Searches for HH production at 13 TeV with the CMS detector

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on behalf of CMS collaboration
-- University and INFN Padova --

European Physics Society HEP2017

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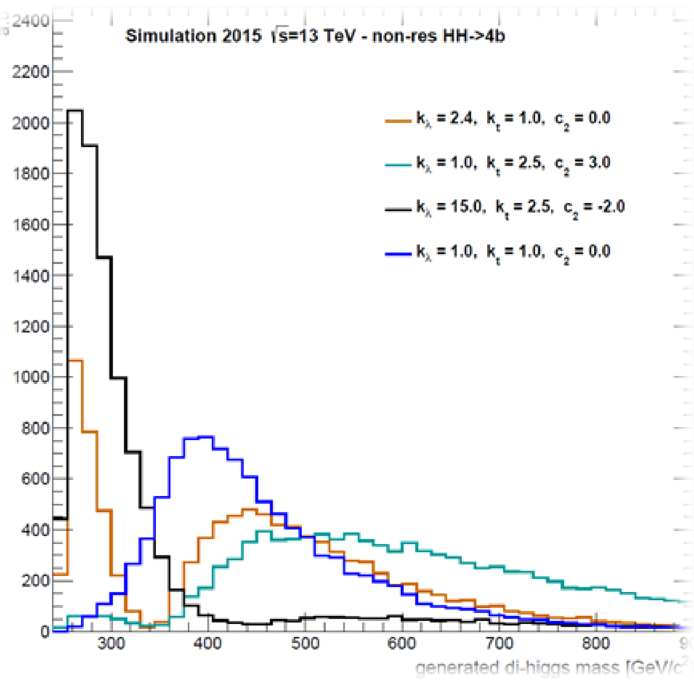
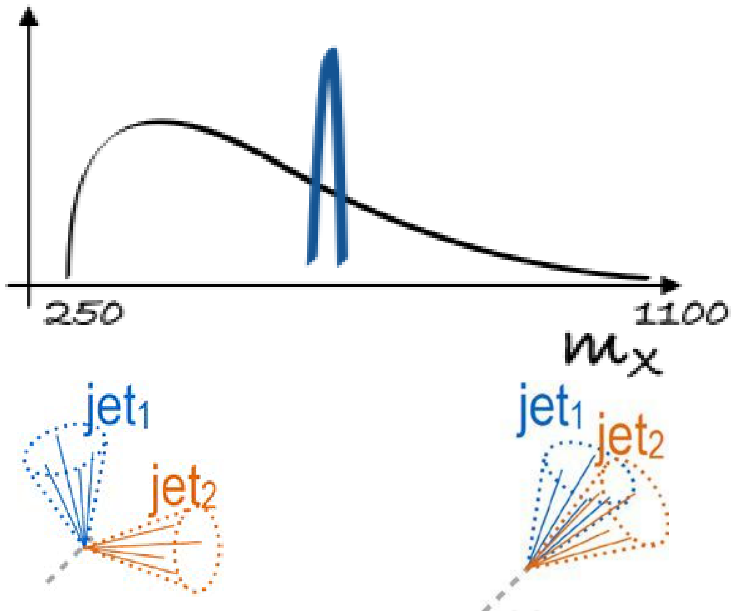
Higgs pairs at LHC

NON-RESONANT



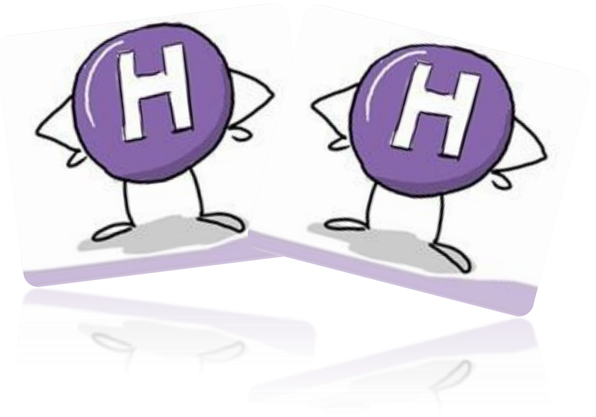
m_{HH}

RESONANT



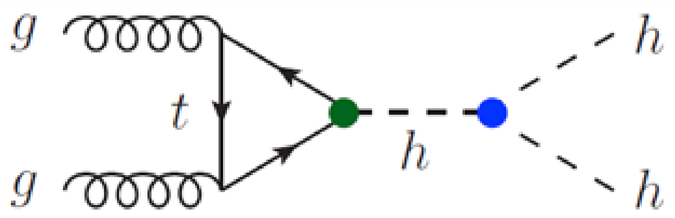
Physics motivations

Search for Standard Model (SM) di-Higgs (hh) production at LHC:
- is a baseline SM topic
- allows to measure the Higgs self-coupling (λ_{hhh})



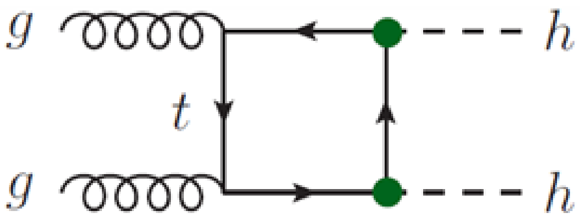
SM Higgs pairs production in p-p collisions at LHC:

- mainly via **gluon-gluon fusion**
- **small prod. cross section** due to destructive interference among diagrams :



$$\sigma^{SM}_{hh}(\text{p-p } 13 \text{ TeV}) = 33.53 \text{ fb}$$ [1]

- SM measurements possible starting from 3 ab^{-1}
- BSM effects would lead to:
  - the presence of **resonant** hh process
  - the enhancement of the **non-resonant** σ_{hh}



σ^{SM}_{h}(p-p 13 TeV) = 4858 fb
σ^{SM}_{hh}(p-p 8 TeV) = 10.16 fb

[1] +4.3% -6.0% (scale unc.) ± 3.1% (PDF+α_S unc) -- NNLO+NNLL. LHCHXSWG Yellow Report 4

Physics motivations

BSM effects

RESONANT

- **MSSM/2HDM** (250-400 GeV) or **Singlet model** (250-1000 GeV)
- **Warped Extra Dimensions** (250-3000 GeV):
  spin-2 (KK-graviton) [1] and spin-0 (Radion) [2] resonances

[1] Warped Gravitons at LHC
[2] Radion phenomenology, Csaba Csaki et al
[3] Phys. Rev. **D91** (2015), no. 11, 115008

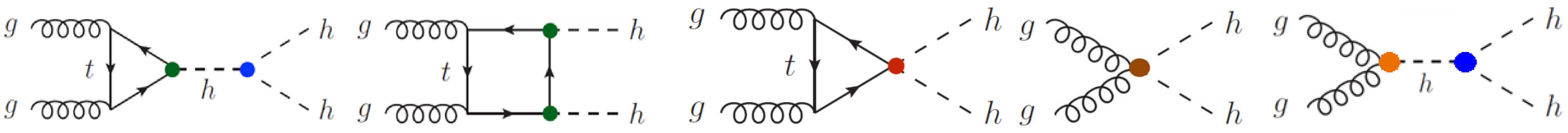
NON-RESONANT

- General extension to **BSM effects** is modelled in EFT adding dim-6 operators[3], the process can be described with **5 parameters** in the following Lagrangian.

k_λ k_T C_2 C_g C_{2g}

$$\mathcal{L}_h = \frac{1}{2}\partial_\mu h \partial^\mu h - \frac{1}{2} m_h^2 h^2 - \kappa_\lambda \lambda_{SM} v h^3 - \frac{m_t}{v}\left(v + \kappa_t h + \frac{c_2}{v} h h\right)(\bar{t}_L t_R + h.c.) + \frac{1}{4}\frac{\alpha_s}{3\pi v}\left(c_g h - \frac{c_{2g}}{2v} h h\right) G^{\mu\nu} G_{\mu\nu} \,.$$

Where:
$k_\lambda = \lambda_{HHH}/\lambda_{HHH}^{SM}$;
$k_t = y_T/y_T^{SM}$;
$\lambda_{SM} = m^2_H/(2v^2) = 0.129$.



Tri-linear coupling | **Yukawa interaction** | **ttHH interaction** | **Higgs-gluon contact interactions**

Physics motivations

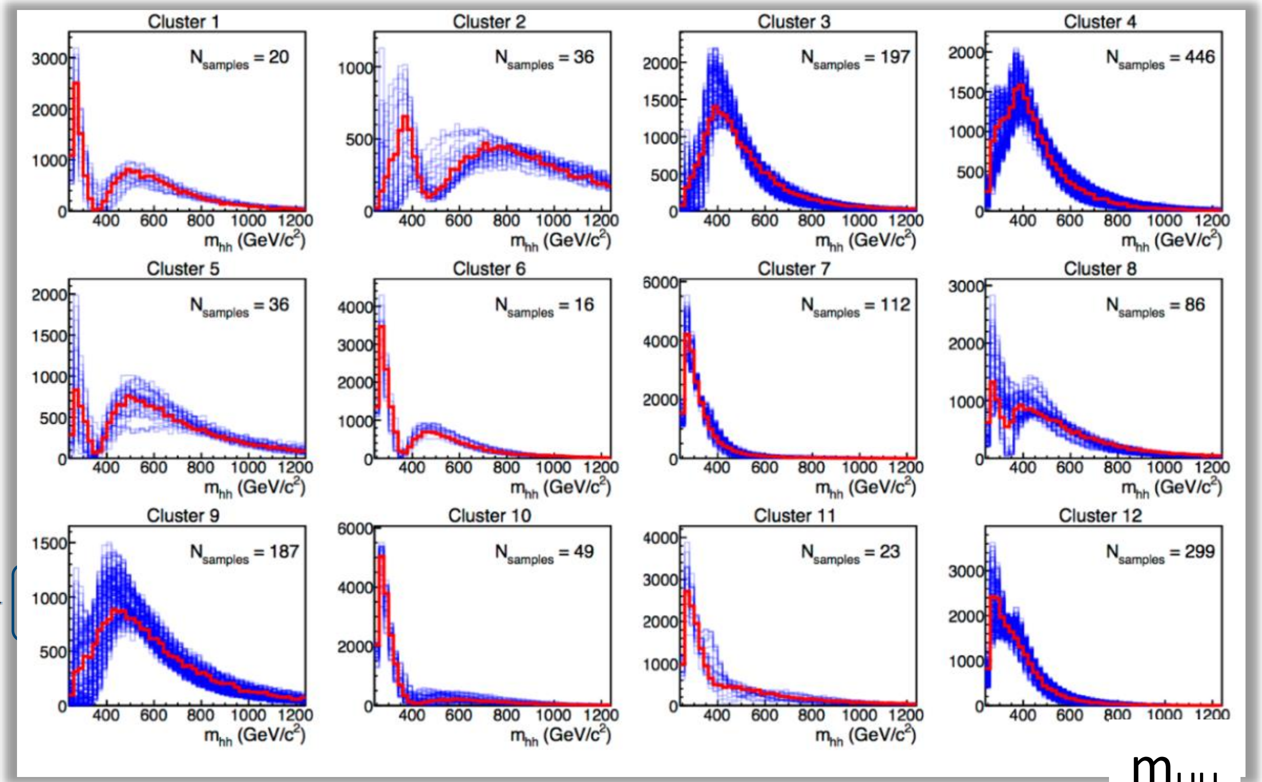
BSM effects

- σ_{hh} and kinematics of the final state vary in the 5D phase space. **12 benchmarks** identified[4].

