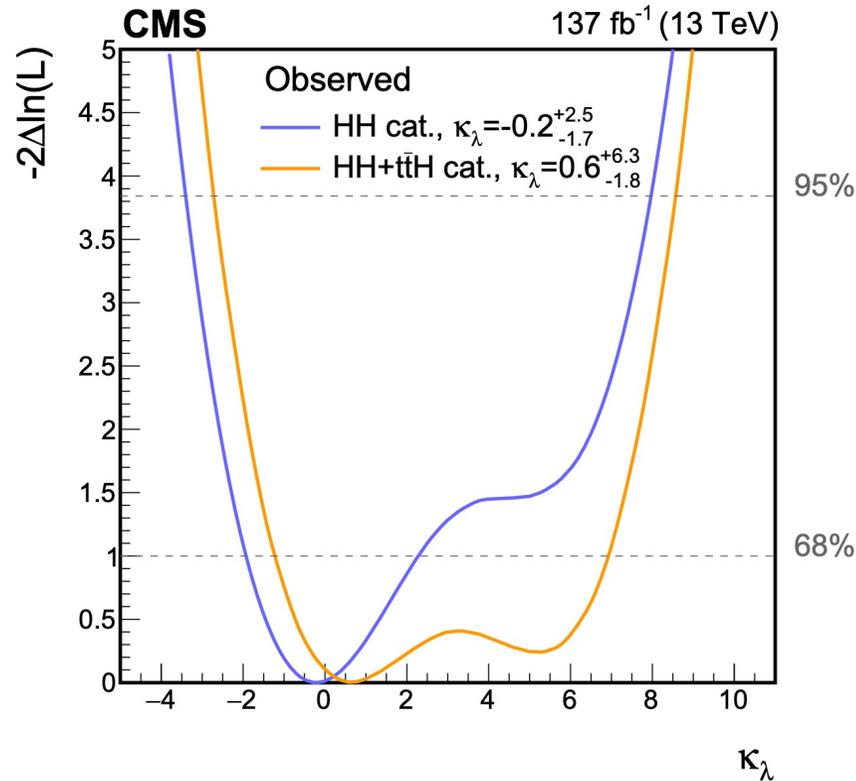
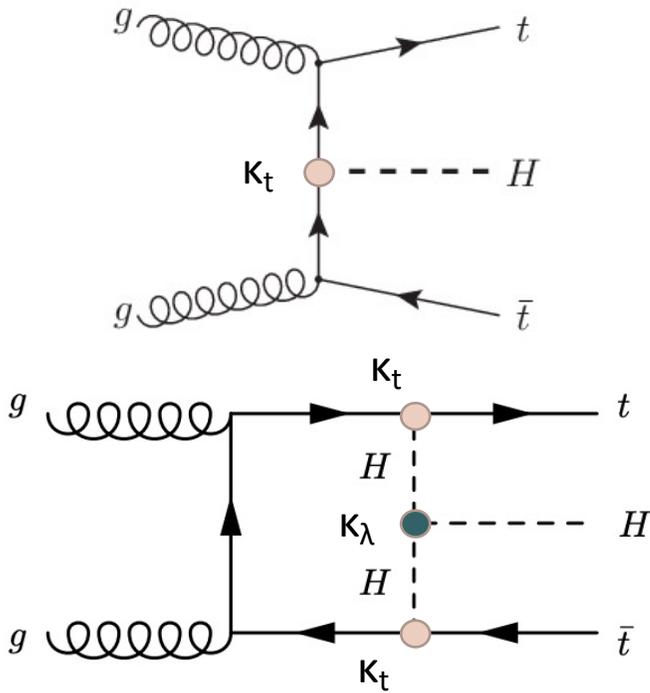
- HH $\rightarrow \gamma\gamma bb$ signal was combined with the single H production mode to provide an improved constraint on the κ_λ and κ_t parameters.



