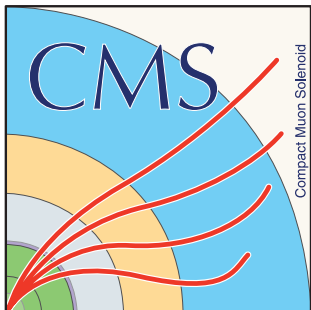# HH searches in CMS

Agni Bethani for the CMS collaboration

Higgs Pairs 2021
29th September

Higgs pair production at the LHC
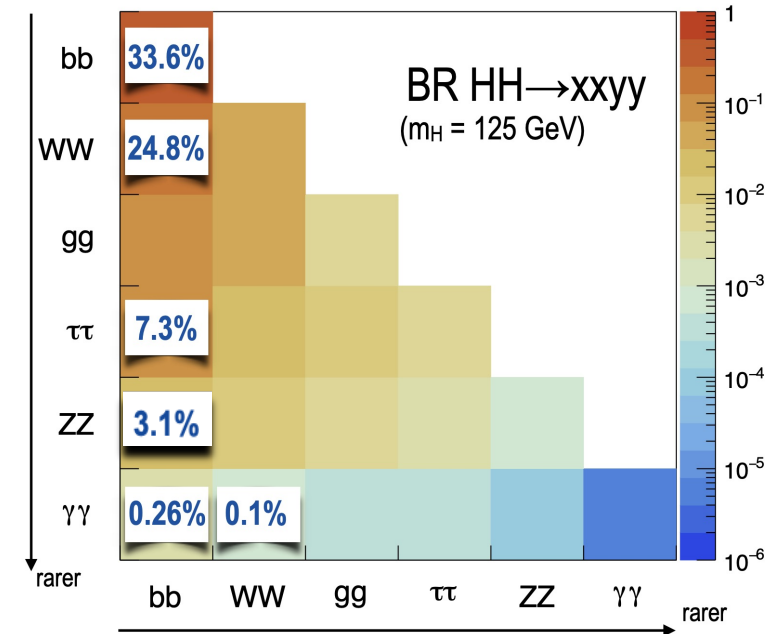
- Higgs field potential:

$$V(h) = V_0 + \frac{1}{2}m_h{}^2 h^2 + \frac{m_h{}^2}{2v^2}vh^3 + \frac{1}{4}\frac{m_h{}^2}{2v^2}h^4 + \cdots$$
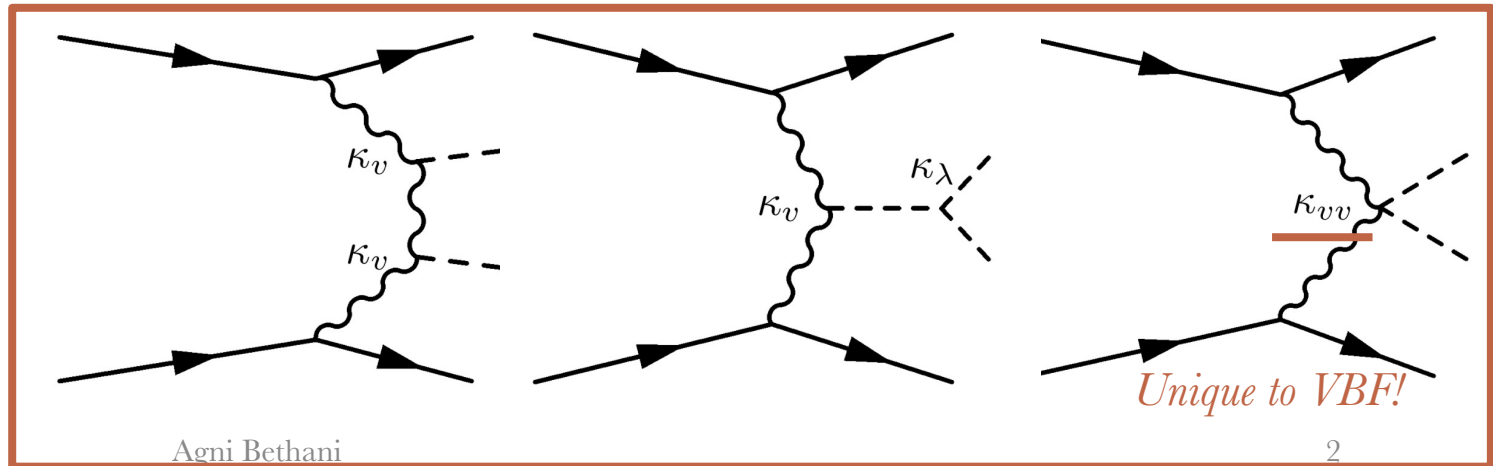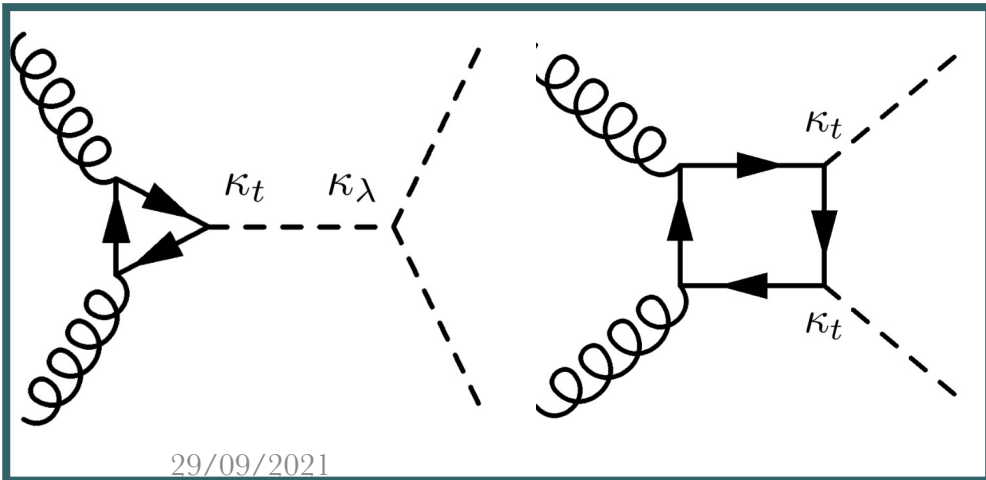
Mass term

Higgs trilinear self-coupling (κλ)
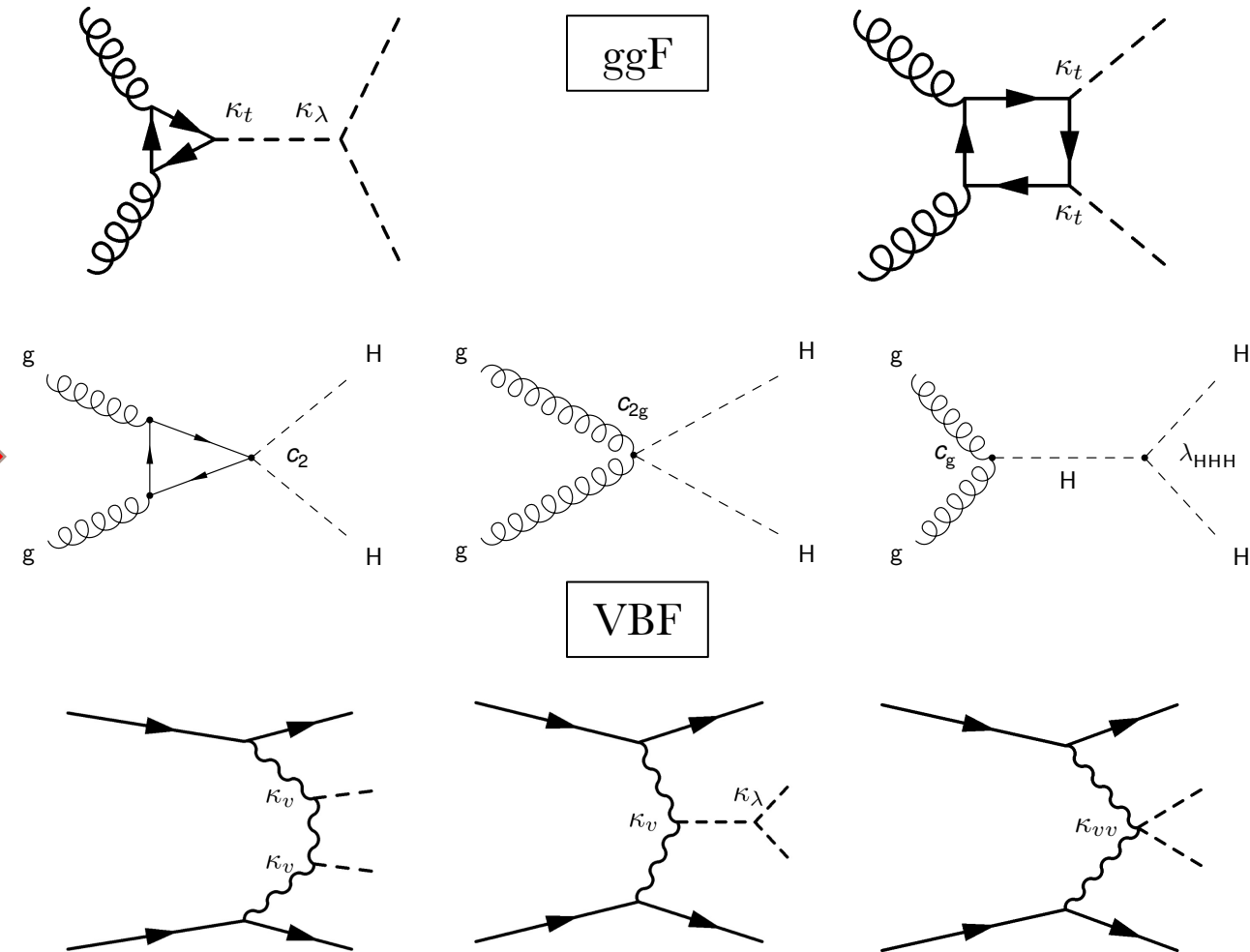**Higgs pair production**

Higgs quadratic self-coupling

BR HH→xxyy
(m_H = 125 GeV)

Gluon Gluon Fusion (GGF)

Vector Boson Fusion

Unique to VBF!

29/09/2021

Agni Bethani

2

Higgs pair production at the LHC (BSM)

- Beyond the standard model
  - Modified κ_t, κ_λ, κ_v, κ_{2v} couplings
  - κ_{2v} only accessible via VBF production!
  - BSM couplings (c_2, c_{2g}, c_g)
- Effective Field Theory
  - 12 +1benchmarks with various combinations of values for the coupling modifiers
  - can be reweighted to any coupling configuration (κ_λ, κ_t, c_2, c_g, c_{2g})

ggF

VBF

[JHEP04(2016)126](#)
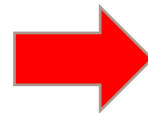
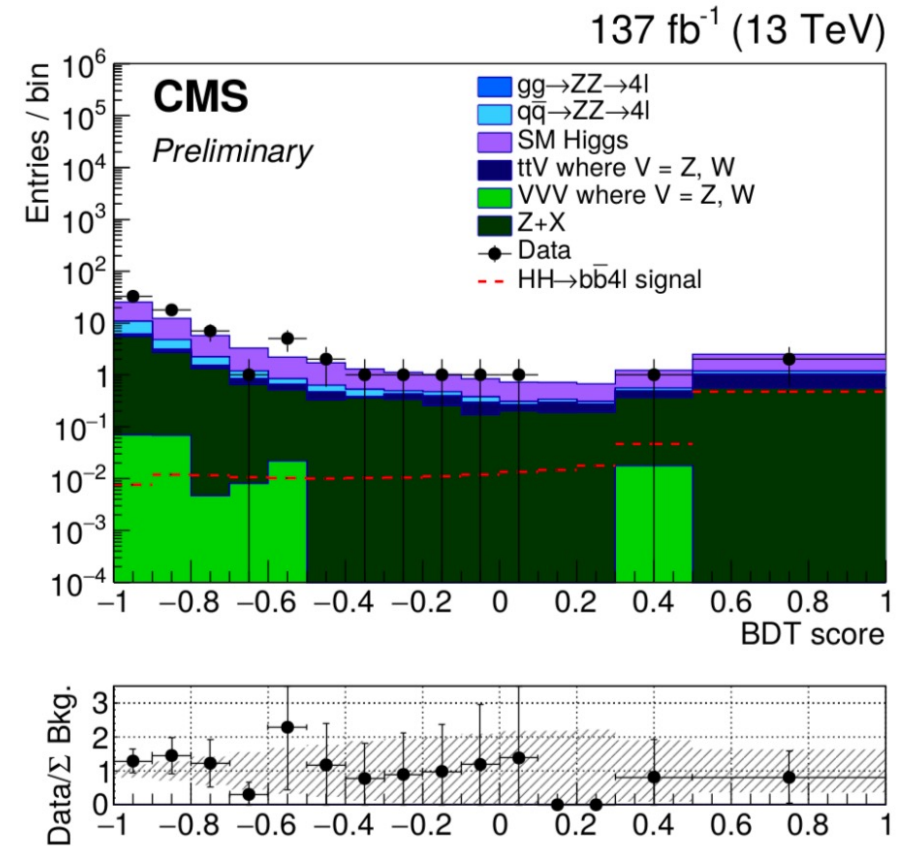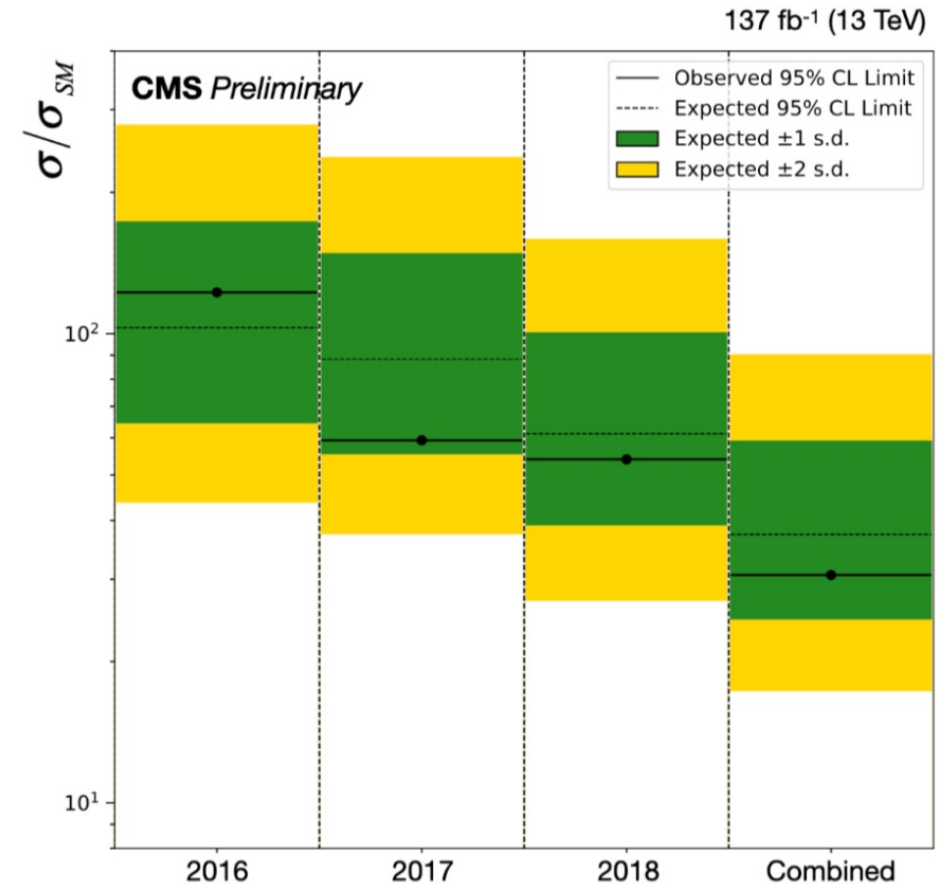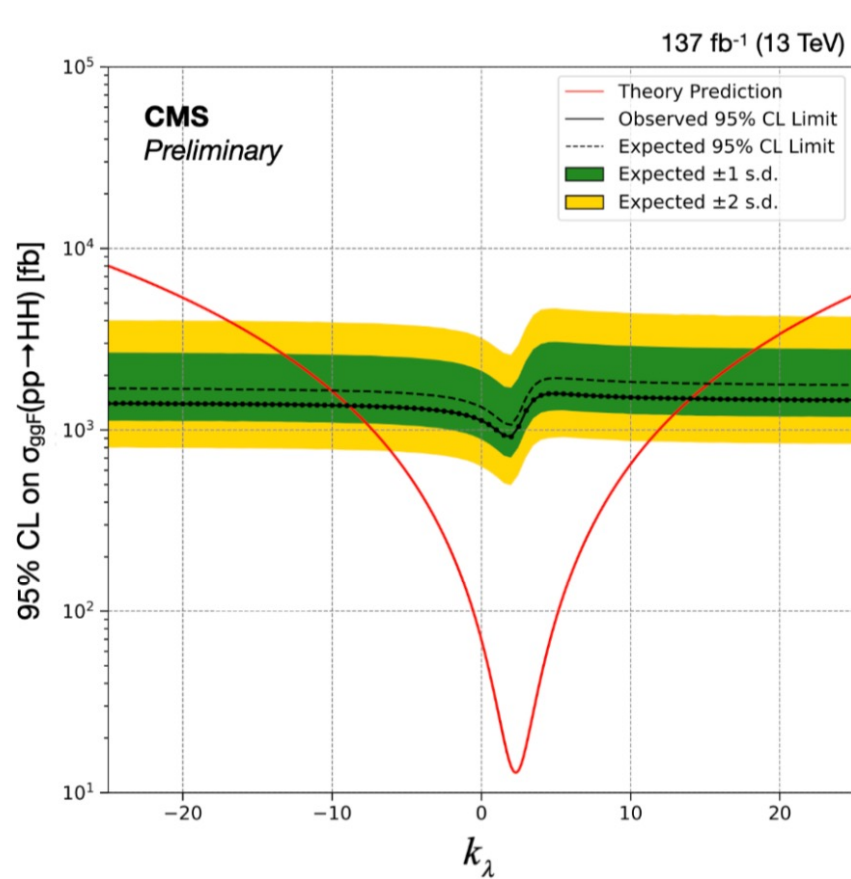# Non-resonant and SM searches

