Searches for pair-production of Higgs bosons using the CMS detector at the LHC

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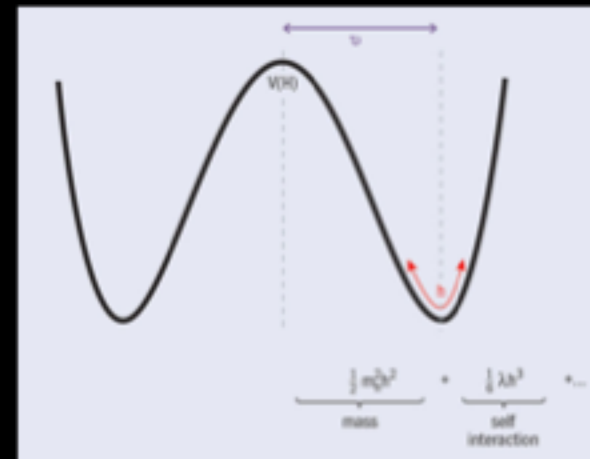
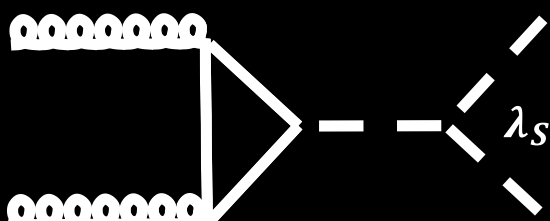
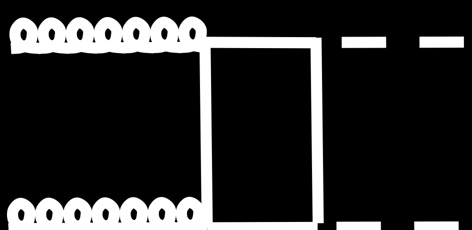
HH in the SM

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





$\lambda_{SM} = \frac{m_h^2}{2v^2}$



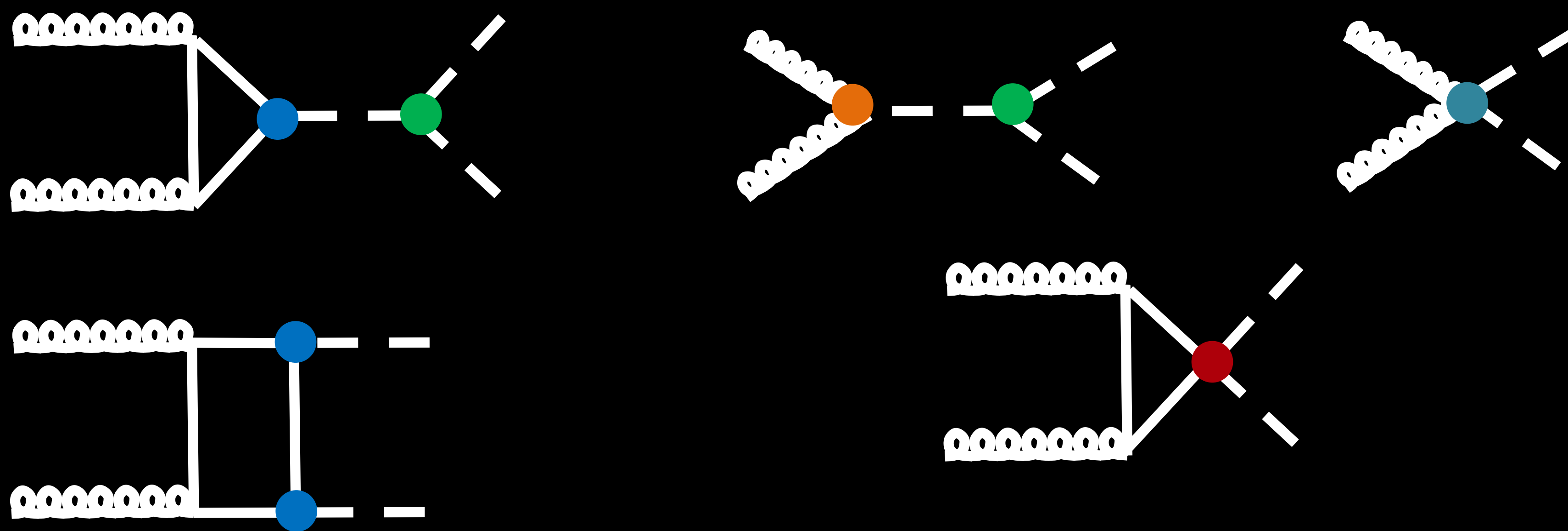
- Destructive interference between the two terms leads to a small cross section
- $\sigma(gg \to HH)_{SM} = 33.53\ \mathrm{fb}\ ^{+4.3\%}_{-6.0\%}(\mathrm{scale}) \pm 5.9\%\ (\mathrm{PDF})$
- $\sigma(\mathrm{VBF\ HH})_{SM} = 1.64\ ^{+0.05}_{-0.06}\ \mathrm{fb}$
- BSM contribution can modify the Higgs boson coupling parameters and enhance the HH cross section

Di-Higgs non-resonant with BSM contribution

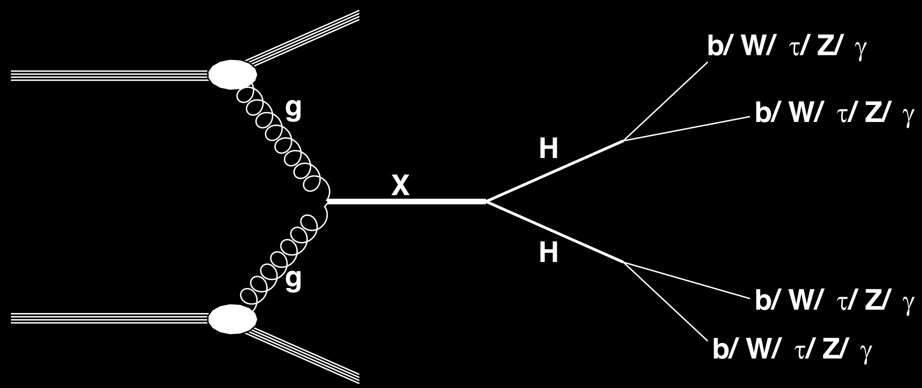
- EFT approach (PRD 91 (2015) 115008) using higher dimension operators
- $$L_{hh} = \frac{1}{2}\partial_\mu\partial^\mu h - \frac{1}{2}m_h^2h^2 - \kappa_\lambda\lambda_{SM}vh^3 - \frac{m_t}{v}\left(v + k_t h + \frac{c_2}{v}hh\right)(t_Lt_R + h.c.) + \frac{\alpha_S}{12}\left(c_{1g}h - \frac{c_{2g}}{2v}hh\right)G^A_{\mu\nu}G^{A\mu\nu}$$

$$\kappa_\lambda = \frac{\lambda}{\lambda_{SM}}$$

$$\kappa_t = \frac{y_t}{y_{t,SM}}$$

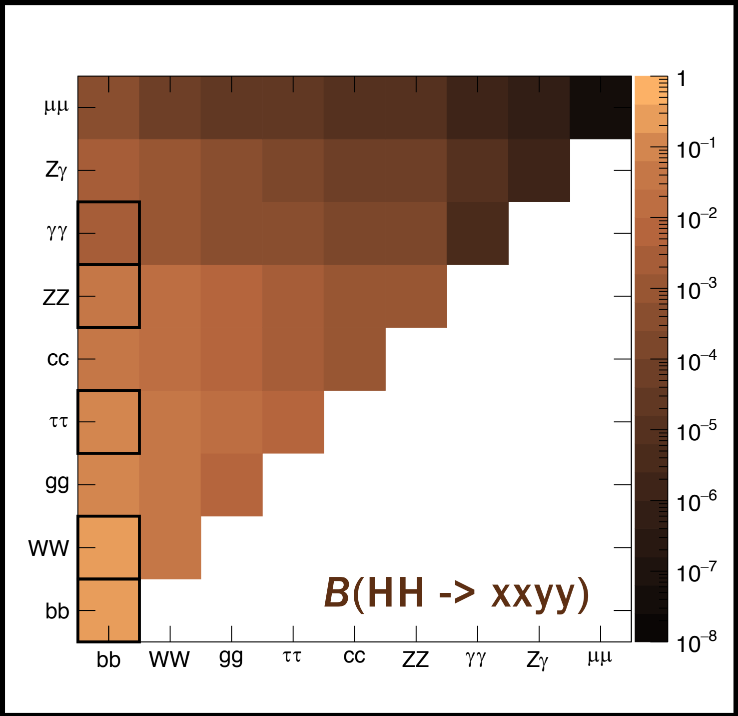


Di-Higgs resonant production



- Resonant production
  - **BSMs with new contributions**
  - **KK graviton, radion, heavy higgs bosons.**
  - **Overall enhancement of hh production cross section**
- Searches look for a narrow resonance X with a mass m_X using the invariant mass spectrum m_{HH}.

Explored final states



- bbbb:
  - Resolved
  - Boosted
  - Semi-boosted
- $bb\tau\tau$
  - Resolved
  - Boosted
- $bb\ell^{+}\ell\nu\nu$
- $bb\gamma\gamma$

- The bbbb final state has the branching fraction advantage
- Other decay channels give cleaner final states: lower backgrounds, trigger advantage.
- **Combination of all analysis for the best signal sensitivity.**

Overview of analyses

35.9 fb^{-1} (2016)

Final state	Targeted search	Documentation
4b	Low mass resonance	CMS-PAS-HIG-17-009 arXiv:1806.03548
	High mass resonance	CMS-PAS-B2G-16-026 PLB 781 (2018) 244
	Intermediate mass resonance and non-resonant HH	CMS-PAS-B2G-17-019
	Non-resonant HH NEW	CMS-PAS-HIG-17-017
$bb\tau\tau$	Low mass resonance and non-resonant HH	CMS-PAS-HIG-17-002 PLB 788 (2018) 101
	High mass resonance	CMS-PAS-B2G-17-006
$bb\ell^{+}\ell^{-}\nu\nu$	Low mass resonance and non-resonant HH	CMS-PAS-HIG-17-006 JHEP 01 (2018) 054
$bb\gamma\gamma$	Low mass resonance and non-resonant HH	CMS-PAS-HIG-17-008 arXiv:1806.00408
Combination	Resonant and non-resonant HH NEW	**CMS-PAS-HIG-17-030**

Low mass resonance searches mostly for m_X < 1 TeV (dependent on final state).