bb $\gamma\gamma$: combined with ttH

See also talk by [Soumya](#)

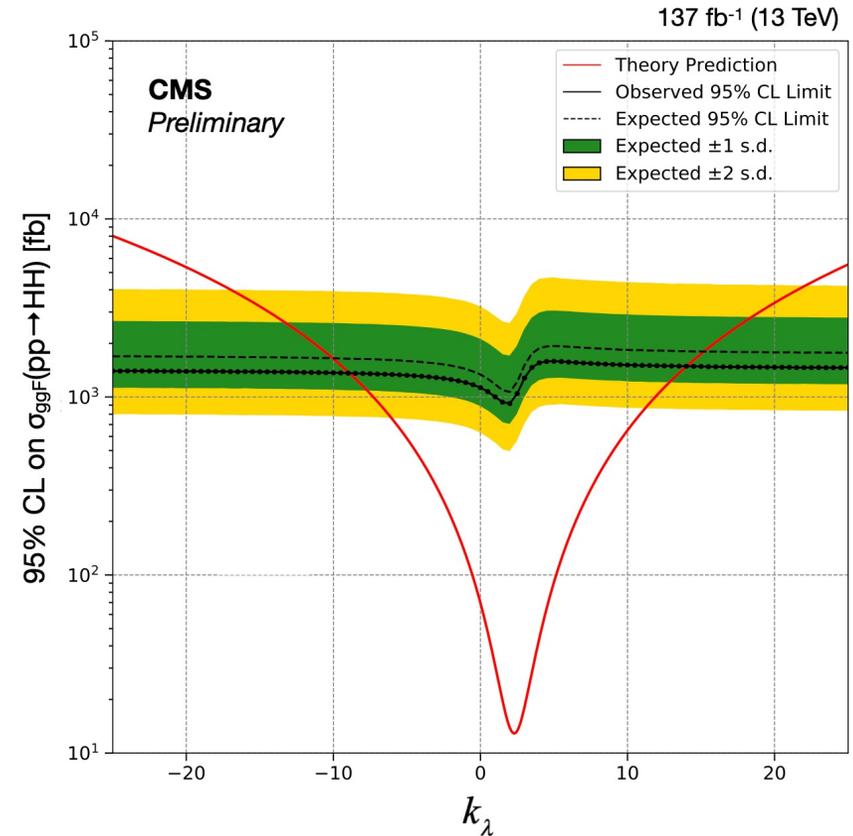
- HH \rightarrow $\gamma\gamma$ bb signal was combined with the single H production mode to provide an improved constraint on the κ_λ and κ_t parameters.



bbZZ(4l) [HIG-20-004](#)

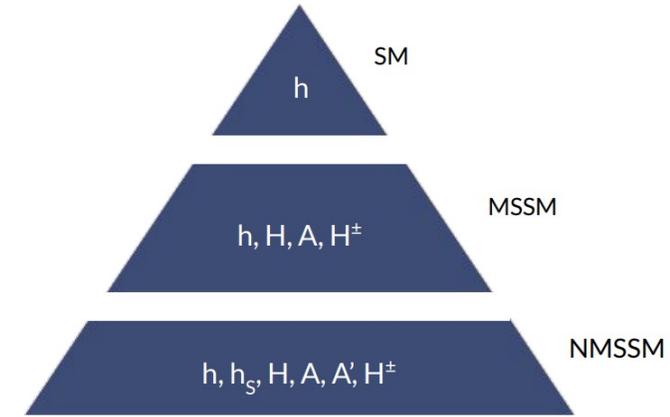
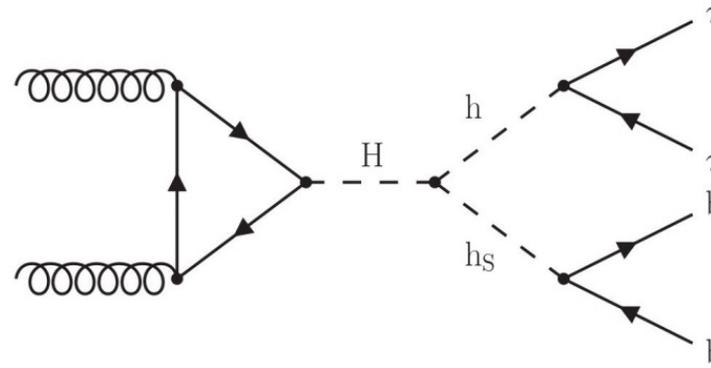
- Final state: 2 pairs of opposite-charge leptons (4 μ , 4e, 2e2 μ) and 2 b-jets
- Main background: Single Higgs production
- Signal region $|m_{4l} - 125| < 10$ GeV + number of jets ≥ 2
- BDT trained discriminate between signal and background
- BDT score used in the maximum likelihood fit