bbZZ(4l)

- Final state: 2 pairs of opposite-charge leptons (4μ, 4e, 2e2μ) 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

bbZZ(4l)

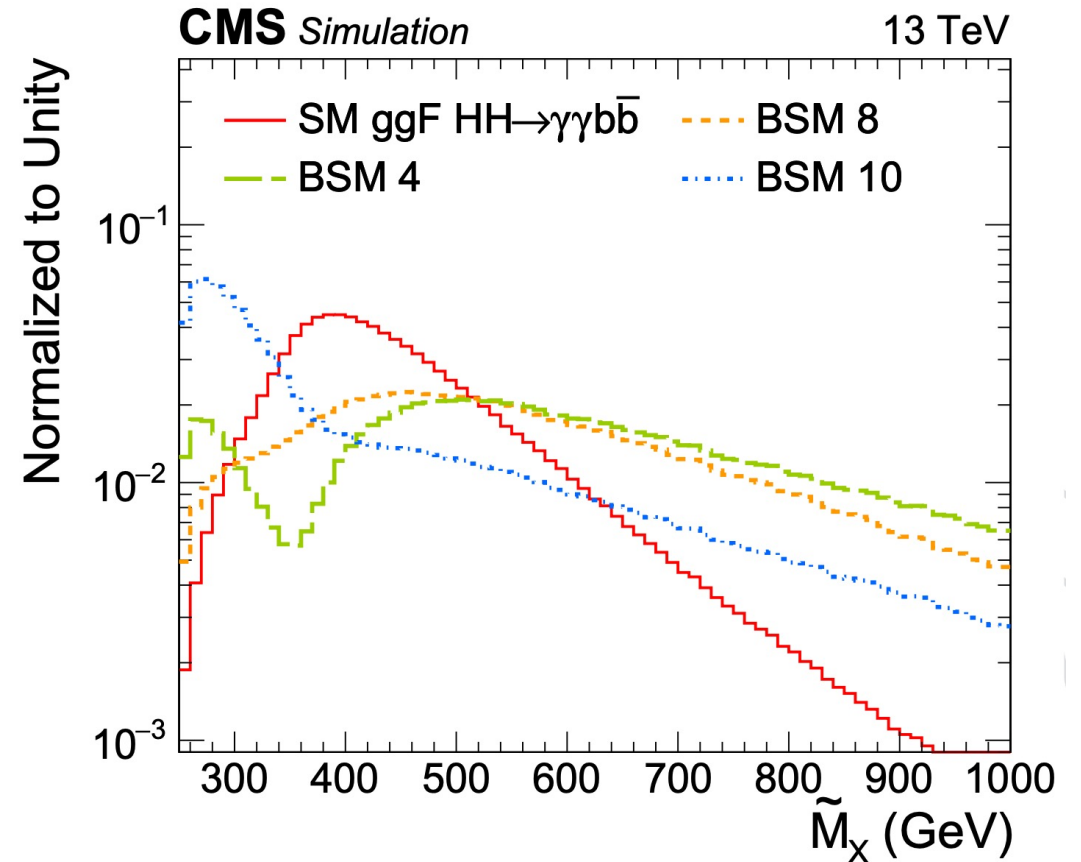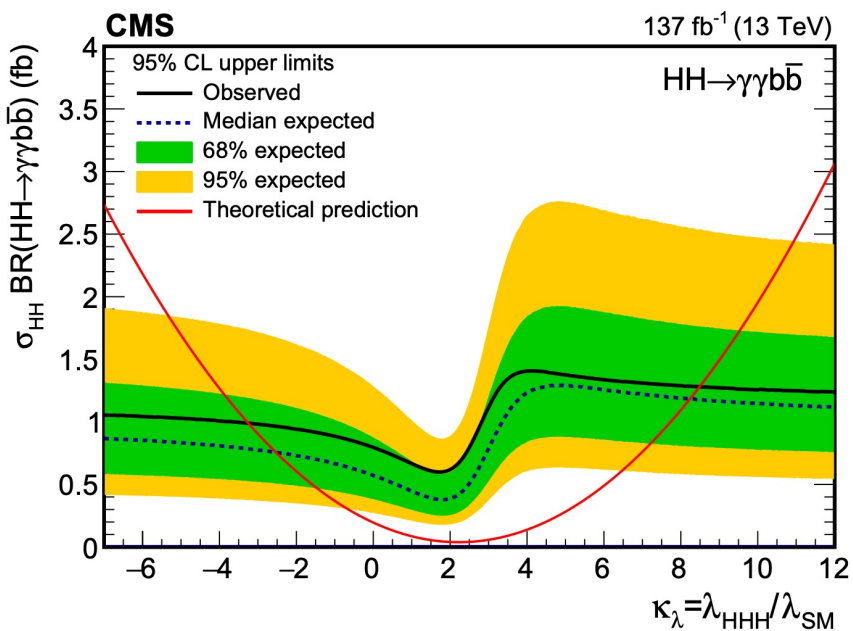- Observed (expected) $\sigma/\sigma_{SM} < 30(37)$ at 95% CL

bbγγ

- Final state: 2 γ and 2 b-jets
- Both gluon fusion (ggf) and VBF production studied
- Dedicated DNN (ttHScore) against ttH
- 1 BDT for ggf and 1 for VBF against
  γγ + jets and γ + jets backgrounds
- Several categories depending on the BDT output and $\widetilde{M}_X$
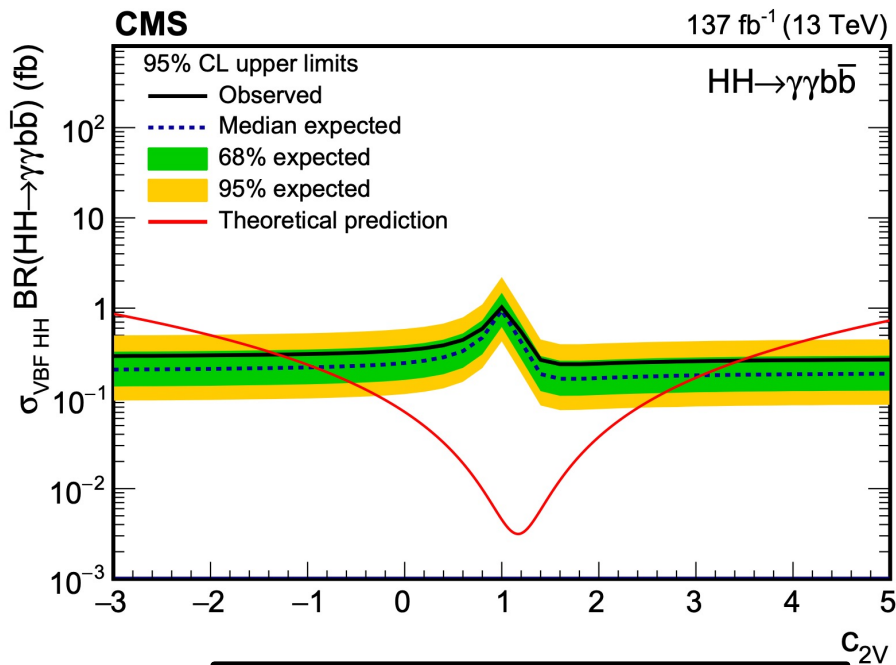- Simultaneous 2D fit ($m_{\gamma\gamma}$, m_{bb}) in all categories.

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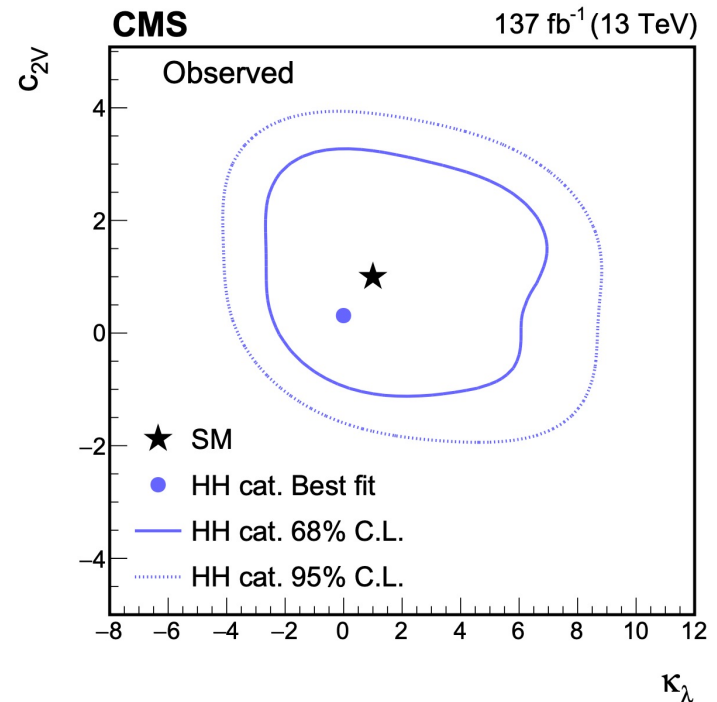
bbγγ

Observed (expected) σ/σ_{SM} <7.7(5.2) at 95% CL

Observed: -3.3 < κ_λ < 8.5
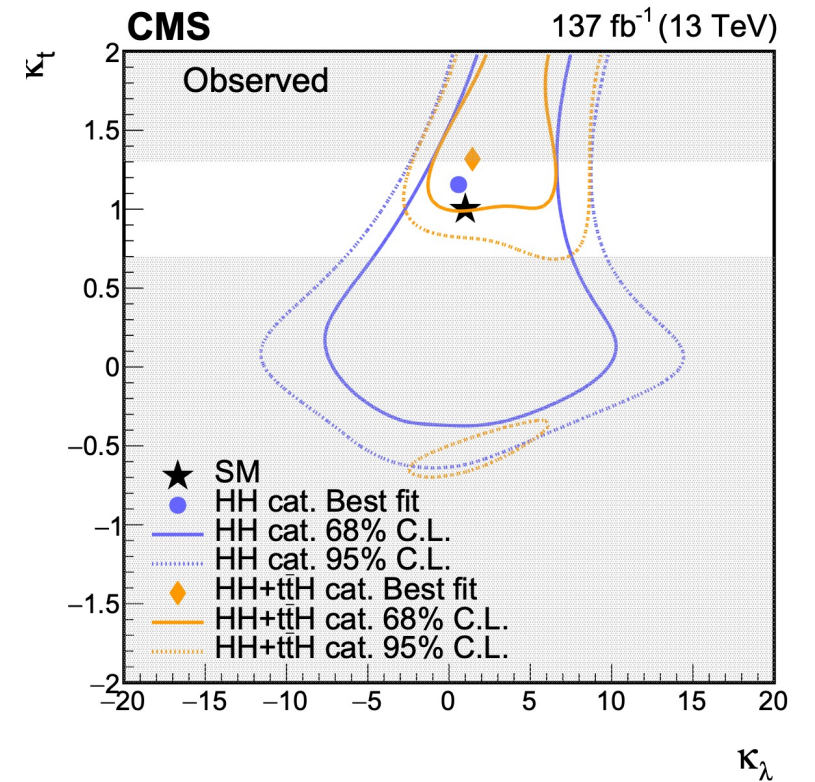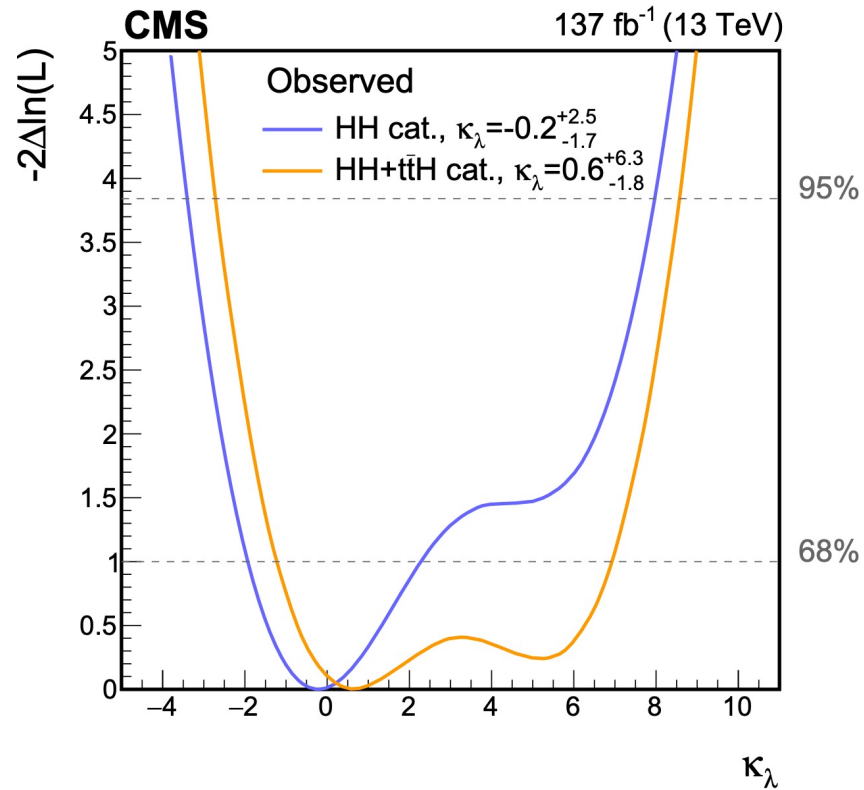**Expected: -2.5 < κ_λ < 8.2**