HH→4b resonant

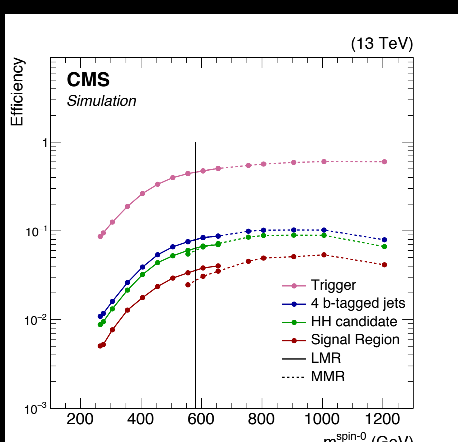
arXiv:1806.03548
PLB 781 (2018) 244
CMS-PAS-B2G-17-019

- 3 analyses for different resonance mass ranges:
  - **Resolved: 4 b jets used to reconstruct the HH->4b**
  - **Fully-merged: 2 large–area jets each identifying a boosted H->bb**
  - **Semi-resolved: 1 large-area jet and 2 b jets**

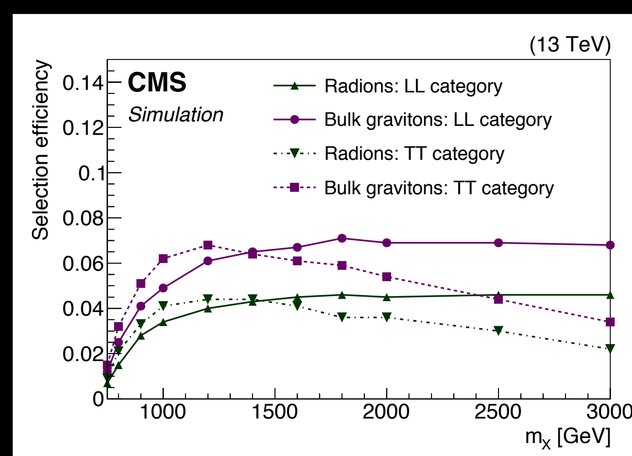
- Background estimation from sidebands of Higgs boson candidate masses.
- Low and medium mass regions.

- Fully-merged and semi-resolved: Background estimated from sideband regions using misidentification rate of Higgs jets in QCD background.
- The two analyses are combined.

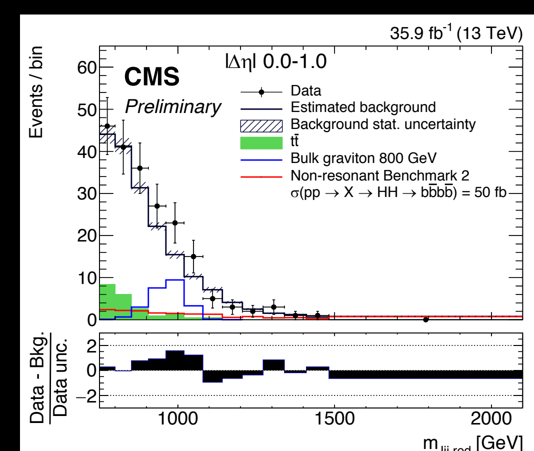
Efficiencies: resolved analysis



Efficiencies: fully-merged analysis



Mass distribution: semi-resolved events



HH→4b resonant

arXiv:1806.03548
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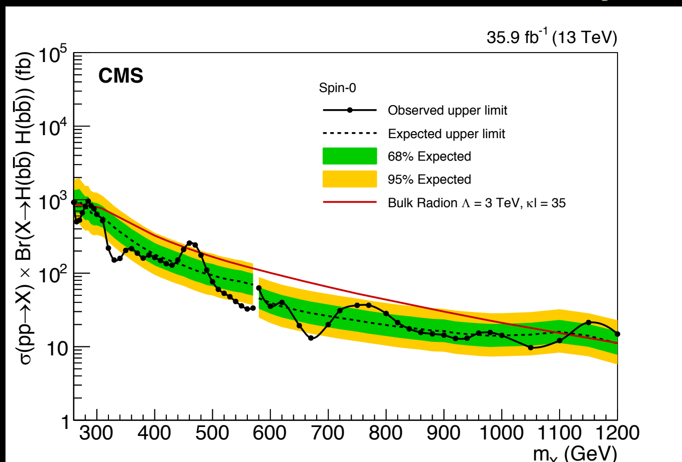
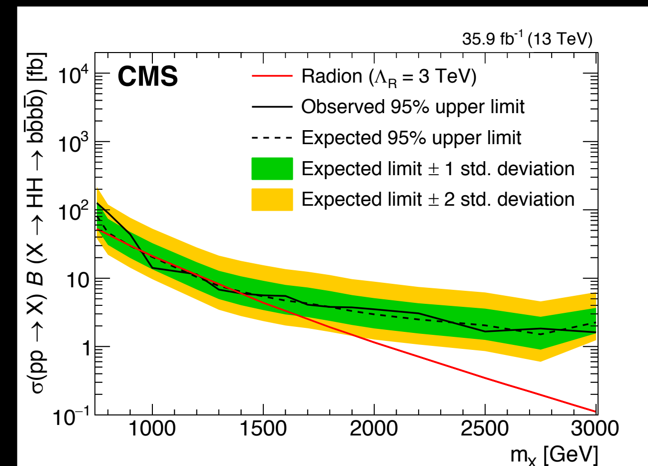
CMS-PAS-B2G-17-019

Low mass: Resolved analysis

Spin 0



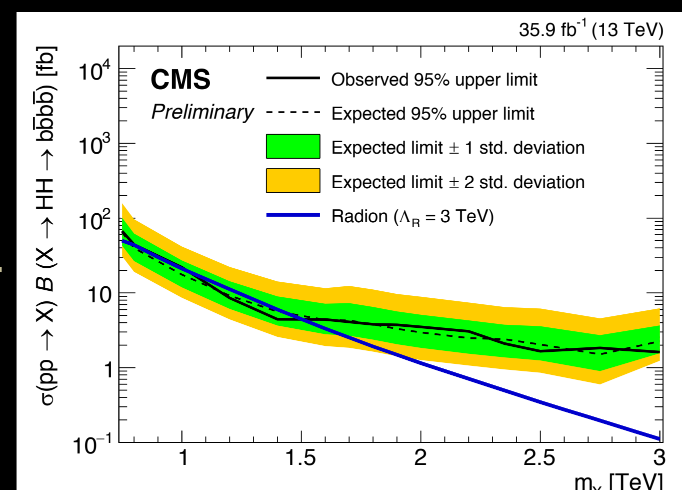
High mass: Fully-merged analysis



- Upper limits set on the cross section of bulk gravitons and radions in the warped extradimensional models
- Including semi-resolved events improve limits between 55—8% for the radion in the mass range 750—1600 GeV.
- Non-resonant HH production also probed with boosted final states.

Fully-merged + semi-resolved

Spin 0

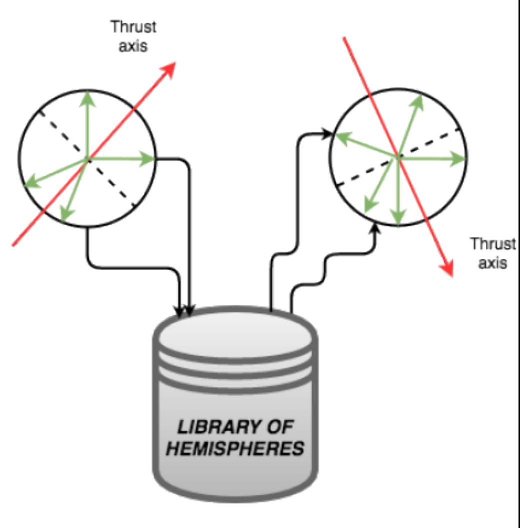


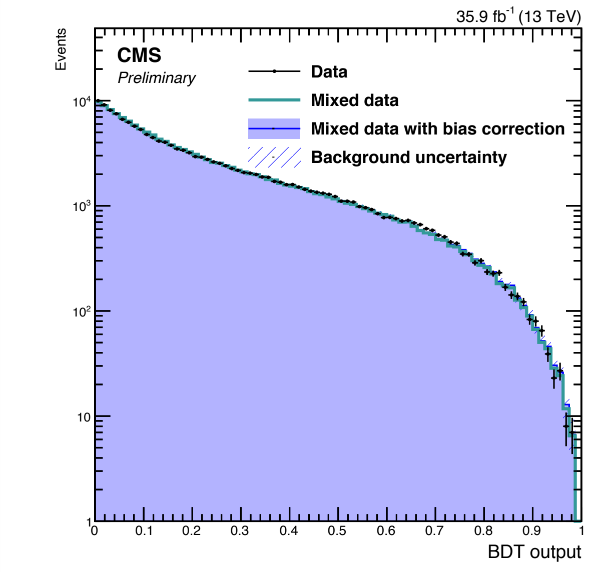
HH→4b non-resonant

CMS-PAS-HIG-17-017

NEW

- Analysis optimized to be sensitive to the SM gg->HH->4b process.
- Main background: QCD multijets. Reduced requiring 4 b jets and a BDT classifier.
- A hemisphere mixing technique is used to provide samples for BDT training and for predicting the background BDT shape.