Observed (expected) $\sigma/\sigma_{\text{SM}} < 30(37)$ at 95% CL

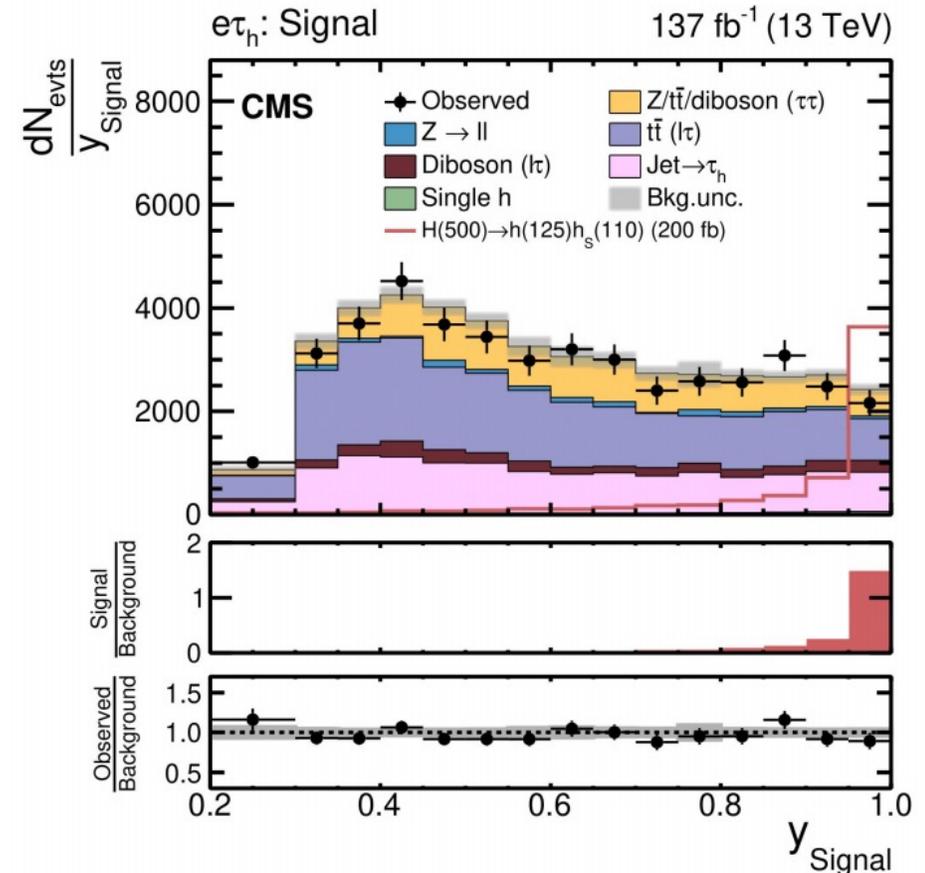


