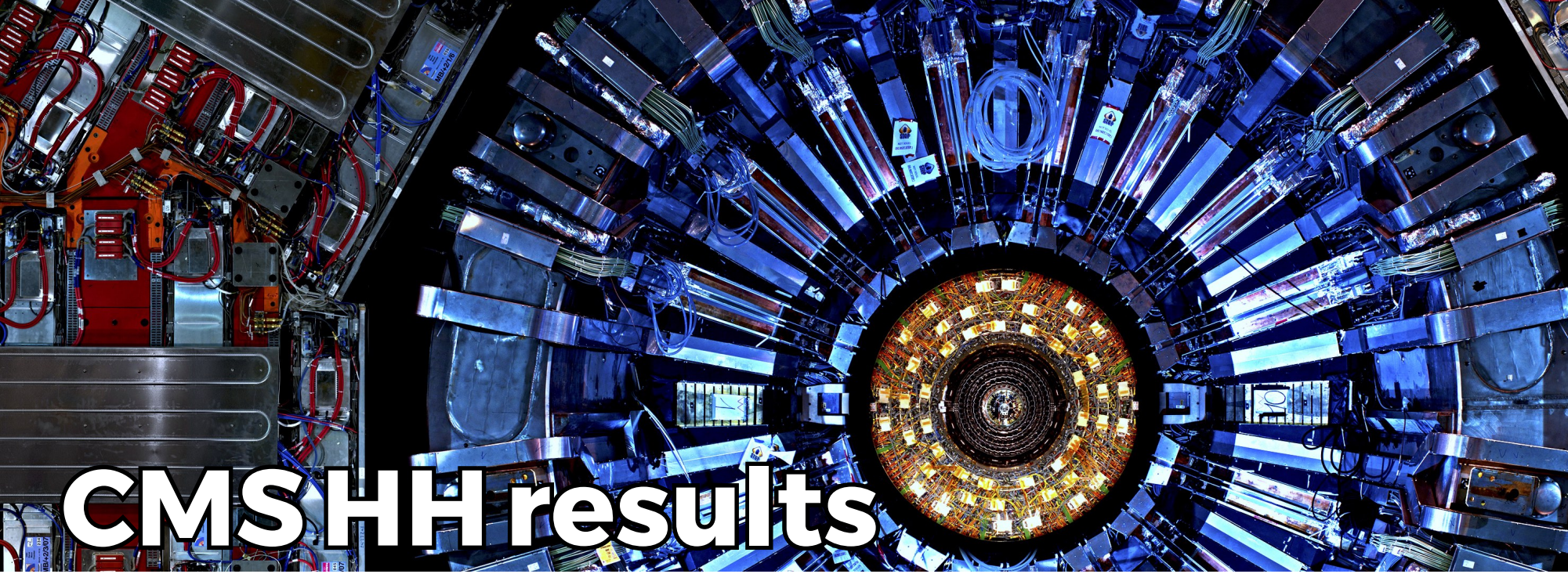


CMS HH results

Chiara Amendola

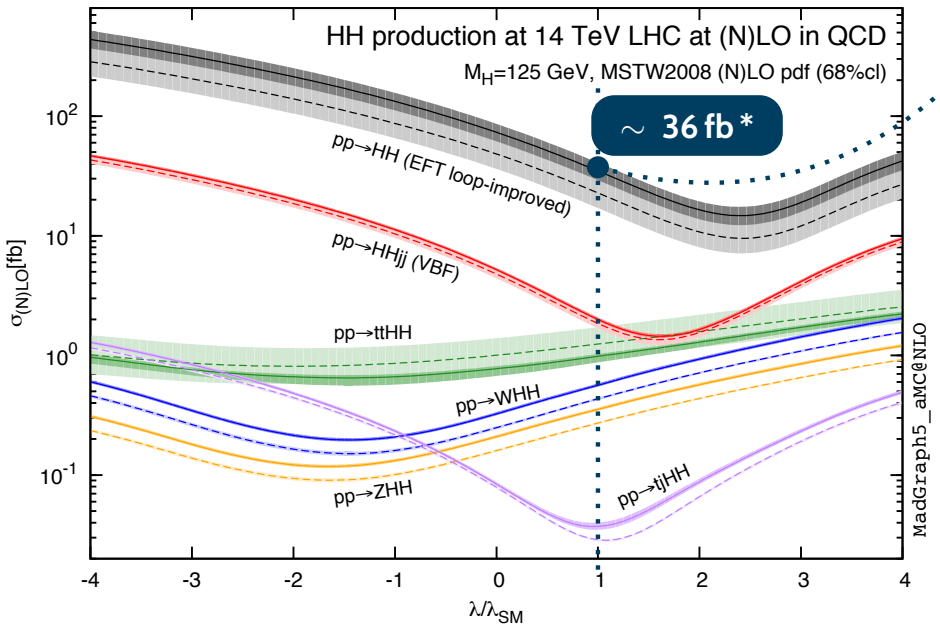
Laboratoire Leprince-Ringuet
École polytechnique

on behalf of the CMS Collaboration

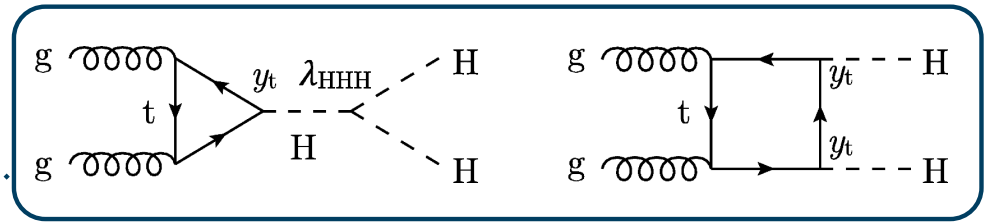
Higgs Hunting
July 30, 2019

Non-resonant HH production

- Unique probe of the B.E.H. mechanism
  - provides access to the measurement of the Higgs self-coupling λ
  - brings information on the shape of the Higgs potential



Gluon Fusion (ggF) dominant production mode



- Process predicted by the SM
- BSM effects can result in anomalous couplings: λ, y_t + 3 contact interactions (EFT approach)

Small variation
of the couplings from the prediction

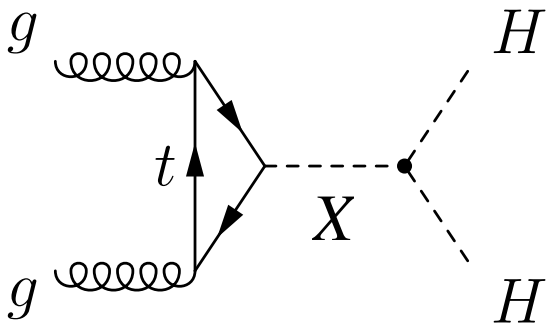
Large modification
of the cross section

e.g. $\delta k_\lambda = 1 \rightarrow \sigma_{ggF}^{BSM}/\sigma_{ggF}^{SM} \sim 20$

*State-of-the-art NNLO prediction of ggF cross section at 13 TeV: $31.05^{+2.2\%}_{-5.0\%}$ fb JHEP 05 (2018) 059
In the 2016 analyses, $\sigma_{ggF}(13TeV) = 33.49^{+4.3\%}_{-6.0\%}$ fb is used 10.23731/CYRM-2017-002