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

bbγγ

- HH → bbγγ signal was combined with the ttH

bbγγ

- HH → bbγγ signal was combined with the ttH

bbγγ

CMS — 137 fb⁻¹ (13 TeV)
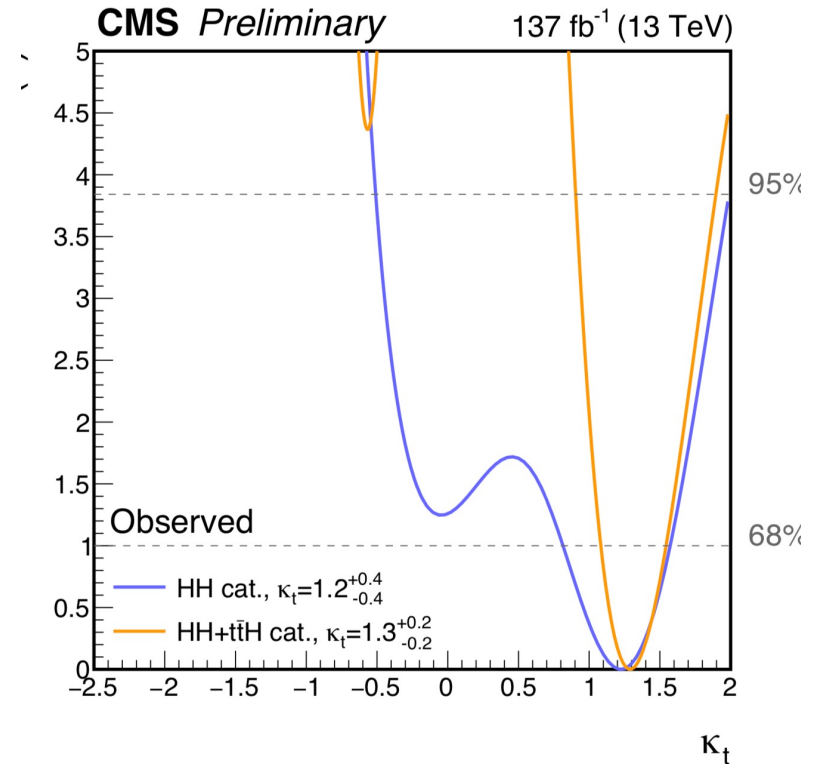
95% CL upper limits
- Observed
- Median expected
- 68% CL expected
- 95% CL expected

HH → γγbb̄

CMS — 137 fb⁻¹ (13 TeV)

95% CL upper limits
- Observed
- Median expected
- 68% CL expected
- 95% CL expected
- Theoretical prediction

HH → γγbb̄

	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
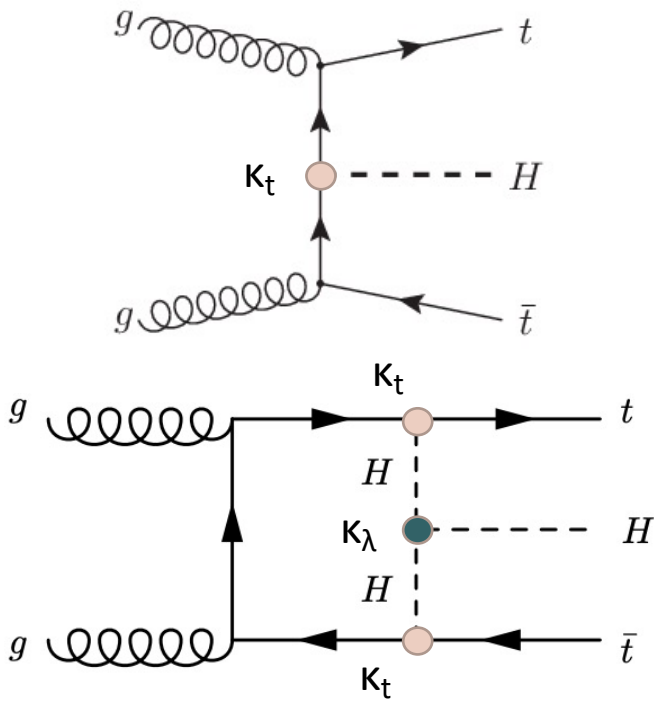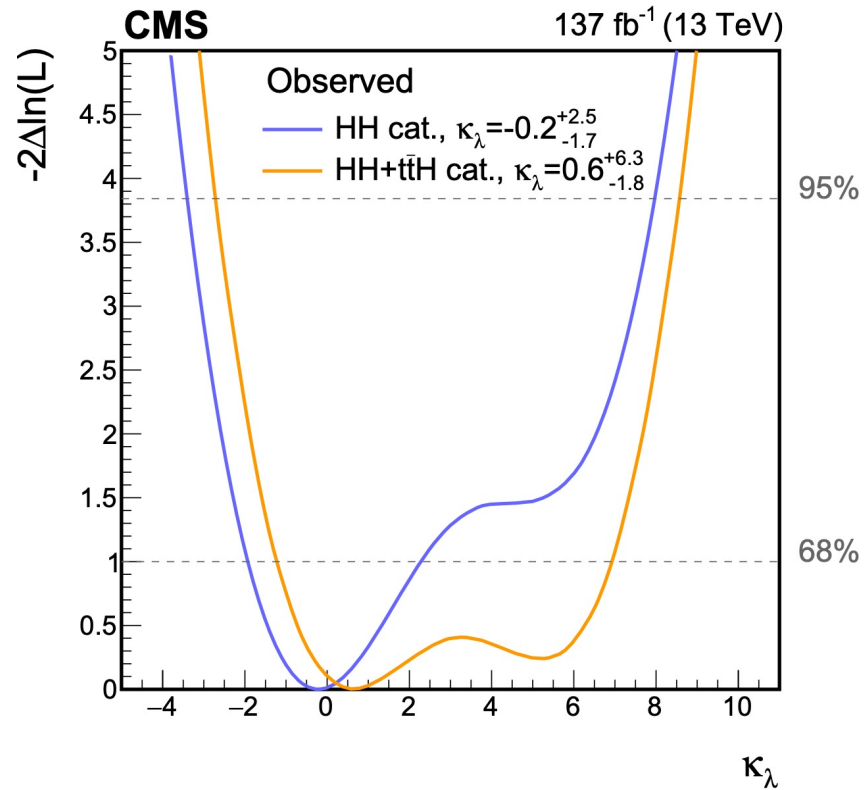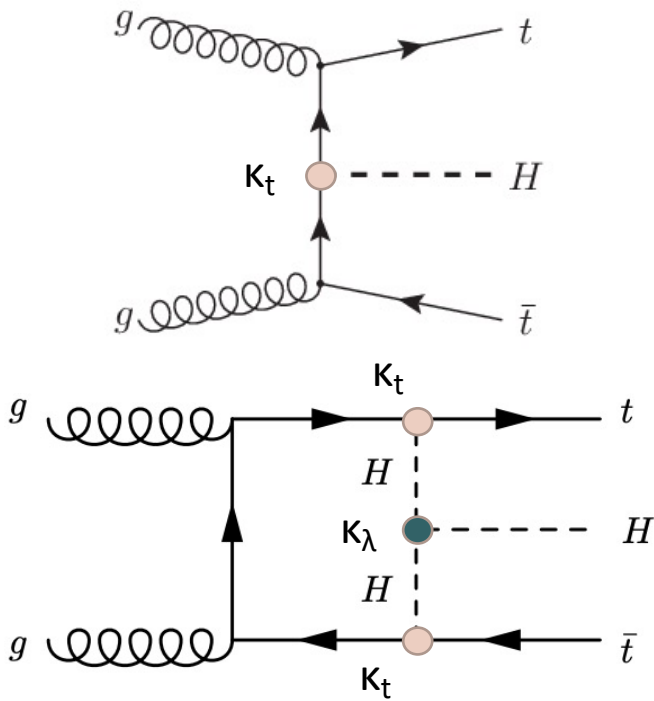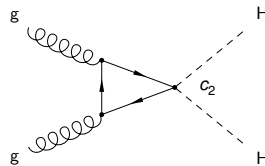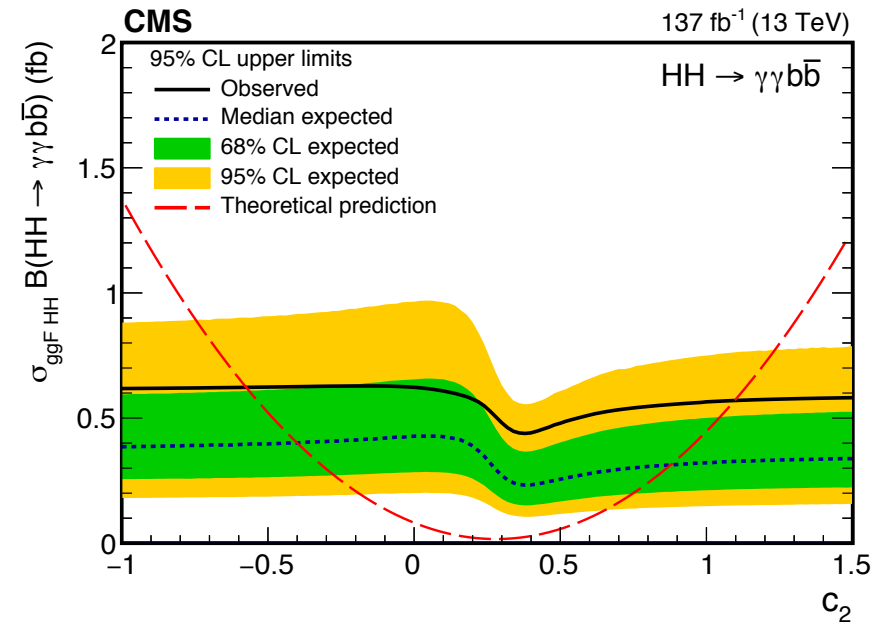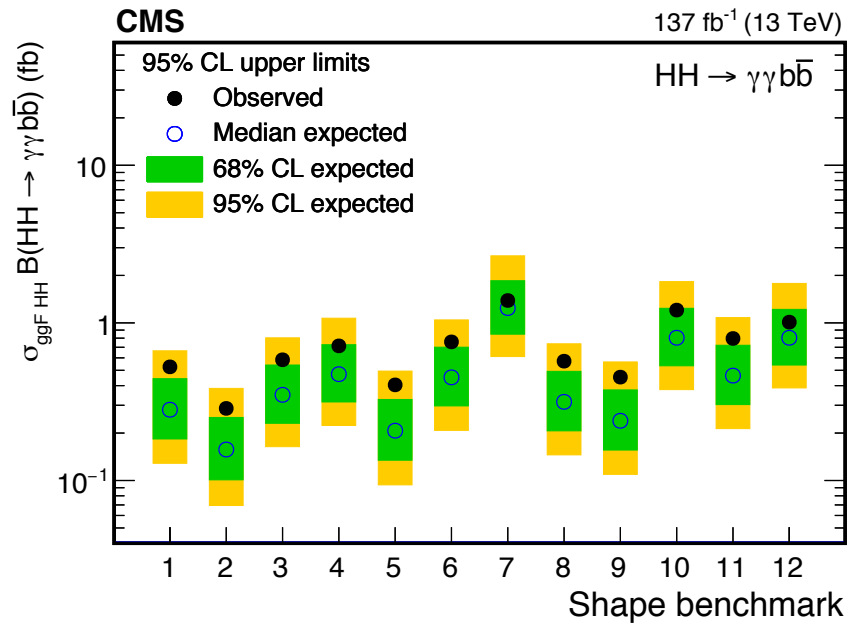
BSM coupling

observed: −0.6< c2 < 1.1
expected: −0.4< c2 <0.9.

JHEP04(2016)126

bbbb (resolved) HIG-20-005

- 4 dinstict 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
  - Fit on BDT discriminator

- VBF strategy (requiring 2 extra jets)
  - BDT to discriminate GGF and VBF (GGFKiller)
  - Categories based on GGF killer
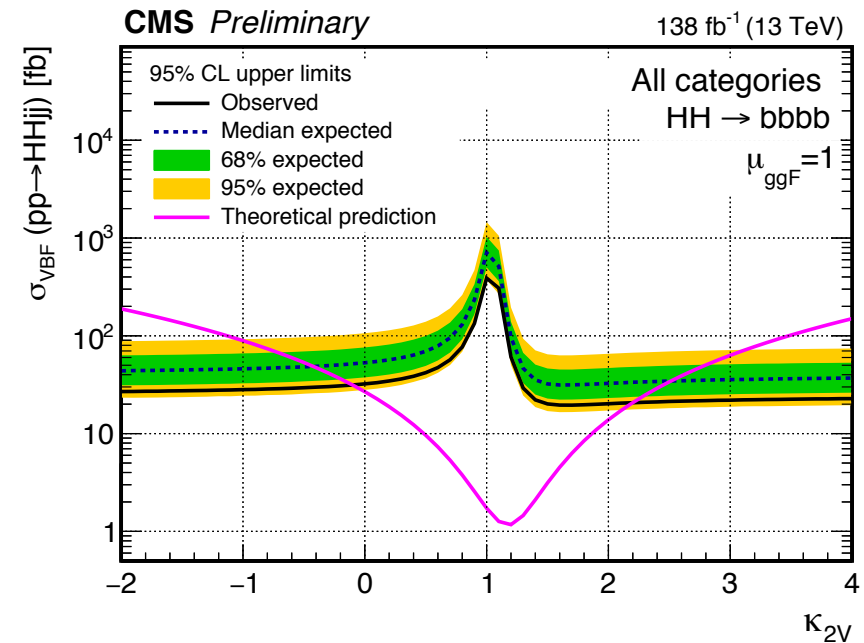   - VBF SM
    - VBF anomalous couplings
  - Fit on mHH
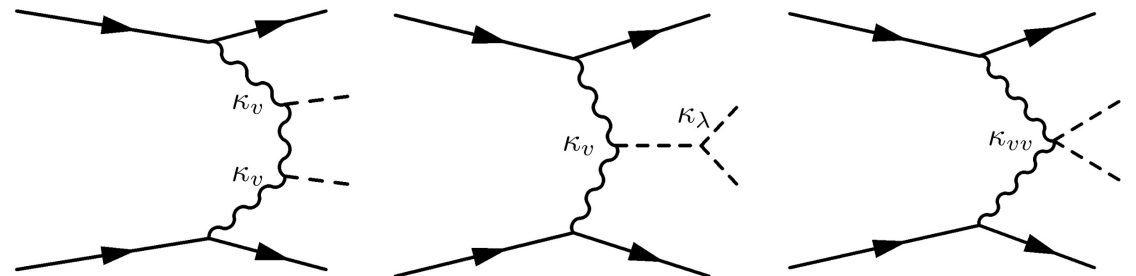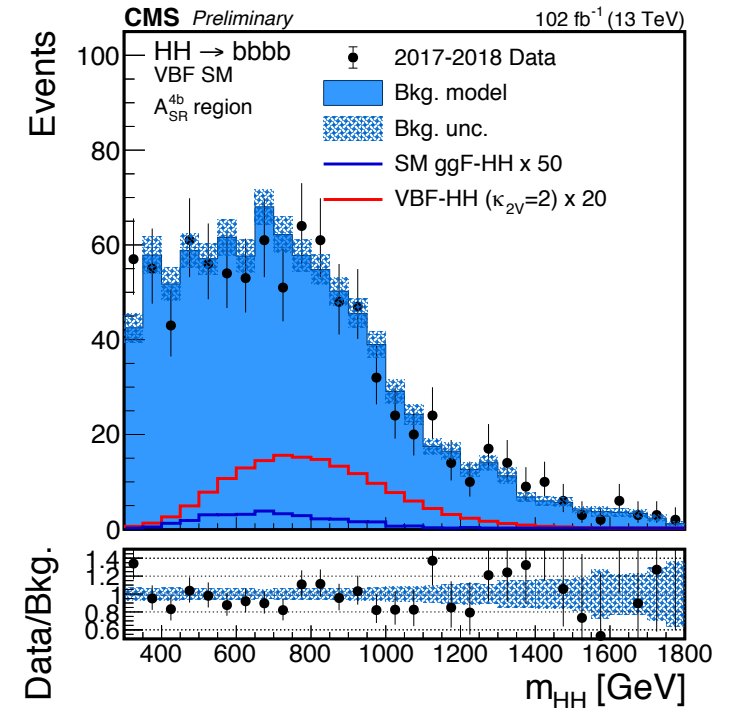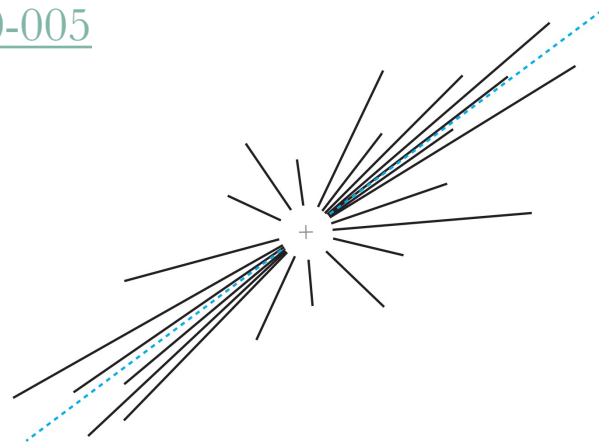
bbbb (resolved)