$$H \rightarrow Y h \rightarrow bb\tau\tau$$

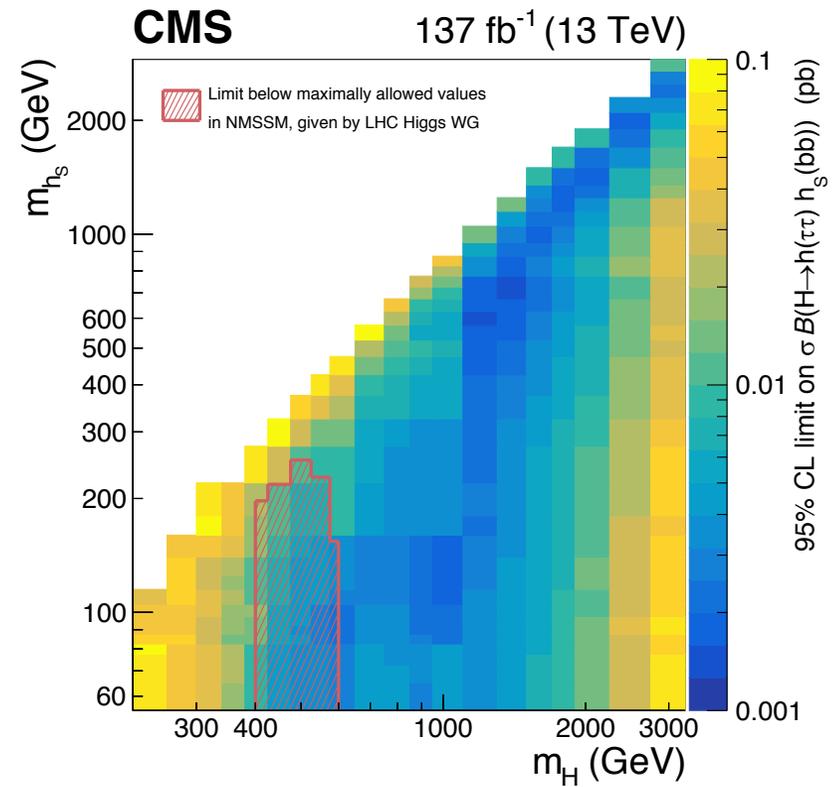
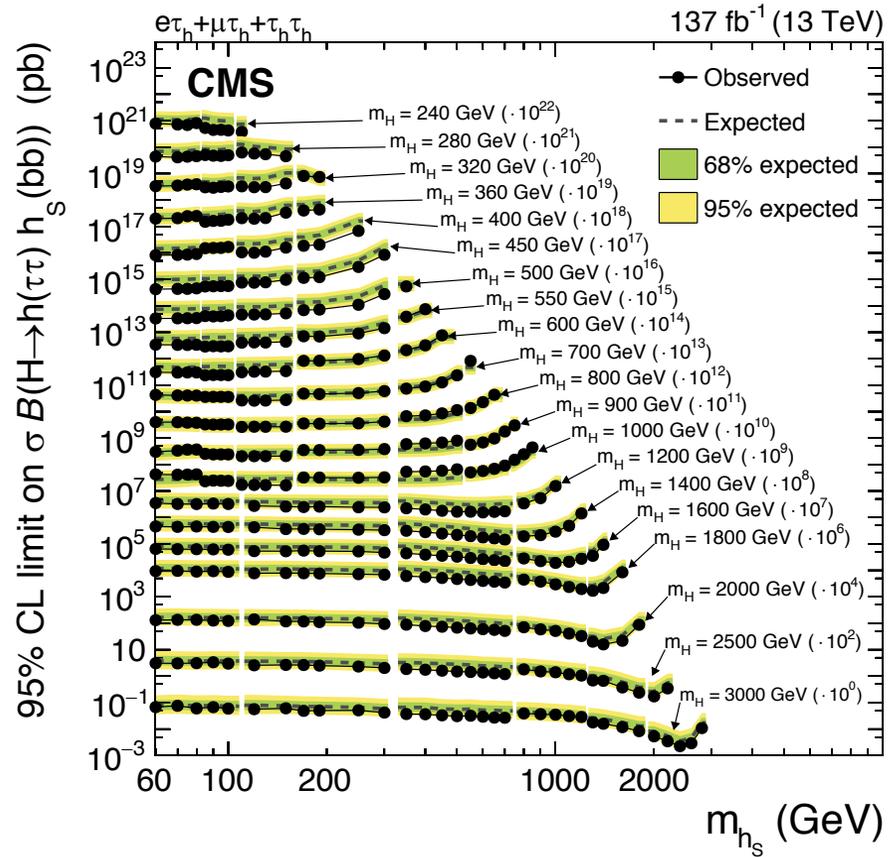
[HIG-20-014](#)