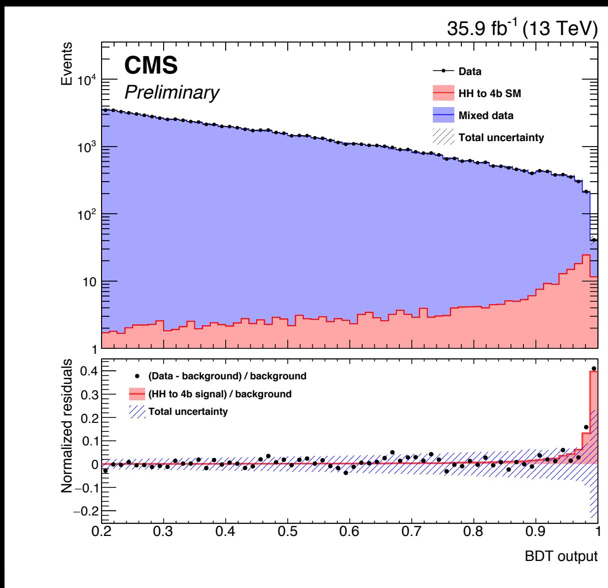
- BDT modelling checked using data sidebands which exclude m(bb) around the Higgs boson mass.
- Background BDT shape corrections extracted by comparing the training on the original sample with 200 replicas of same sample size.
- Shape correction validated in data sideband regions

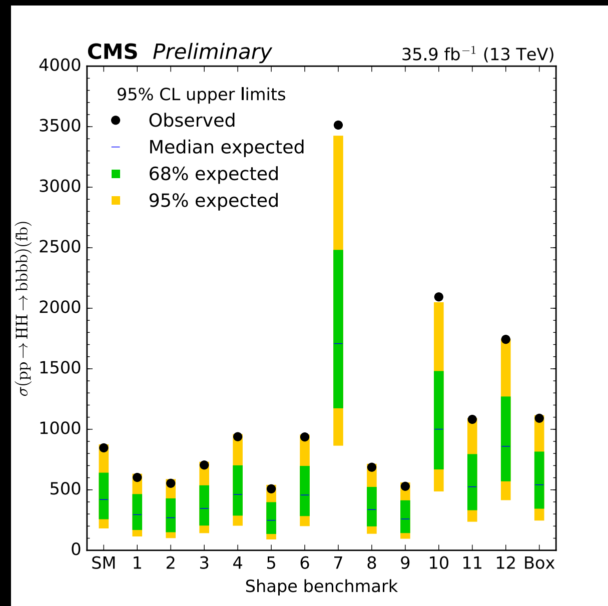
HH→4b non-resonant

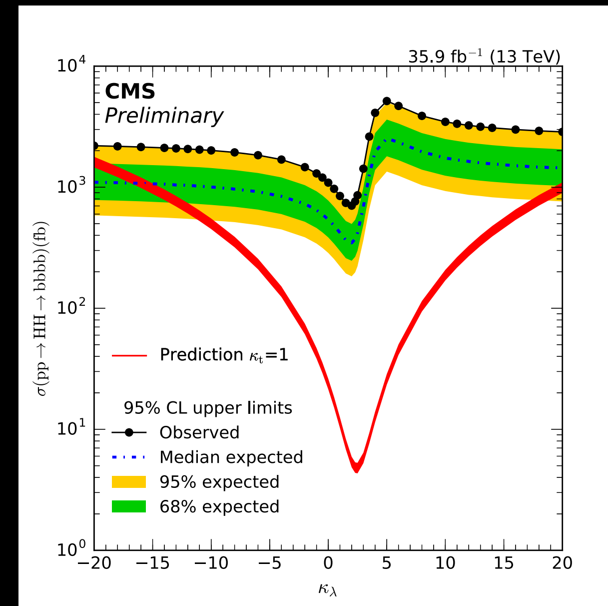
CMS-PAS-HIG-17-017

NEW

BDT output: background, signal, data





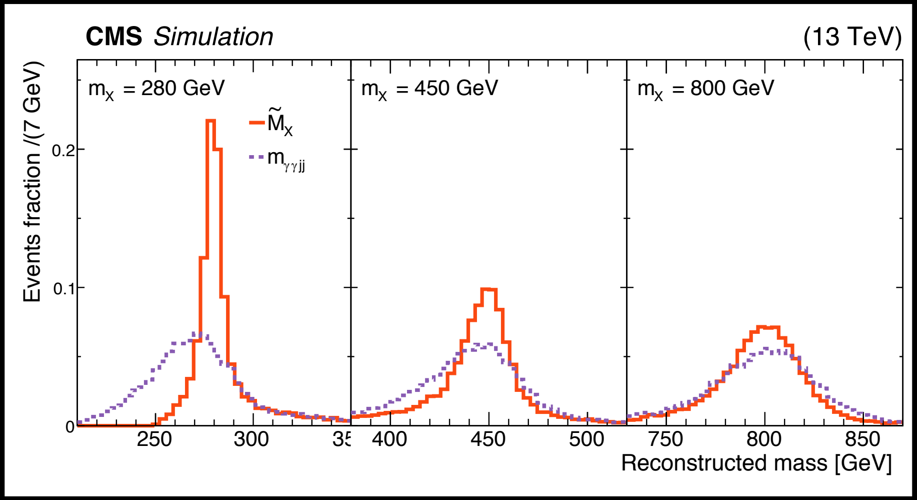


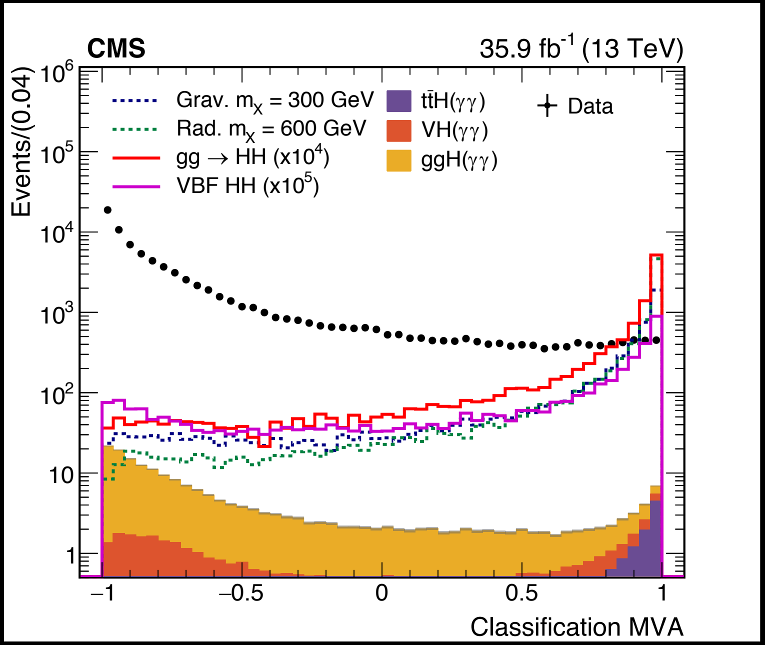
- BDT discriminator > 0.2 is used only to take advantage of the better data-background compatibility.
  - **Sensitivity loss ≈ 1.5%.**
- Minor backgrounds from ttH, VH, bbH and gg->H
- Limits set on different shape benchmarks:
  - **SM, 12 BSM benchmarks,** $\kappa_\lambda = 0$
- Sensitivity varies depending on the kinematic distributions, mainly m_{HH}.
- Limits set also as a function of κ_λ assuming $\kappa_t = 1$.

HH→bbγγ

arXiv:1806.00408

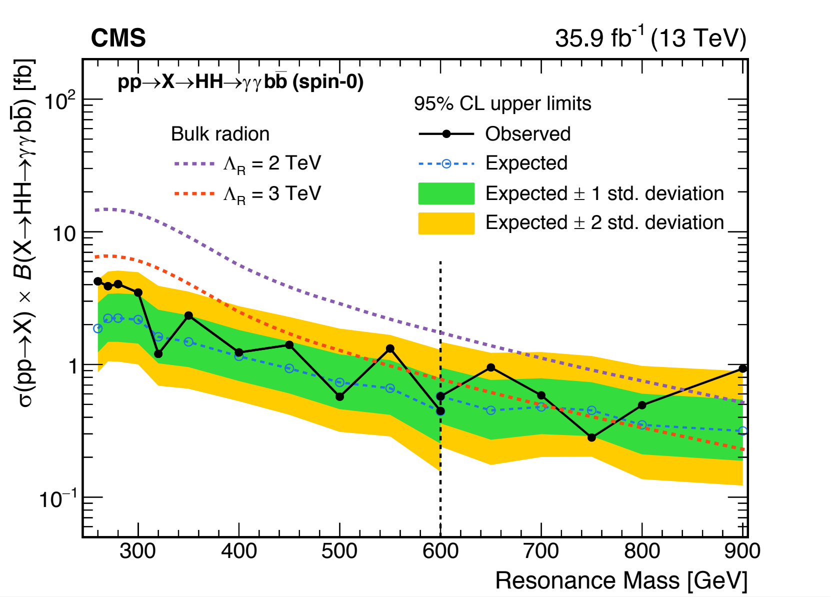
- Small BR (0.26%) but clean signature
- 2 photons+2 b-tagged jets (triggering using 2 photons)
- Resonant mass
- $\widetilde{M}_X = M(jj\gamma\gamma) - M(jj) - M(\gamma\gamma) + 250$
- MVA categorization
- Signal searched for using a parametric fit to M(jj) and M(γγ)