**Observed (expected) σ/σ_{SM} < 3.7(7.3) at 95% CL**
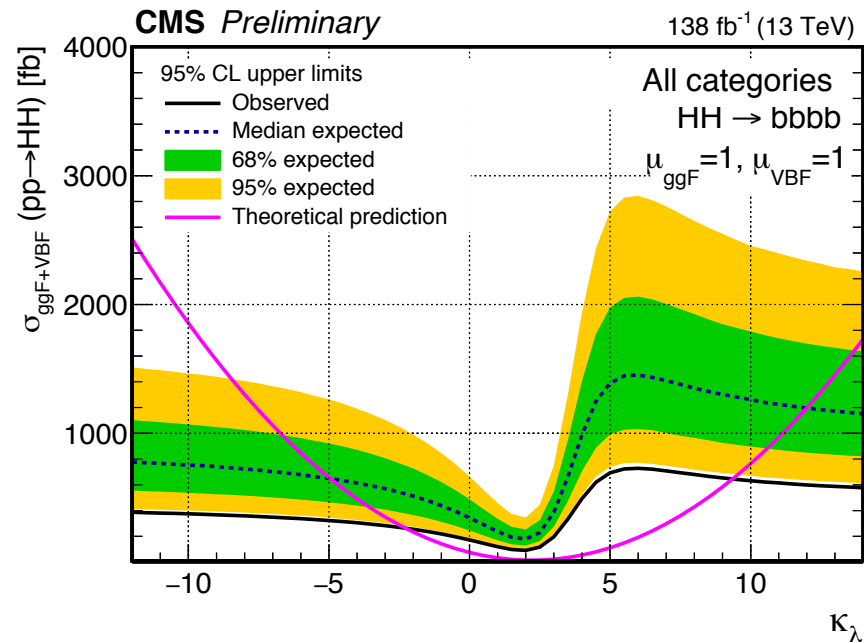
Observed: -2.5 < κ_λ < 9.5
Expected: -5.0 < κ_λ < 12.0

Observed: -0.1 < κ_{2v} < 2.2
**Expected: -0.4 < κ_{2v} < 2.5**

bbbb(VBF boosted)

- 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
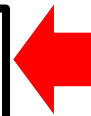
- Fit is performed on m_{HH}
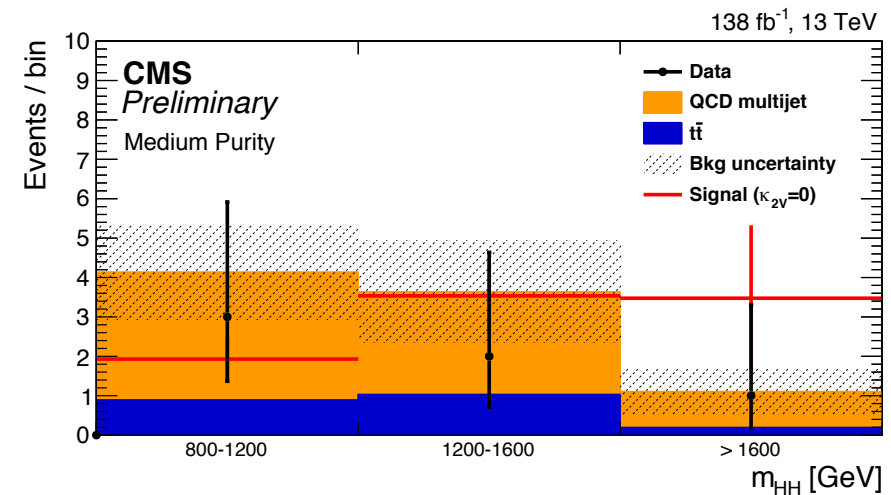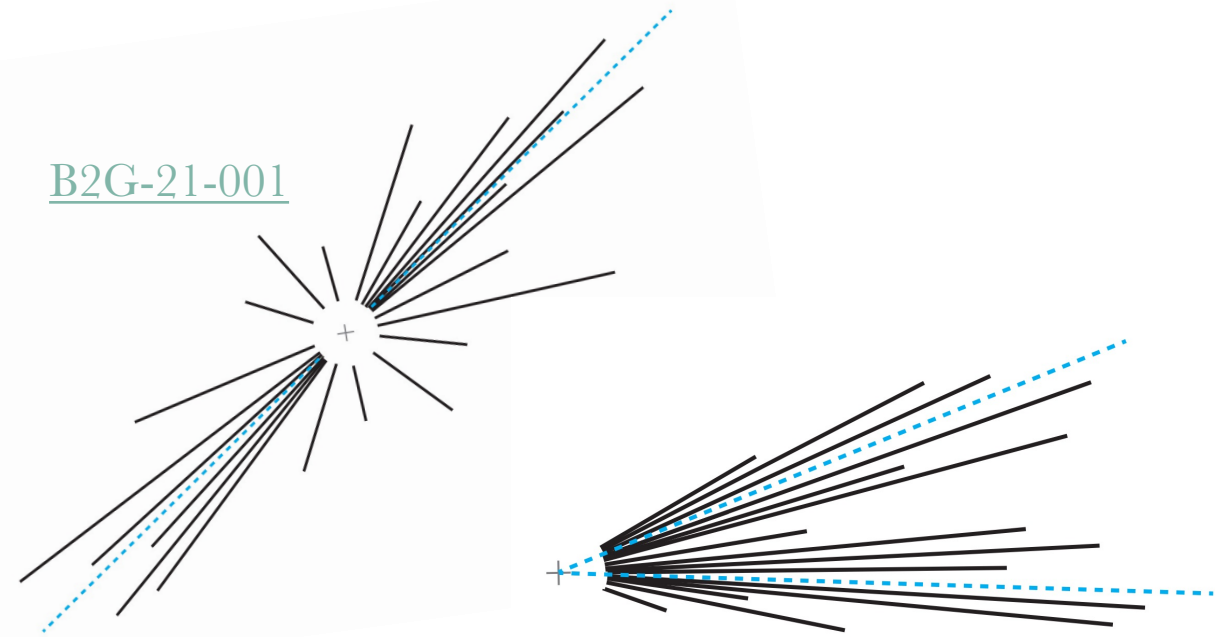
$\kappa_{VV}=0$ is shown in red

Very sensitive search!

bbbb(VBF boosted)
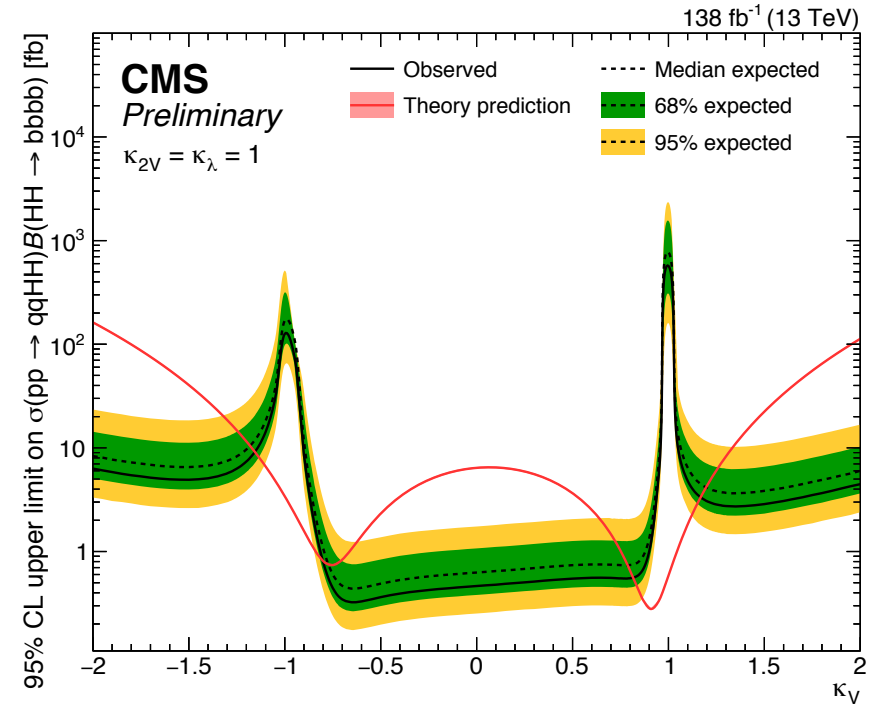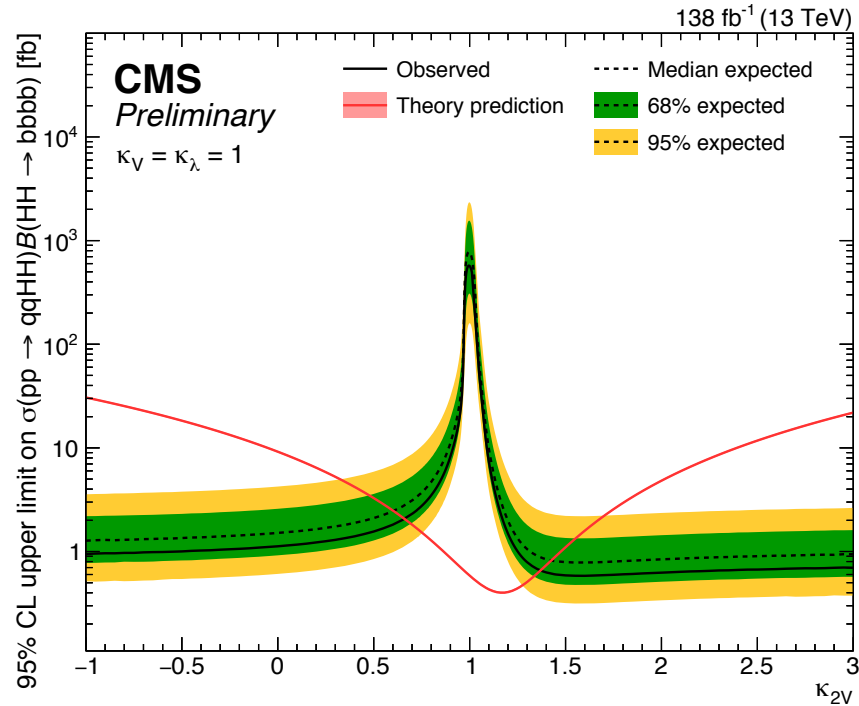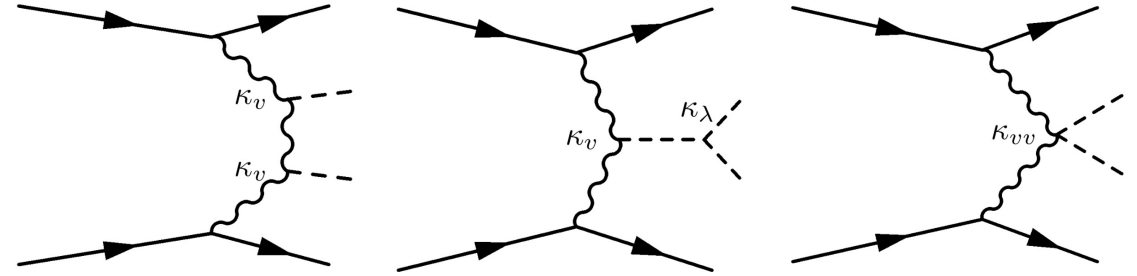
Observed: 0.6< κ_{vv} < 1.4
Expected: 0.6 < κ_{vv} < 1.4

Best to date!
Assuming $\kappa t = \kappa v = 1$,
$\kappa vv = 0$ is excluded at a
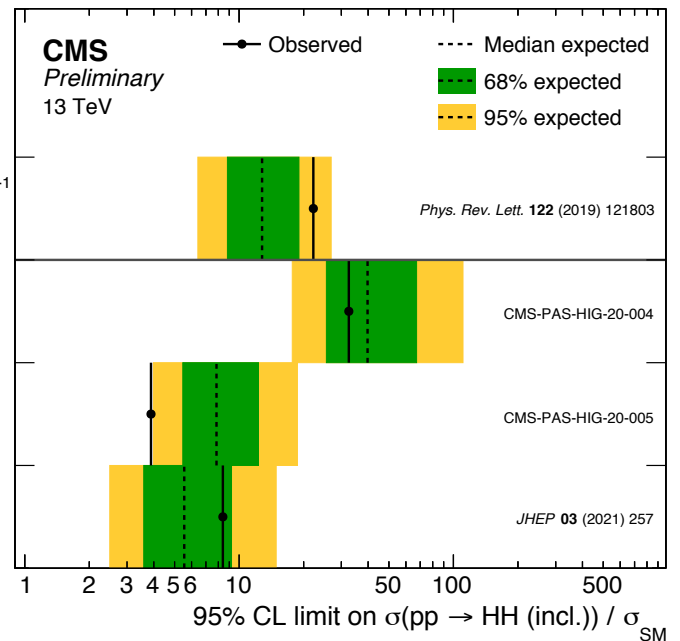CL higher than 99.99%.

κ_v compatible with SM

Combination and upcoming results

Previous combination
First Run II data, 36 fb⁻¹

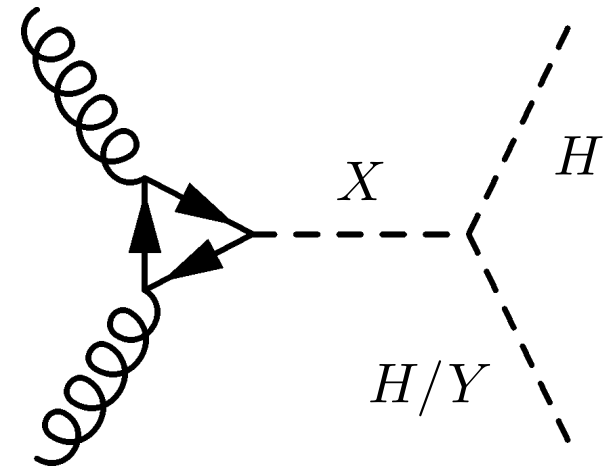New results from individual channels exceed the previous results

More results still in the making!