[4] JHEP **04** (2016) 126

NON-RESONANT

$$\mathcal{L}_h = \frac{1}{2}\partial_\mu h \partial^\mu h - \frac{1}{2}m_h^2 h^2 -$$



m_{HH}

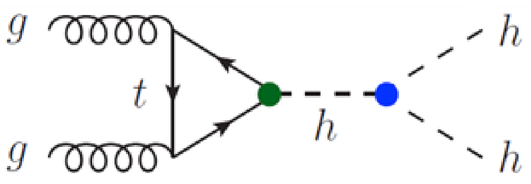
k_λ k_T C_2 C_g C_{2g}

Where:

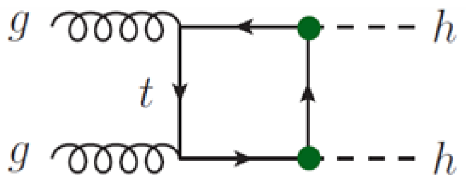
$k_\lambda = \lambda_{HHH}/\lambda_{HHH}^{SM}$;

$k_t = y_T/y_T^{SM}$;

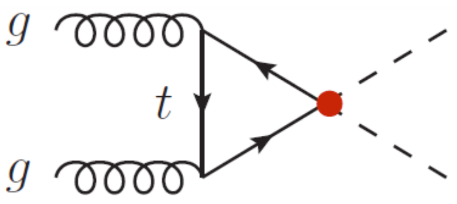
$\lambda_{SM} = m^2_H/(2v^2) = 0.129$.



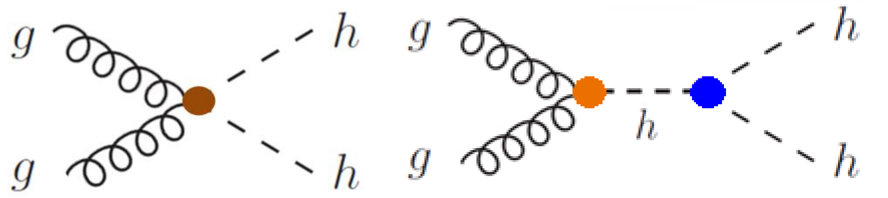
Tri-linear coupling



Yukawa interaction



ttHH interaction



Higgs-gluon contact interactions

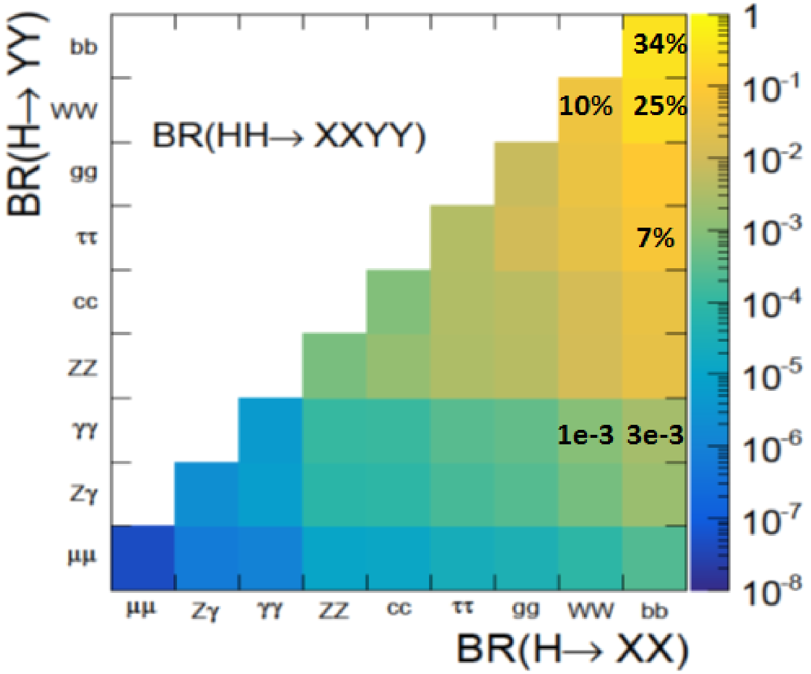
Final States

RESONANT | **NON-RESONANT**

di-Higgs searches can be performed looking at several final states

Due to the relatively low production cross section -->

one Higgs is searched for in bb decay to exploit the higher branching ratio.



<u>**Four main decay channels**</u>:

- **bb bb** -> highest BR, high QCD/tt bkg
- **bb lνlν** -> high BR, large irreducible tt
- **bb ττ** -> relatively low background
- **bb γγ** -> high purity, very low BR **NEW** (shown for the first time to public)

Studies on-going on additional channels.

<u>On each channel:</u>

Model independent search of narrow width resonance + interpretations.
Upper limit on SM non-resonant production + searches for BSM effects.

Strongly improved sensitivity wrt Run1 but combination is still competitive [1].

[1] 8 TeV - bbττ plus combination

HH → bbbb

OBJECTS: 4 resolved and b-tagged jets

2.3 fb-1 (13TeV)

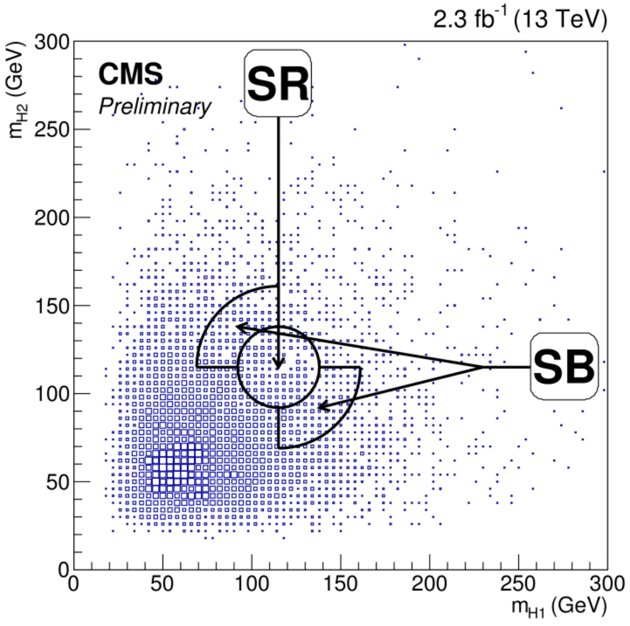
Both searches will be updated soon

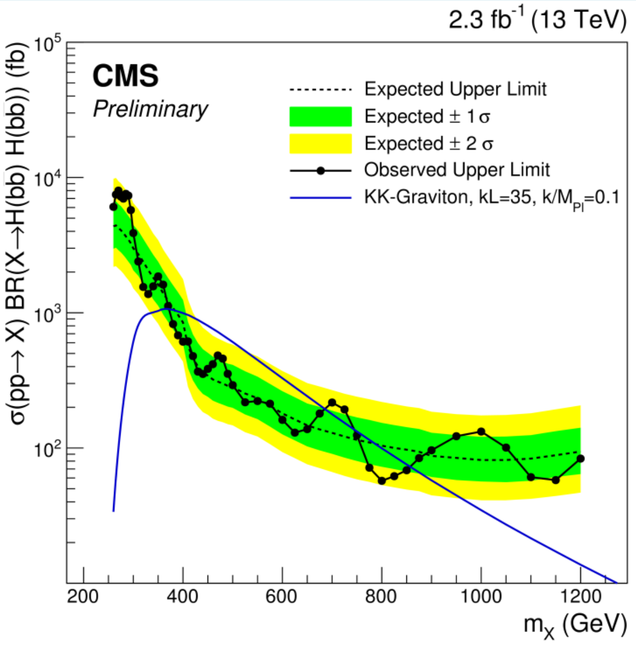
RESONANT

CMS-PAS-HIG-16-002

- On-line cut: >= 3 b-tagged anti-k_T R=0.4 jets
- Bkg: **multijets QCD and tt** (2-10%)
- First 4 jets sorted in bTag + selection on jet/di-jet ΔR/Δm
- Bkg shape from sidebands on data in 2D mass plane
- **Signal search on m_{4j} distribution**

Exclusion: KK-Graviton of mass ϵ [350-725]GeV ; ϵ [775-850]GeV.

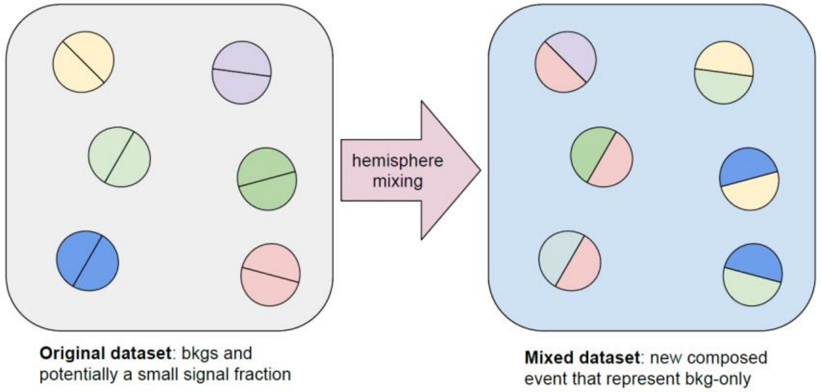




NON-RESONANT

CMS-PAS-HIG-16-026

- First analysis performed on 2015 data
- BDT to improve significance
- **"Hemisphere mixing" technique** to extract bkg template (see T.Dorigo's talk at QCD parallel)
- **Signal search on 2D plane m_{jj} vs m_{jj}**



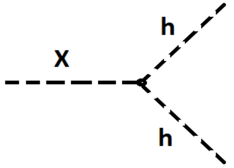
Limit on σ_{hh} : 3880 (exp 3490) fb

HH → bbbb

RESONANT – BOOSTED TOPOLOGY

CMS-PAS-B2G-16-026

for M_X > 800 GeV Higgs bosons are Lorentz-boosted, each H->bb reconstructed as 1 hadronic jet ('fat jet')



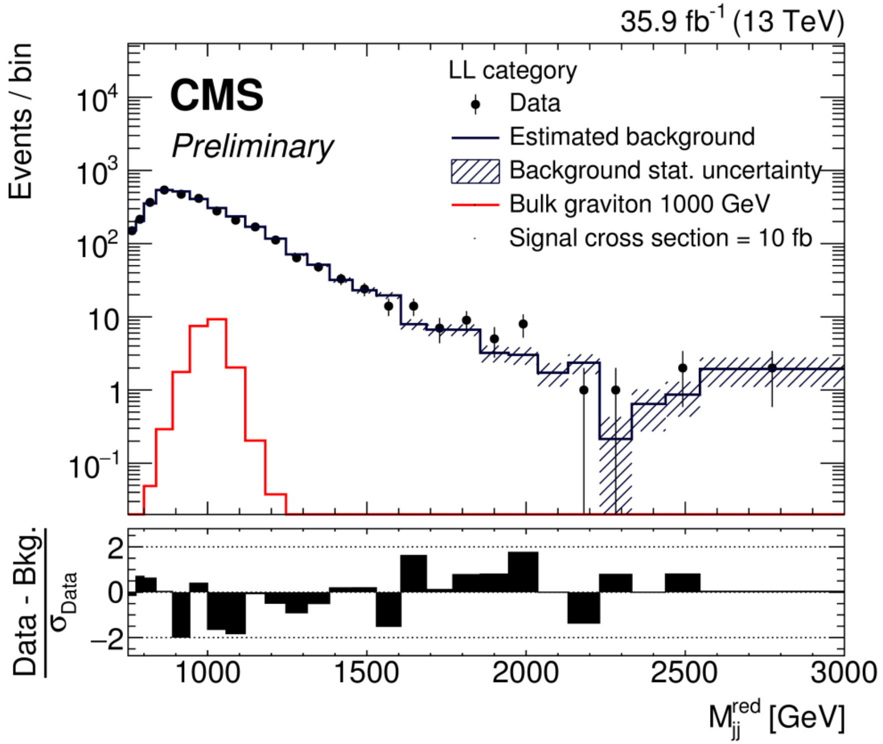
- 2 jets with highest p_T selected
- Veto on isolated muon. Technique to get 'cleaned' m_H (soft drop mass)
- b-tagging for fat jet: ***double b-tagger.*** *(Details in C. Vernieri's talk)*
- $\Delta\eta(jj)<1.3$ (searches for scalar favoured)
- **Multijets background**, template from