- $240 < m_H < 3000 \text{ GeV}$
 $60 < m_{h_s} < 2800 \text{ GeV}$
- $e\tau_h, \mu\tau_h, \tau_h\tau_h$
- multiclass DNN: returns probability-like score for each category, events get assigned to category with highest score.
 - 4 background categories and 1 for each signal
 - 68 trainings
- This NN score is also used as final discriminator in the analysis



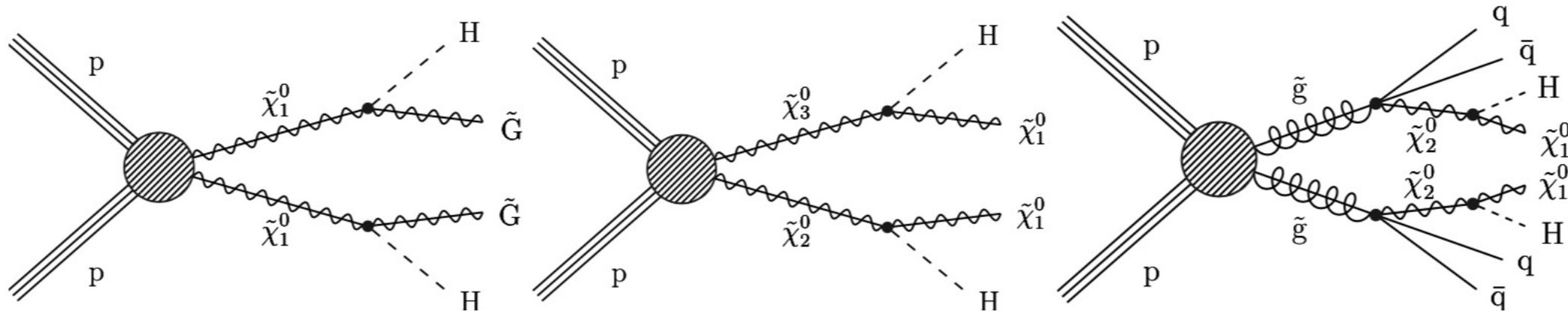
$H \rightarrow Y h \rightarrow bb\tau\tau$