Run II 2016, 35.9 fb⁻¹
Expected 12.8
Observed 22.2

bbZZ, 138 fb⁻¹
Expected 39.8
Observed 32.5

bbbb, 138 fb⁻¹
Expected 7.84
Observed 3.88

bbγγ, 138 fb⁻¹
Expected 5.55
Observed 8.40

CMS
Preliminary
13 TeV

Observed
Median expected
68% expected
95% expected

Phys. Rev. Lett. **122** (2019) 121803

CMS-PAS-HIG-20-004

CMS-PAS-HIG-20-005

JHEP **03** (2021) 257

95% CL limit on $\sigma(pp \rightarrow HH\ (incl.)) / \sigma_{SM}$

Sensitivity to HH signal exceeds previous expectations for HL and beyond based on extrapolation

Resonant searches

Resonant searches

- X->HH
  - Spin 0 and Spin 2 resonances
  - Narrow width approximation (~10%)
  - Model independent
    - interpretation as radion (spin 0) and graviton (spin 2)
  - Resolved topology
    - Mx [260-1000] GeV
  - Boosted topology
    - Mx [1000< up to 4500]GeV
- X->YH in NMSSM
  - (a.k.a H->Yh in NMSSM notation)

Agni Bethani
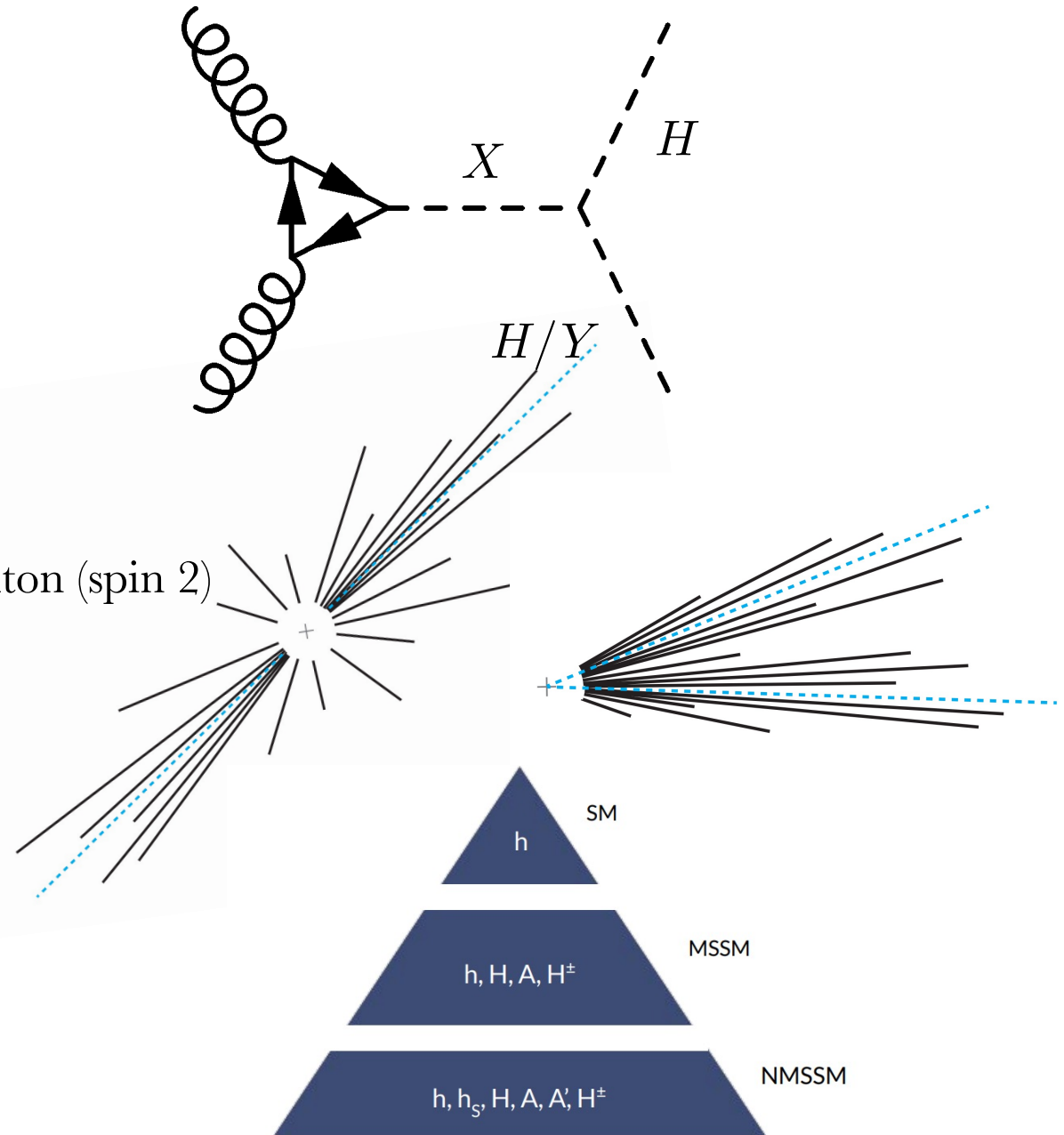
bbbb (boosted and semi-boosted)
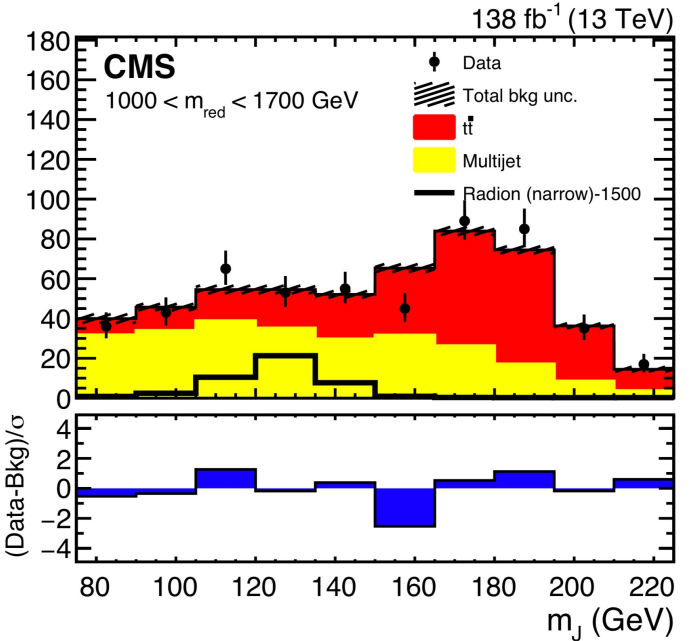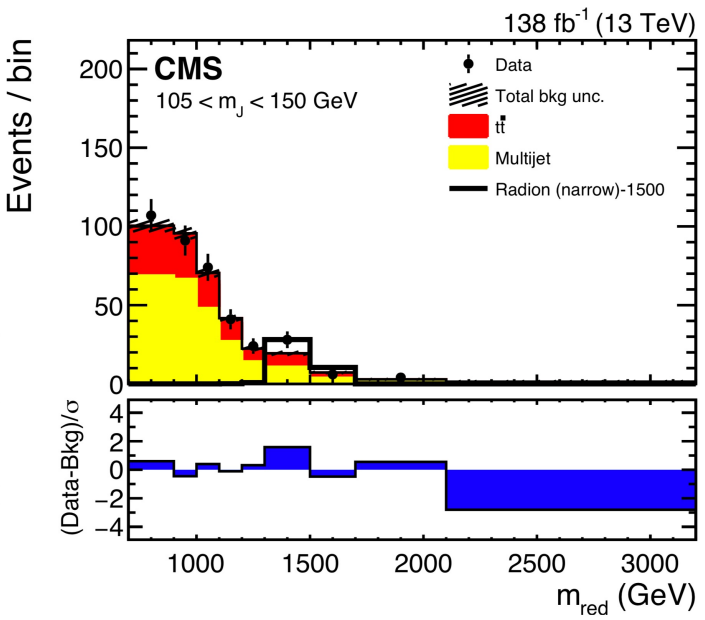
- Search for resonances
  1TeV<mx<3 TeV
  spin 0 (Radion) and spin 2 (Graviton)

- Large R jets identified by DeepAk8

- 3 event categories
  - 1 large R jet and 2 resolved jets
  - 2 large R jets both pass tight selection
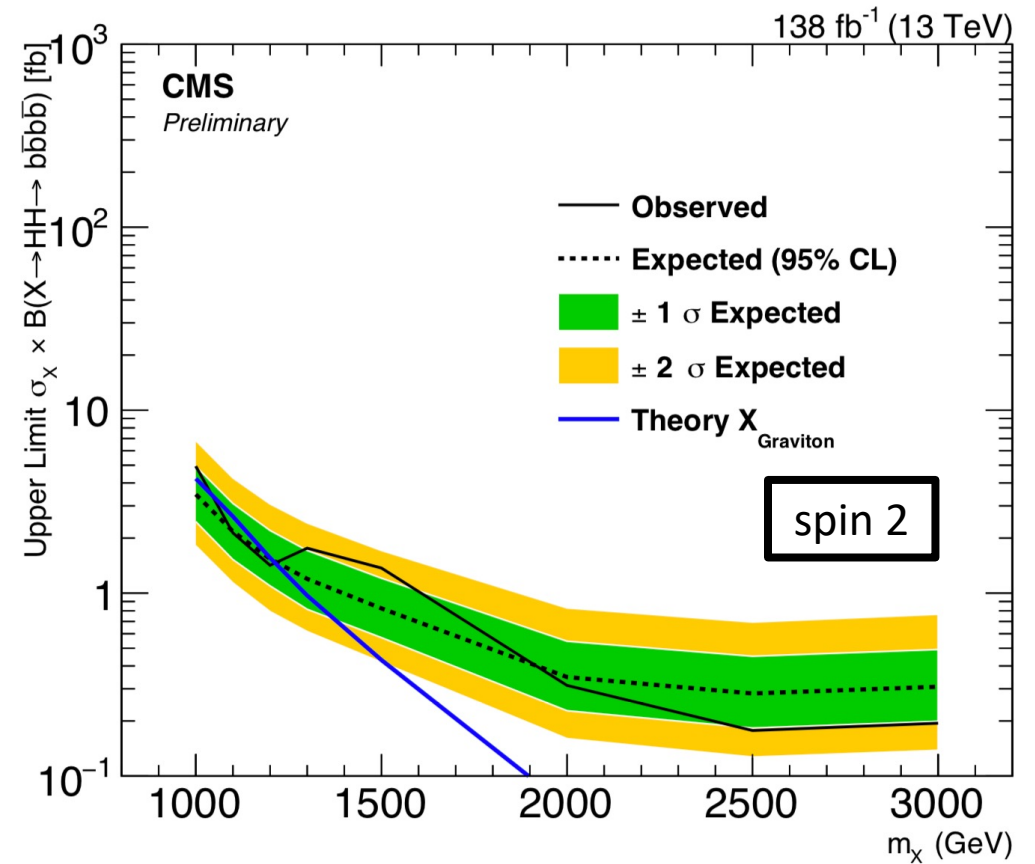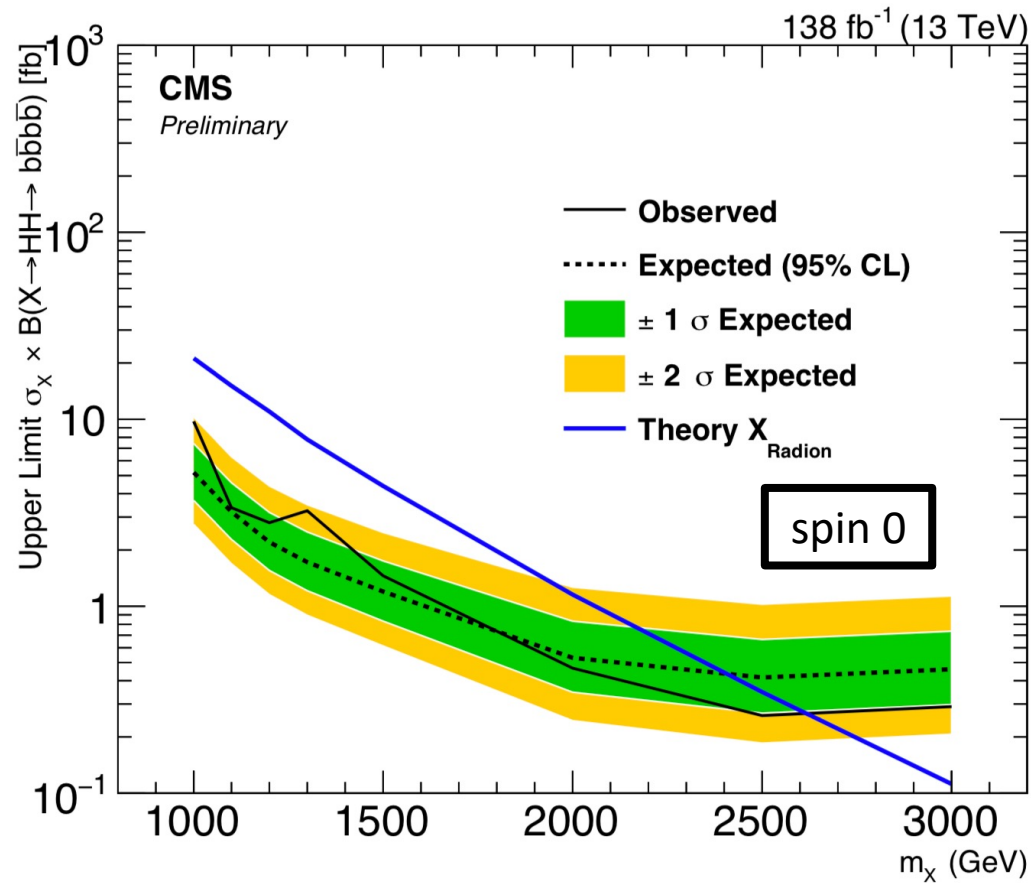 - 2 large R jets both pass loose selection
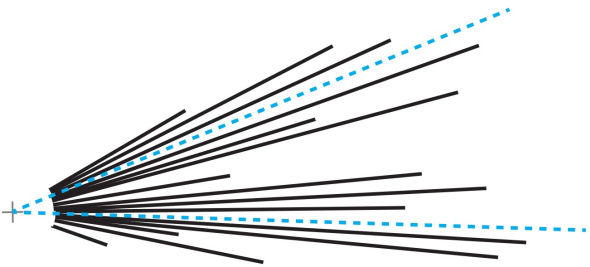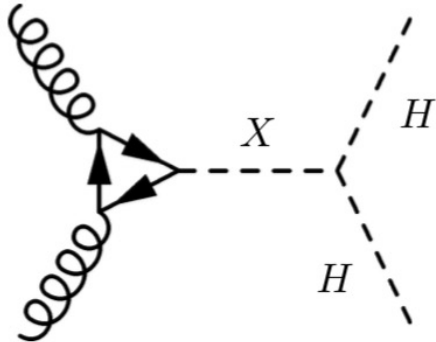
- QCD multijets background: datadriven