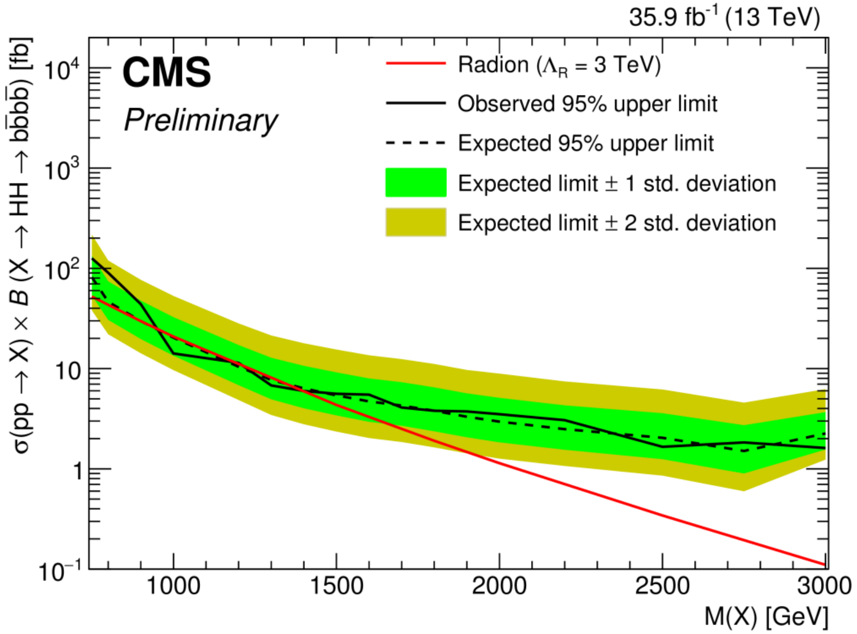
  m_X<1200 GeV: data-driven '*Alphabet*' method (ABCD with more sidebands)

  m_X>1200 GeV: levelled exponential function

  Normalization extracted from sidebands in b-tag and Mj.
- **Signal extraction from m_{jj}^{red}** $= M_{jj} - (M_{j_1} - M_H) - (M_{j_2} - M_H)$

No signal excess.
For Λ_R = 3 TeV, Radion of mass between 970 and 1450 GeV excluded.





HH → bblνlν

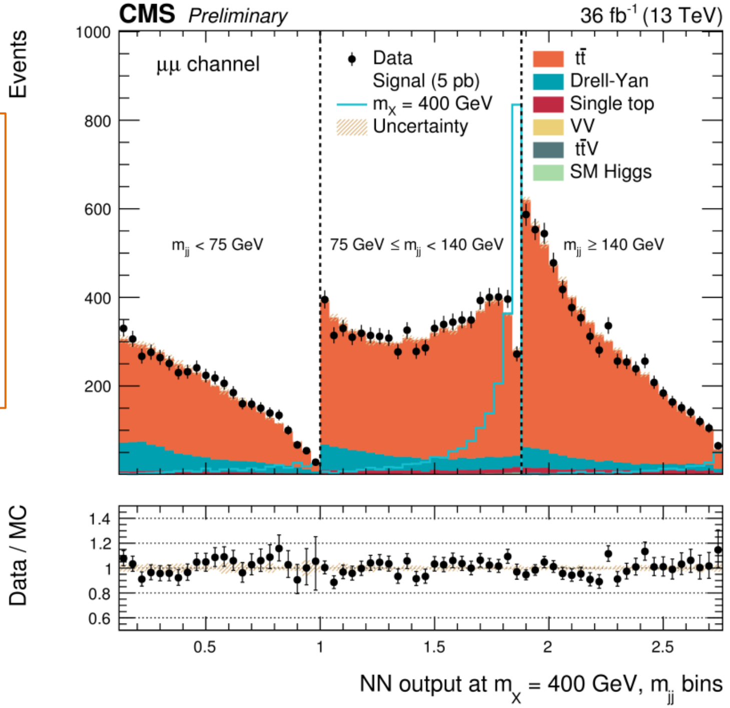
CMS-PAS-HIG-17-006

Decays from both W and Z considered (with $12 < m_{ll} < m_Z - 15$ GeV).
3 channels: e^+e^-, $\mu^+\mu^-$, ($e^+\mu^-$ and $e^-\mu^+$).
OBJECTS: 2 b-tagged jets && 2 oppositely charged leptons.

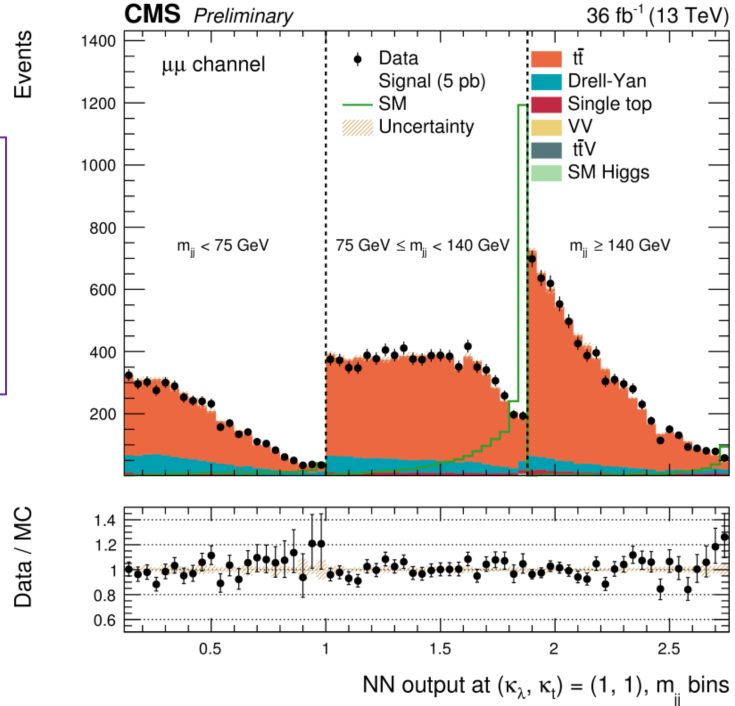
- Dilepton triggers. $\Delta_R(jl) > 0.3$.
- **Main backgrounds: *tt, Drell-Yan, single top***
  Templates from simulations but Drell-Yan (data-driven for e^+e^-, $\mu^+\mu^-$).
  BDT to discriminate Drell-Yan +bb,cc from DY associated prod.
- **2 Deep Neural Networks to improve S/B** (for resonant and for non-res)
  The *Parameterised machine learning technique*[1] is used:
  inputs: $m_{ll}, \Delta R_{ll}, \Delta R_{jj}, \Delta\phi_{ll,jj}, p_T^{ll}, p_T^{jj}, \min(\Delta R_{j,l})$, and M_T
  plus pysics parameters (e.g. m_X, k_λ, k_t).
  It ensures optimal sensitivity on wide signal range with one single training.
- Three categories on M(jj) to enhance sensitivity
- **Signal extraction on DNN discriminant**

[1] Phys. J. C **76:235** (2016)

RESONANT



NON-RES.



HH → bblνlν

CMS-PAS-HIG-17-006

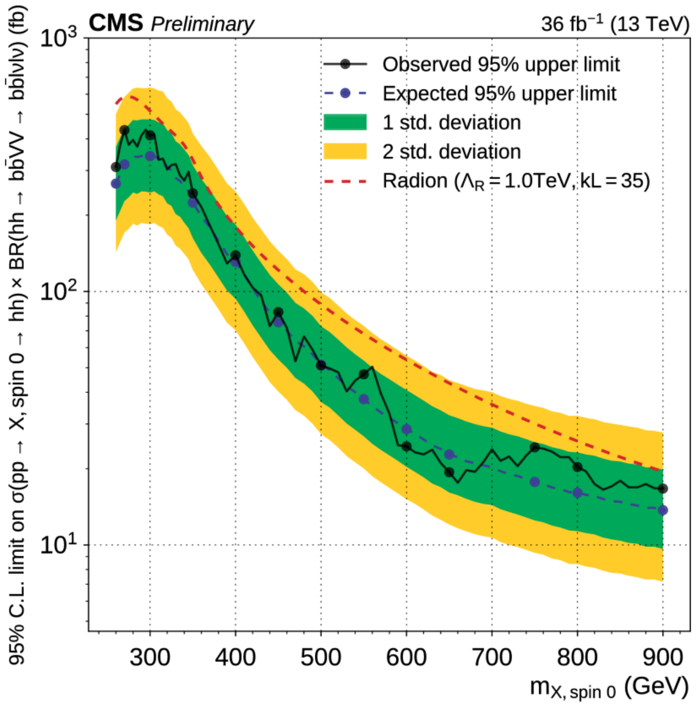
RESONANT

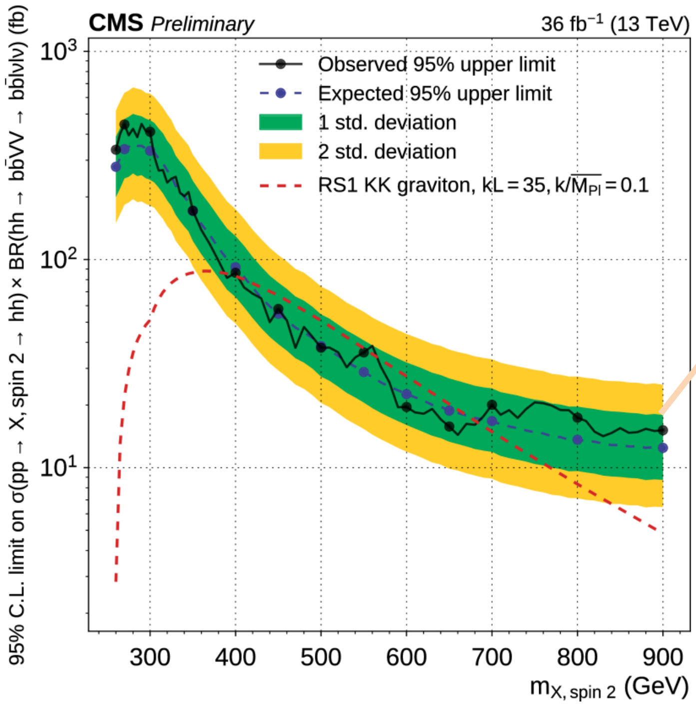
No signal excess.

Limit set for $250<m_X<900$ GeV.

Excluded KK-Graviton in ranges [400;690] GeV

($kL=35$, $k/M_{Pl}=0.1$).