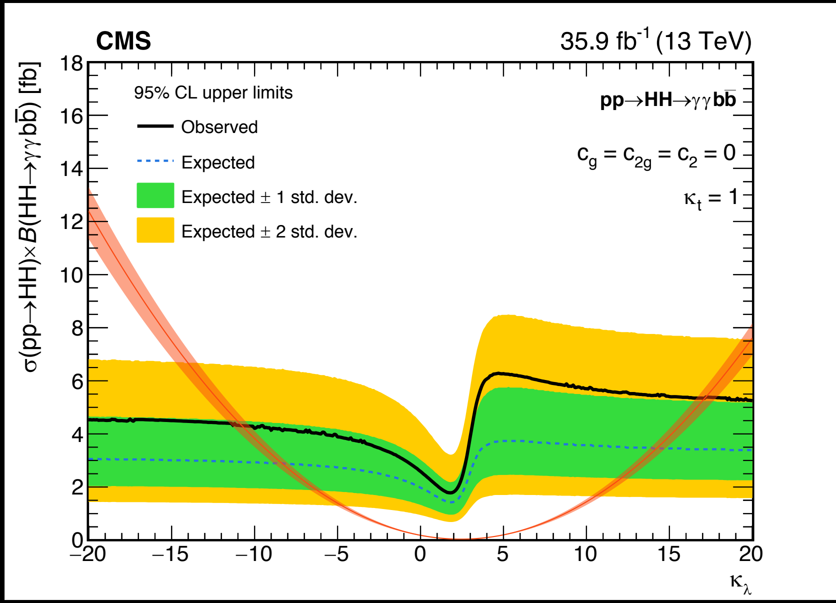




HH→bbγγ

arXiv:1806.00408





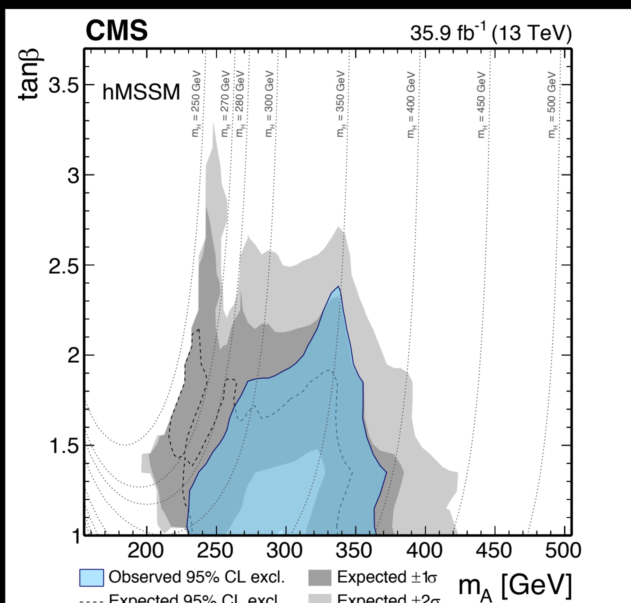
- Limits computed on the cross section of bulk gravitons and radions in the warped extradimensional models.
- Limit on SM cross section of gg->HH->bbγγ: 2 fb (obs) 1.6 fb (exp)
  - Corresponds to 24 (obs) 19 (exp) times the SM expectations.
  - Including VBF HH production improves sensitivity by 1.3%
- Constraint on κ_λ between -11 and 17.

HH→bbττ

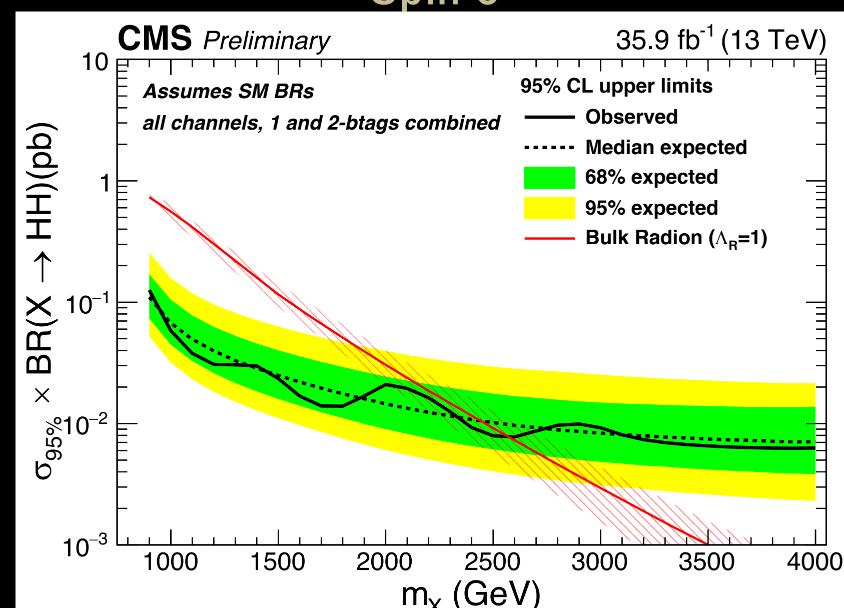
PLB 788 (2018) 101
CMS-PAS-B2G-17-006

- Final state with 2 b jets and >= 1 hadronically decaying tau lepton.
- Taus decaying to leptons (e/ μ) included.
- Low mass and high mass resonance analyses.
- Non-resonant HH search also sets limits in NMSSM parameter space in the low tanβ region.

NMSSM Interpretation



Spin 0

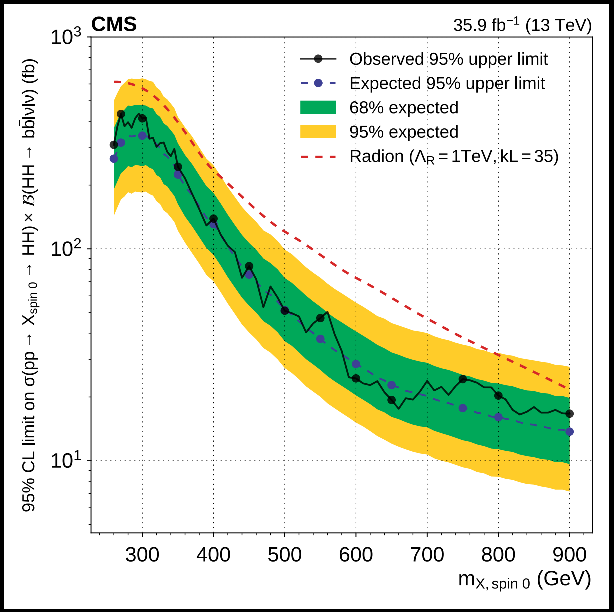


HH→bbℓ⁺ℓ⁻νν

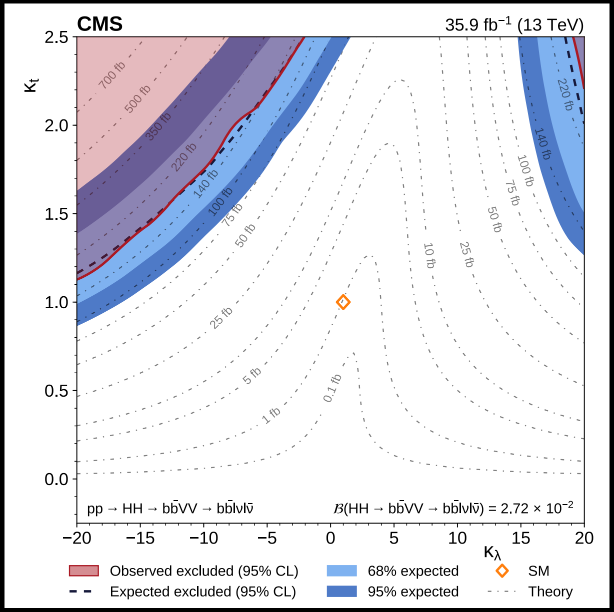
JHEP 01 (2018) 054

- Event categories: e+e-, μ+μ-, e±μ.
- Neural network training used to improve signal-background separation.
  - Parametric training as function of mass (resonance) or κ_t (non-resonant) signals.