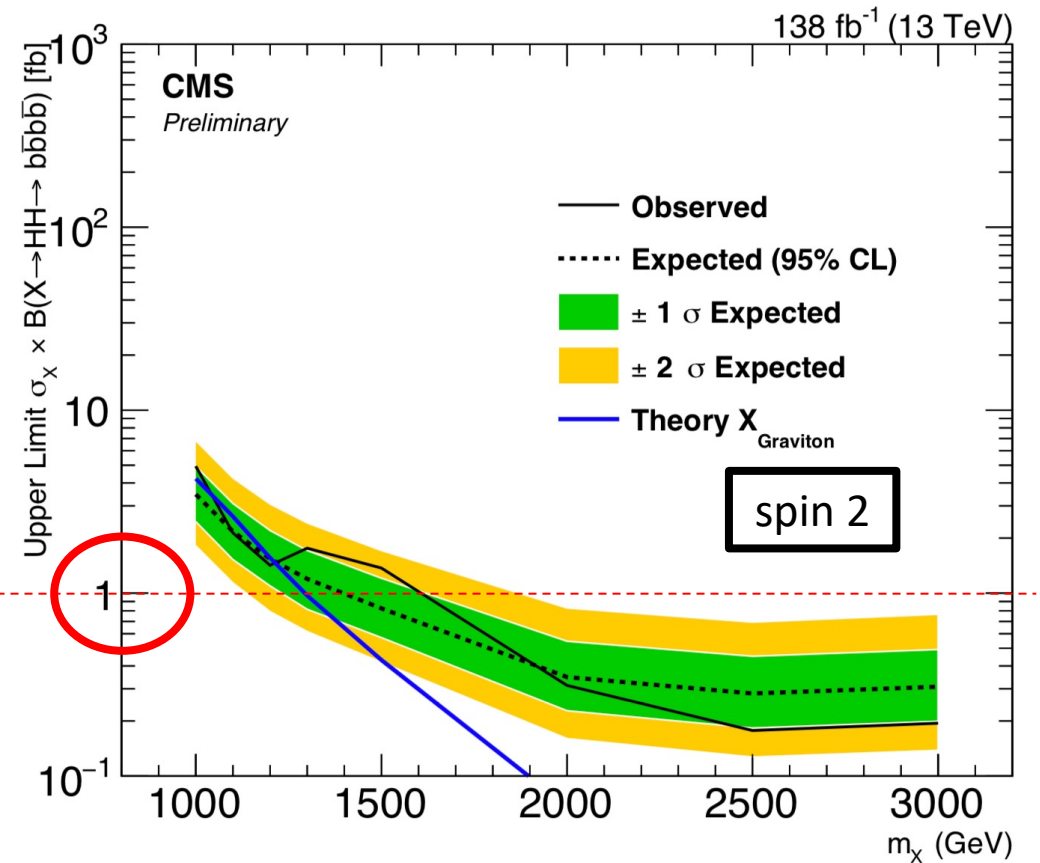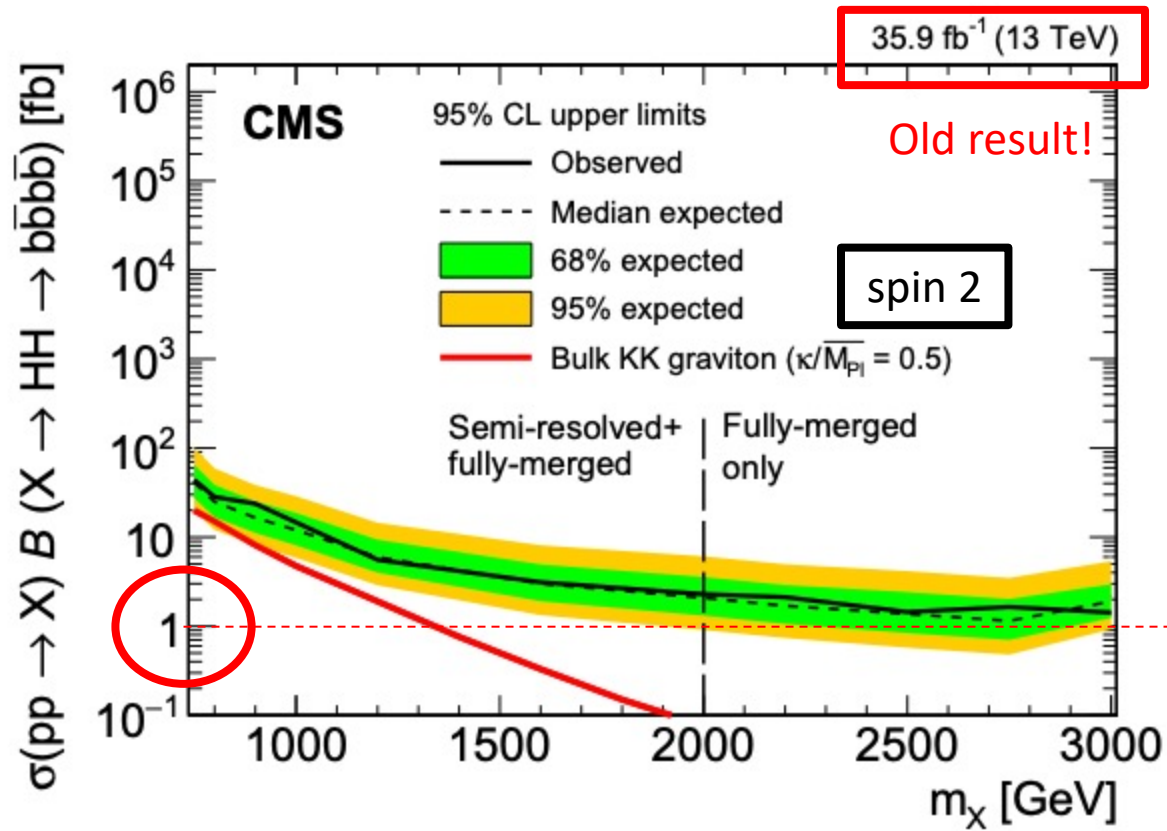- Fit is performed on 2D m_{J1} vs m_{jjred}

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

Agni Bethani

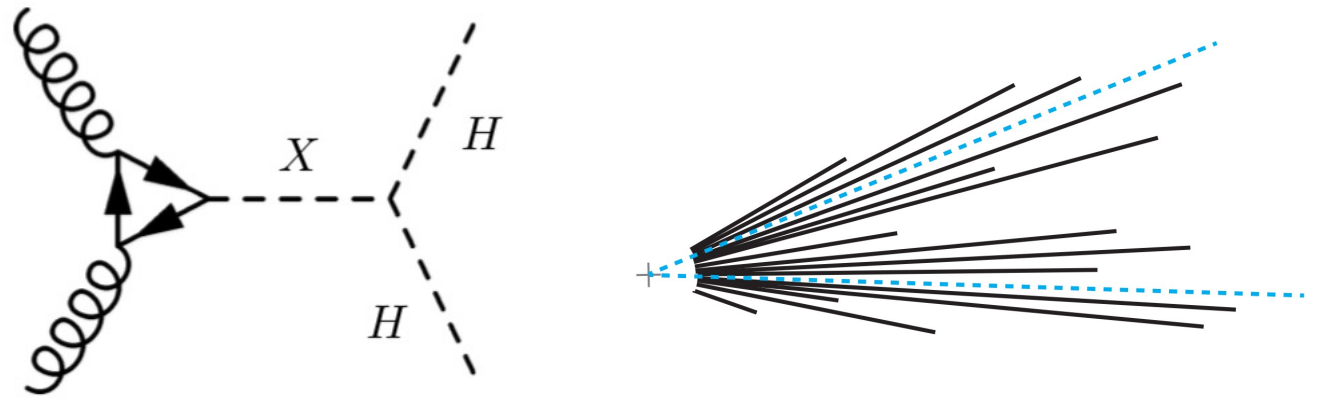# bbbb (boosted and semi-boosted)

bbbb (boosted and semi-boosted)

35.9 fb⁻¹ (13 TeV)

Old result!

spin 2

138 fb⁻¹ (13 TeV)

spin 2

bbWW

- Search for resonances
  800 GeV<mx<4.5 TeV
  spin 0 (Radion) and spin 2 (Graviton)

- H→bb
  - Large R jet indentified by H→bb tagger ($D_{Z/H \to bb}$)

- H→WW (or H→ττ)
  - Single-lepton (1l) channel
  - Dilepton (2l) channel

- 8 categories in 1l, 4 categories in 2l
  - according the lepton flavour and $D_{Z/H \to bb}$ and signal purity (1l)

- Simultaneous fit in 2D m_{bb}-m_{HH} plane

bbWW

Agni Bethani

bbWW

H → Y h →bbττ
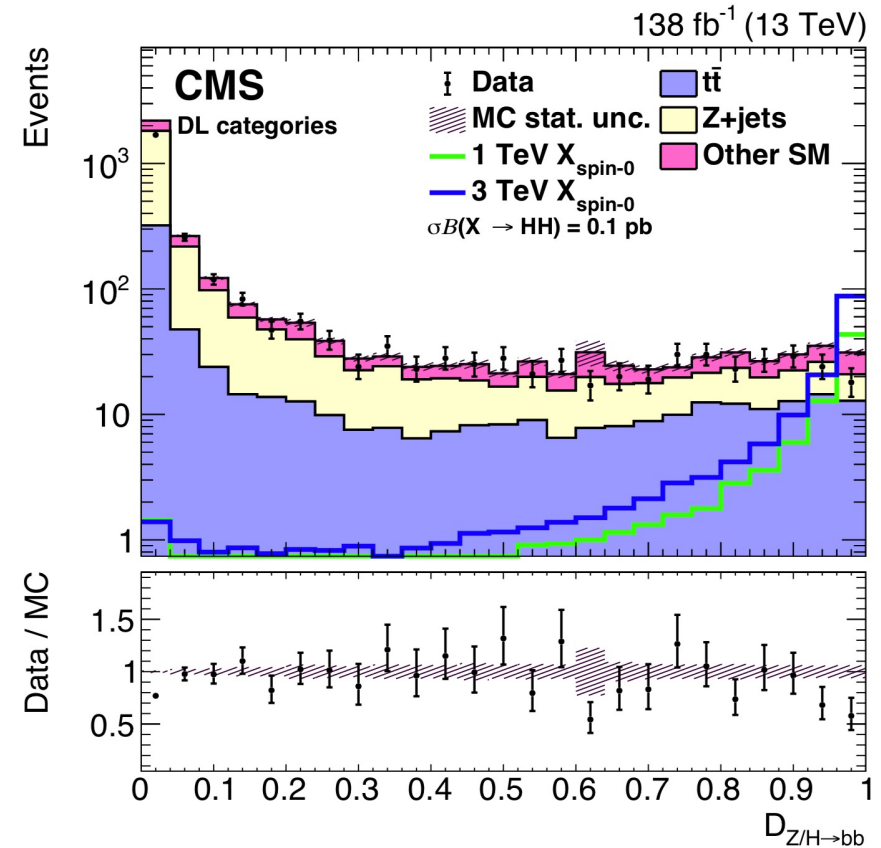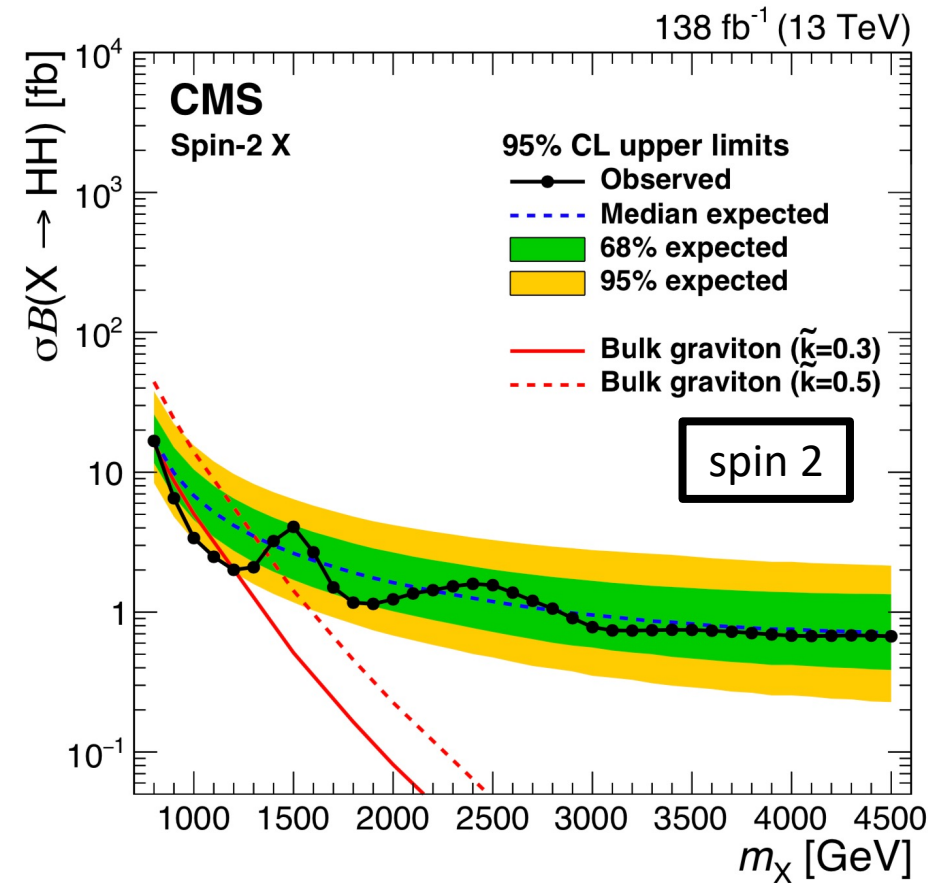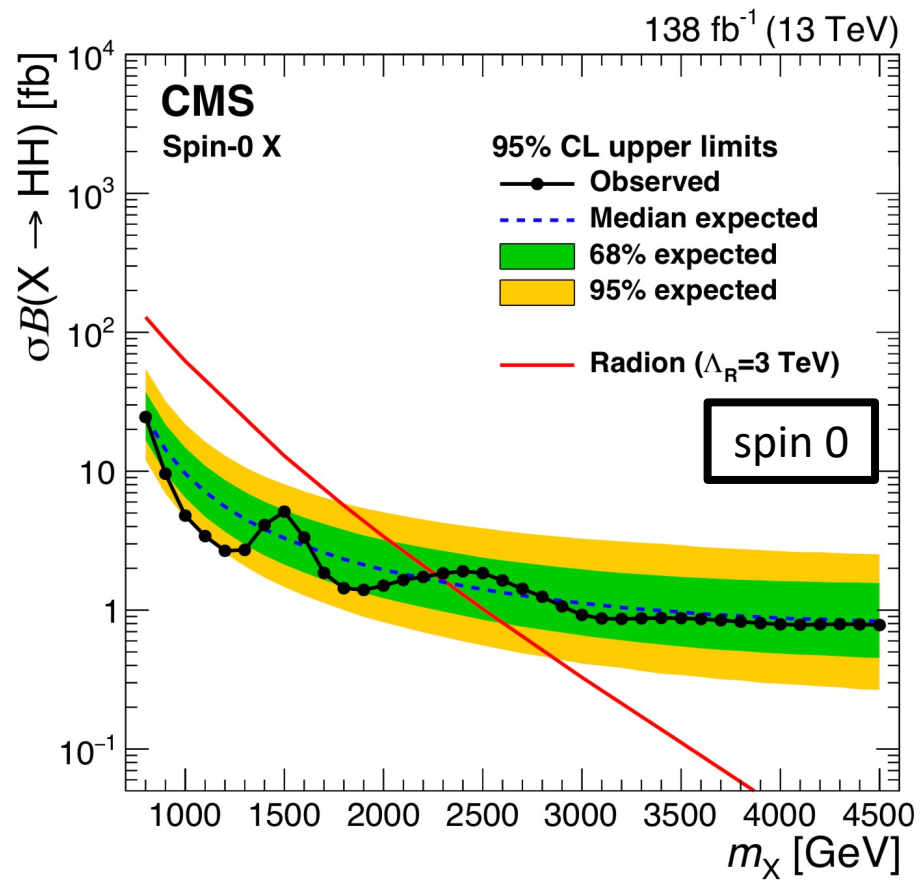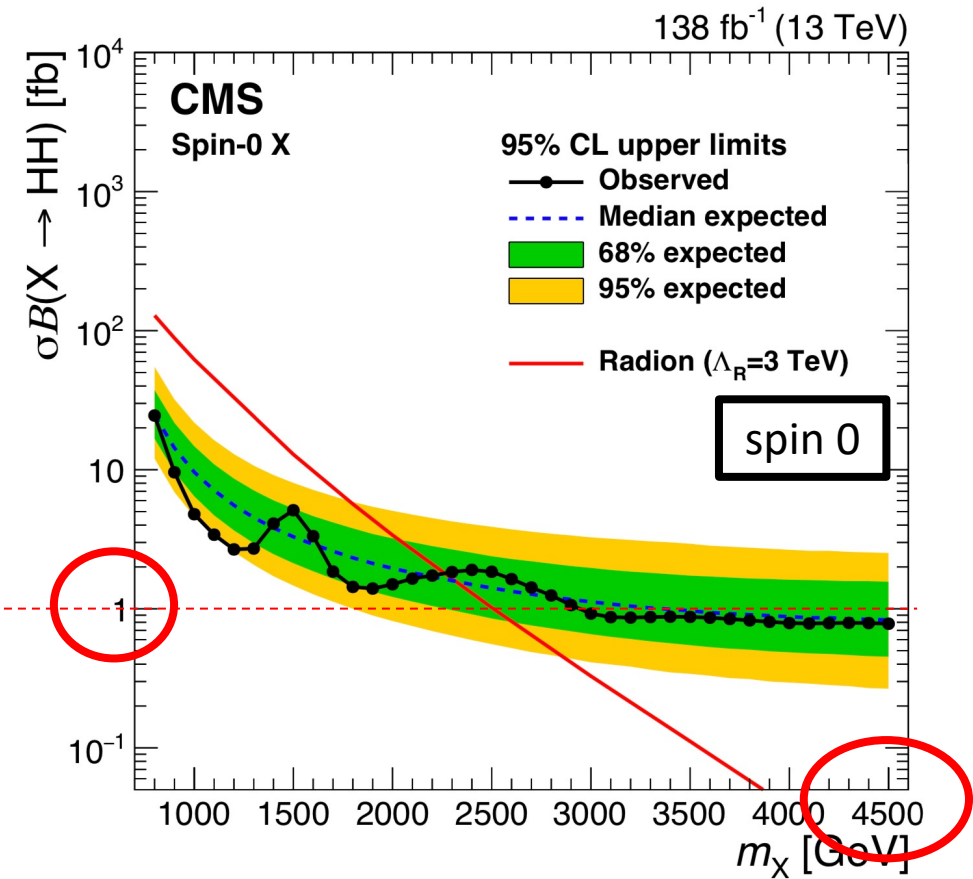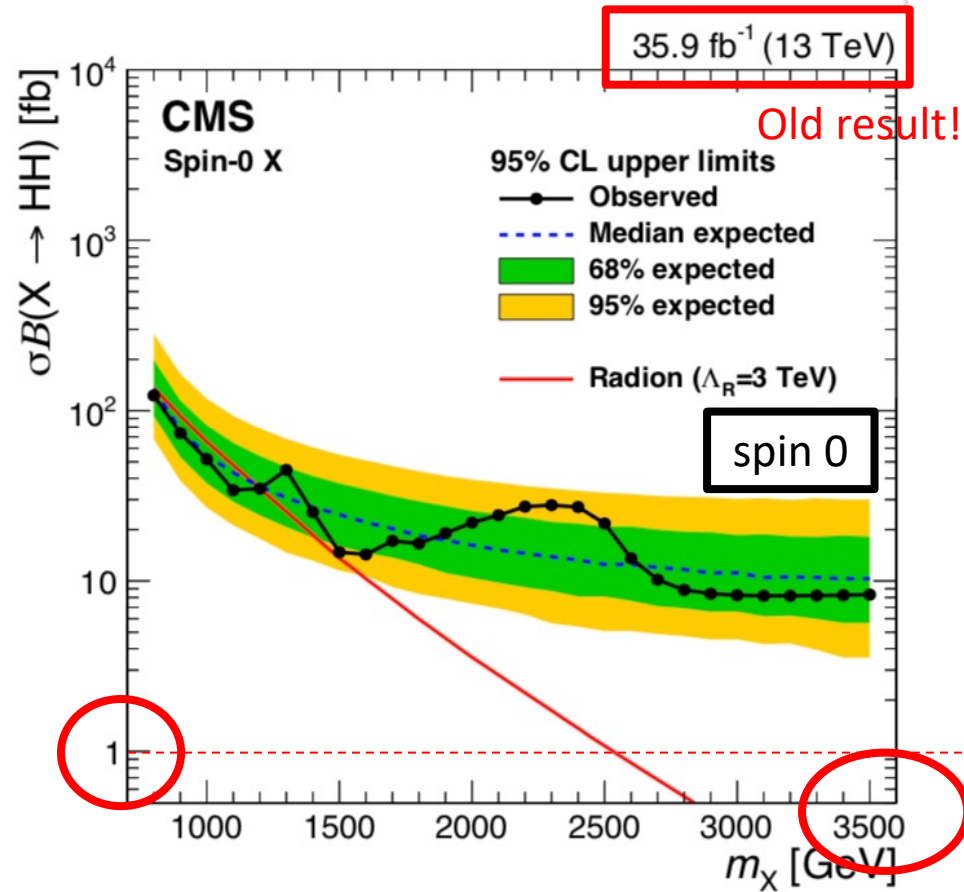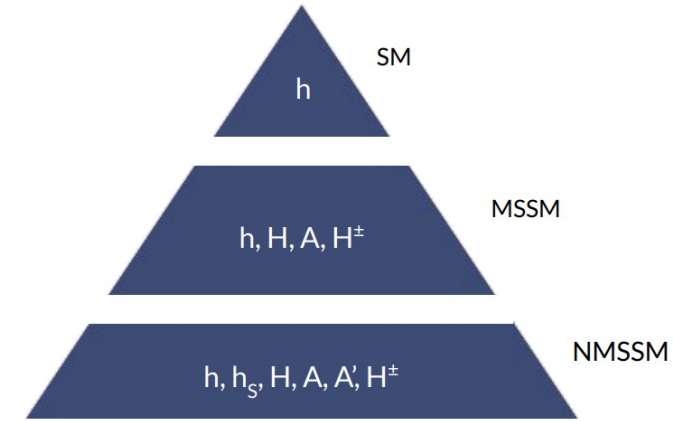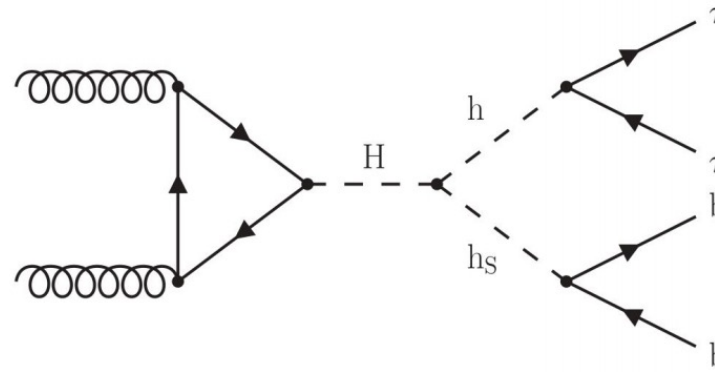
- 240<m_H<3000 GeV
  60<m_{hs}<2800 GeV