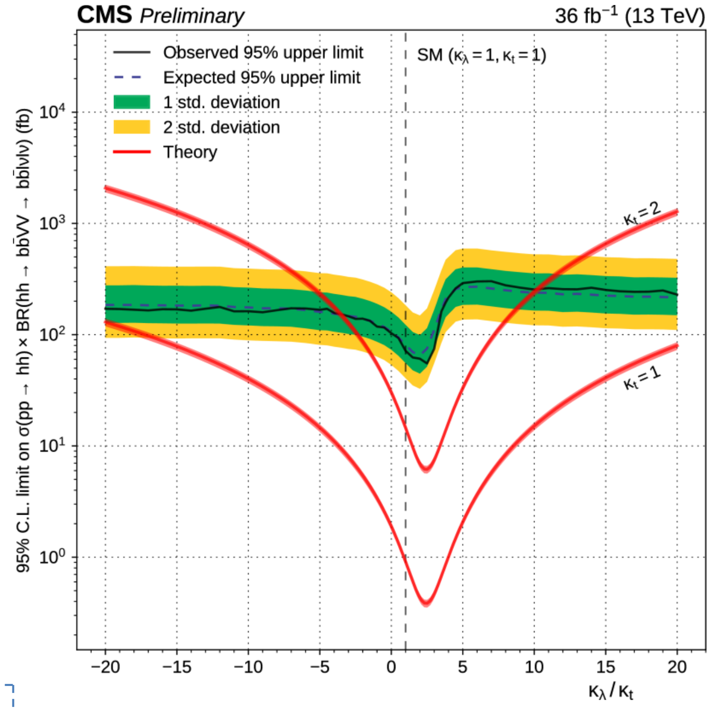


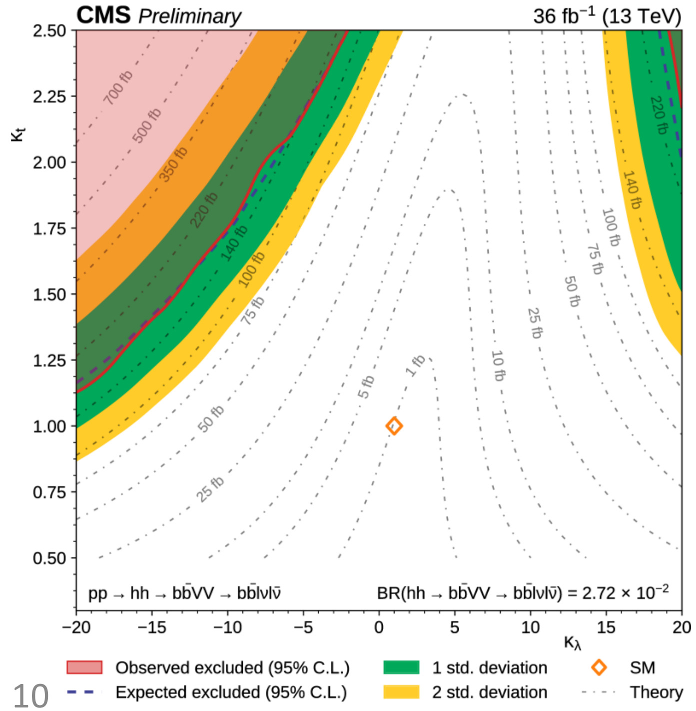
Shaky behaviour of the observed limit is due to different NN for each point (different mass hypothesis as input).

NON-RESONANT

Limit on σ_{hh} :
72 (exp 81^{+42}_{-25}) fb
equal to 79 times $\boldsymbol{\sigma^{SM}_{hh}}$

Limit as a function of k_λ k_t (BSM).





HH → bbττ

CMS-PAS-HIG-17-002

3 channels: $\tau_H\tau_H$, $\tau_H\tau_e$, $\tau_H\tau_\mu$ ($_H$ == hadrons). 85% of ττ decays.

3 categories: 2 b-tags, 1 b-tag, boosted (high mass).

OBJECTS: b-tagged 'resolved' or 'fat' jets, 2 oppositely charged lept, MET.

- Single lepton triggers OR $\tau_H\tau_H$ at trigger level.

  Isolation for both leptons and τ_H.

  $M_{\tau\tau}$ recontructed via dynamical likelihood technique.

  Selection on M_{bb} $M_{\tau\tau}$ plane (different for resolved and boosted).

- **Main backgrounds: *tt, Drell-Yan, QCD (data-driven)*.**

- **2 BDTs** to select against tt process (for $\tau_H\tau_e$, $\tau_H\tau_\mu$)

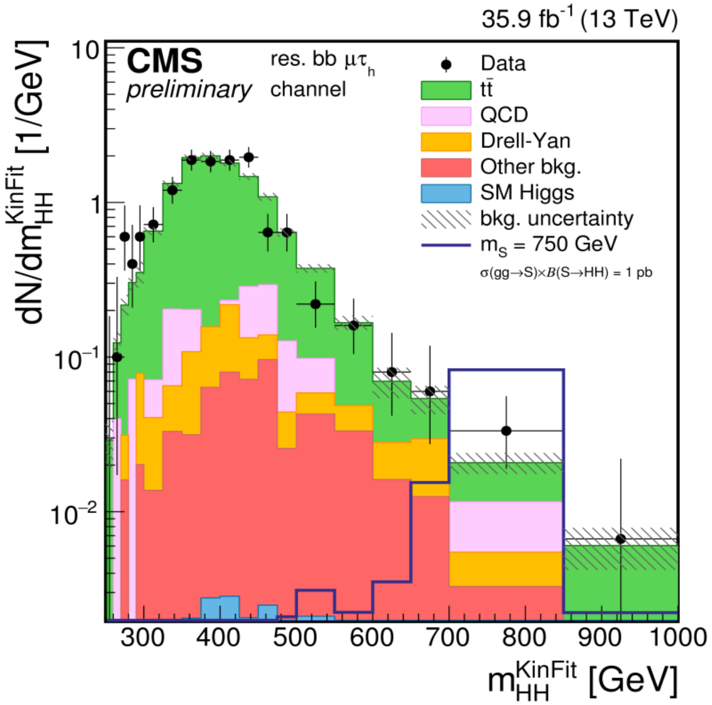
  for m_{HH} < 350 GeV and for m_{HH} > 350 GeV.

- **Signal extraction from:** - resonant : $\mathbf{m_{HH}^{kinfit}}$ (p_T^τ, p_T^j, MET)

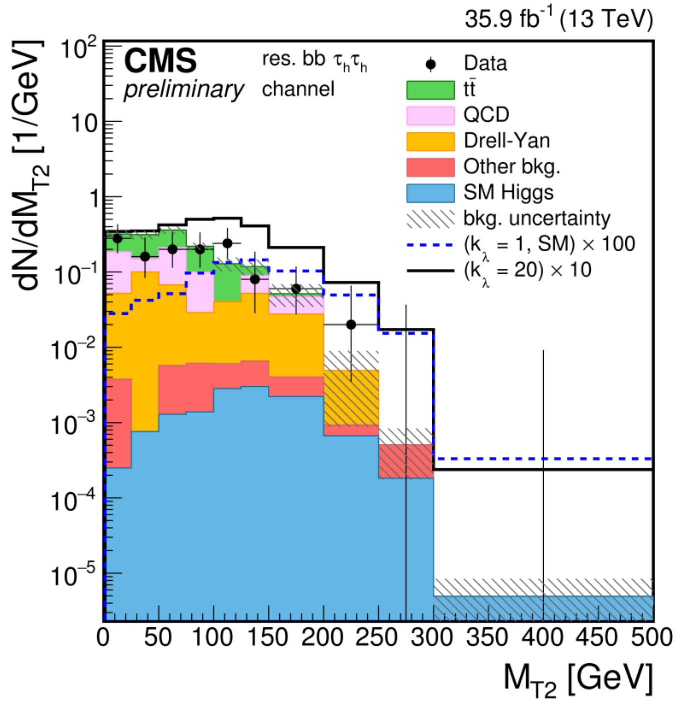
  - non-resonant: **'stransverse' mass m_{T2}**

$$M_{T2} = \min_{p_{T1} + p_{T1} = p_T^{\tau\tau}} \{\max[m_T(m_{b1}, p_T^{b1}, m_{vis}^{\tau 1}, p_{T1}), m_T(m_{b2}, p_T^{b2}, m_{vis}^{\tau 2}, p_{T2})]\}$$

RESONANT



NON-RES.



HH → bbττ

CMS-PAS-HIG-17-002

RESONANT

No signal excess.

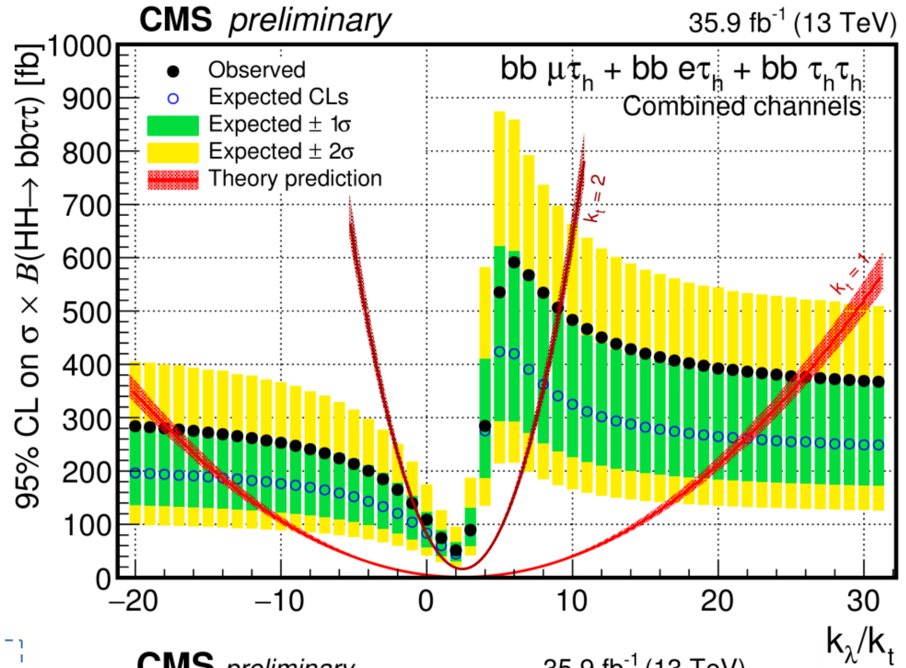
Model independent limits set for
$250 < m_X < 900$ GeV.

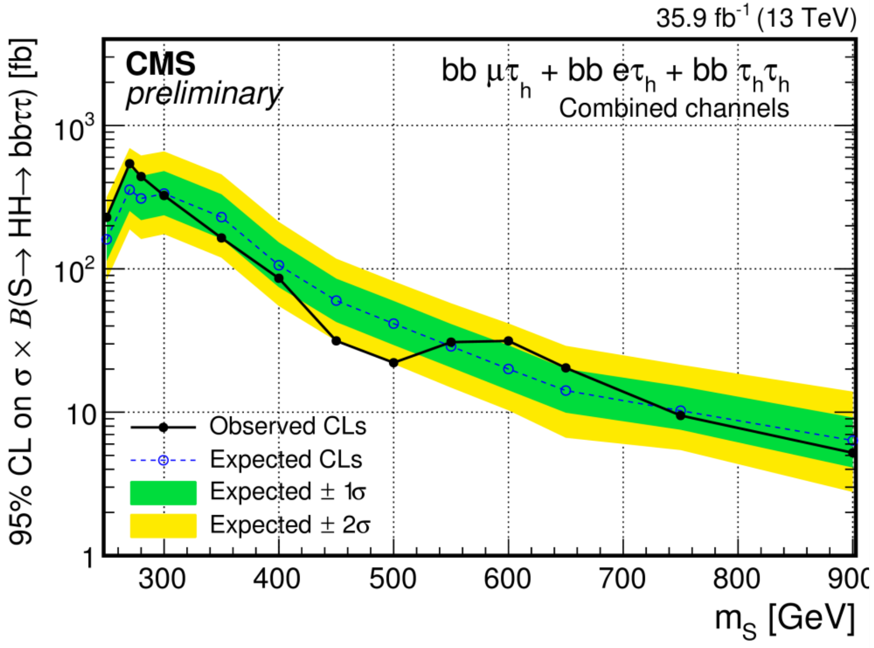
Interpreted in MSSM scenarios with HH prod parametrized as a function of m_A and tanβ.