Spin 0



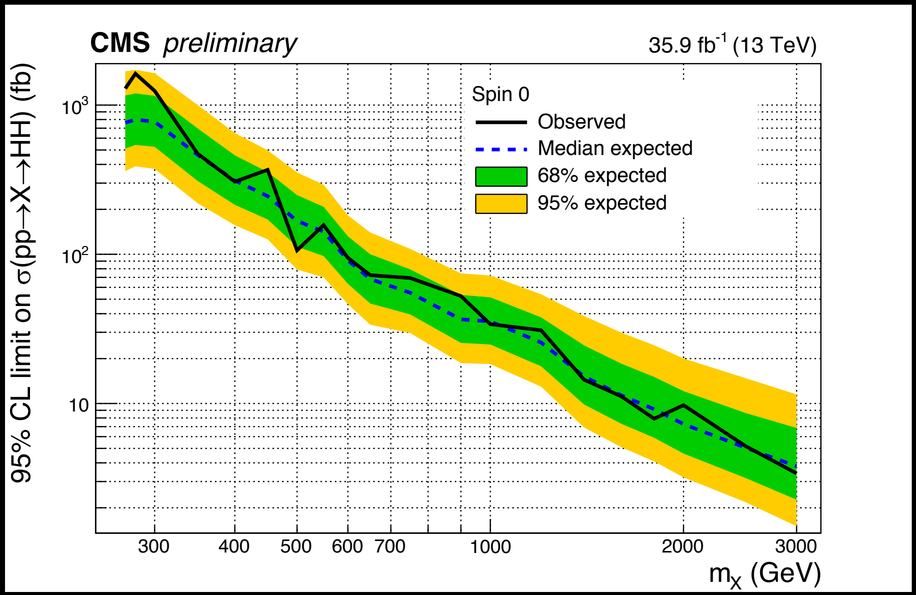
Limits over κ_λ and κ_t parameter space



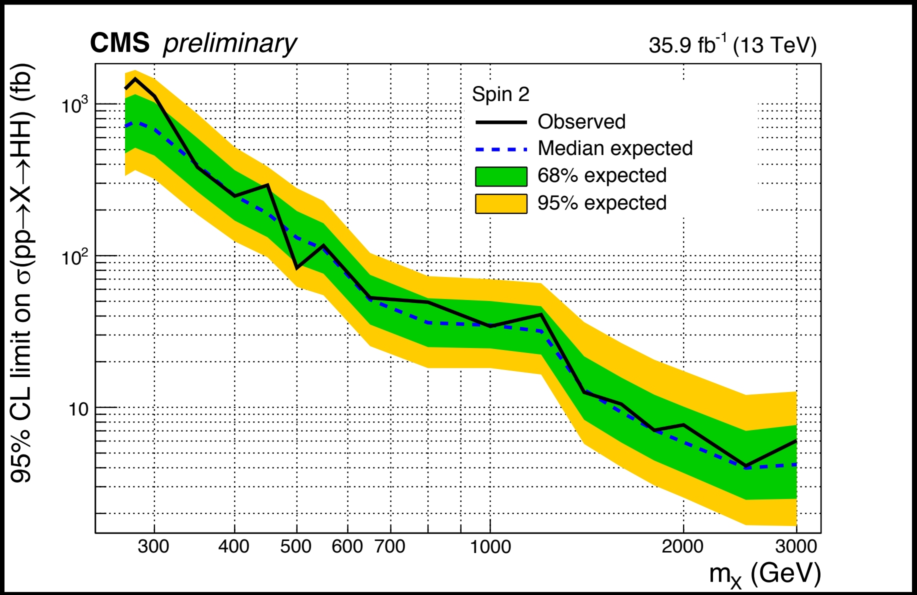
Resonant searches summary

NEW CMS-PAS-HIG-17-030

Spin-0



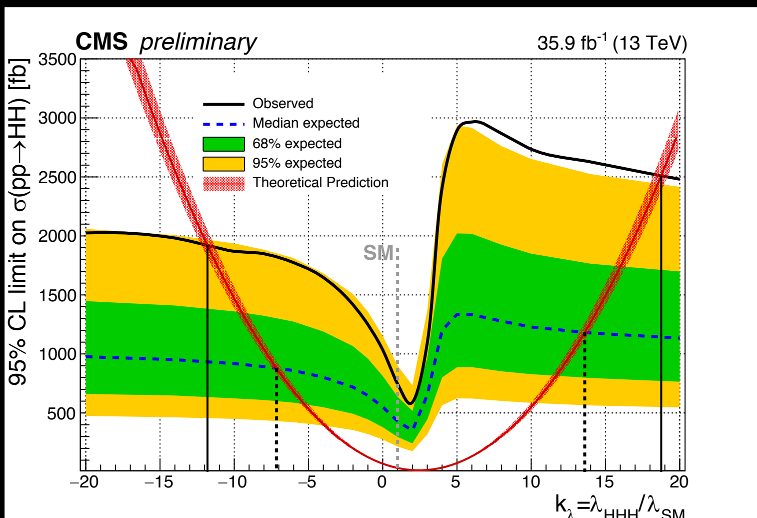
Spin-2

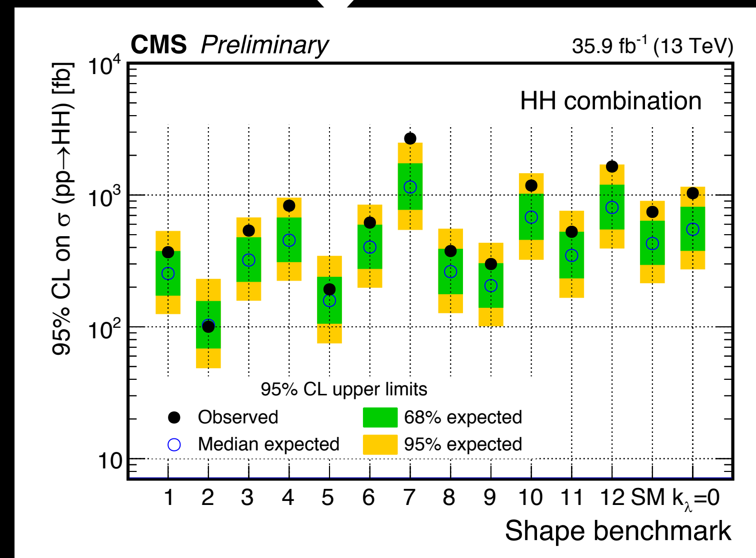


- Combination of several HH decay channels.
- Interpretation in terms of spin-0 (radion) and spin-2 (bulk graviton) production cross section times the branching fraction to HH.
- Narrow width approximation used.

Non-resonant search summary

NEW CMS-PAS-HIG-17-030





Final state	σ/σ_{SM} Obs (Exp)	Lumi
$bb\gamma\gamma$	24 (19)	35.9 fb^{-1}
$bb\tau\tau$	31 (25)	
$bb\ell^+\ell^-\nu\nu$	79 (89)	
bbbb	75 (37)	
Combined	**22.2 (12.8)**	

- Limits set on 12 BSM shape benchmarks, SM, and κ_λ=0.
- **Limit on f κ_λ for $\kappa_t = 1$:**
  - **Observed: −11.8–18.8**
  - **Expected: −7.1–13.6**
- Sensitivity to benchmarks with higher m_{HH} improved by including boosted topologies.

Summary

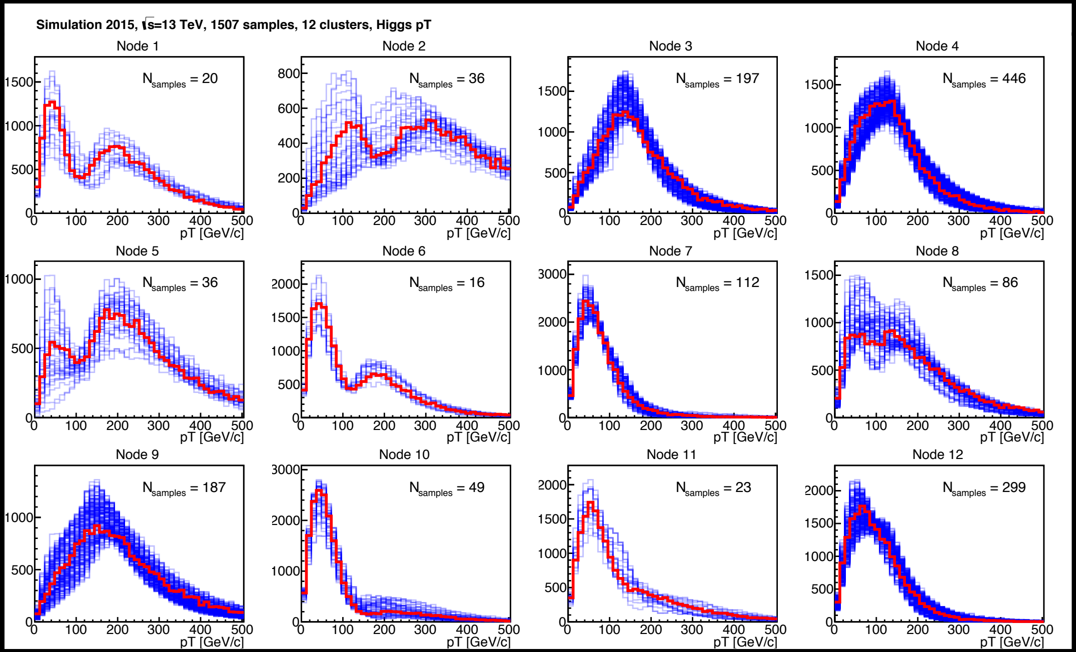
- CMS searches for HH production presented
- Several analyses depending on
  - **Decay channels: bb$\tau\tau$, bb$\gamma\gamma$, bbVV, bbbb**
  - **HH mass range: Low mass, high mass**
- All results consistent with SM backgrounds so far
  - **Upper limits on resonance cross sections, anomalous couplings**
- Combination of searches performed.
  - **Observed upper limit of 22.2 and expected upper limit of 12.8 times the SM prediction.**
  - **Improved sensitivity to non-SM couplings using boosted topologies.**
- Limits also set on the resonant production of HH from the decay of spin-0 radions and spin-2 bulk gravitons in warped extradimensional models.

BACKUP

Interpreting non-resonant results

- Connecting L_{hh} to observables at the experiments
- Clusters in parameter space with similar Higgs boson kinematics (JHEP 04 (2016) 126)

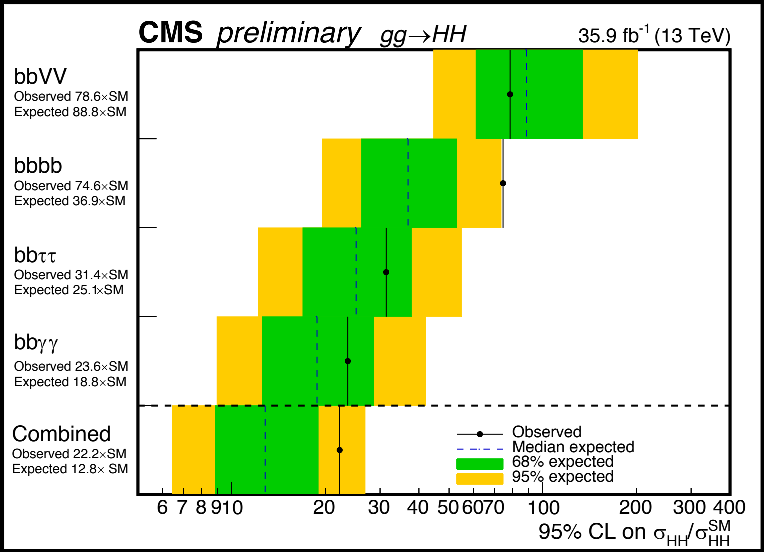
Benchmark	κ_λ	κ_t	c_2	c_g	c_{2g}
1	7.5	1.0	−1.0	0.0	0.0
2	1.0	1.0	0.5	−0.8	0.6
3	1.0	1.0	−1.5	0.0	−0.8
4	−3.5	1.5	−3.0	0.0	0.0
5	1.0	1.0	0.0	0.8	−1
6	2.4	1.0	0.0	0.2	−0.2
7	5.0	1.0	0.0	0.2	−0.2
8	15.0	1.0	0.0	−1	1
9	1.0	1.0	1.0	−0.6	0.6
10	10.0	1.5	−1.0	0.0	0.0
11	2.4	1.0	0.0	1	−1
12	15.0	1.0	1.0	0.0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