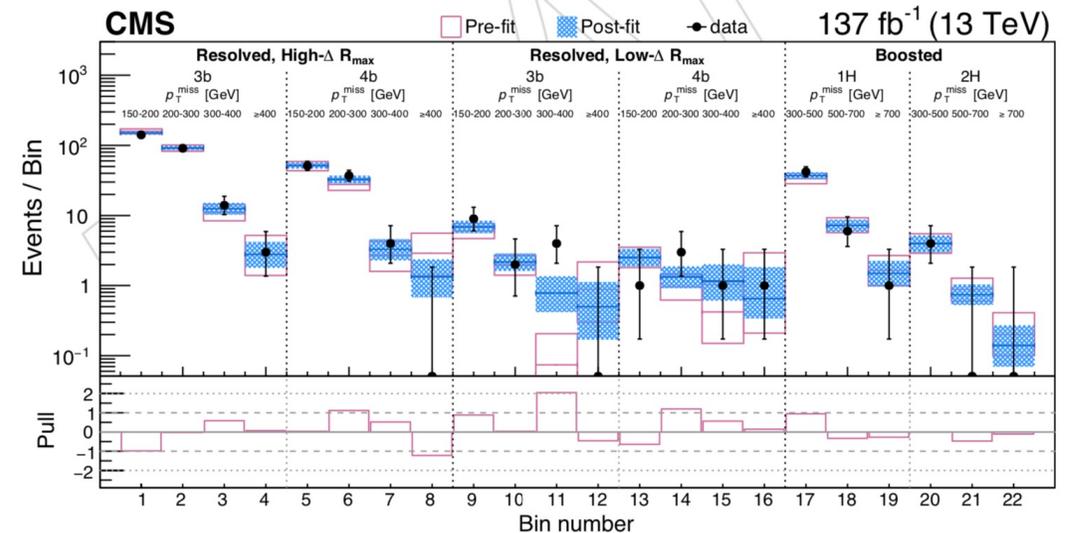
bbbb+MET, a SUSY search

New!

SUS-20-004



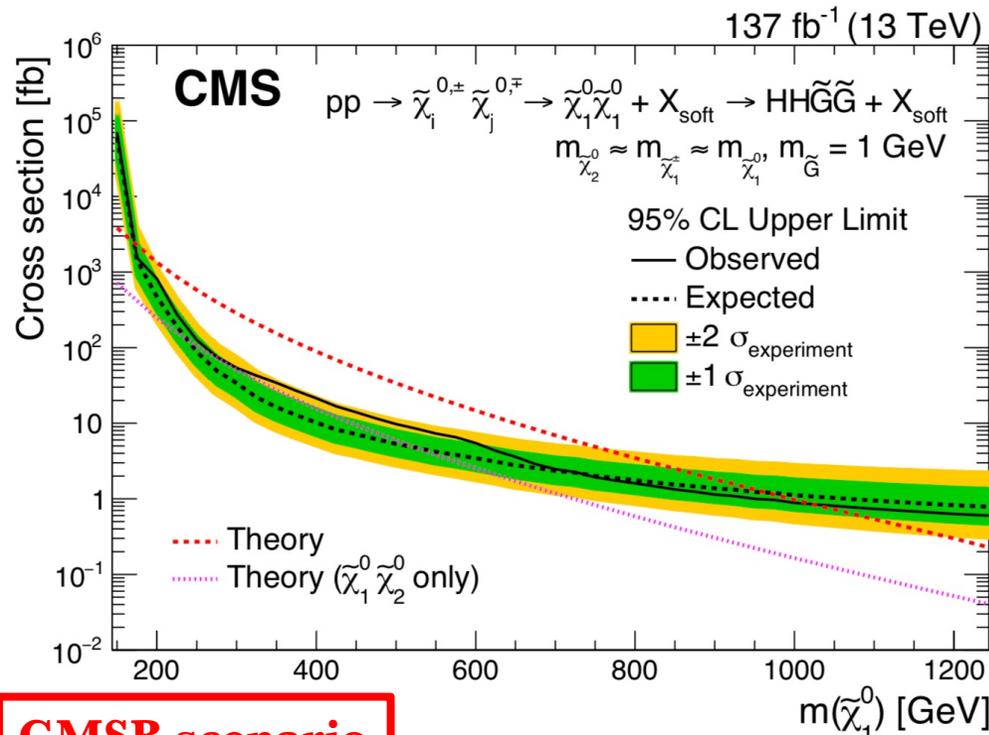
- Higgs bosons produced together with supersymmetric particles
- $HH \rightarrow bbbb +$ missing transverse energy
- Analysis analysing both boosted and resolved topologies.
- Fit performed in several categories



bbbb+MET, a SUSY search

New!

2D scan of higgsino neutral-neutral (N2N3 scenario)



GMSB scenario
N2N3 scenario