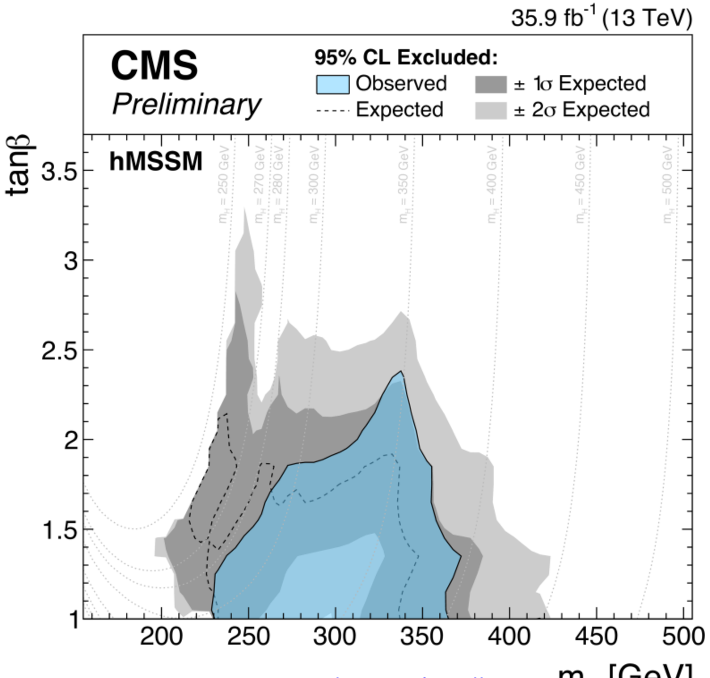
NON-RESONANT

Limit on σ_{hh} :
25 (exp 28) times σ^{SM}_{hh}

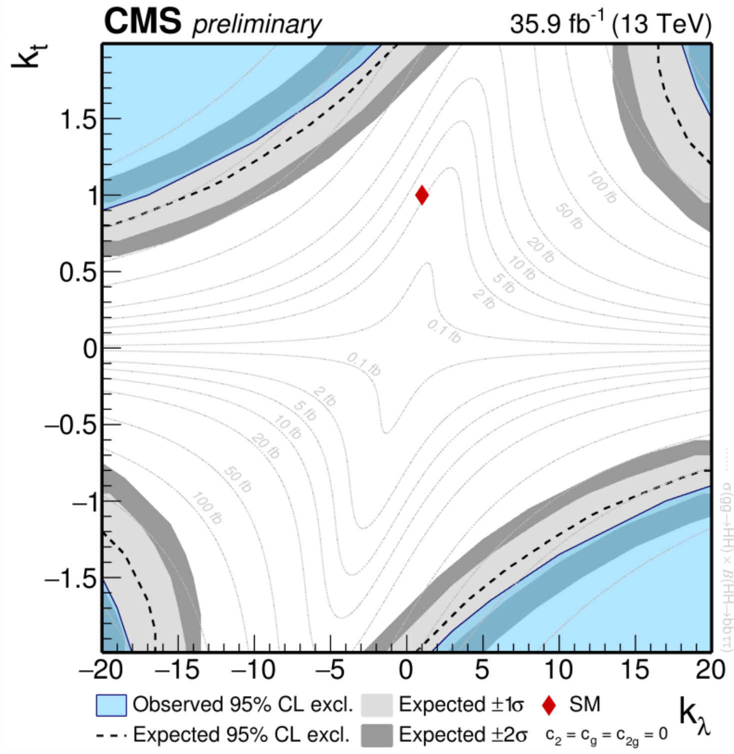
Limit as a function of k_λ k_t (BSM).







more on MSSM in Chayanit's talk.



HH → bbγγ NEW

CMS-PAS-HIG-17-008

OBJECTS: 2 photons and 2 b-tagged resolved jets.

Categories based on system invariant mass and MVA output.

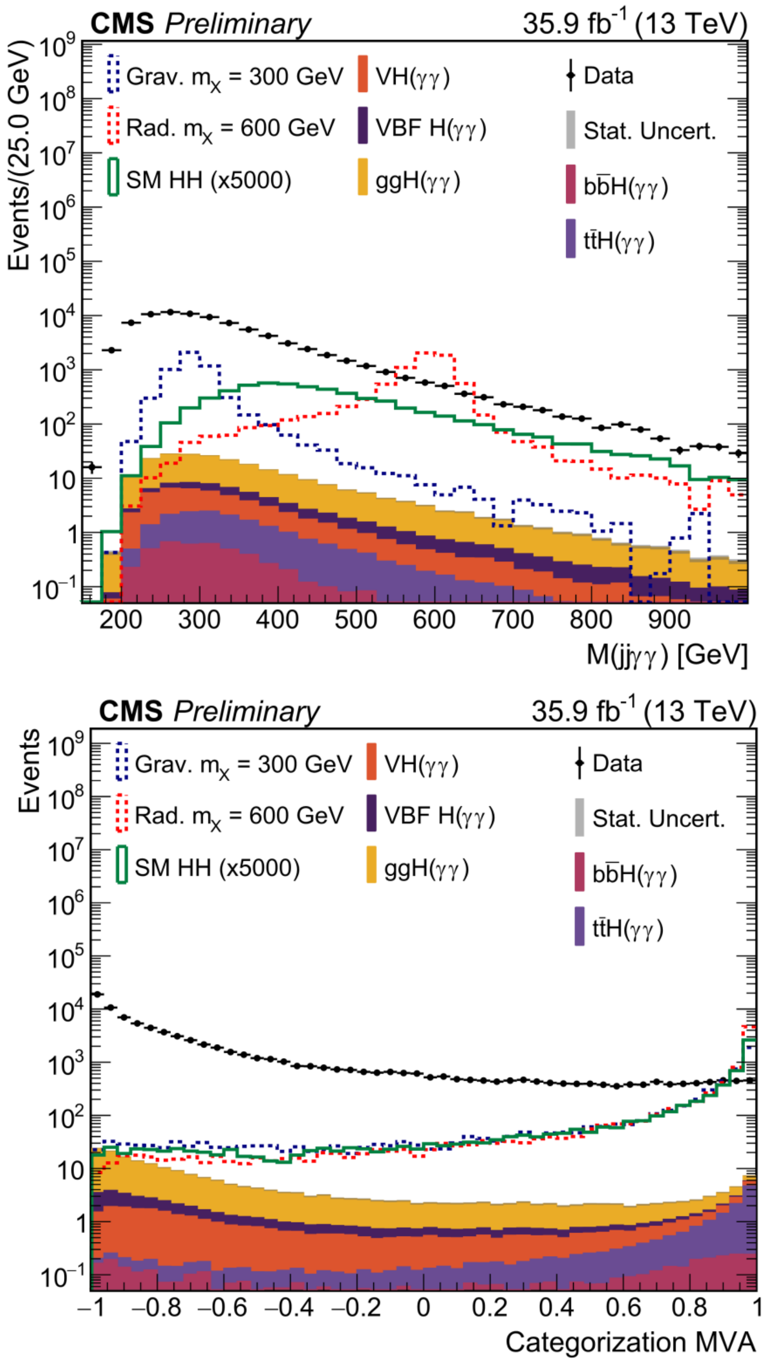
- Double photon trigger. MVA to identify vertex (same as single H).
- Selection on E_T, $m_{\gamma\gamma}$, m_{jj}, pT, ΔR(j, γ)>0.4.

  2 leading jets on b-tag. **Jets energy regression** applied.

  To improve resolution, HH mass approximated by:

$$\tilde{M}_X = M(jj\gamma\gamma) - M(jj) - M(\gamma\gamma) + 250$$

- **BDT to classify events** in purity categories.
  Trained on b-tagging variables, helicity angles, pT(jj)/m(..).
- For non-resonant, **2 additional categ**: $m_X < 350$ GeV OR $m_X > 350$ GeV.
- **Backgrounds:** γ+Jets from QCD (data-driven), single H->γγ, ttH, bbH, VH.
  Described through polynomials in the Bernstein basis.
- **Signal extraction from 2D plane: $m_{\gamma\gamma}$, m_{jj}.**



HH → bbγγ

NEW

CMS-PAS-HIG-17-008

RESONANT

No signal excess.

Limits set for $250 < m_X < 900$ GeV.

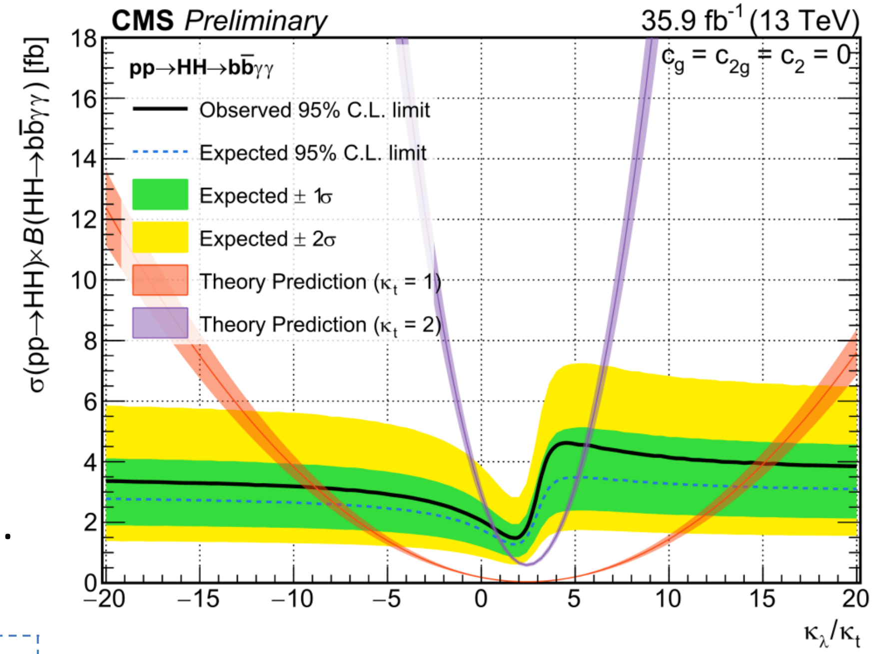
Excluded any Radion for Λ_R = 1 TeV hypothesis and mX < 550 GeV for Λ_R = 3 TeV.

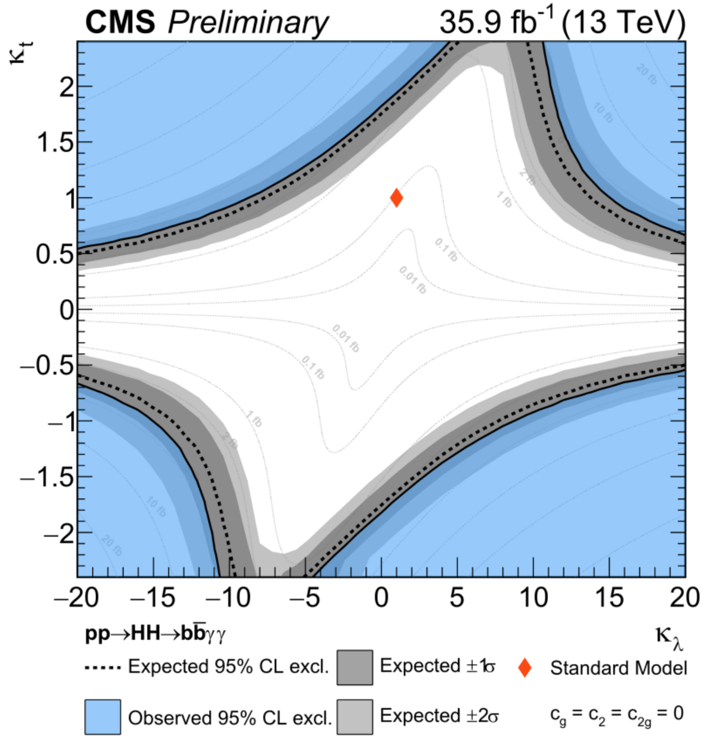
Exlusion for KK-Graviton in ranges [280;900] GeV (k/M_{Pl}=1.0) and [300;550] GeV (k/M_{Pl}=0.5).