- **Kinematic vary widely for the different shape benchmarks.**
- **Searches in different final states provide good sensitivity for the different kinematic variations**

HH combination κ_λ scan

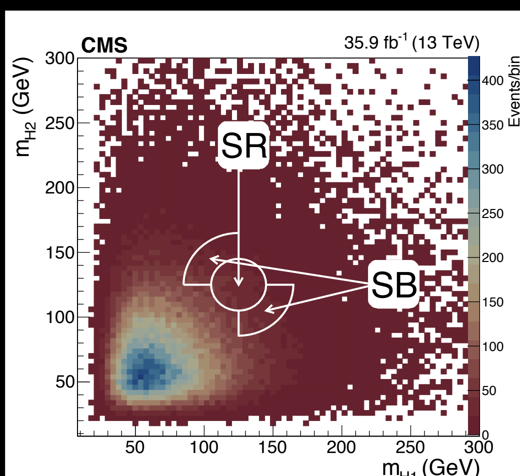
NEW CMS-PAS-HIG-17-030



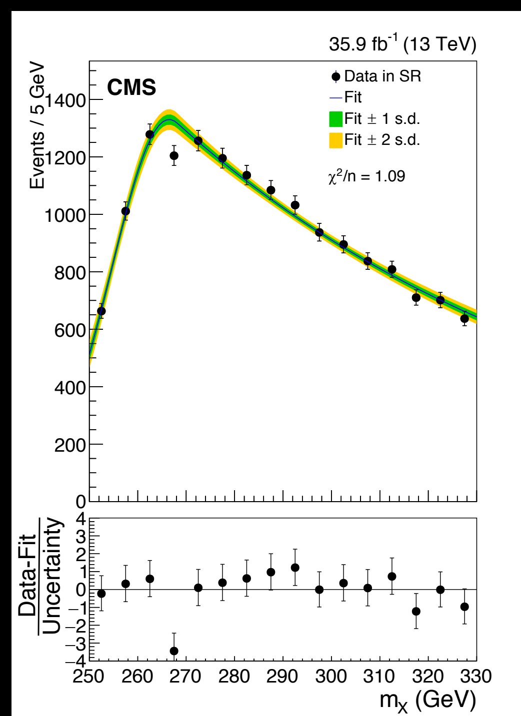
HH->4b resonant

arXiv:1806.03548

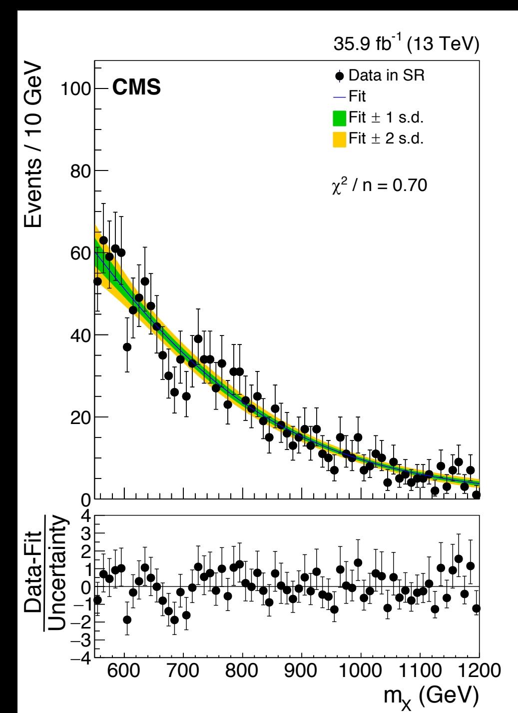
- Signal modelled using a sum of two Gaussians or Gaussian+exponential tails using MC simulations
- Background uses parametric fits derived from sideband regions in the m_H mass spectrum.