- $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$

- 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

- Maximum likelihood fit performed on the NN score

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H → Y h → bbττ
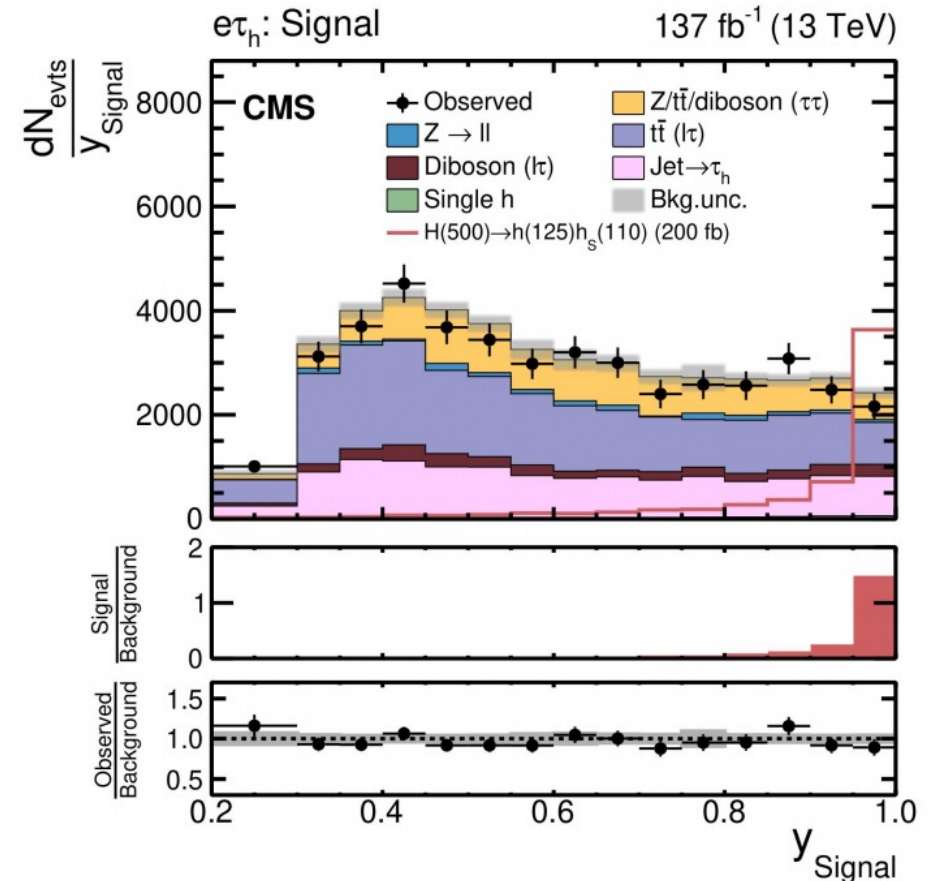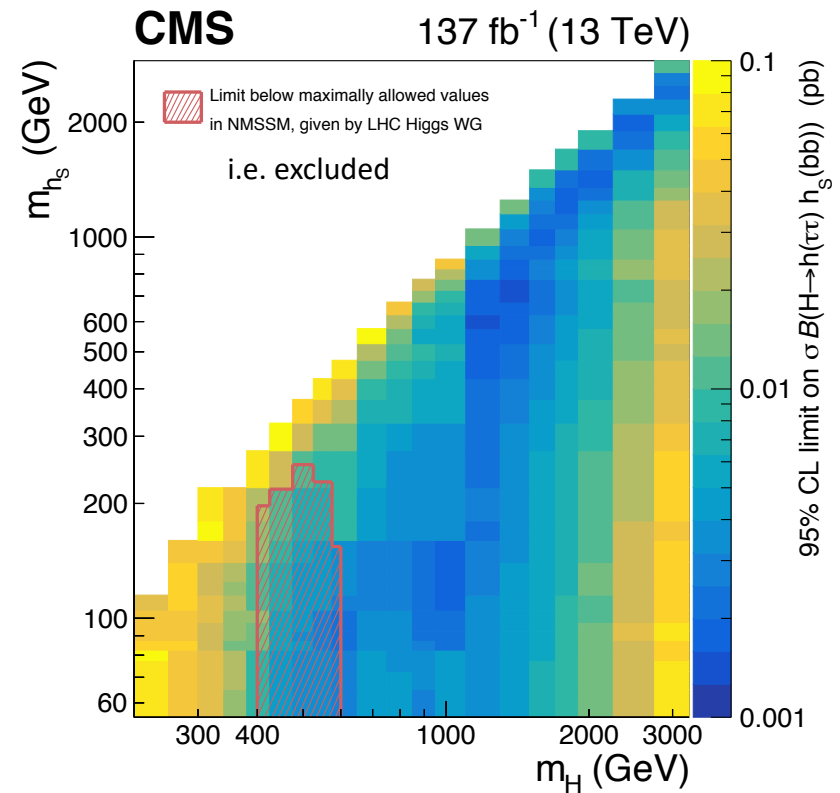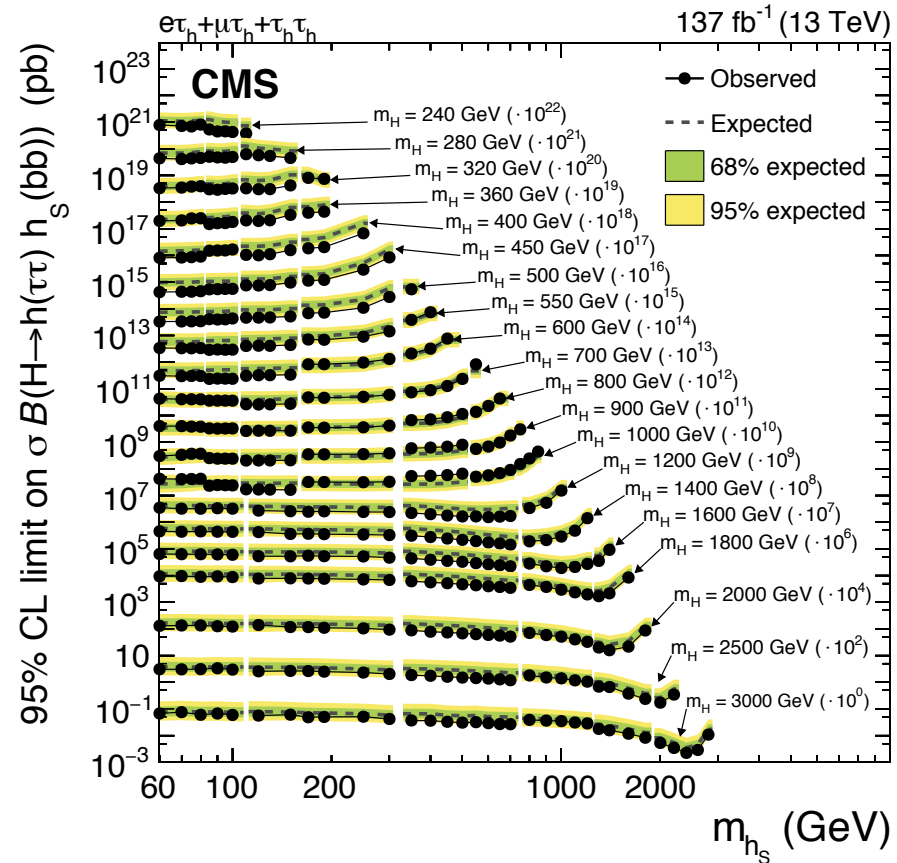
Summary

Searches for non-resonant HH production

- ggF and VBF studied
- CMS' best limits on SM production cross-section:
  - bb$\gamma\gamma$: Observed (expected) σ/σ_{SM} <7.7(5.2) at 95% CL
  - bbbb: Observed (expected) σ/σ_{SM} < 3.7(7.3) at 95% CL

- constraints on κ_λ and κ_{2v}
  - bbbb (boosted)
    Best constraint in κ_{vv} to date! Assuming SM values for all other couplings (κ_t, κ_v, κ_λ) we can exclude κ_{vv}=0!

- constraints on BSM couplings
  - c2 scan
  - EFT benchmarks/combinations of (κ_λ , κ_t , c_2 , c_g , c_{2g})

Results in more final states coming soon!