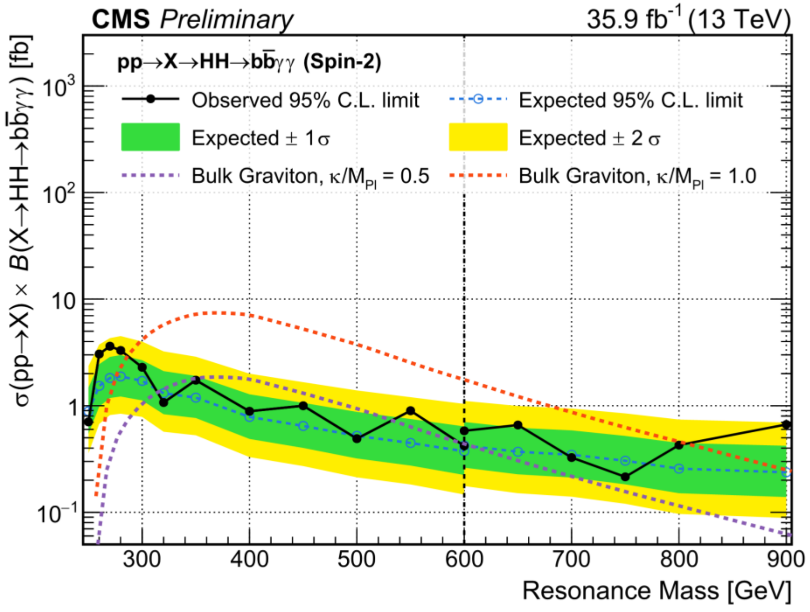
NON-RESONANT

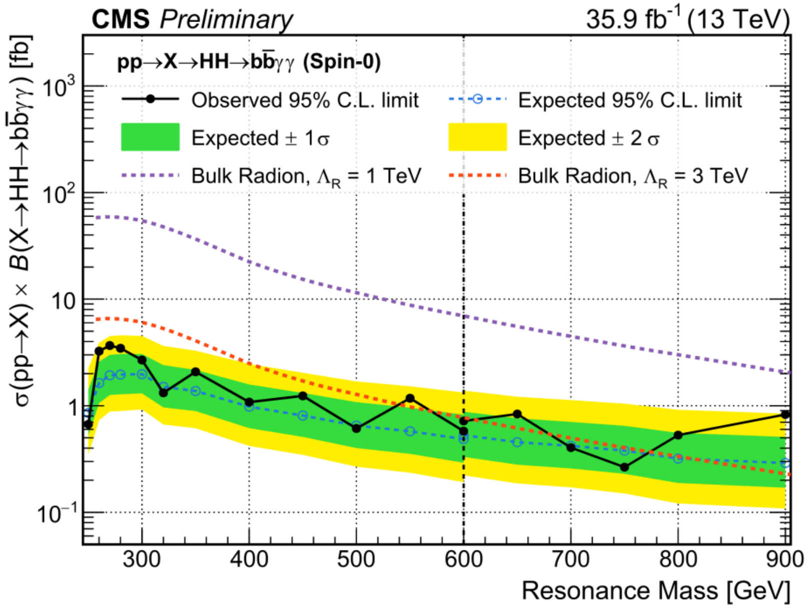
Limit on σ_{hh} :
1.67 (exp 1.44) fb
equal to **19.2 times σ^{SM}_{hh}**

Limit as a function of k_λ k_t .
k_t = 2 excluded with k_λ=1.





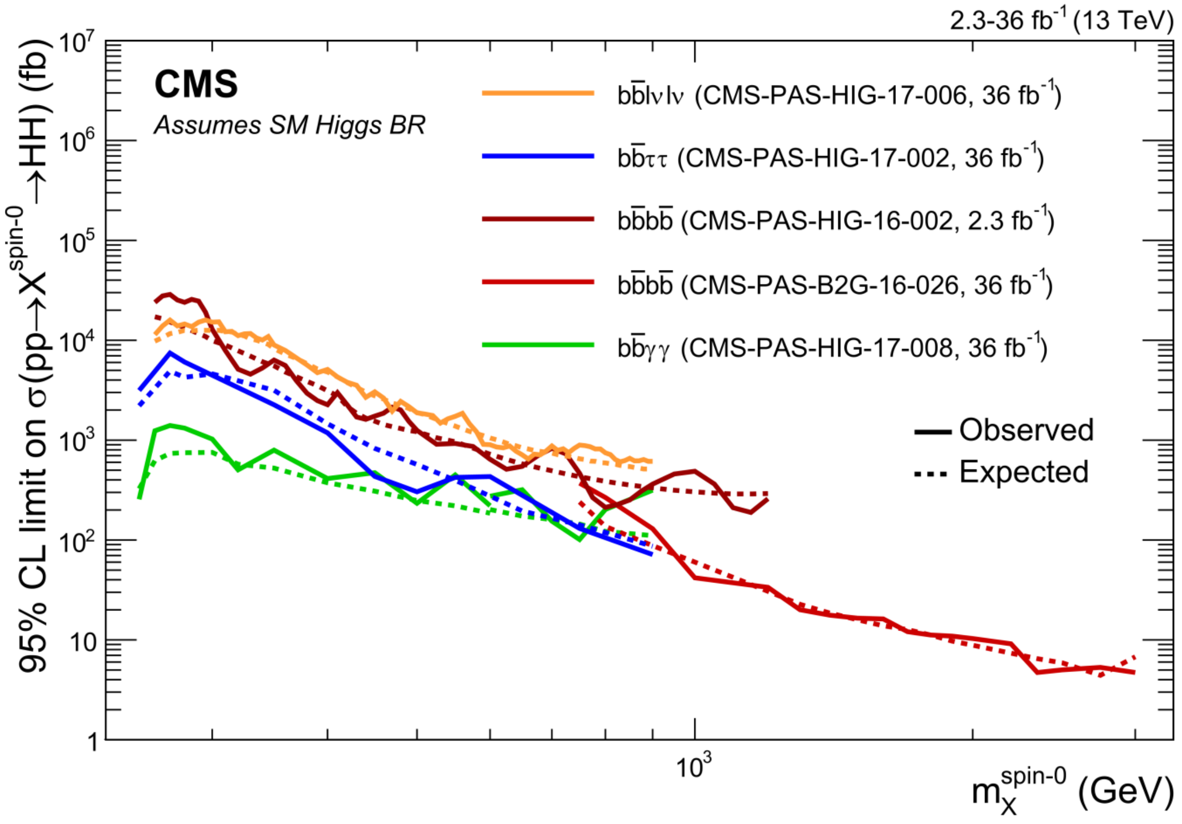




Results - Summary

NEW

RESONANT



NON-RESONANT

Assuming SM Higgs branching fractions [1]

HH to	SM observed (expected) σ/σ_{SM} 95% CL limits	BSM (excluded phase space)	PAS
bbbb	342 (308)	-	CMS-PAS-HIG-16-026
bblvlv	79 (89)	-	CMS-PAS-HIG-17-006
bbττ	28 (25)	K_λ (<-18;>26) with k_t =1.	CMS-PAS-HIG-17-002*
bbγγ	19 (17)	K_λ (<-8;>15) with k_t =1. K_t>=2 if K_λ=1.	CMS-PAS-HIG-17-008

2.3 fb^{-1} 35.9 fb^{-1}

* just submitted to arxiv.

From combination of 8 TeV results (arXiv:1707.00350):
non-resonant SM observed (expected) σ/σ_{SM} 95% CL limits = 43.

[1] LHCHXSWG Yellow Report 4

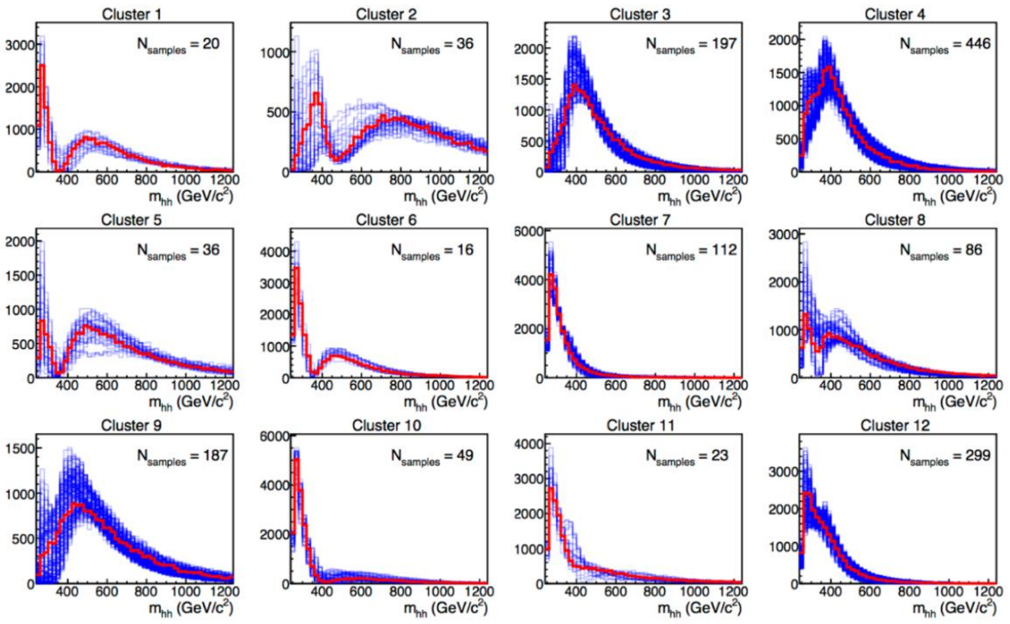
Results - Summary

NEW

NON-RESONANT

BSM, 5 parameters phase space: k_λ k_T C_2 C_g C_{2g}

12 shape benchmarks:



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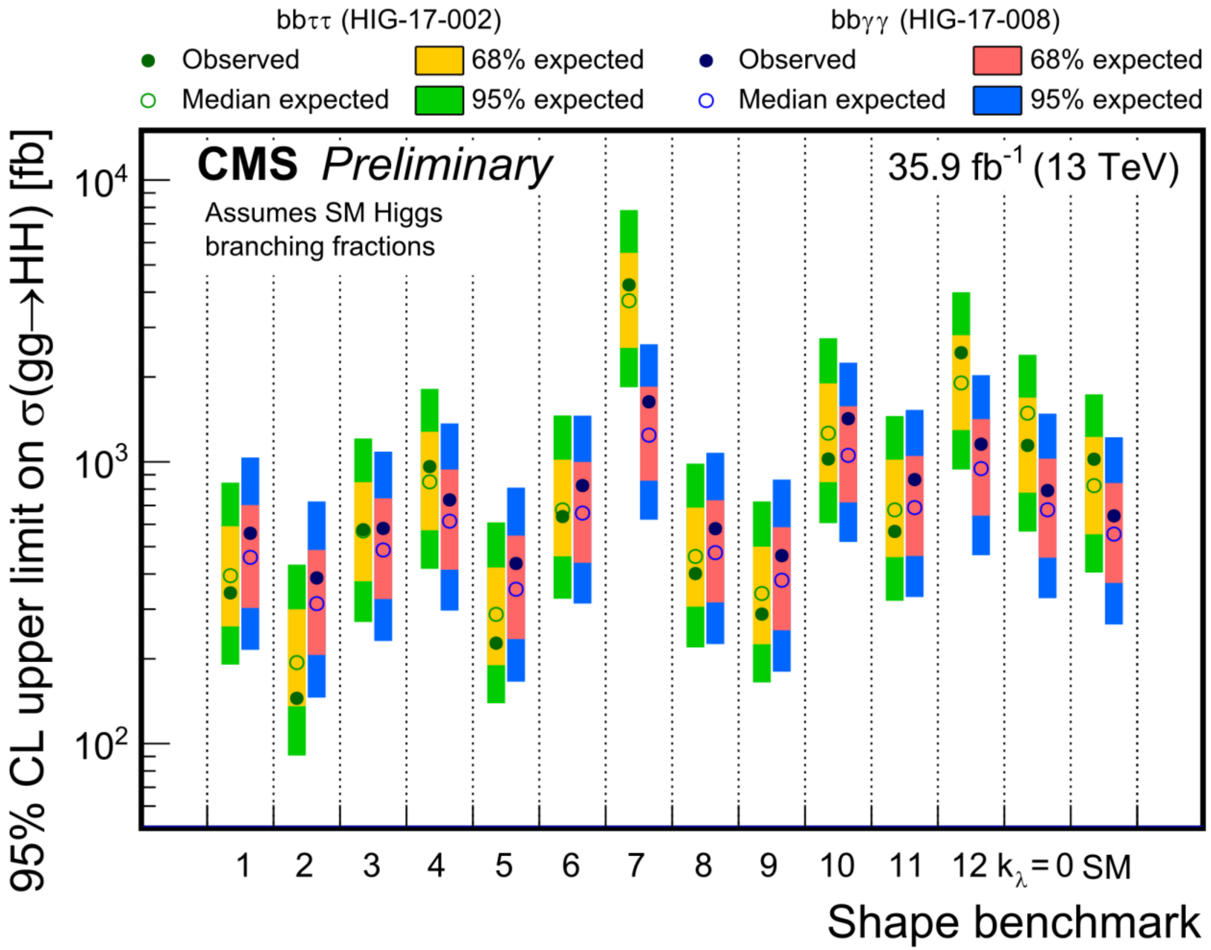


Conclusions

LHC Run 2 (2016 data):

- **Searches on all main decay channels but bbbb, performed on 2016 data**.
  Analysis technique improved with a impressive increments in sensitivity wrt 2015.
- **No signal excess** in searches for resonant production.
  Mass ranges excluded for Radion, KK-Graviton and MSSM hypothesis.
- Non-resonant SM process still not accessible but upper limit set.
  Best constraints obtained from bbγγ and bbττ (**~20 times SM expectation**).
- No evidence of signal with variation of Higgs couplings wrt SM values.
  k_t = 2 excluded with **k_λ = 1** hypothesis.

Prospects:

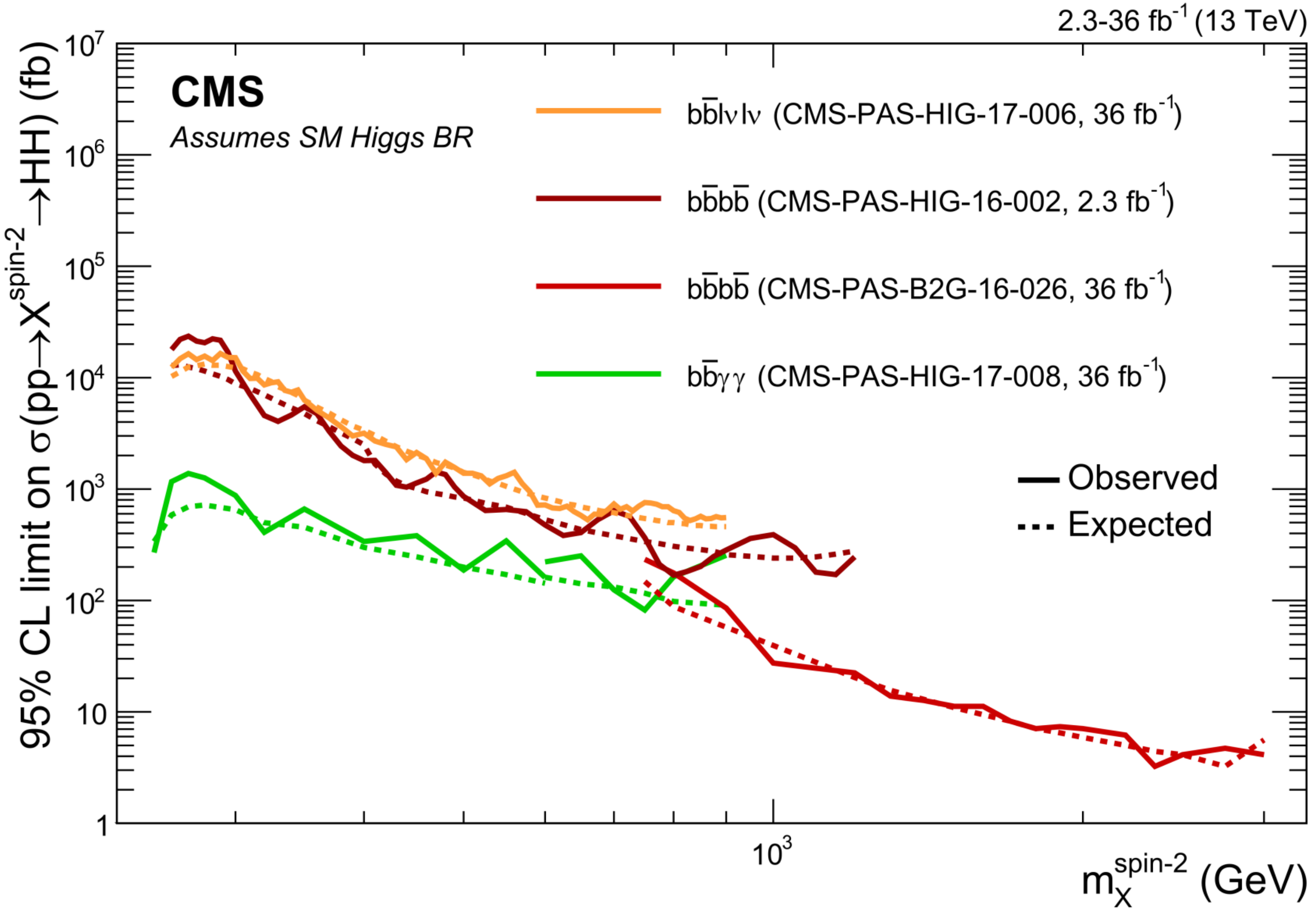
- Update searches in bbbb channel
- Extend searches on other decay channels
- Combination of all the channels and further studies on BSM with non-resonant HH