Low mass

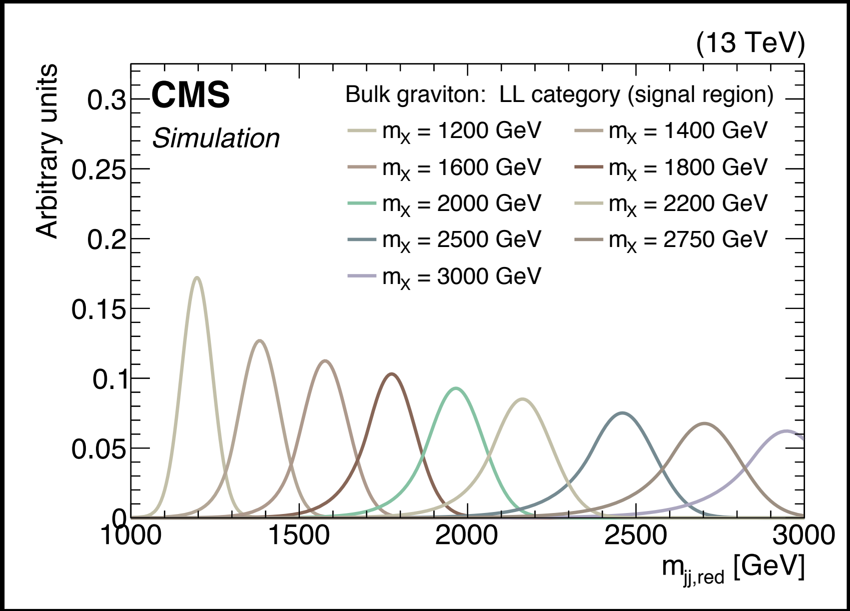


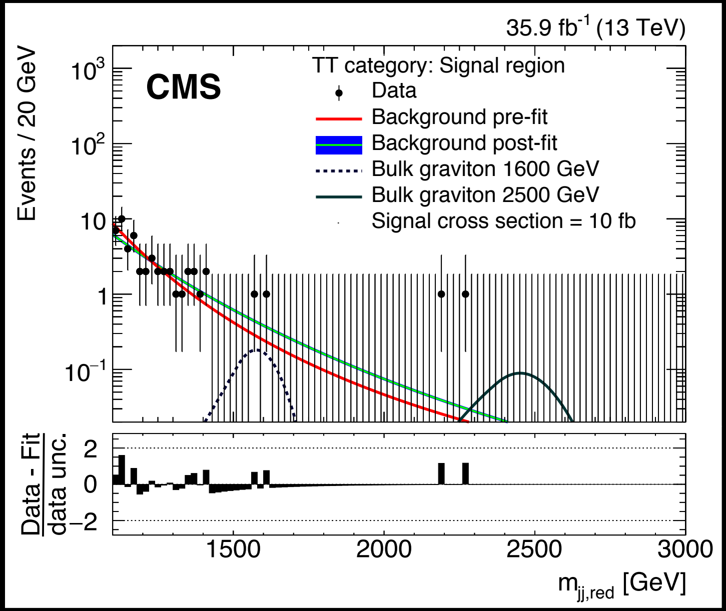
Medium mass



HH->4b resonant

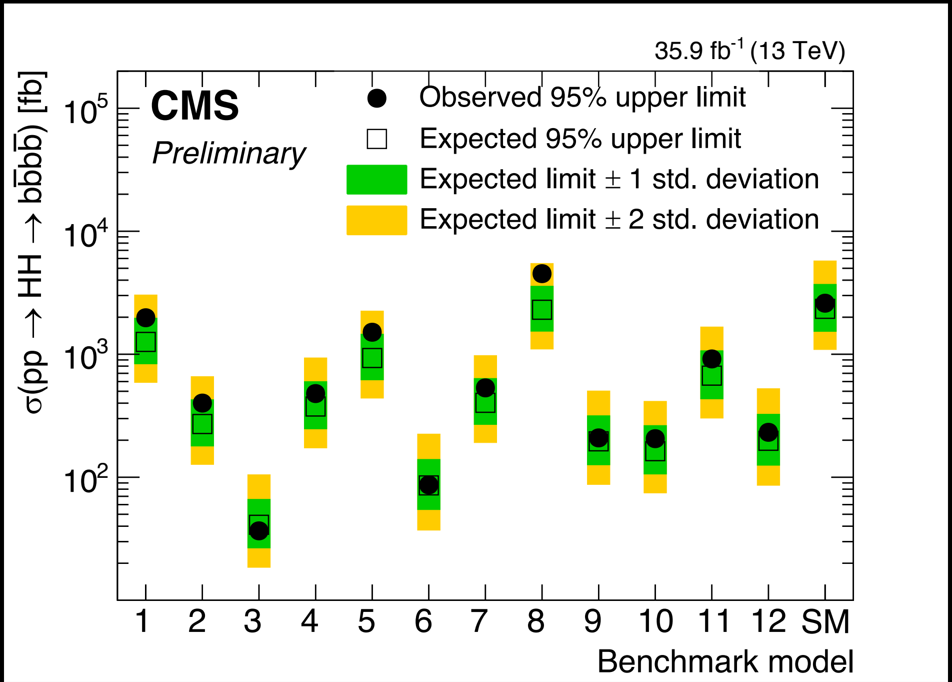
PLB 781 (2018) 244





HH->4b boosted non-resonant

CMS-PAS-B2G-17-019



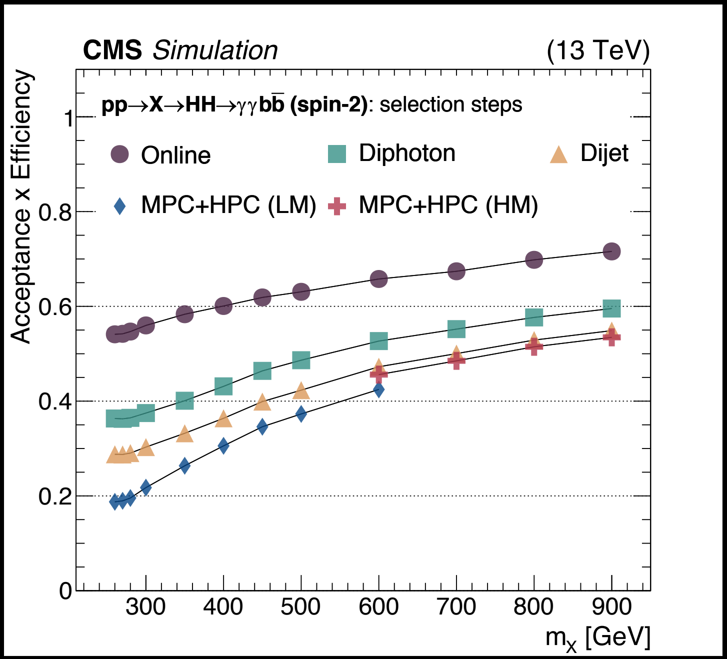
Highest sensitivity to the benchmarks 2 and 5.

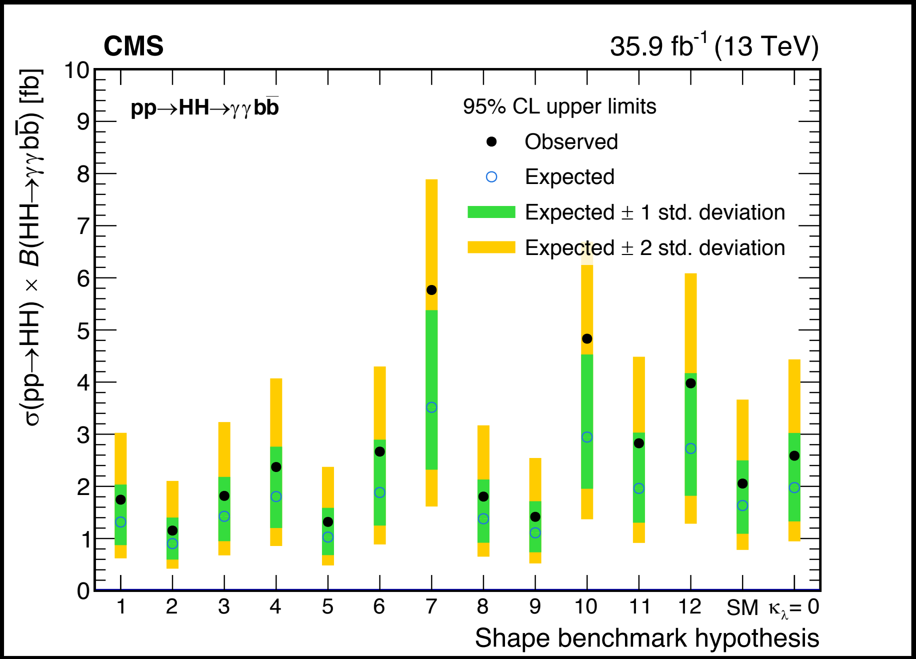
Also good sensitivity to the benchmarks 8, 9, and 11.

- In the SM the m_{HH} peaks at ~400 GeV.
- BSM couplings can boosted Higgs bosons and result in higher m_{HH} distributions.
- Using boosted topologies gives good sensitivity to those shape benchmarks which have high m_{HH} distributions.

HH->bbγγ

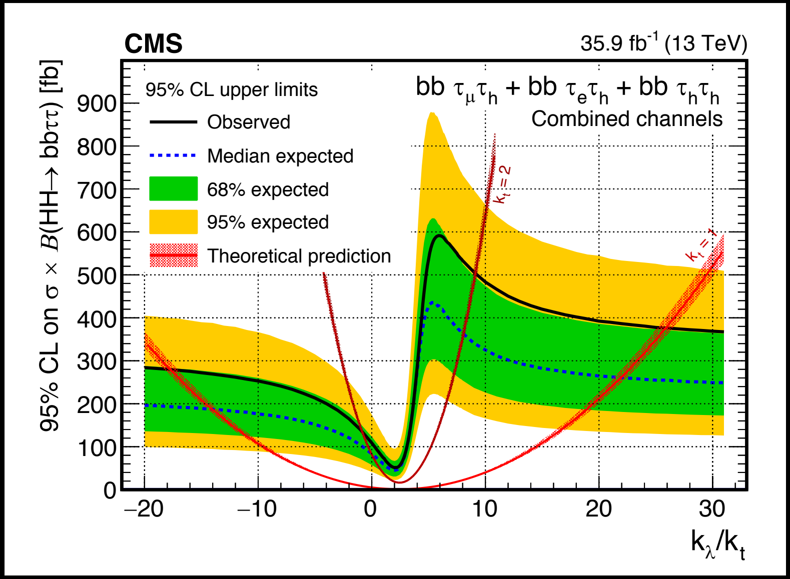
PLB 788 (2018) 101

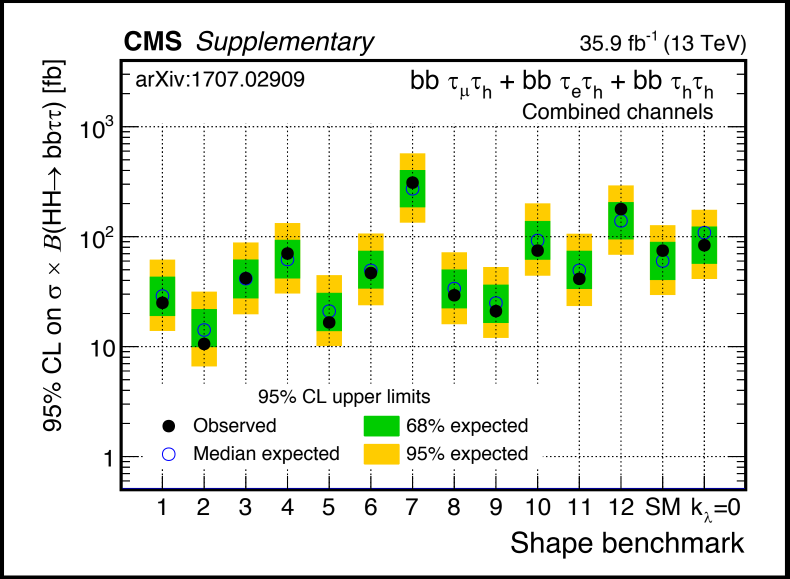




HH->bbττ non-resonant

PLB 788 (2018) 101





- Non-resonant HH cross section limit at 30 times SM.
- Cross section limits also set for different benchmarks for the Higgs boson coupling.

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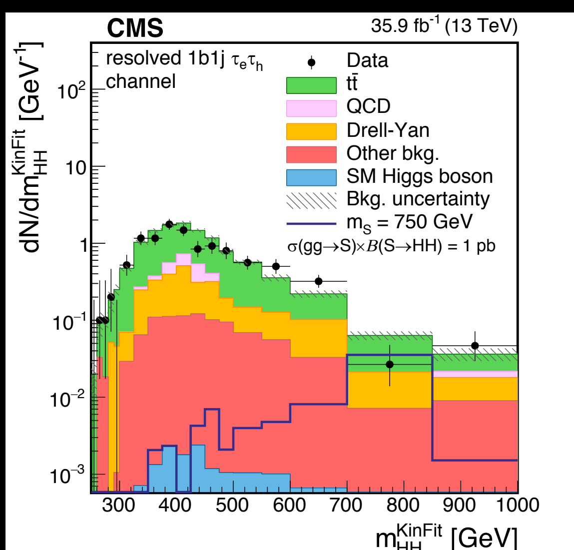
CMS

HH->bb$\tau\tau$ resonant

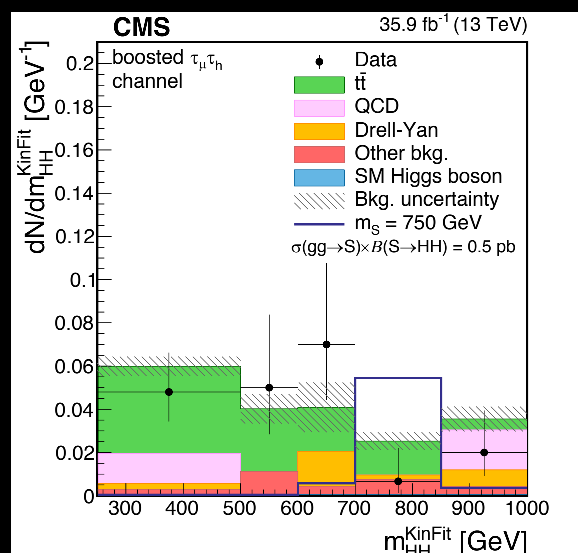
- >= 1 hadronic tau decay τ_h
- Resolved H decay: 1 or 2 b jet
- Boosted H decay: Fat jet (AK8) with subjets matched to AK4 jets
- MVA discriminator for $\tau_\mu\tau_h/\ \tau_e\tau_h$ to reject ttjets