Searches for resonant HH production

- model independent spin 0, spin 2
- boosted and resolved categories (250 up to 4500 GeV)
- NMSSM YH production

CMS publications featured

- Results using all data collected 2016-2018 (137-138fb^{-1})
  - Non-resonant:
    - bbZZ(4l) resolved (GGF) HIG-20-004
    - bb$\gamma\gamma$ resolved (GGF and VBF) JHEP03(2021) 257
    - bbbb resolved (GGF and VBF) HIG-20-005
    - bbbb boosted (VBF) B2G-21-001
  - Resonant:
    - bbbb boosted B2G-20-004
    - bbWW(1 or 2 l) boosted B2G-20-007
    - NMSSM HY bb$\tau\tau$ HIG-20-014

Additional material

Agni Bethani

Double Higgs production in the Standard Model (SM)

- Higgs complex doublet

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

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

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

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

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

In the SM v=246 GeV and λ=0.13

Mass term

Higgs trilinear self-coupling **Double Higgs production**

Higgs quadratic self-coupling

Higgs pair 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 +1benchmarks with various combinations of values for the coupling modifiers JHEP04(2016)126
  - 7+1 more benchmarks are described here: no results using these yet.
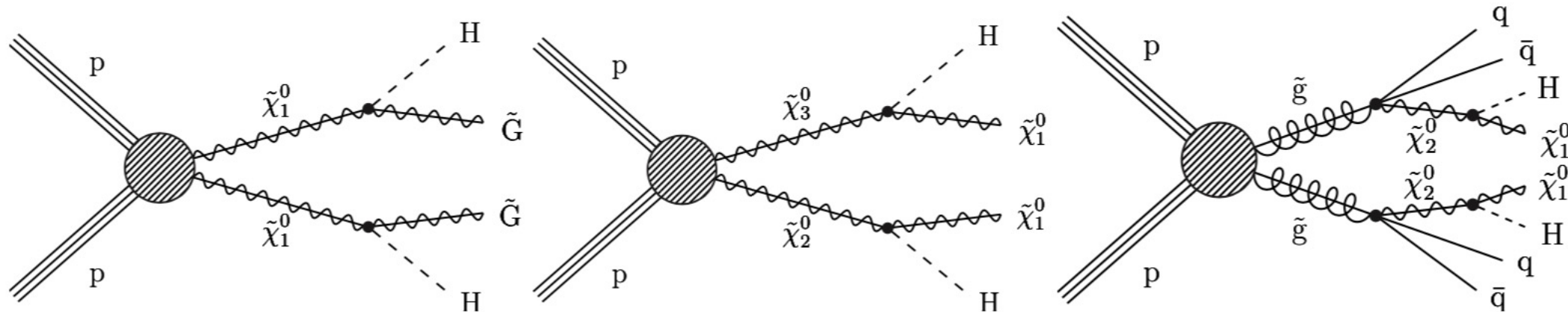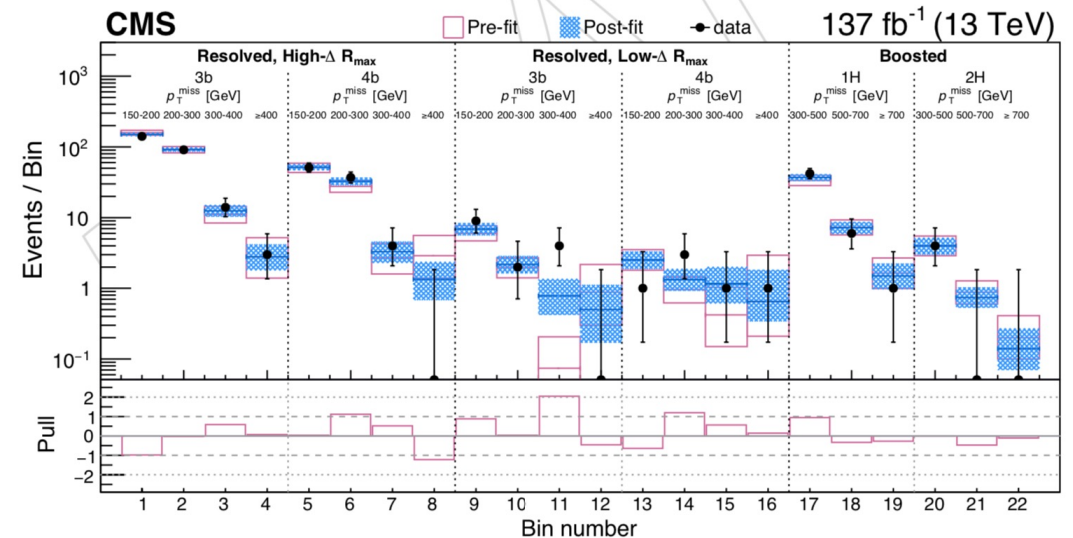   JHEP03(2020)091

ggF

VBF
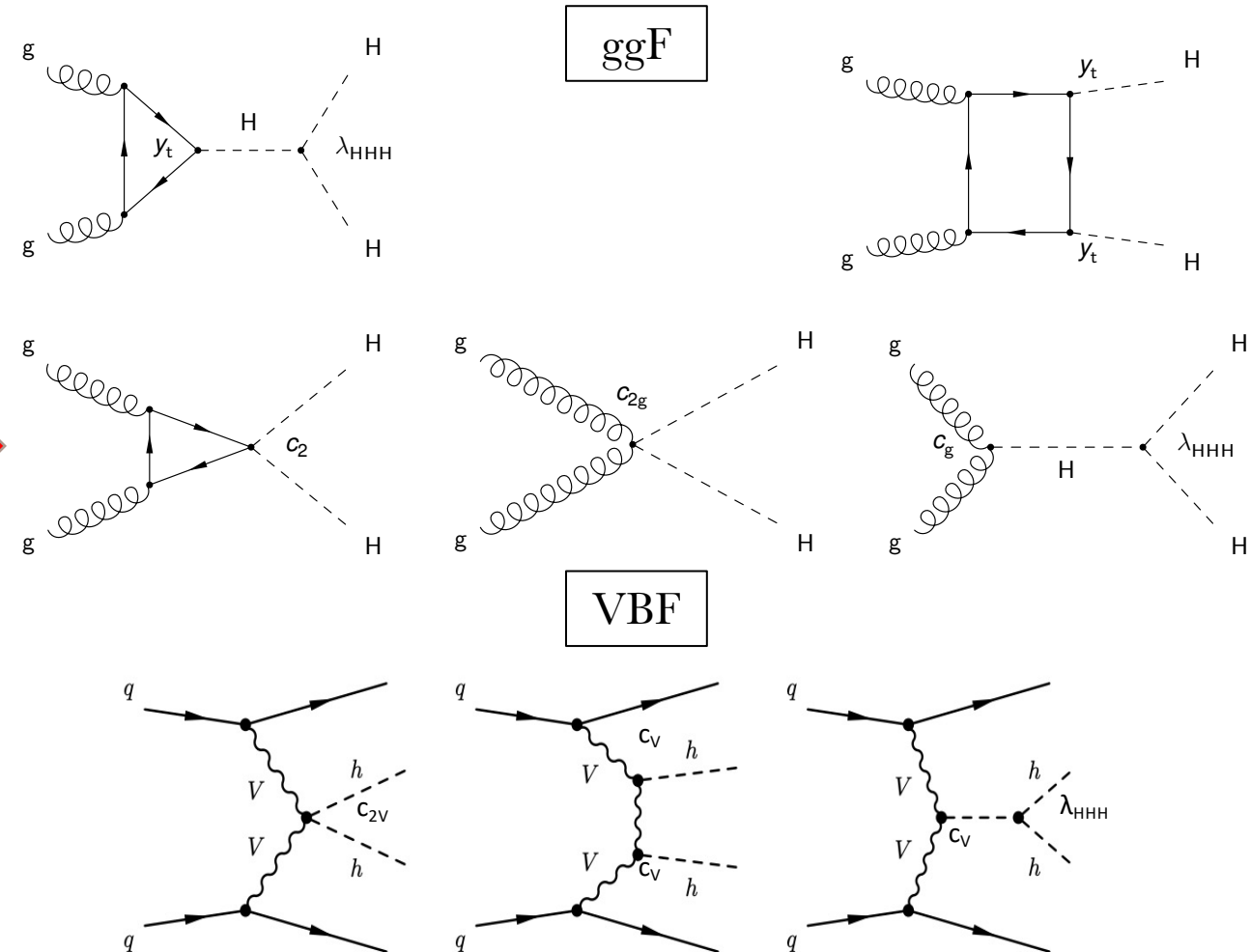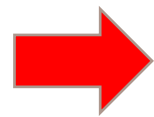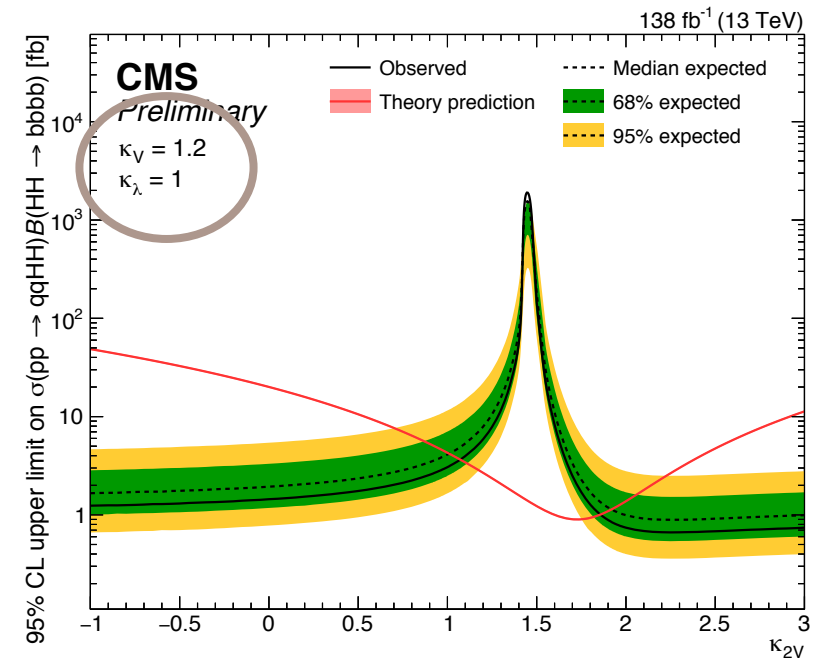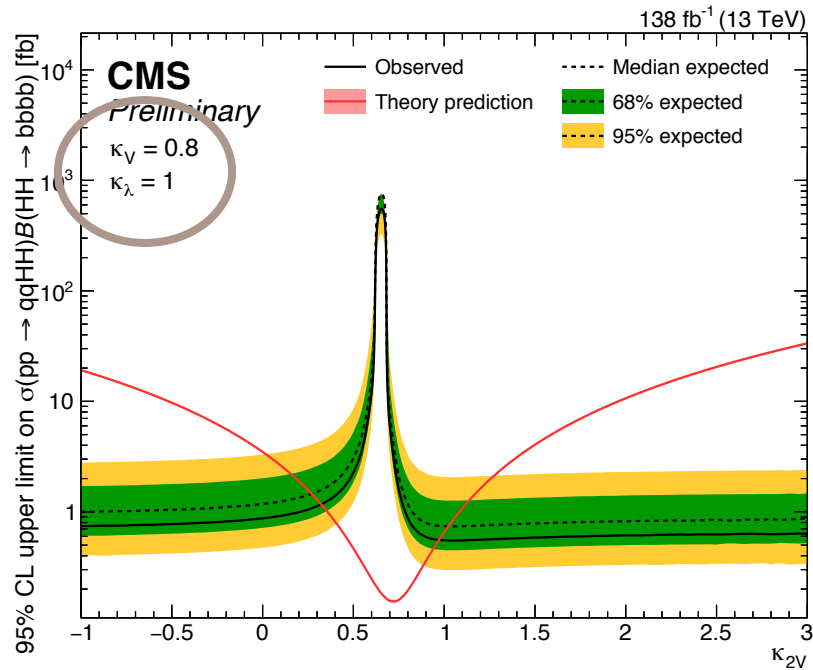
bbbb(VBF boosted)

bbbb(VBF boosted)
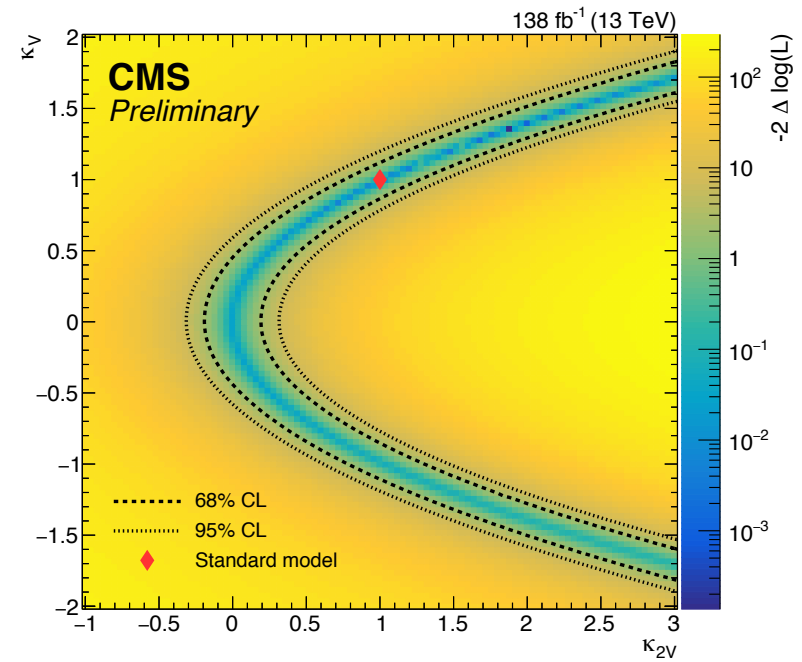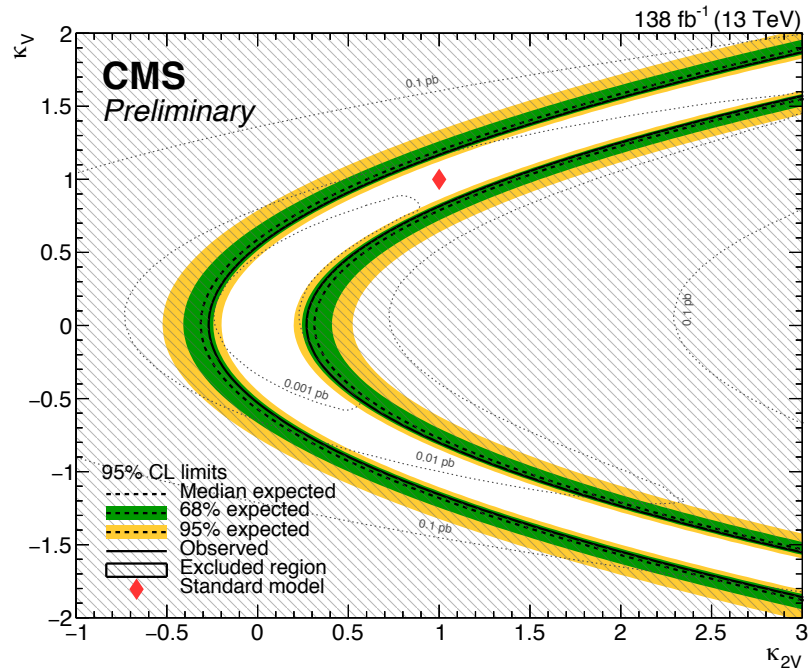
bbbb+MET, a SUSY search

New! SUS-20-004
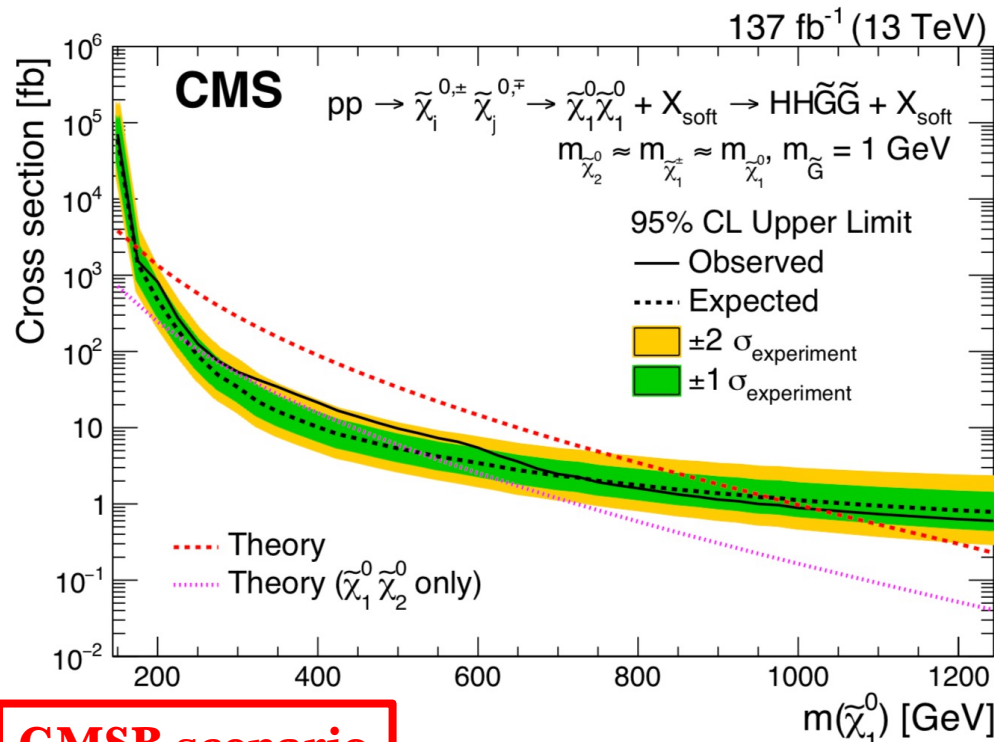

- Higgs bosons produced together with supersymmetric particles
- HH->bbbb+ missing transverse energy
- Analysis analysing both boosted and resolved topologies.
- Fit performed in several categories

bbbb+MET, a SUSY search

New!

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

GMSB scenario
N2N3 scenario