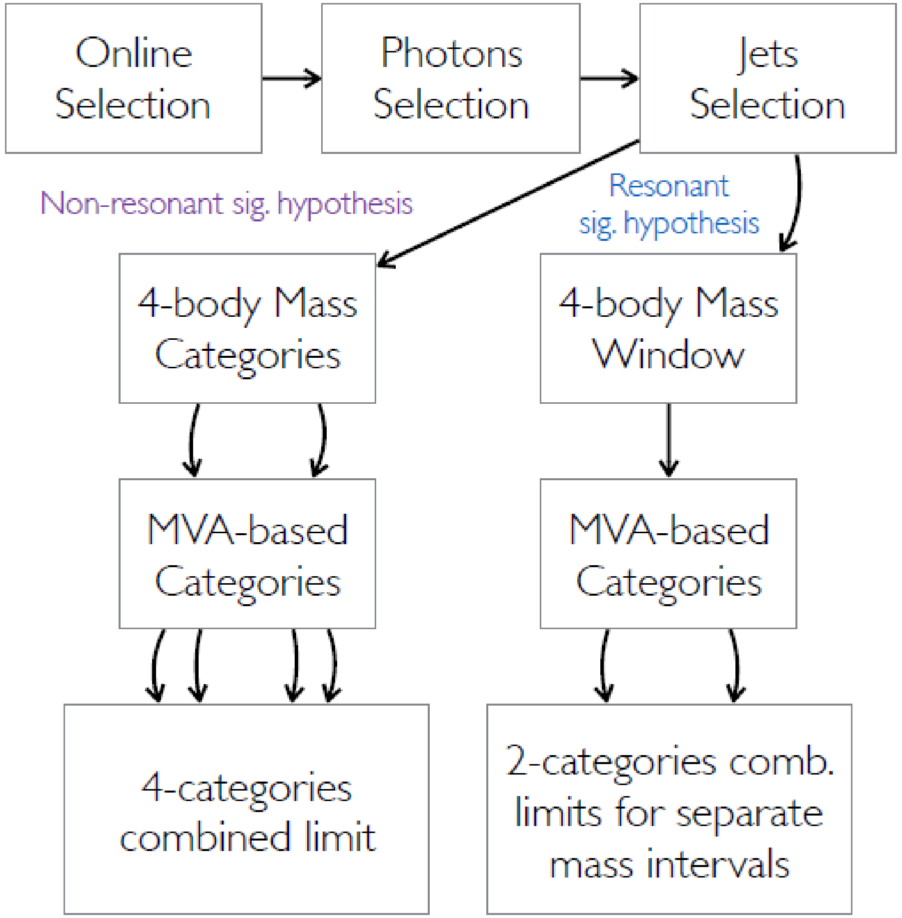
Additional Material

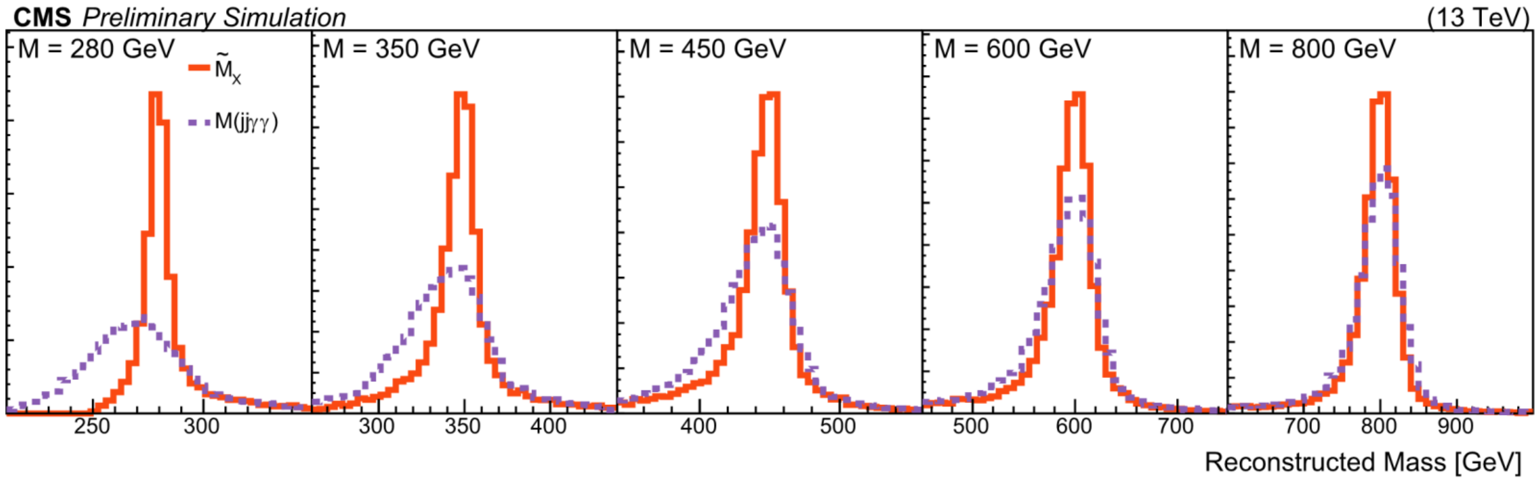
Results - Summary

NEW

RESONANT

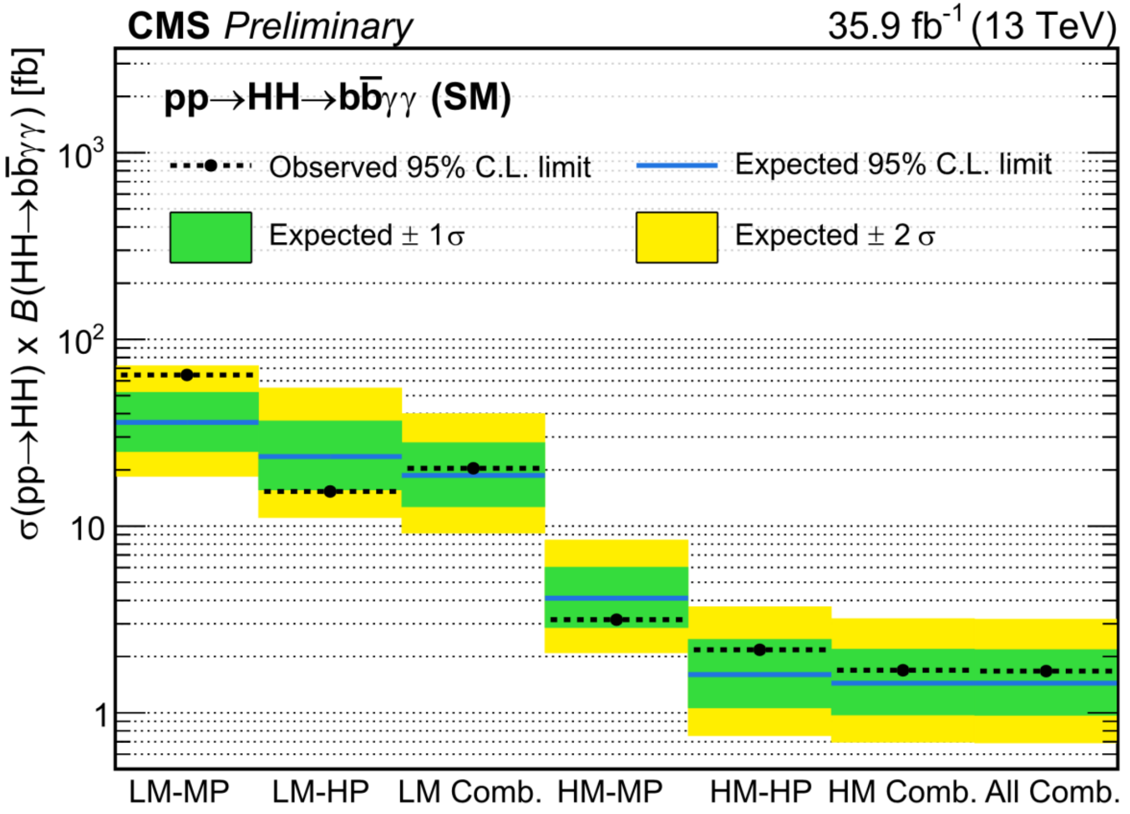


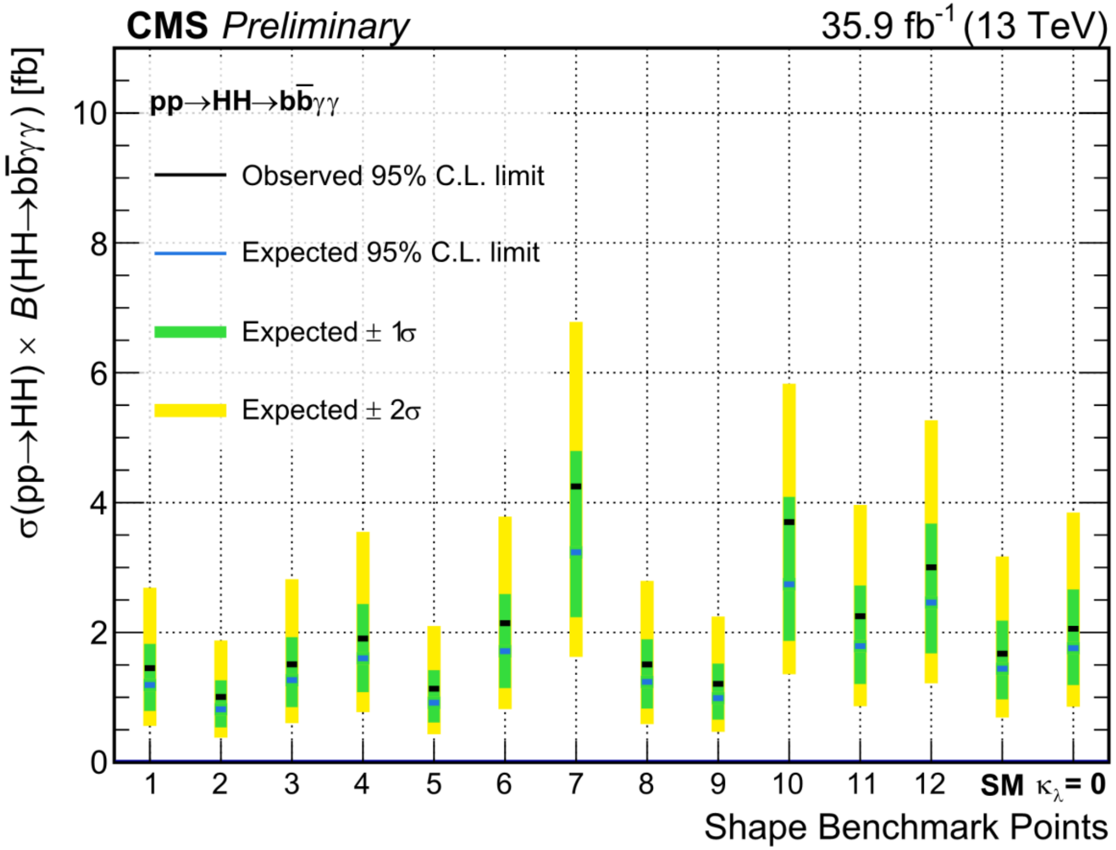




$$\tilde{M}_X = M(jj\gamma\gamma) - M(jj) - M(\gamma\gamma) + 250$$

Analysis	Region	MVA Categorization
Nonresonant	High mass	HPC: MVA > 0.97
		MPC: 0.6 < MVA < 0.97
	Low mass	HPC: MVA > 0.985
		MPC: 0.6 < MVA < 0.985
Resonant	High mass	HPC: MVA > 0.5
		MPC: 0 < MVA < 0.5
	Low mass	HPC: MVA > 0.96
		MPC: 0.7 < MVA < 0.96


CMS Preliminary
35.9 fb-1 (13 TeV)
pp→HH→bb̄γγ (SM)
Observed 95% C.L. limit
Expected 95% C.L. limit
Expected ± 1σ
Expected ± 2 σ
σ(pp→HH) x B(HH→bb̄γγ) [fb]
LM-MP
LM-HP
LM Comb.
HM-MP
HM-HP
HM Comb.
All Comb.


CMS Preliminary
35.9 fb-1 (13 TeV)
pp→HH→bb̄γγ
Observed 95% C.L. limit
Expected 95% C.L. limit
Expected ± 1σ
Expected ± 2σ
σ(pp→HH) × B(HH→bb̄γγ) [fb]
SM
κλ = 0
Shape Benchmark Points

HH → bbbb

RESONANT – BOOSTED TOPOLOGY

CMS-PAS-B2G-16-026

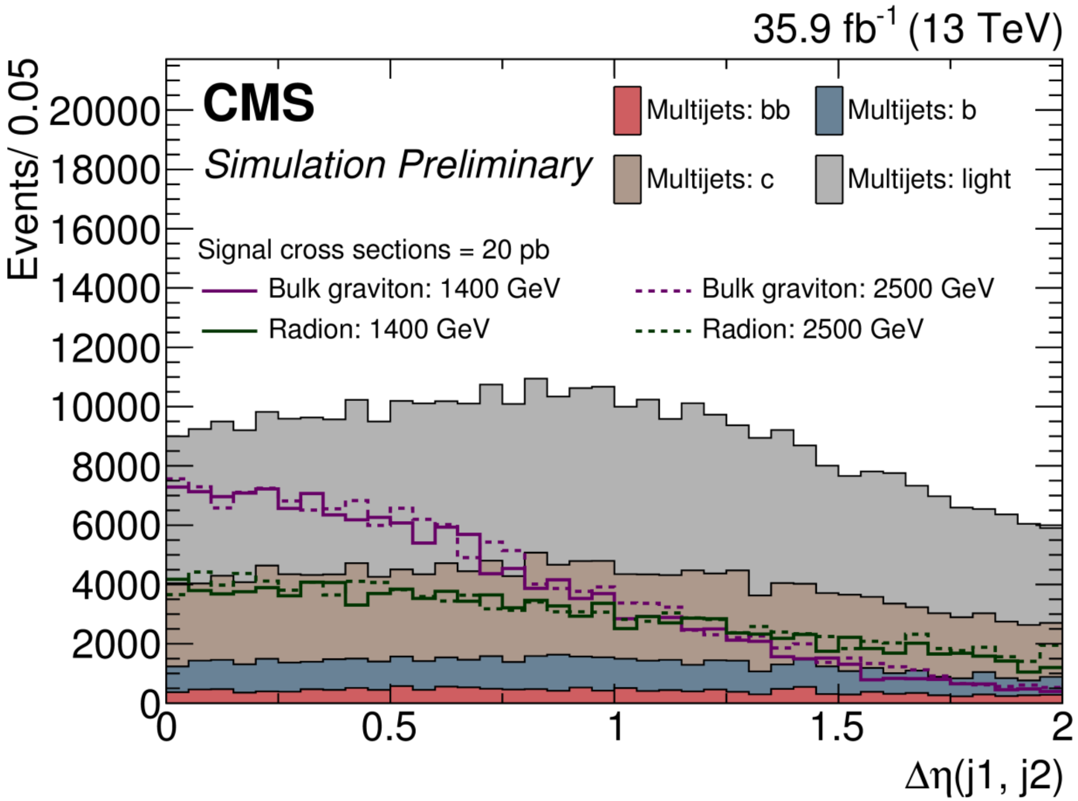


Table 1: Comparison of expected and observed limits on the production cross section of a resonance decaying to HH for the bulk graviton and the radion signal hypotheses, for different values of the resonance mass. The limits for masses below 1200 GeV are obtained using the "Alphabet" background estimation method, while those above, using the "AABH" method described in Section 4.

Resonance Mass	Radion		Bulk graviton	
(GeV)	Expected (fb)	Observed (fb)	Expected (fb)	Observed (fb)
750	81.6	125.9	50.2	79.4
800	46.4	90.4	29.9	59.9
900	29.8	44.0	19.5	29.0
1000	20.4	14.2	13.4	9.3
1200	10.4	11.4	6.9	7.6
1400	6.3	6.0	4.4	4.3
1600	4.7	5.5	3.2	3.8
1800	3.8	3.8	2.4	2.4
2000	3.0	3.5	2.0	2.4
2500	2.0	1.7	1.4	1.4
3000	2.3	1.6	1.9	1.4

HH → bblνlν

CMS-PAS-HIG-17-006

RESONANT | **NON-RESONANT**