mHH for resonant search

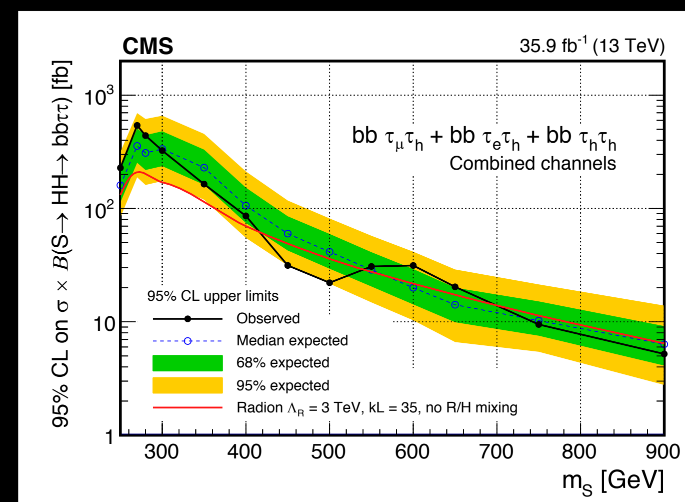
Resolved



Boosted



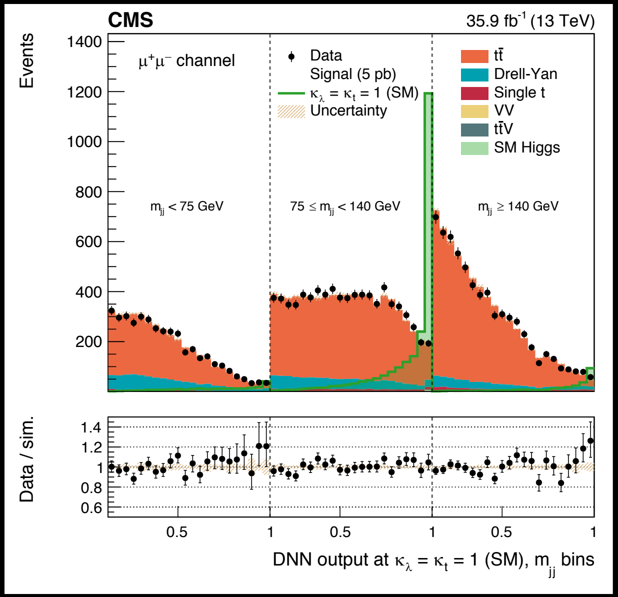
Low mass spin 0



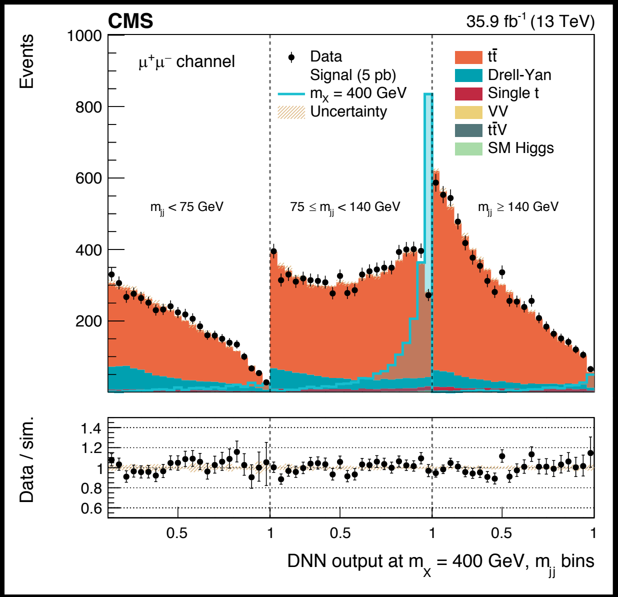
HH->$bb\ell^+\ell^-\nu\nu$

JHEP 01 (2018) 054

- Dilepton triggers
- Event categories: e^+e^- , $\mu^+\mu^-$, $e^\pm\mu^-$
- $12 < m_{\ell\ell} < m_Z - 15$ GeV: Reject quarkonia and Z->$\ell\ell$
- 2 b-tagged jets
- DY background estimated from the data using a BDT to classify events according to jet flavours: $\ell\ell$+bb, $\ell\ell$+cc, and $\ell\ell$+light flavour jets.
- 3 m_{jj} categories
- Neural network training is used to improve signal-background separation. Training parametrized as a function of the mass (resonant search) and κ_λ and κ_t (non-resonant search.



Non-resonant



Resonant

HH->bb$\ell^+\ell^-$νν interpretation

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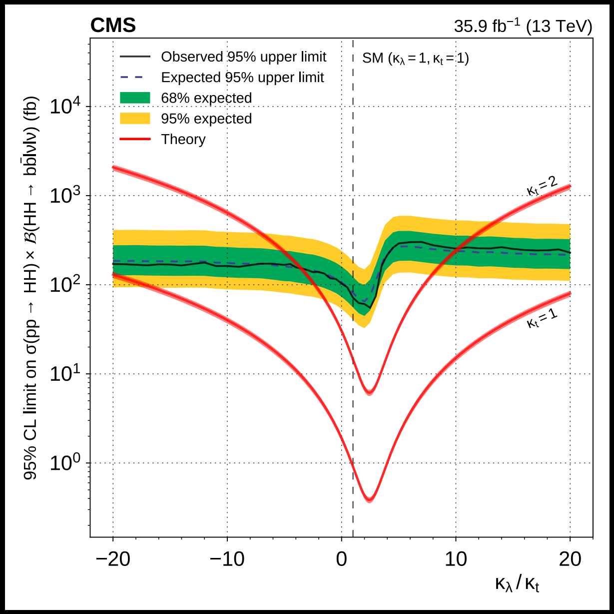
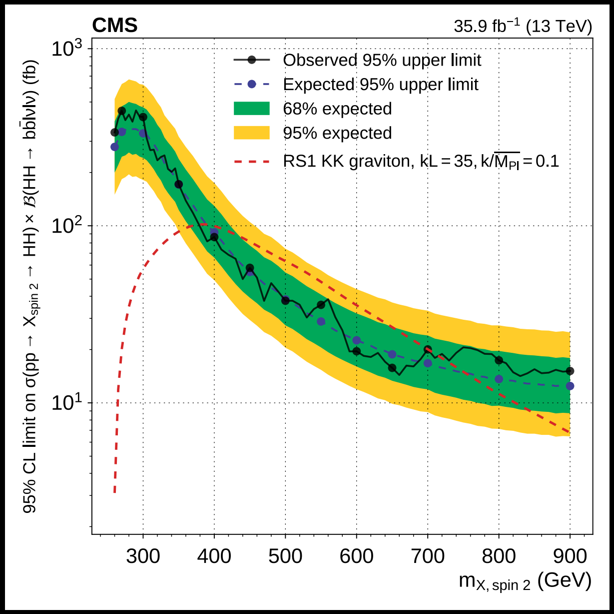
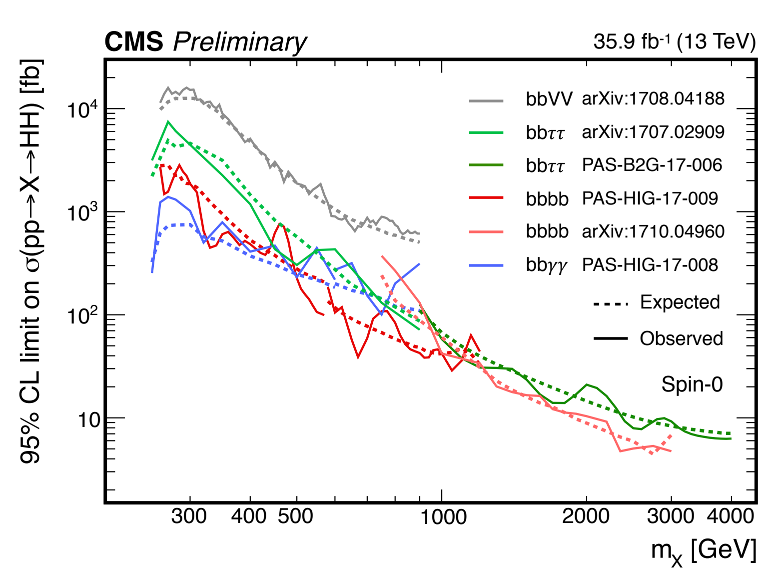


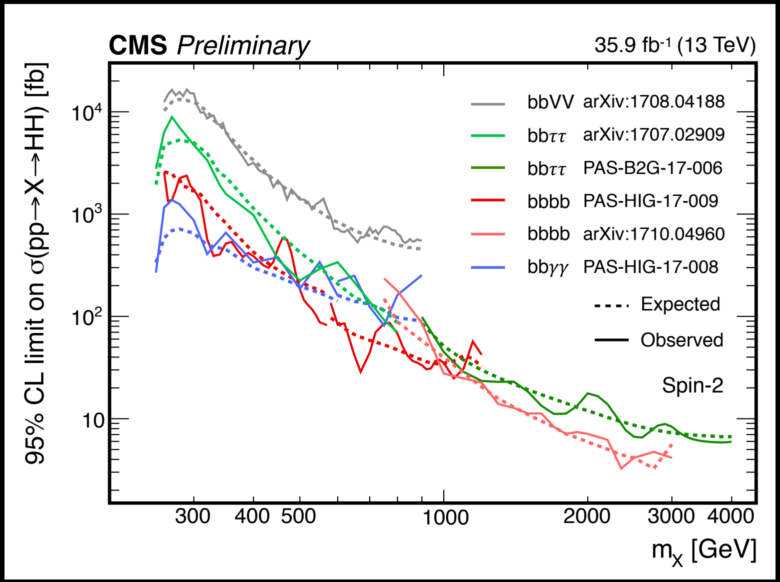
Spin 2



- Limits set on spin-0 radion and spin-2 bulk graviton.
- Non-resonant HH cross section limit at 79 times SM.
- Limit for different κ_λ/κ_t values.
- Limit also set over κ_λ and κ_t parameter space.

Summary of resonant searches





https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryResultsHIG