Search for new physics in HH final state in CMS

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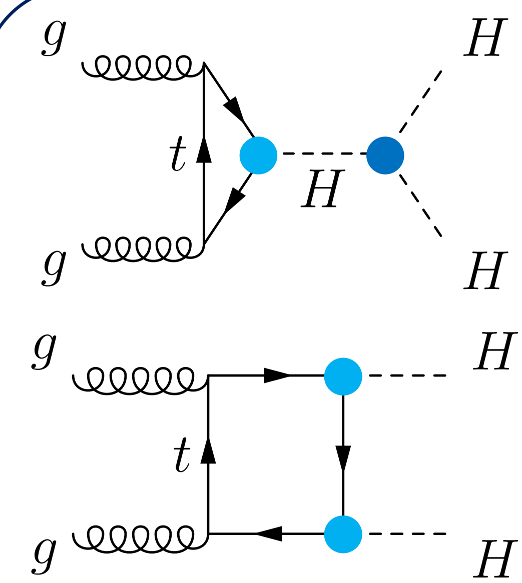
Outline

- Physics motivations
  - Non-resonant HH production
  - Resonant HH production
- Run 1 summary
- Run 2 analyses:
  - $HH \rightarrow bbbb$
  - $HH \rightarrow bb\ell\upsilon\ell\upsilon$
  - $HH \rightarrow bb\tau\tau$
  - $HH \rightarrow bb\gamma\gamma$
- Conclusions

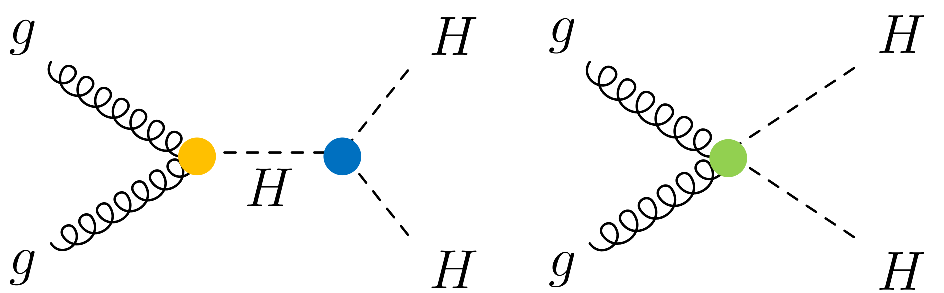
Physics motivations: non-resonant HH

- In the Standard Model (SM), double Higgs production allows to measure the Higgs self-coupling
  - $\sigma_{SM}(HH) = 33.53\ fb$ is too small to being accessible in Run 2 $\Longrightarrow$ limits on production cross-section can be set
- The beyond standard model (BSM) scenarios can be explored by defining effective filed theory (EFT) Lagrangian [1]:

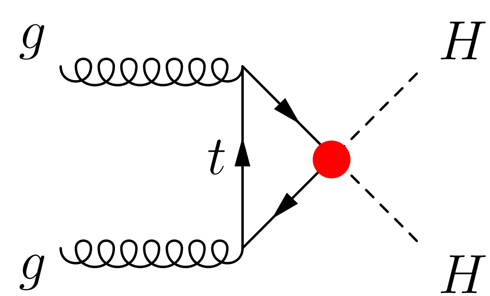
$$L_{hh} = \frac{1}{2}\partial_\mu h \partial^\mu h - \frac{m_h^2}{2}h^2 - k_\lambda \lambda_{SM} v h^3$$
$$- \frac{m_t}{v}\left(v + k_t h + \frac{c_2}{v}hh\right)(\bar{t}_L t_R + h.c.)$$
$$+ \frac{\alpha_s}{12\pi v}\left(c_{1g}h - \frac{c_{2g}}{2v}hh\right)G^A_{\mu\nu}G^{A,\mu\nu}$$



SM-like processes



Contact interactions between Higgs and gluons



***tt HH* contact interaction**

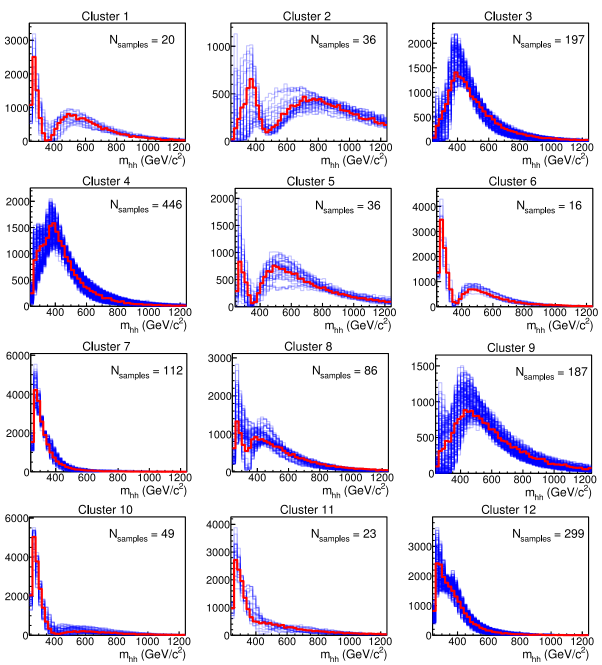
[1] doi:10.1103/PhysRevD.91.115008

Physics motivations: non-resonant HH

- The non-resonant EFT has five free parameters: $k_\lambda, k_t, c_2, c_{1g}, c_{2g}$.
  - The SM case: $k_\lambda = k_t = 1, c_2 = c_{1g} = c_{2g} = 0$.

How to interpret the experimental results into the 5D parameter space?:

1. Define 2D-planes (e.g. $k_t k_\lambda$-plane) within the parameter space and perform a grid scan inside each plane.
2. The parameter space can be divided into 12 clusters with a similar kinematics [2]:



For each cluster one representative point is chosen

$\Longrightarrow$

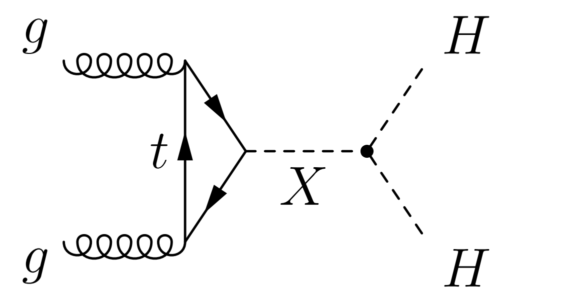
12 benchmarks are defined

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

[2] doi:10.1007/JHEP04(2016)126

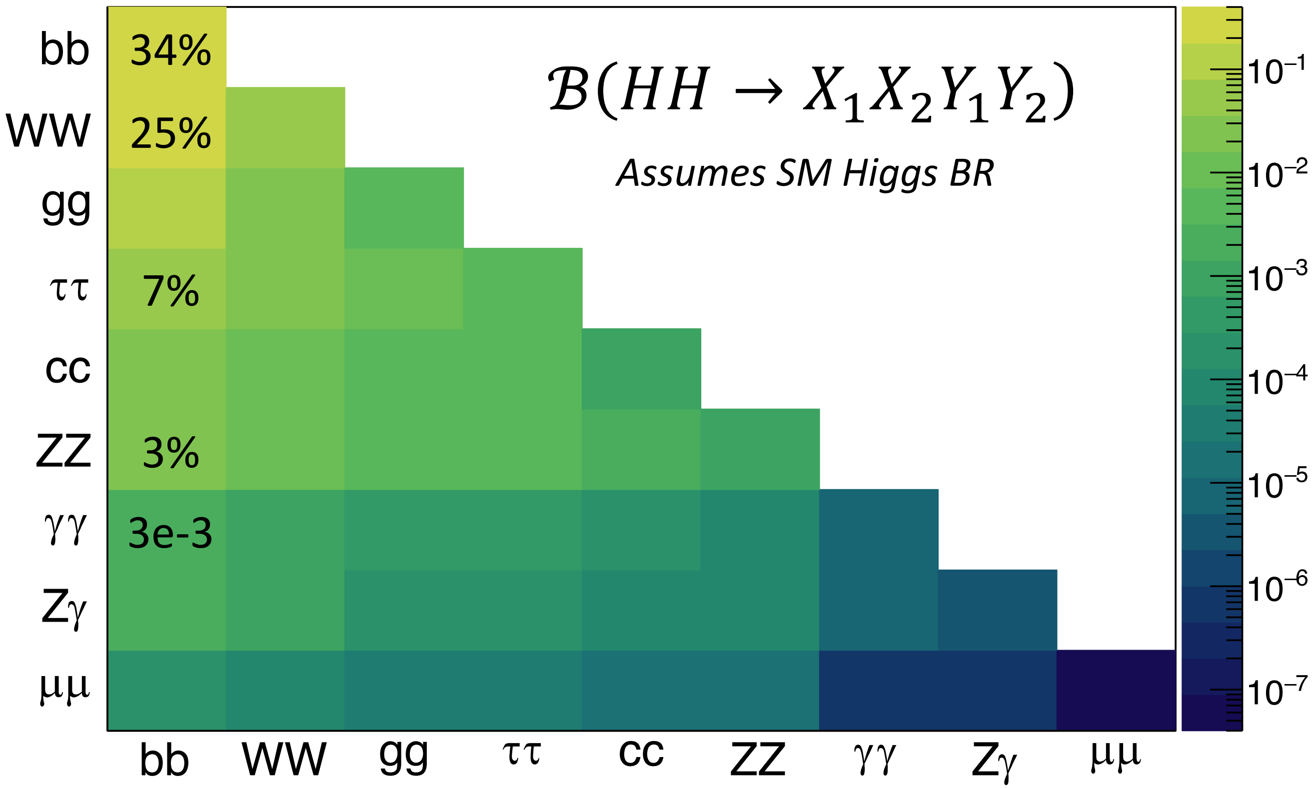
Physics motivations: resonant HH

- MSSM scenarios in low $\tan\beta$ region ($1 \lesssim \tan\beta < 10$):
  - The hMSSM scenario [3]:
    - Described using only the tree-level relations for masses and mixing angles
    - m_h fixed to be 125 GeV
    - Minimal dependency on the unobserved SUSY sector
  - The low $\tan\beta$ high scenario [4]:
    - SUSY parameters are tuned in order to have m_h near 125 GeV in most part of the $(m_A, \tan\beta)$ plane.
- The 2 Higgs doublet models (2HDM) [5]
  - 5 physical bosons: h^0, H^0, A^0, $H^{\pm}$
  - 7 free parameters: m_h, m_H, m_A, $m_{H^{\pm}}$, α, $\tan\beta$ and m_{12}^2.
- Singlet model [6]
  - Minimal model for dark matter and for electroweak baryogenesis
- Warped extra dimensions
  - spin-0 Radion [7] and spin-2 KK-graviton [8]



[3] doi:10.1140/epjc/s10052-013-2650-0
[4] doi:10.1007/JHEP10(2013)028
[5] doi:10.1016/j.physrep.2012.02.002
[6] doi:10.1007/s002880050442
[7] doi:10.1103/PhysRevD.76.125015
[8] doi:10.1103/PhysRevD.76.036006

HH final states



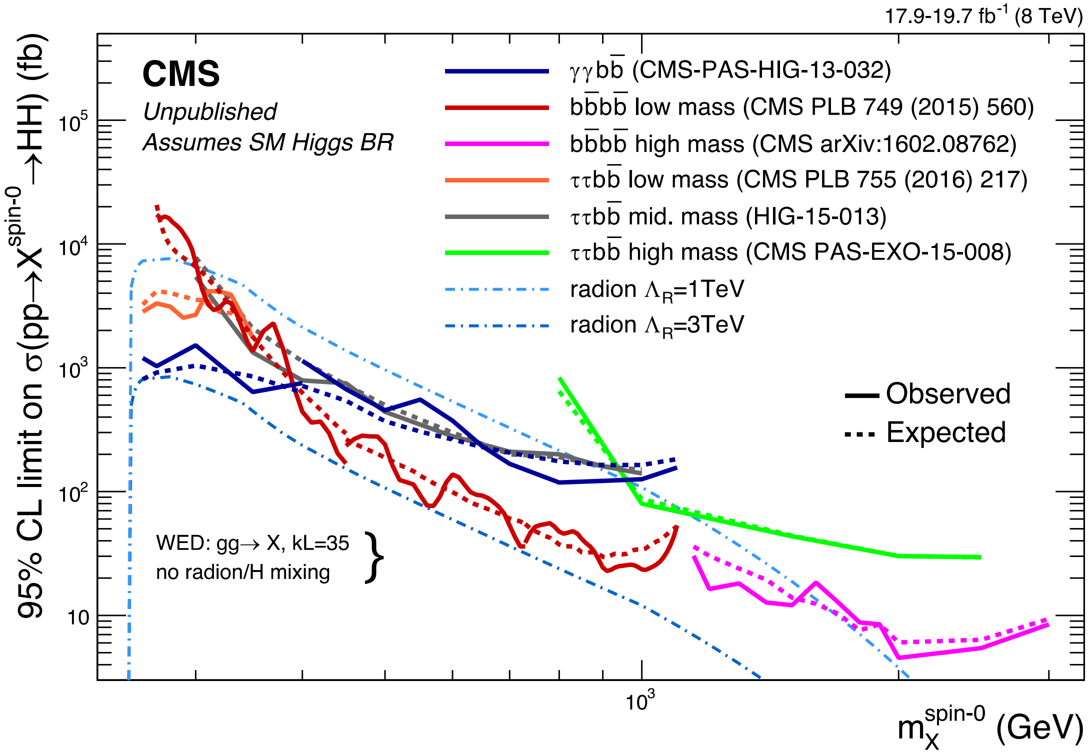
$HH \to bbbb$
Highest BR, but large QCD background

$HH \to VV \to bb\ell\upsilon\ell\upsilon$
Medium BR (2.7%), but irreducible $t\bar{t}$ background

$HH \to bb\gamma\gamma$
Low BR, but high purity

$HH \to bb\tau\tau$
Medium BR and relatively low background

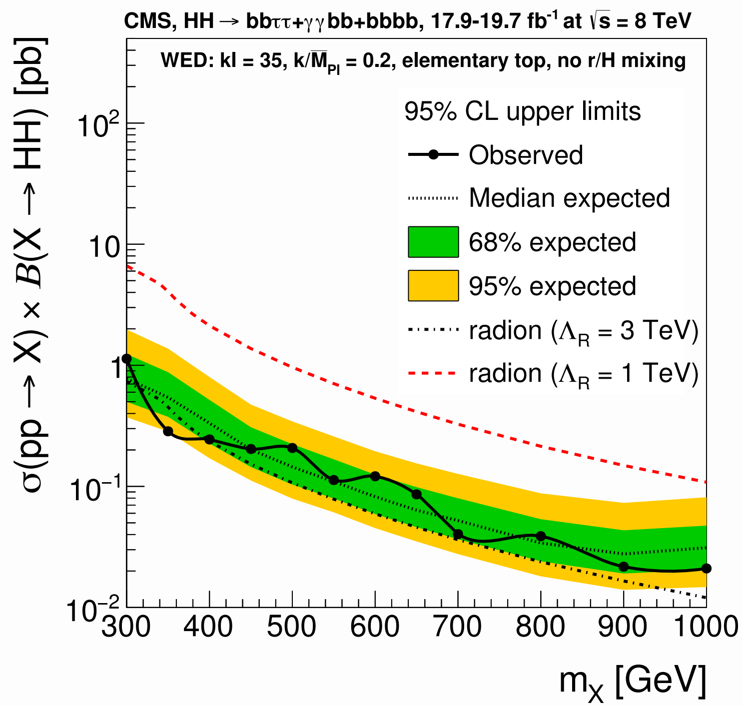
Run 1 summary



Run 1 combination

$HH \to bb\gamma\gamma + bb\tau\tau + bbbb$

arXiv:1707.00350



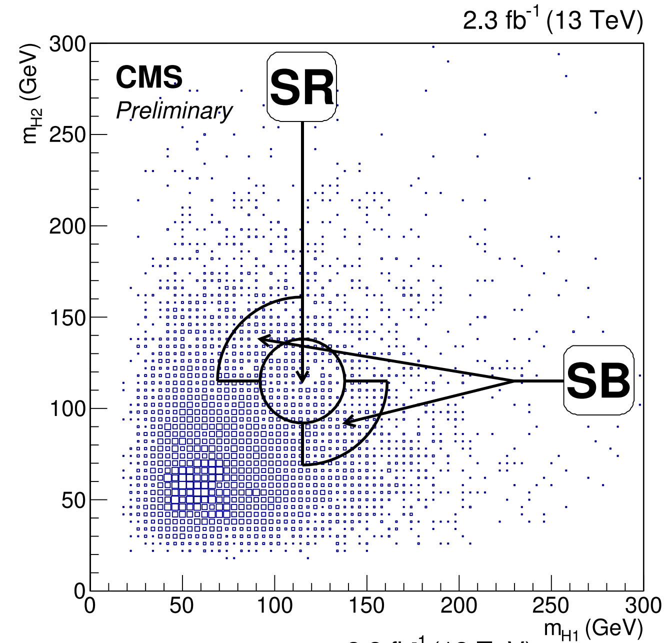
- For non-resonant HH production, the combination of $bb\tau\tau$ and $bb\gamma\gamma$ decay channels yields an observed (expected) limit that is a factor of 43 (47) times the SM rate.

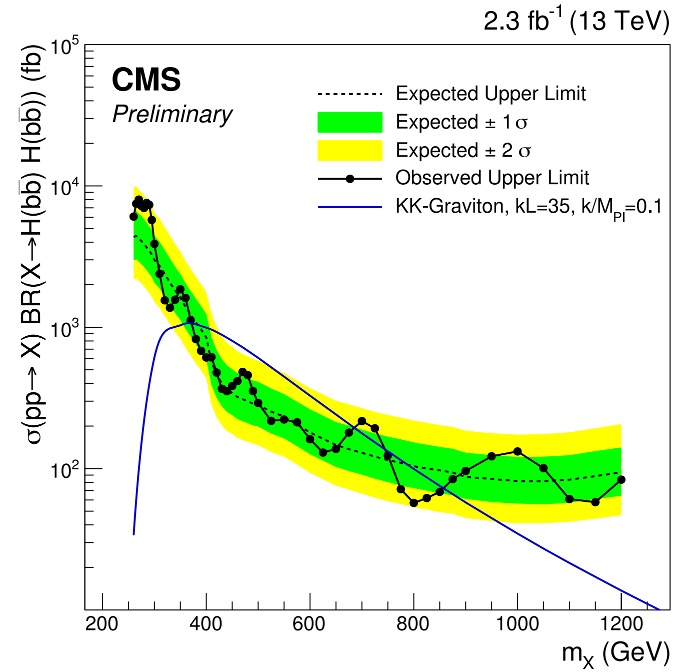
$HH \to bbbb$

RESONANT

CMS-PAS-HIG-16-002

- Analysis is based on 2015 data (2.3 fb^{-1})
- Jet reconstruction algorithm: anti-k_t with $R = 0.4$
- Online selection: 4 jets with $p_T > 30 \ldots 90\ GeV$, with at least 3 of them are b tagged
- Offline HH-candidate selection highlights:
  - first 4 jets with highest b tag score are selected
  - mass window in 2D di-jet mass plane
- Background shape estimated from the data sideband regions
- Signal is extracted using m_X distribution
- No evidence for a signal is observed



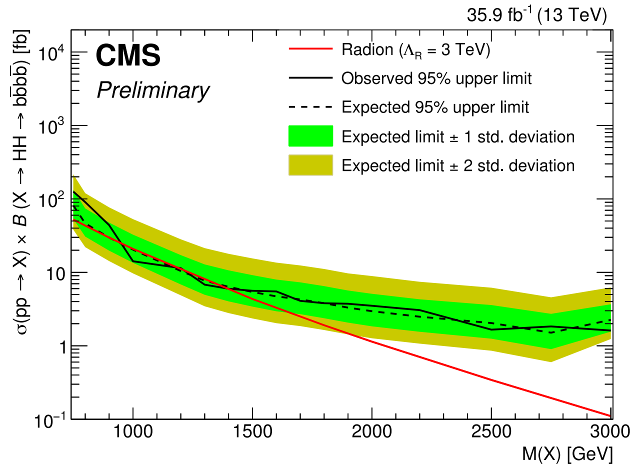


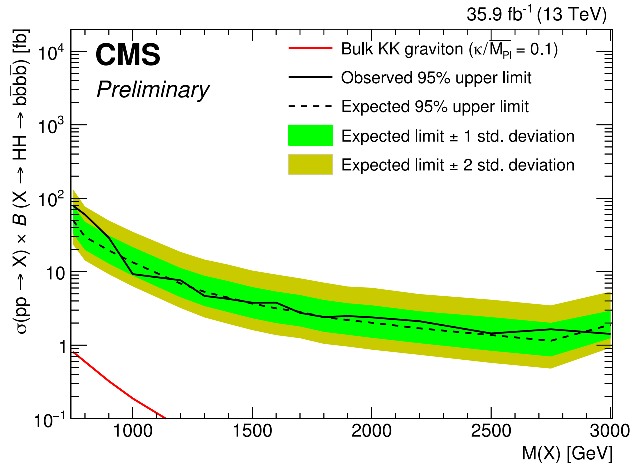
$HH \to bbbb$

RESONANT - *boosted topology*

[CMS-PAS-B2G-16-026]

- Analysis is based on 2016 data ($35.9\ fb^{-1}$)
- Jet reconstruction algorithm: anti-k_t with $R = 0.4$ (AK4) and $R = 0.8$ (AK8)
- Mass of AK8 jets is reconstructed using soft drop algorithm, which removes soft and wide-angle radiation contributions
- AK8 jets are b tag by double b-tagger algorithm that is able to identify two boosted b jets within one AK8 jet
- Online selection: combination of triggers with requirements on H_T of AK4 jets and p_T, η and mass of AK8 jets
- Offline HH-candidate selection highlights:
  - 2 AK8 jets with the highest p_T are selected, requiring $p_T > 300\ GeV$ and $|\eta| < 2.4$ for each selected jet
  - $|\Delta\eta(j_1, j_2)| < 1.3$ is required to reduce multi-jet background
- Data driven techniques to estimate multi-jets background:
  - For $m_X < 1200\ GeV$: “alphabet” estimation (extended ABCD method)
  - For $m_X > 1200\ GeV$: parametric fit of signal and background models
- Signal is extracted using reduced $\mathrm{m}(j_1, j_2)$
- No evidence for a signal is observed



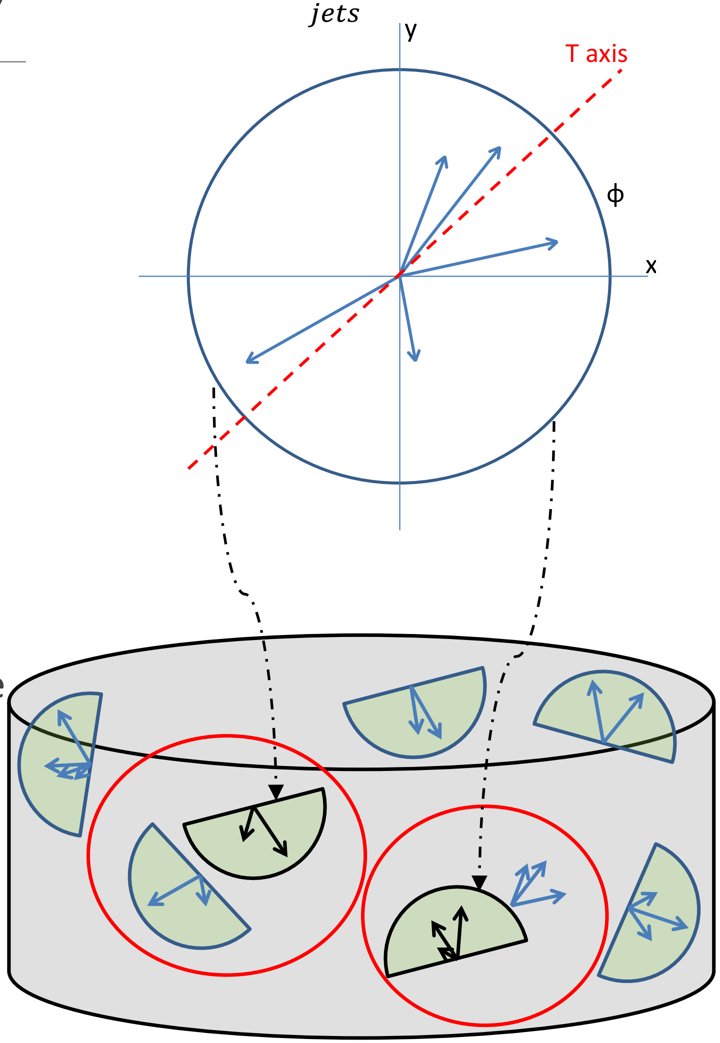


$HH \to bbbb$

NON-RESONANT
CMS-PAS-HIG-16-026

- Analysis is based on 2015 data (2.3 fb^{-1})
- Jet reconstruction algorithm: anti-k_t with $R = 0.4$
- Online selection: 4 jets with $p_T > 30 \dots 90\ GeV$, with at least 3 of them are b tagged
- Offline HH-candidate selection highlights:
  - first 4 jets with highest b tag score are selected
  - requiring that all jets within b tag acceptance pass b tag requirement
  - Multivariate (MVA) technique based on a boosted decision tree (BDT) discriminator is used to improve the sensitivity
- Fully data-driven background estimation using "hemisphere mixing" technique
  - Each data event is divided into two hemispheres in order to create new background events from those hemispheres
- Signal is extracted from 2D di-jet mass plane
- The obtained observed (expected) upper limit on σ_{HH} is equal to $3880\ (3490)\ fb$, which is $\approx 342 \cdot \sigma_{SM}(HH)$

$$T = \sum_{jets} p_T^{jet} \cos(\varphi - \varphi_{jet})$$

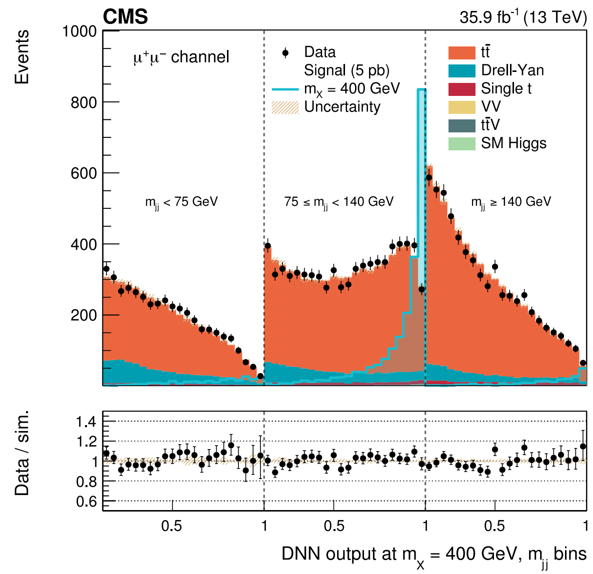


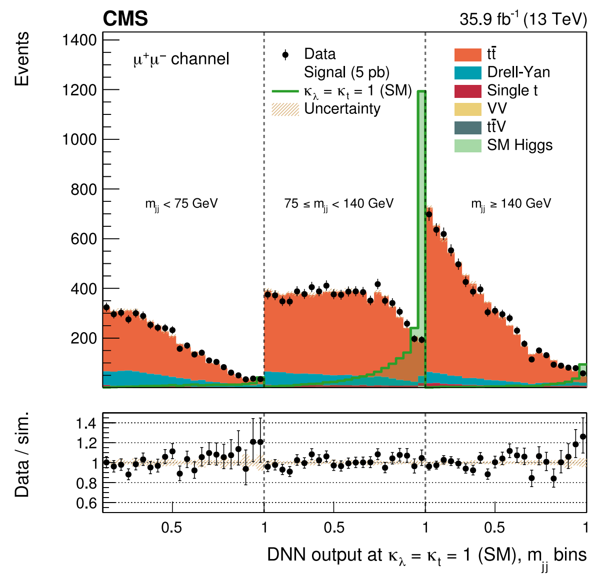
For details, see T. Dorigo talk about Hemisphere Mixing method at EPS link

$HH \to bb\ell\nu\ell\nu$

arXiv:1708.04188

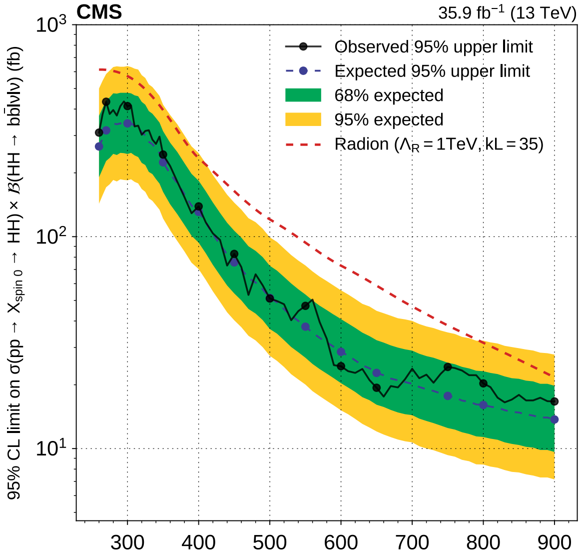
- Analysis search for $HH \to VV \to bb\ell\nu\ell\nu$ decays, where $V = W, Z$ and $\ell = e, \mu$
- Online selection: set of isolated di-lepton triggers with p_T threshold 17 … 23 GeV for the leading lepton and 8 … 12 GeV for the sub-leading
- Events are divided into three categories based on m_{jj} to enhance the sensitivity
- Offline HH-candidate selection highlights:
  - Oppositely charged lepton pair (e^+e^-, $\mu^+\mu^-$, $e^\pm\mu^\mp$)
  - $\Delta R(lepton, jet) > 0.3$
  - $12\ GeV < m_{ll} < m_Z - 15\ GeV$ for main backgrounds suppression
  - First 2 jets with highest b tag score are selected as $H \to bb$ candidate
- Drell-Yan background in e^+e^-, $\mu^+\mu^-$ channels is estimated from the DY enriched sideband region from the data.
  - BDT is used to parametrise the fraction of jets with the given flavours as a function of event kinematics
- All remaining backgrounds are estimated from simulation.
- Two parametrised multivariate discriminators based on Deep Neural Networks (DNN) are used for the signal extraction:
  - Parametrised machine learning technique [9] allows to have a single training for a range of signal parameter space (e.g. m_X) without lose in sensitivity
  - The input variables are: m_{ll}, ΔR_{ll}, ΔR_{jj}, $\Delta\varphi(ll, jj)$, p_T^{ll}, p_T^{jj}, ΔR_{lj} and m_T

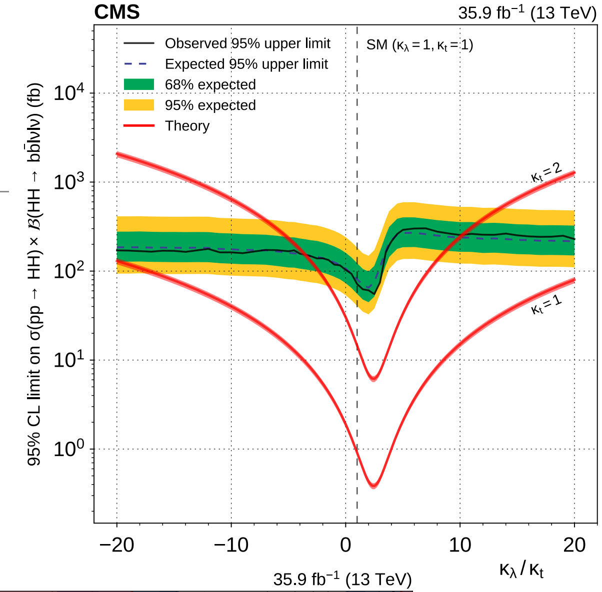




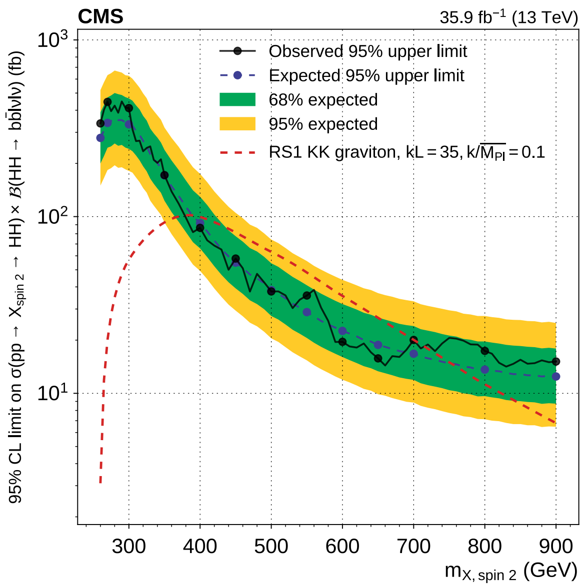
$HH \to bb\ell\nu\ell\nu$

arXiv:1708.04188



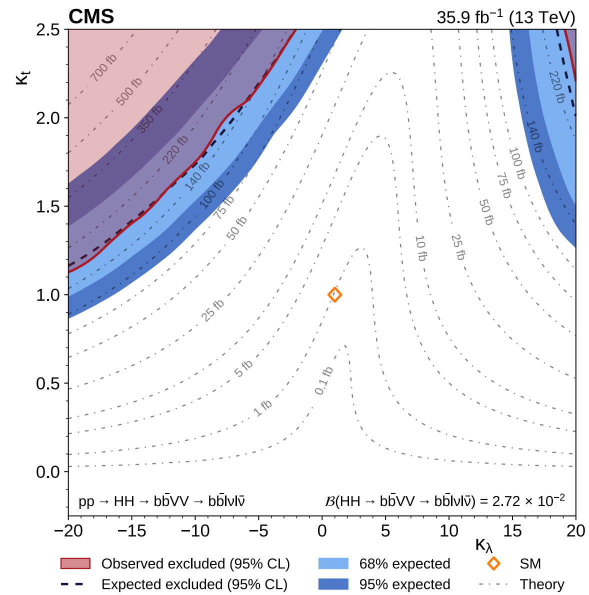


No evidence for a signal is observed



RESONANT

NON-RESONANT

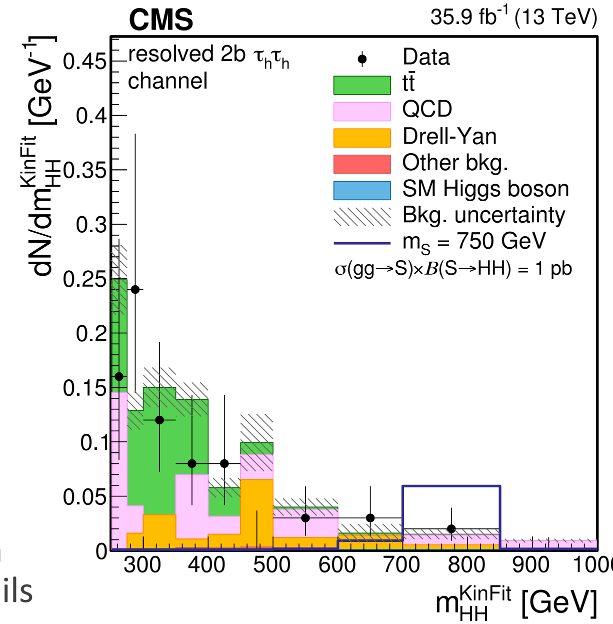


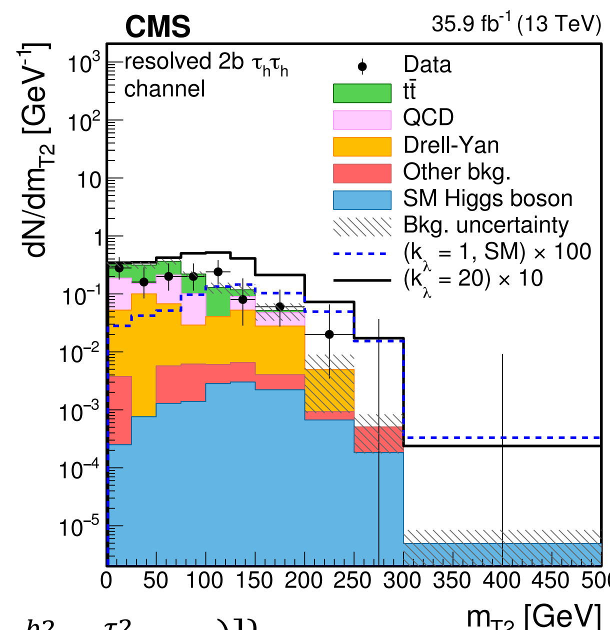
The observed (expected) upper limit on SM HH production XS $\approx 79\ (89) \cdot \sigma_{SM}(HH)$

$HH \to bb\tau\tau$

arXiv:1707.02909

- Analysis search for $HH \to bb\tau\tau$ considering 3 di-tau final states: $\tau_e\tau_h$, $\tau_\mu\tau_h$ and $\tau_h\tau_h$
  - this covers $\approx 88\%$ of $\tau\tau$ decays
- Online selection: single isolated muon (electron) with $p_T > 22\ (25)\ GeV$ or two tau candidates with $p_T > 35\ GeV$
- Events are split into 3 categories: 1-btag, 2-btags and boosted
  - Boosted category uses AK8 jets to improves sensitivity for resonances with high mass and, in non-resonant case, it allows extract information from high mass tails
- Offline HH-candidate selection highlights:
  - Oppositely charged τ-candidate pair
  - First 2 jets with highest b tag score are selected as $H \to bb$ candidate
  - $m_{\tau\tau}$ is reconstructed using dynamical likelihood-based algorithm
  - Elliptical mass window cut in $(m_{\tau\tau}, m_{jj})$ plane in 1-btag and 2-btag categories
- Main backgrounds: $t\bar{t}$, Drell-Yan, QCD (data-driven).
  - Yield of Drell-Yan background is estimated via data-driven technique
- 2 BDT discriminators (for $m_X < 350\ GeV$ and $m_X > 350\ GeV$) are applied to discriminate against $t\bar{t}$ background in $\tau_e\tau_h$, $\tau_\mu\tau_h$ channels.
- Signal is extracted using:
  - resonant: m_{HH} distribution after a kinematical fit
  - non-resonant: s-transverse mass (m_{T2})





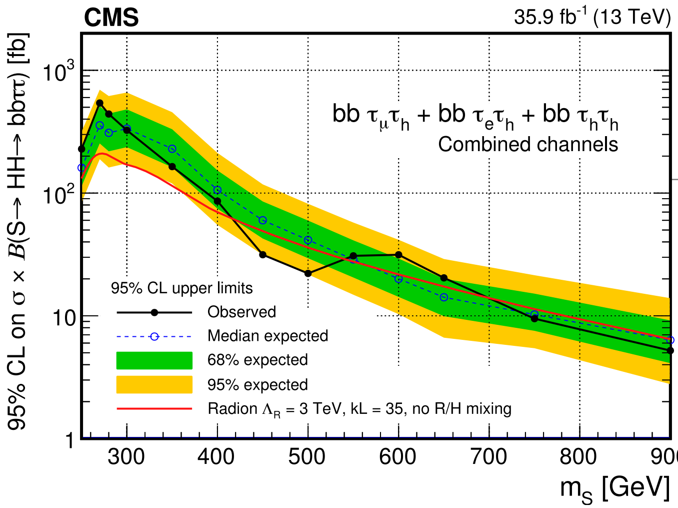
$$m_{T2} \equiv \min_{\boldsymbol{p}_{T1}+\boldsymbol{p}_{T2}=\boldsymbol{p}_T^{\tau\tau}} \{\max[m_T(m_{b1}, \boldsymbol{p}_T^{b1}, m_{vis}^{\tau1}, \boldsymbol{p}_{T1}), m_T(m_{b2}, \boldsymbol{p}_T^{b2}, m_{vis}^{\tau2}, \boldsymbol{p}_{T2})]\}$$

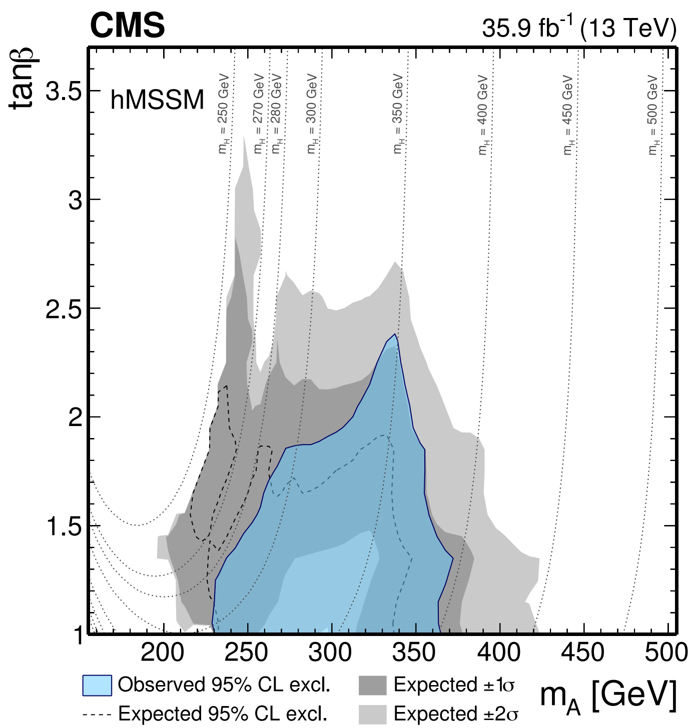
$HH \to bb\tau\tau$

arXiv:1707.02909

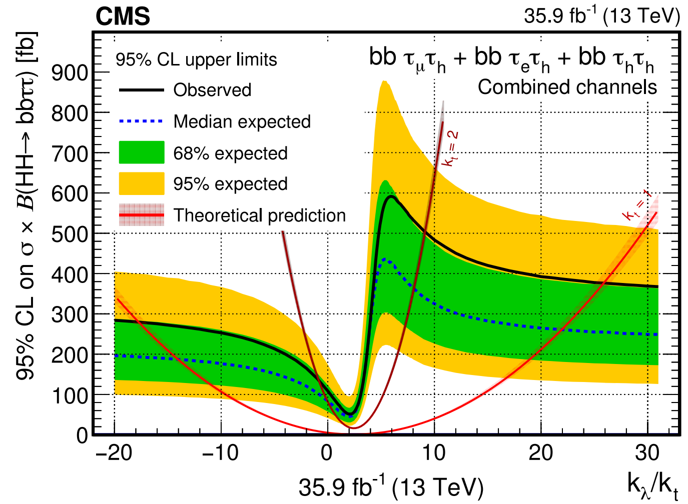
No evidence for a signal is observed

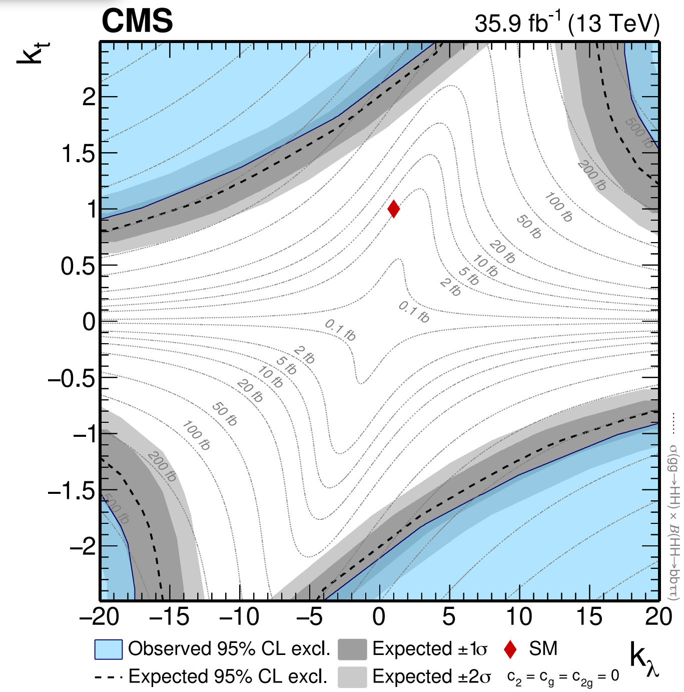
RESONANT





NON-RESONANT



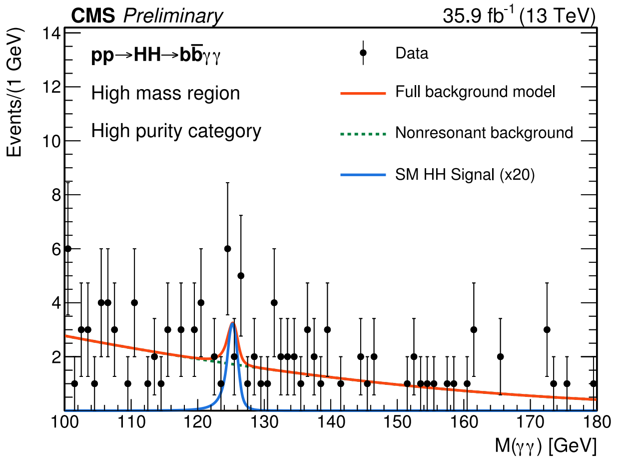


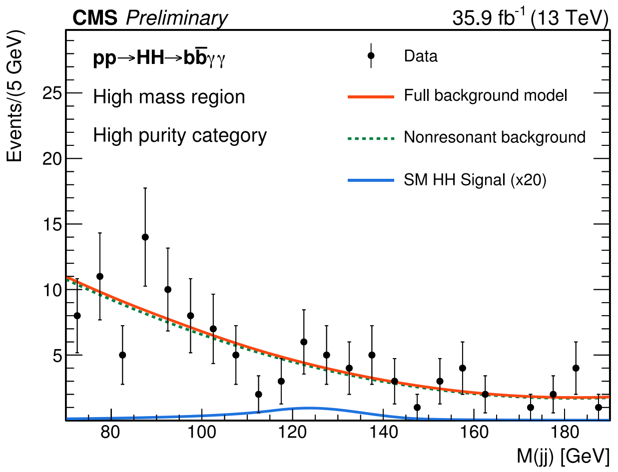
The observed (expected) upper limit on SM HH production XS $\approx 30\ (25) \cdot \sigma_{SM}(HH)$

$HH \to bb\gamma\gamma$

CMS-PAS-HIG-17-008

- Online selection: two isolated photons, requiring $p_T > 30\ (18)\ GeV$ for leading (sub-leading) photon
- Events are split into several categories based on m_{HH} estimation ($\widetilde{M}_X$) and selection purity
  - BDT discriminator is used to classify events into purity category
  - The BDT discriminator is trained on b-tagging variables, helicity angles and HH p_T balance variables
- Offline HH-candidate selection highlights:
  - $E/m_{\gamma\gamma} > 1/3\ \ (1/4)$ for leading (sub-leading) photon
  - $100 < m_{\gamma\gamma} < 180\ GeV$ and $70 < m_{jj} < 190\ GeV$
  - $\Delta R(\gamma, jet) > 0.4$
  - First 2 jets with highest b tag score that pass previous cuts are selected as $H \to bb$ candidate
  - Sliding mass window around m_X for resonant analysis
- Main backgrounds: $\gamma + jets$ from QCD (data-driven) and SM single Higgs production channels with $H \to \gamma\gamma$ final state
- Signal is extracted from $(m_{\gamma\gamma}, m_{jj})$-plane
- The signal and background probability density distributions are modelled using parametric fits:
  - For signal double-sided Crystal Ball function is used
  - The non-resonant background is described through Bernstein polynomials





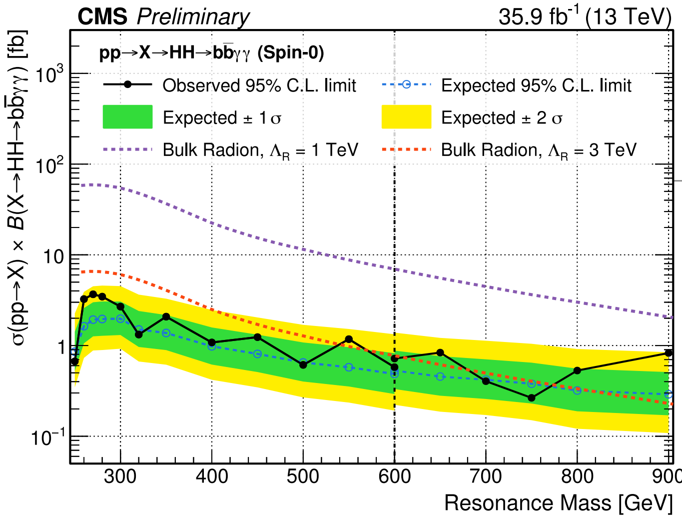
$$\widetilde{M}_X = m_{\gamma\gamma jj} - m_{\gamma\gamma} - m_{jj} + 250\ GeV$$

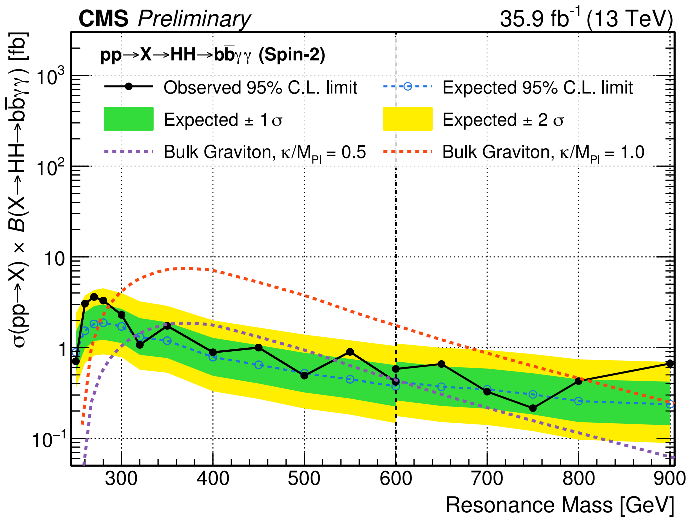
$HH \rightarrow bb\gamma\gamma$

CMS-PAS-HIG-17-008

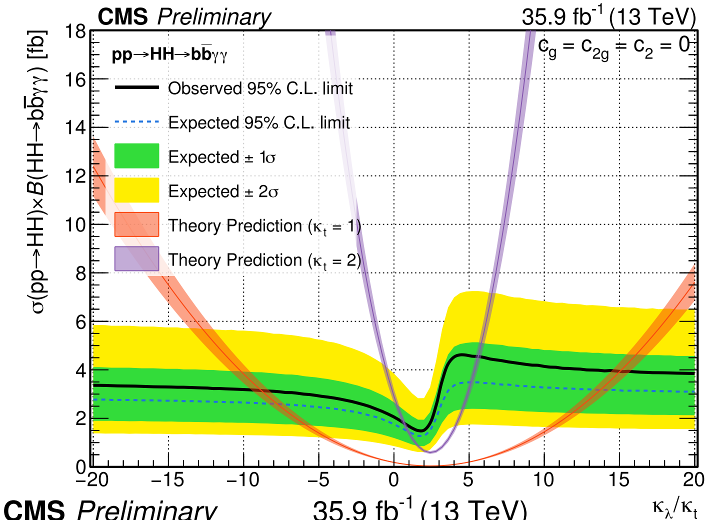
No evidence for a signal is observed

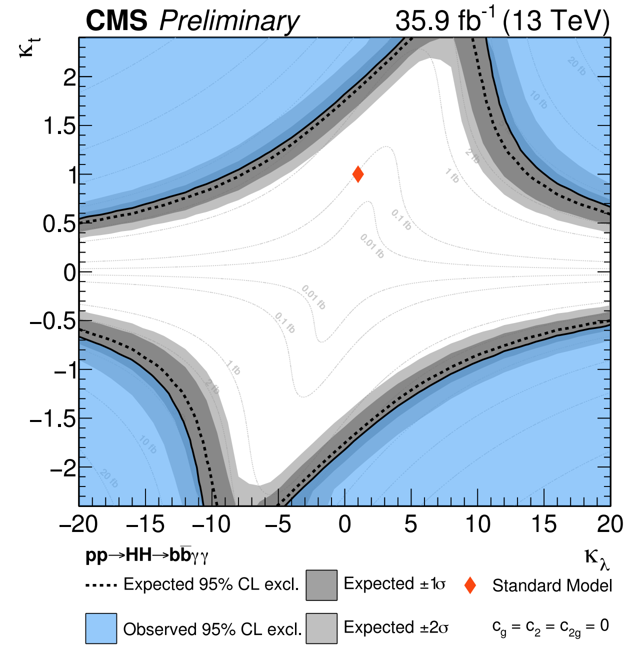
RESONANT





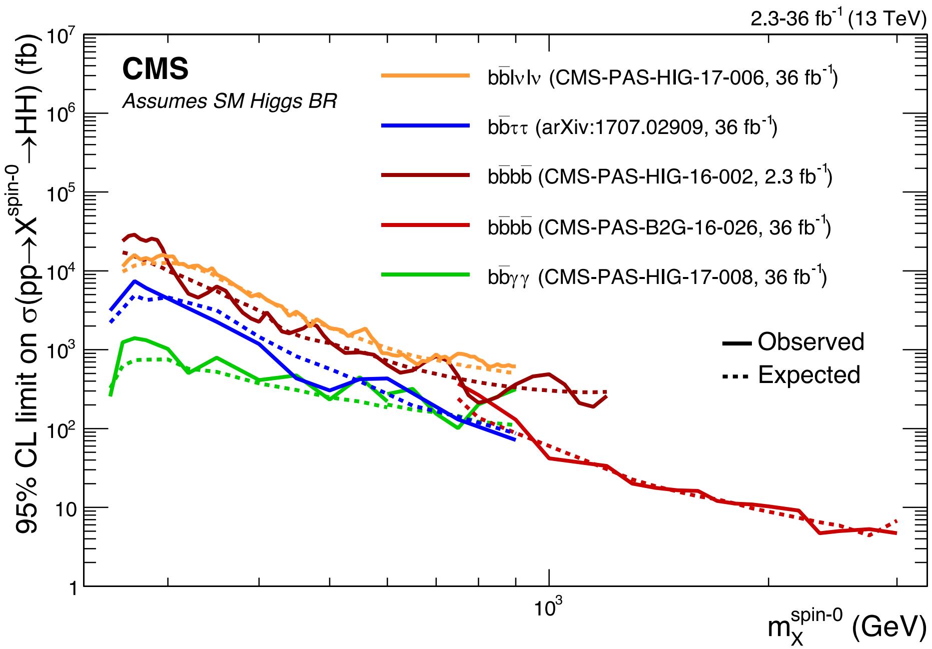
NON-RESONANT

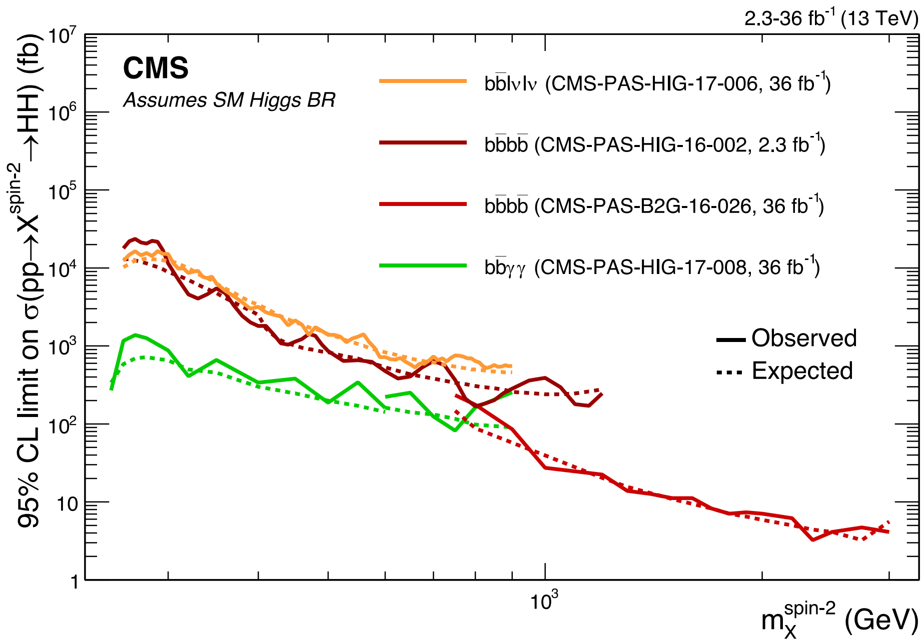




The observed (expected) upper limit on SM HH production XS ≈ $19.2\ (16.5) \cdot \sigma_{SM}(HH)$

Resonant HH summary

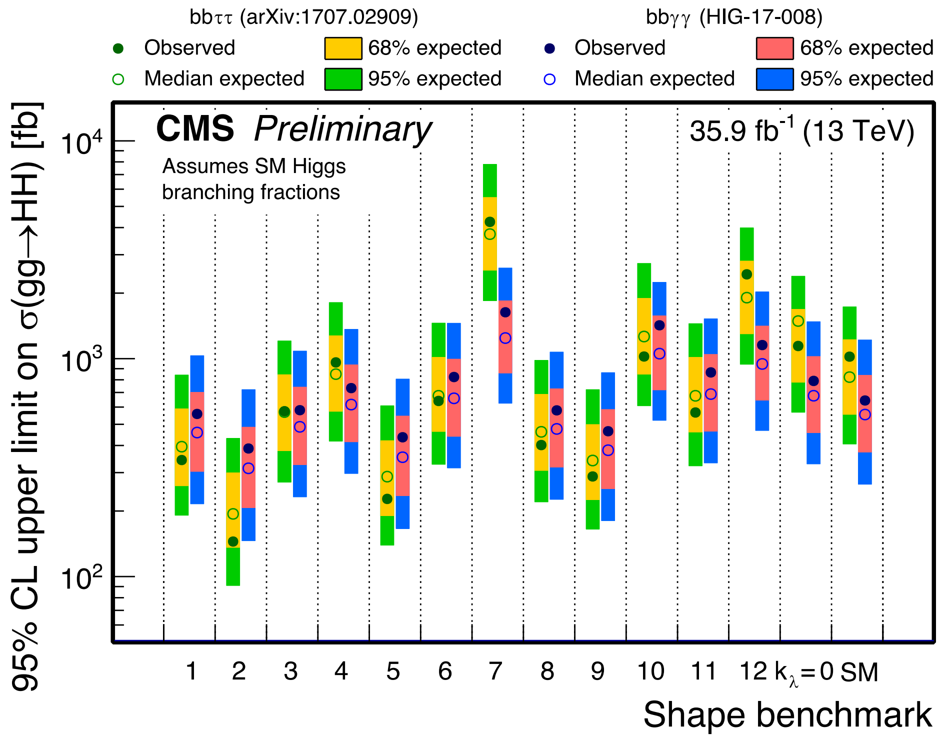




- 95% CL limits on $\sigma(pp \to X \to HH)$ are set in m_X range from 250 to 3000 GeV for narrow width resonance of spin 0 and spin 2 using CMS 2015 and 2016 data
- Four different HH final states were analysed: $bbbb$, $bb\ell\nu\ell\nu$, $bb\tau\tau$ and $bb\gamma\gamma$
- Model dependent interpretation of the exclusion limits into parameter space of two MSSM scenarios are provided ($bb\tau\tau$ final state)
- No evidence of a signal is observed

Non-resonant HH summary

Final state	Observed (expected) 95% CL limit on σ/σ_{SM}
$bbbb$	342 (308)
$bb\ell\nu\ell\nu$	79 (89)
$bb\tau\tau$	30 (25)
$bb\gamma\gamma$	19 (17)



- 95% CL limits on $\sigma(gg \rightarrow HH)$ are set for SM and BSM non-resonant HH production modes using CMS 2015 and 2016 data using the different HH final states:
  - SM: $bbbb$, $bb\ell\nu\ell\nu$, $bb\tau\tau$ and $bb\gamma\gamma$
  - EFT k_t/k_λ scan: $bb\ell\nu\ell\nu$, $bb\tau\tau$ and $bb\gamma\gamma$
  - EFT (k_t, k_λ) plane: $bb\ell\nu\ell\nu$, $bb\tau\tau$ and $bb\gamma\gamma$
  - EFT benchmark scenarios: $bb\tau\tau$ and $bb\gamma\gamma$
- No evidence of a signal is observed

Conclusions

- Searches for resonant and non-resonant HH production into four main HH final state ($bbbb$, $bb\ell\upsilon\ell\upsilon$, $bb\tau\tau$ and $bb\gamma\gamma$) are performed using the CMS data from LHC Run 2
  - $bb\ell\upsilon\ell\upsilon$, $bb\tau\tau$, $bb\gamma\gamma$ and resonant-boosted $bbbb$ analyses are using 2016 data
  - Resonant and non-resonant $bbbb$ analyses are using 2015 and are expected to be updated with 2016 in the near future
- The sensitivity of all analyses are significantly improved with respect to the 2015 results.
- No evidence of a signal is observed for both resonant and non-resonant production mode
- Provided limits for resonant HH production exclude some new ranges into parameter spaces of Radion, KK-Graviton and hMSSM scenarios.
- 95% CL limits on $\sigma(gg \to HH)$ are set for SM HH production mode
  - The lowest observed limit is $\approx 19.2\ (16.5) \cdot \sigma_{SM}(HH)$ obtained by $bb\gamma\gamma$ analysis
- 95% CL limits for non-resonant EFT parameter space are set, excluding some (k_t, k_λ) regions
- Future perspectives:
  - Cover additional HH final states
  - Provide combination of all HH searches
  - Further improve analyses techniques and update the results with 2017 data