Resonant HH production

Look for a **new narrow resonance X** with mass $m_X > 2m_H$



- Not predicted in the SM, but in several extensions
- Different theoretical scenarios, but similar signature
- CP-even spin-0 or spin-2 particles predicted
- Need to cover a wide mass range:

MSSM/2HDM	250 to 350 GeV	Phys. Rep. 516 (2012) 1
Singlet Model	250 GeV to 1 TeV	J. Z Phys C 75 (1997) 17
Warped Extra Dimensions	250 GeV to 3 TeV	Phys. Rev. Lett. 83, 3370

Final states

NEW! = new paper since HiggsHunting2018

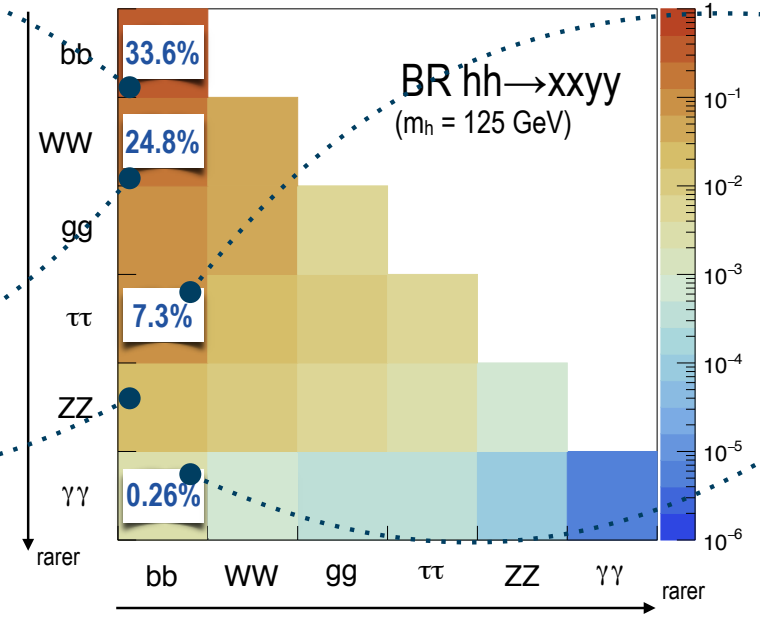
Rich set of final states accessible at the LHC
2016 (35.9 fb^{-1}) CMS public analyses:

bbbb
largest BR, large QCD and $t\bar{t}$ contamination

(non-res) JHEP04 (2019) 112 NEW!
JHEP01 (2019) 040 NEW!
(res) JHEP08 (2018) 152 NEW!
PLB 781 (2018) 244

bbVV
large $t\bar{t}$ contamination, $BR(2\ell 2\nu) = 2.7\%$

JHEP 01 (2018) 054
bbZZ(2ℓ2j) CMS PAS HIG-18-013 NEW!



bbττ
good **compromise** between BR and purity

PLB 778 (2018) 101
JHEP 1901 (2019) 051 NEW!

bbγγ
low branching ratio, high purity

PLB 788 (2019) 7 NEW!

- Trade-off between BR and purity
- coverage of different phase spaces
- different sensitivity in different mass ranges

→ **Combination of the 2016 analyses**
Phys. Rev. Lett. 122, 121803 NEW!

HH→bbbb (non-resonant)

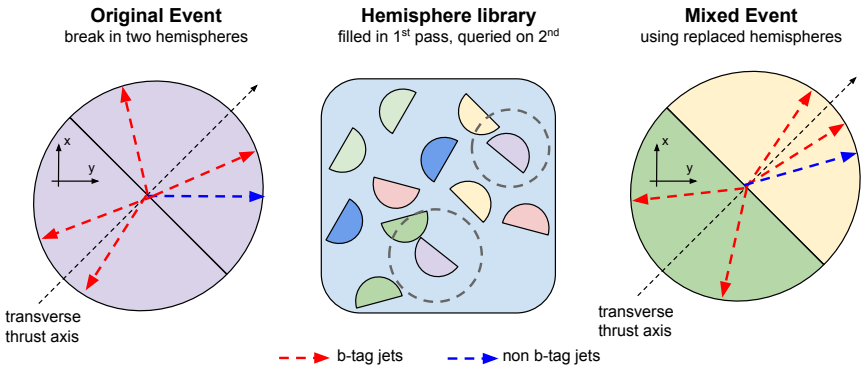
NEW! JHEP04 (2019) 112
NEW! JHEP01 (2019) 040

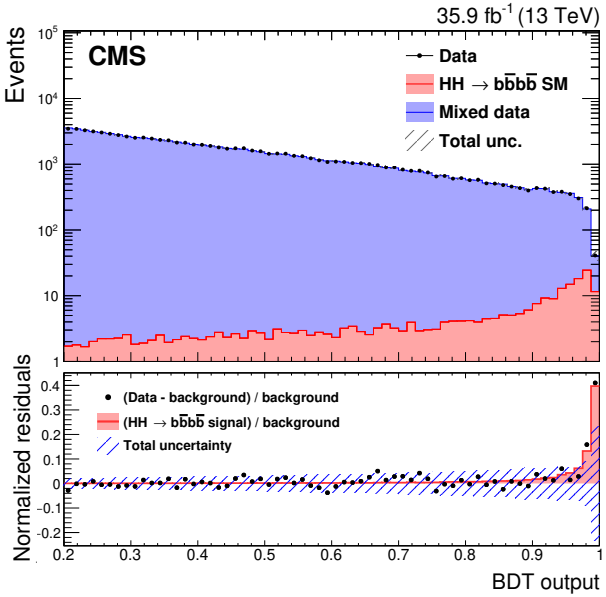
Two searches performed:

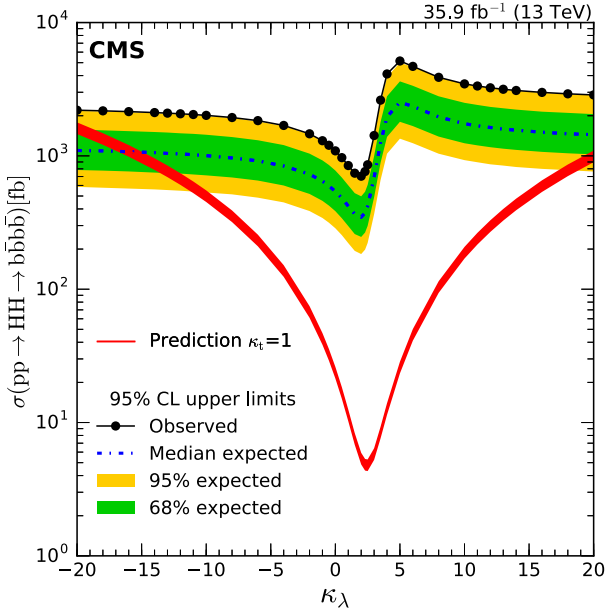
- 4 resolved b-tagged jets (best sensitivity to SM), results shown here
- one bb pair highly boosted (sensitive to specific BSM topologies)

Main challenge: QCD background contamination

- b-tag is crucial, used from trigger level (3 bjets)
- BDT technique optimised for SM HH signal
- Dedicated data-driven method for QCD estimation: hemisphere mixing
- Signal extraction from BDT output





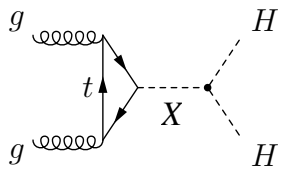


Limits

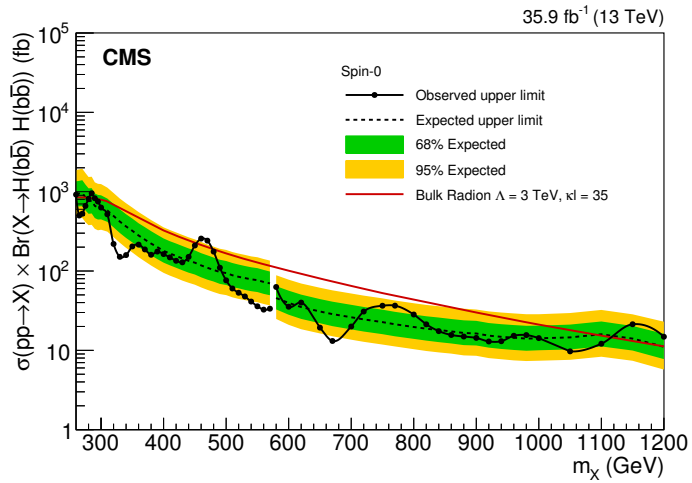
SM obs (exp): 75 (37)$\times\sigma_{SM}$

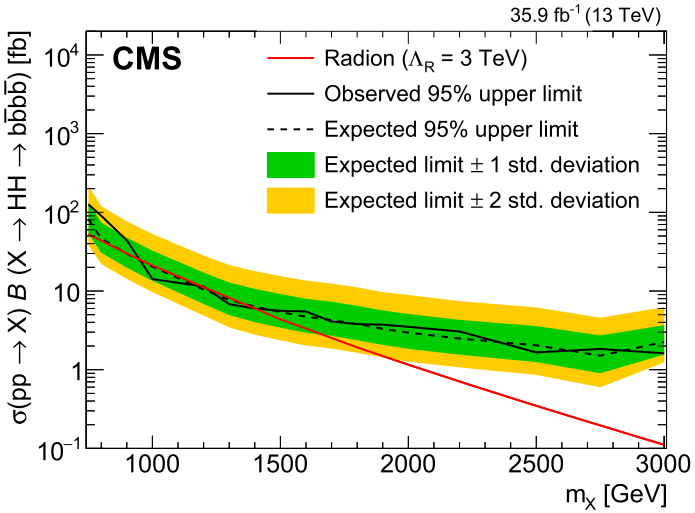
$k_\lambda = \lambda/\lambda_{SM}$ ($k_t = 1$) scan: no exclusion

HH→bbbb (resonant)



NEW! JHEP08 (2018) 152
PLB 781 (2018) 244





Low mass Resolved

- At least 3 b-tagged jets
- Data-driven QCD estimation from sidebands of Higgs candidates masses

High mass Boosted + Semi-boosted

- 2 large-area jets or 1 large-area jet + 2 jets, passing b-tag or double-b discriminator
- QCD background measured from sidebands of large-area jet mass and double-b discriminator

Excluded mass ranges

Radion: 260-280 GeV; 300-450 GeV; 480-1120 GeV; no exclusion in high mass region

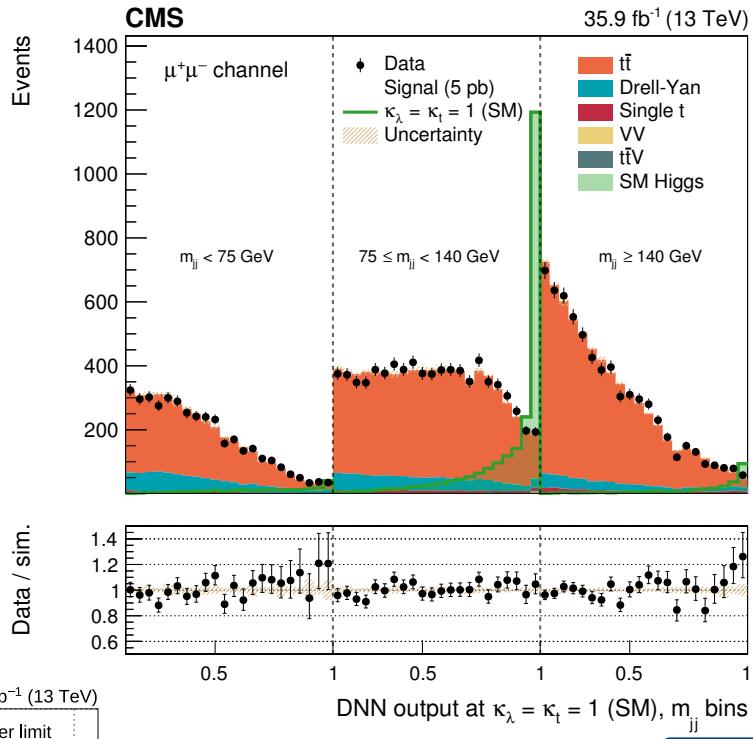
Graviton: 320-450 GeV; 480-720 GeV; no exclusion in high mass region (backup)

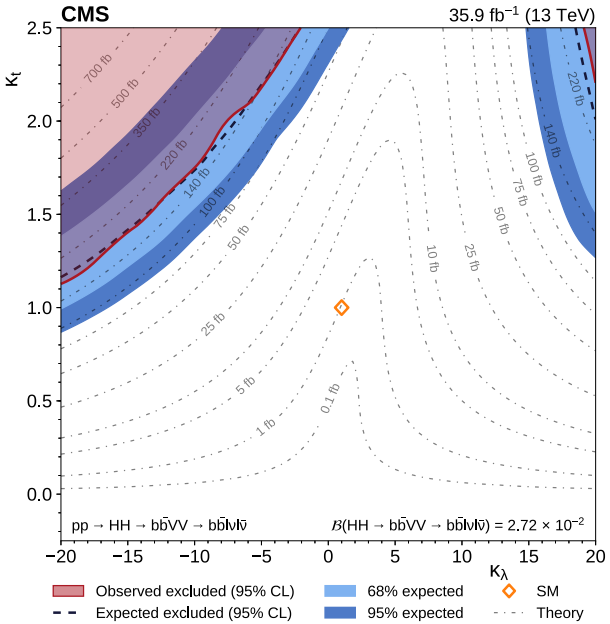
HH→bbVV

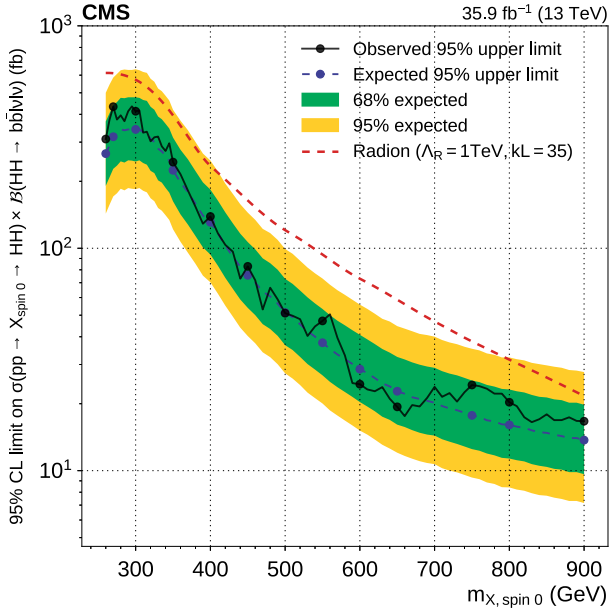
JHEP 01 (2018) 054

Resonant and non-resonant searches performed

- Event categories: bbee, bbμμ, bbeμ
- Dominant backgrounds: tt (irreducible), DY
  - Data-driven DY estimation
- DNN to improve signal-background separation
  - Output used as final discriminant







Limits

SM obs (exp): 79 (89)$\times\sigma_{SM}$

k_λ-k_t scan performed

No exclusion on Radion nor Graviton mass

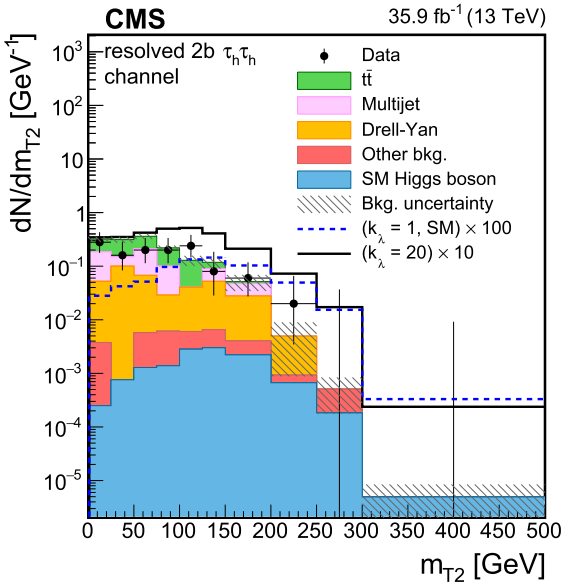
Also public: bbZZ(2ℓ2j) CMS PAS HIG-18-013 NEW!

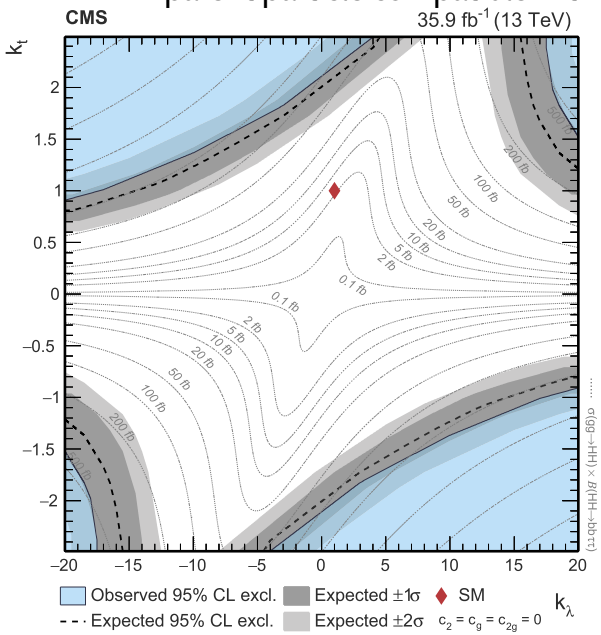
HH→bbττ

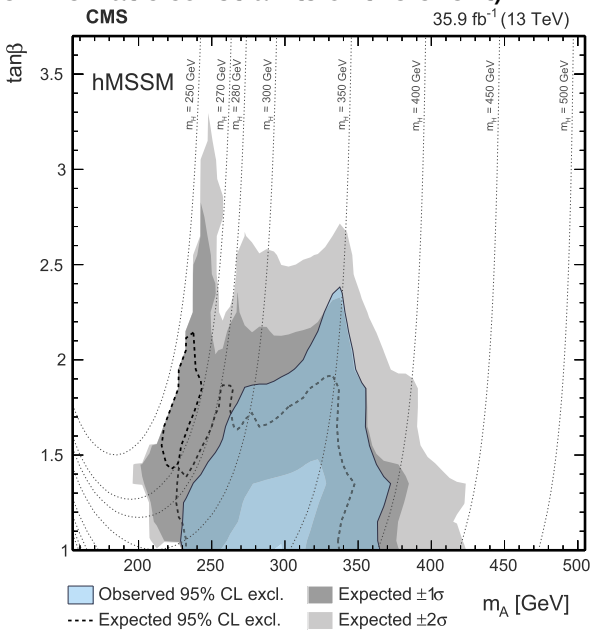
PLB 778 (2018) 101

Comprehensive set of results on resonant and non-resonant searches

- Final states: ($e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$) + 2 jets
- Categorisation on number (1/2) of b-tagged jets
  - Boosted category: only 1 b-tagged large-area jet + substructure requirements
- BDT technique to reject tt background in $e\tau_h$, $\mu\tau_h$ channels
- Signal extraction from kinematic variables:
  - Resonant search: kinematic fit of HH decay (fit based on 4-momenta of the τ and b candidates and on $\vec{p}_T^{miss}$)
  - Non-resonant search: "stransverse mass" MT2 (largest mass of the parent particle compatible with the kinematic constraints of the event)







Limits

SM obs (exp): 31 (25)$\times\sigma_{SM}$

k_λ-k_t scan performed

Additional hMSSM interpretation

No exclusion on Radion nor Graviton mass

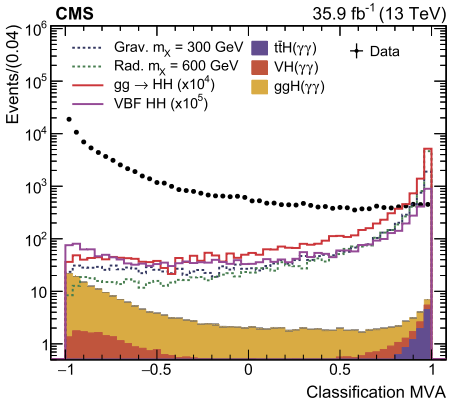
HH→bbγγ

NEW! PLB 788 (2019) 7

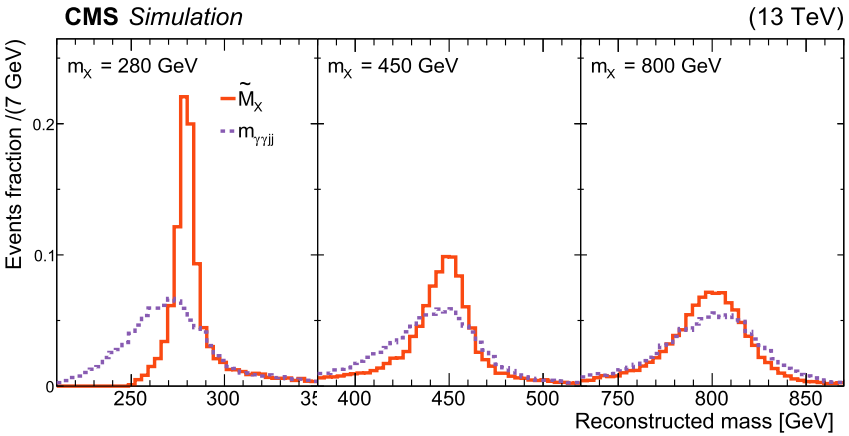
Resonant and non-resonant searches performed: most sensitive channel to SM HH

- Main backgrounds: nγ+jets, single-H
- Categorisation in MVA and reduced mass:

$$M_X = m_{\gamma\gamma bb} - (m_{bb} - m_H) - (m_{\gamma\gamma} - m_H)$$

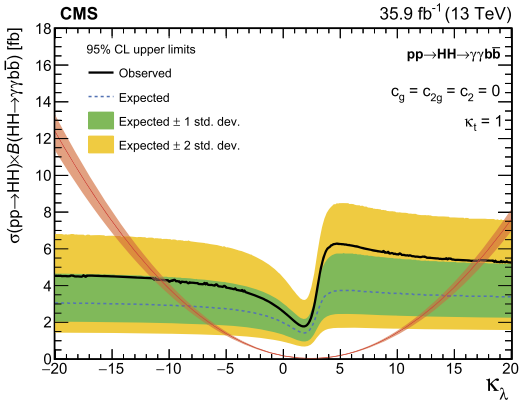


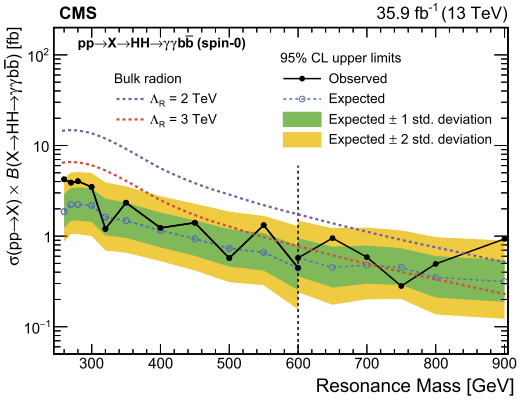
- MVA to efficiently discriminate against nγ+jets
- Striking improvement at low mass using M_X



Signal extraction through 2D likelihood $m_{\gamma\gamma} \times m_{bb}$

- 10% improvement w.r.t. 1D fit on $m_{\gamma\gamma}$: better discrimination against single-H





Limits

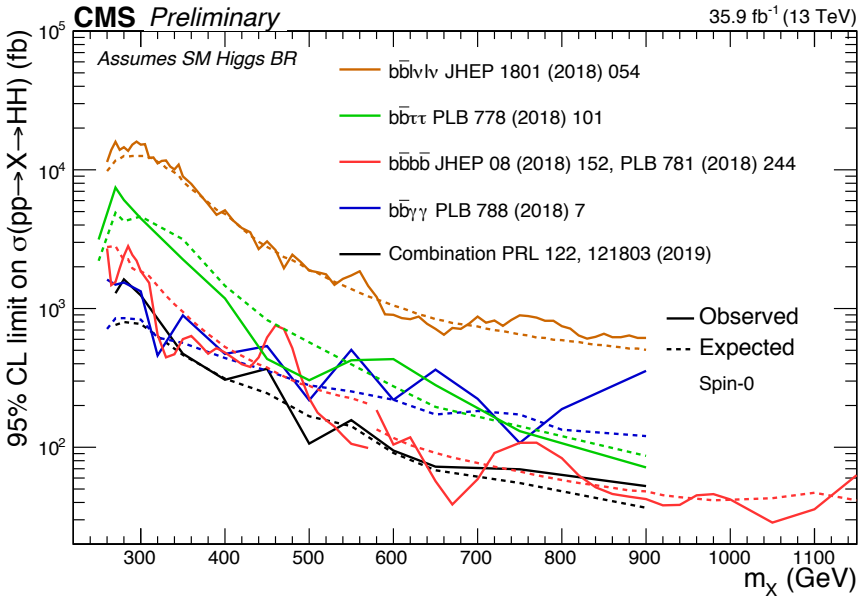
SM obs (exp): 24 (19)$\times\sigma_{SM}$
(VBF HH signal inclusion improves sensitivity by 1.3%)

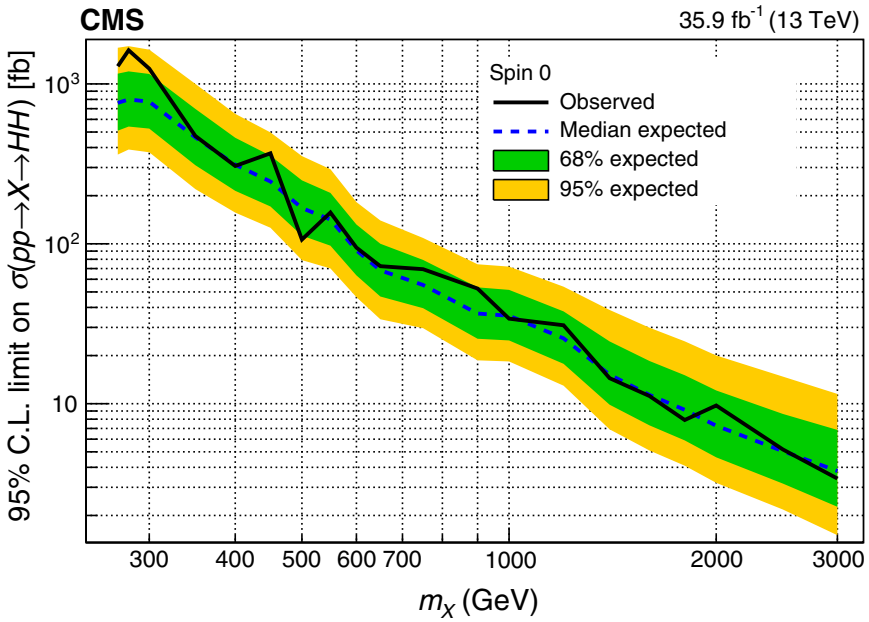
Constrained λ to $-11 < k_\lambda < 17$

Radion (Λ_R = 3 TeV): excluded $m_X < 540$ GeV
Graviton: excluded $290 < m_X < 810$ GeV (backup)

Combination: resonant searches

Different sensitivities in different regions



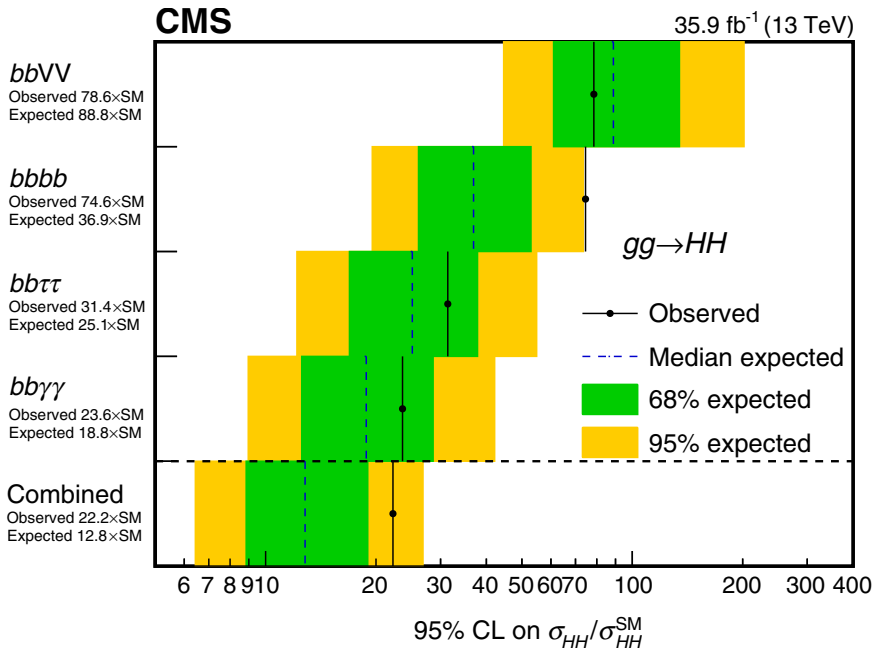


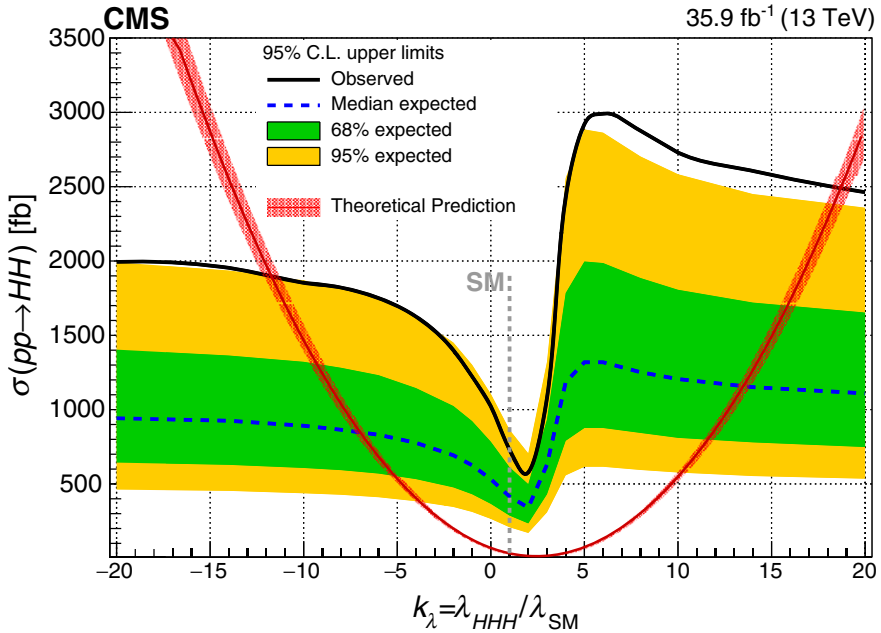
NEW! Phys. Rev. Lett. 122, 121803

- Limits also set for spin-2 hypothesis
- No significant excess observed

Combination: non-resonant production

NEW! Phys. Rev. Lett. 122, 121803





SM combined limit: 22 (13)$\times\sigma_{SM}$

- Run I combination obs (exp) limit: 43 (46)$\times\sigma_{SM}$

BSM obs (exp) constraints:

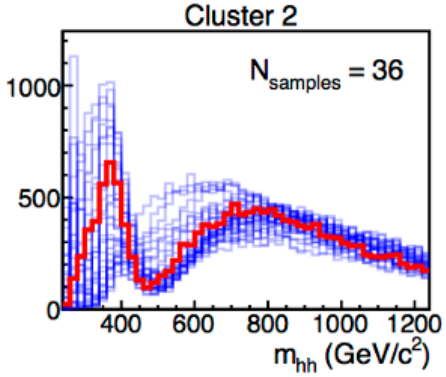
$$-11.8 < k_\lambda < 18.8 \; (-7.1 < k_\lambda < 13.6)$$

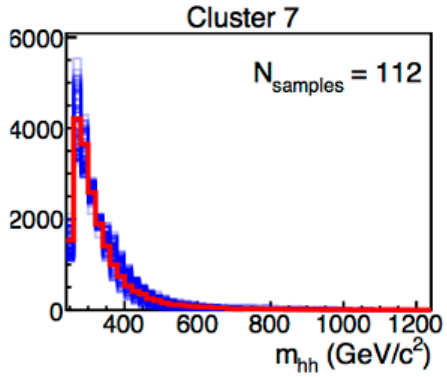
BSM benchmarks

NEW! Phys. Rev. Lett. 122, 121803

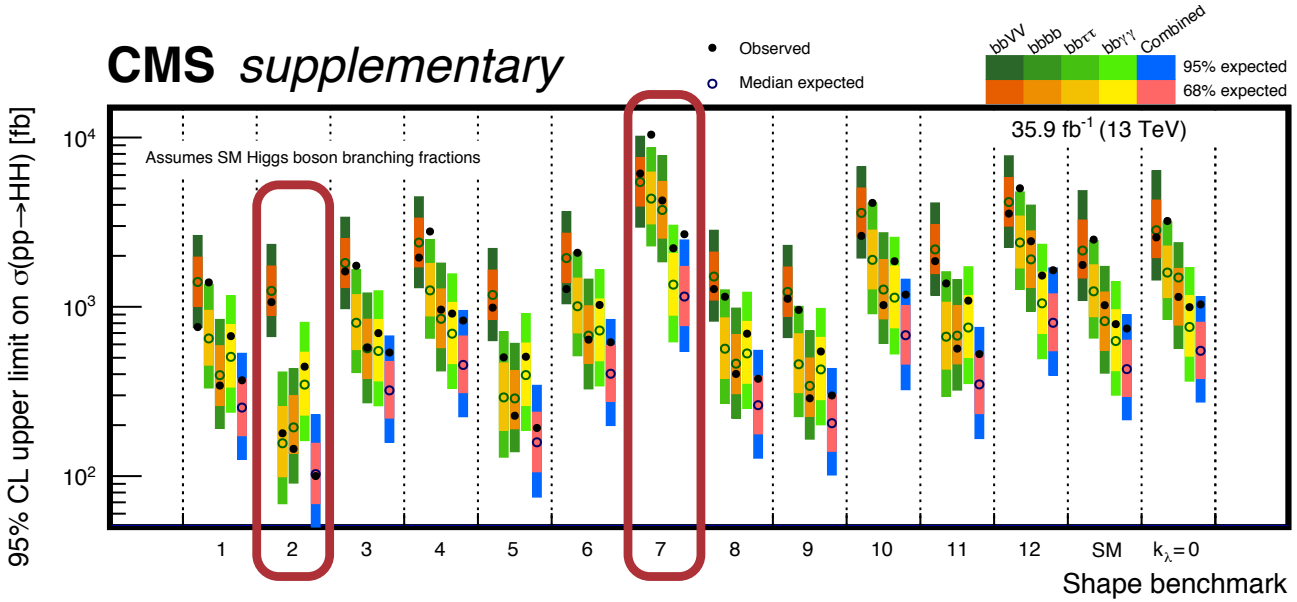
Producing samples for all the combinations of couplings would be computationally prohibitive

➡ Anomalous couplings clustering strategy used in all analyses: JHEP 04 (2016) 126
Parameter space divided into 12 regions (+ SM + $\lambda = 0$ scenarios) with similar kinematics





Benchmark	k_λ	k_t	c_2	c_g	c_{2g}
2	1.0	1.0	0.5	-0.8	0.6
7	5.0	1.0	0.0	0.2	-0.2



Complementary sensitivity of all analyses

The hierarchy of the analyses sensitivity is different in different BSM scenarios

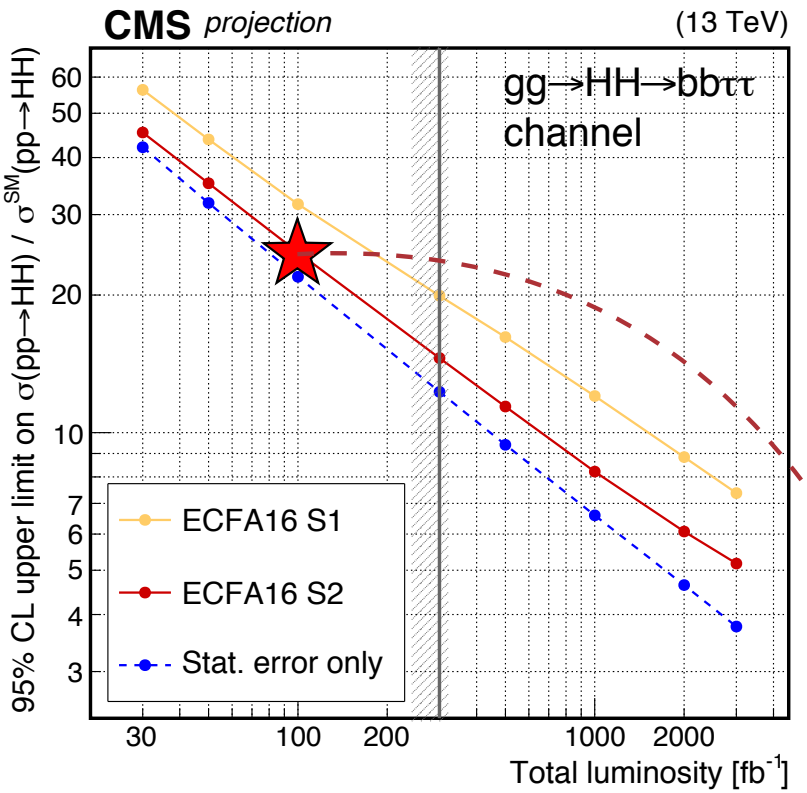
Perspectives for HH searches

- Getting closer to the observation of SM Higgs pair production:

$$22\ (13) \times \sigma_{SM} \text{ with } 35.9\ \text{fb}^{-1}$$

  - the single analyses are constantly improving
  - full Run II statistics: $\sim 150\ \text{fb}^{-1}$

Projection using 2015 data at 13 TeV



CMS PAS FTR-16-002

bbττ already overperformed the projected results

result: $25 \times \sigma_{SM}$ with $35.9\ \text{fb}^{-1}$

- projection: $25 \times \sigma_{SM}$ with $100\ \text{fb}^{-1}$

- Updated projections: CERN-LPCC-2018-04 **NEW!**
  CMS PAS FTR-18-019 **NEW!**

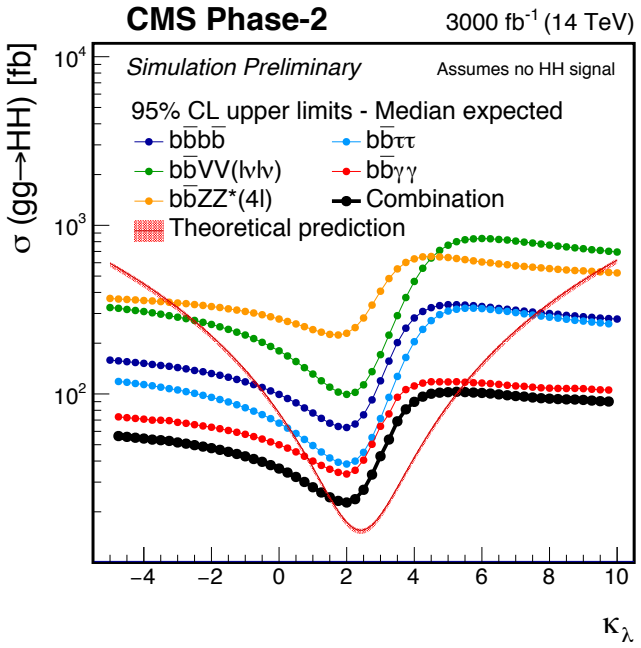
HL-LHC latest projections

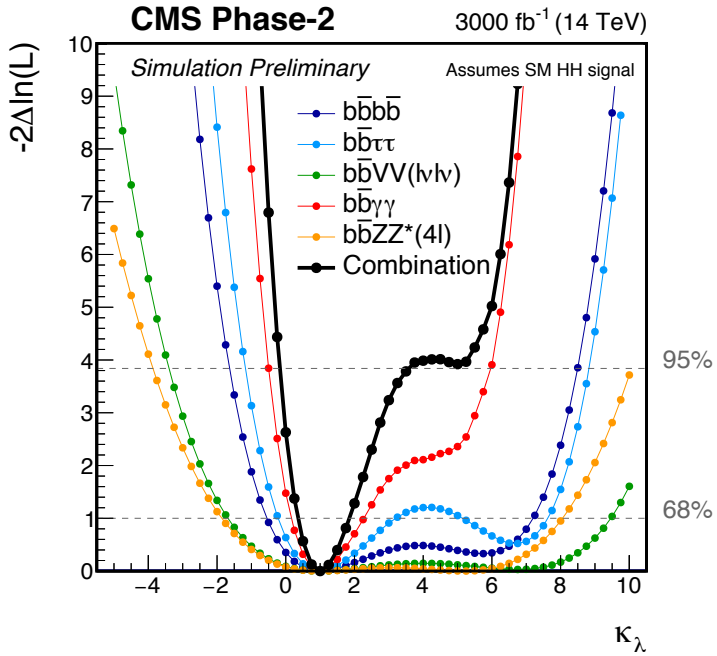
NEW! CMS PAS FTR-18-019

Projected sensitivity of the combination of the 4 existing analyses + rare but clean bbZZ(4ℓ)

- DELPHES fast parametric simulation: upgraded CMS response (see Elisa Fontanesi's talk in this conference)
- PU = 200, $\mathcal{L} = 3000$ fb^{-1}

Channel	Significance		95% CL limit on $\sigma_{HH}/\sigma_{HH}^{SM}$		2016 obs
	Stat. + syst.	Stat. only	Stat. + syst.	Stat. only	
bbbb	0.95	1.2	2.1	1.6	75
bb$\tau\tau$	1.4	1.6	1.4	1.3	31
bbWW($\ell\nu\ell\nu$)	0.56	0.59	3.5	3.3	79
bb$\gamma\gamma$	1.8	1.8	1.1	1.1	24
bbZZ($\ell\ell\ell\ell$)	0.37	0.37	6.6	6.5	–
Combination	2.6	2.8	0.77	0.71	22





Projected constraints on k_λ:

[0.35, 1.9] at 68% CL
[-0.18, 3.6] at 95% CL

HH searches are an excellent case for HL-LHC

Conclusion

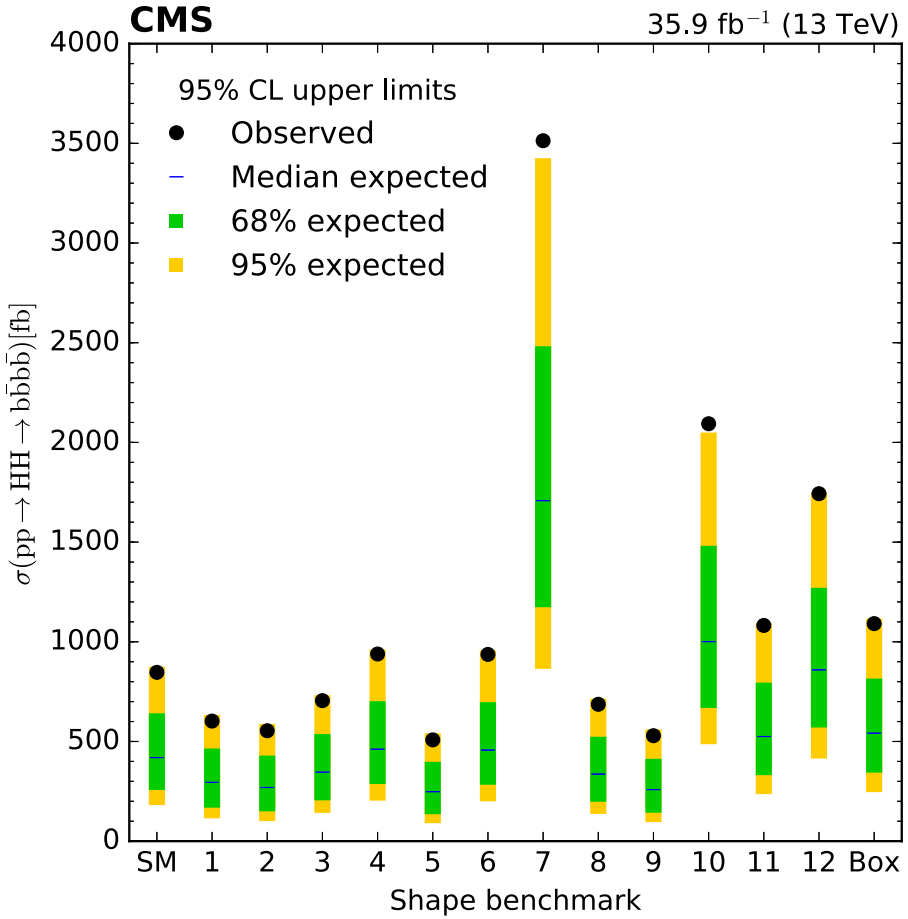
- Non-resonant and resonant Higgs pair production searches are performed in 4 different channels with 2016 data
- Different channels have different sensitivities
  - The combination of channels brings a significant improvement: obs (exp) 22 (13)$\times\sigma_{SM}$ with 35.9 fb^{-1}
- The 2016 analyses performed better than the pre-existing predictions!
  - Advanced analysis techniques not fully exploited yet (e.g. DNN)
  - The observation of the SM Higgs pair production is definitely within reach of HL-LHC

Backup

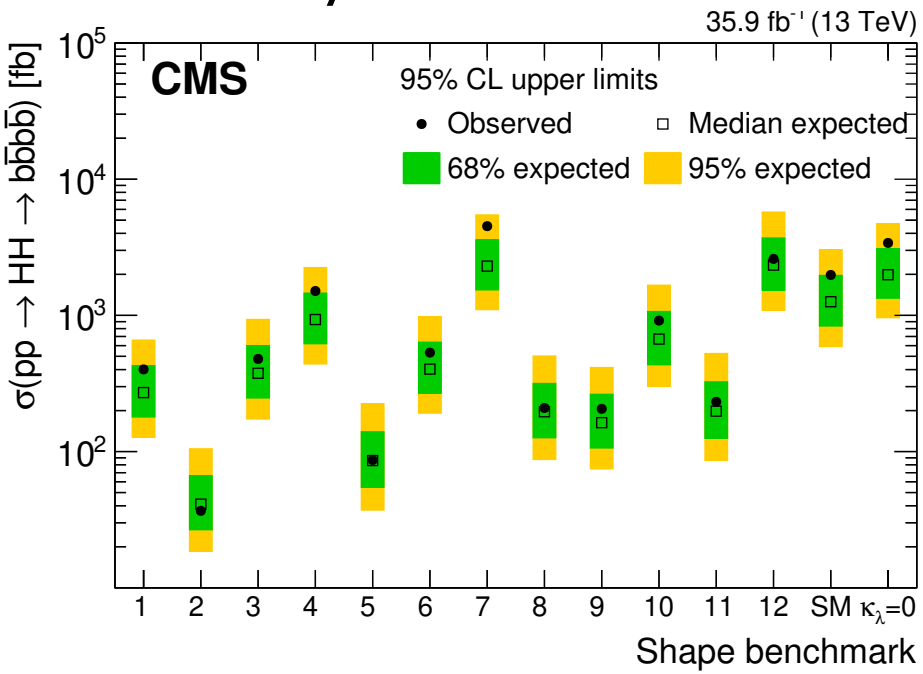
HH→bbbb (non-resonant)

NEW! JHEP04 (2019) 112
NEW! JHEP01 (2019) 040

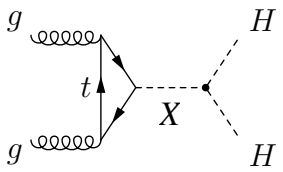
Resolved analysis



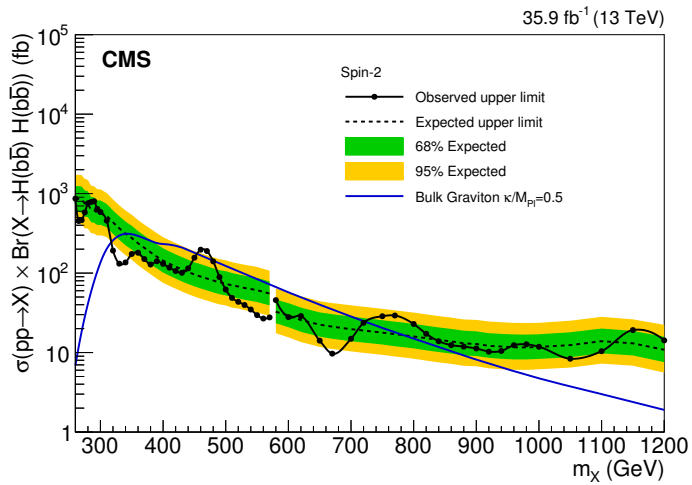
Boosted analysis

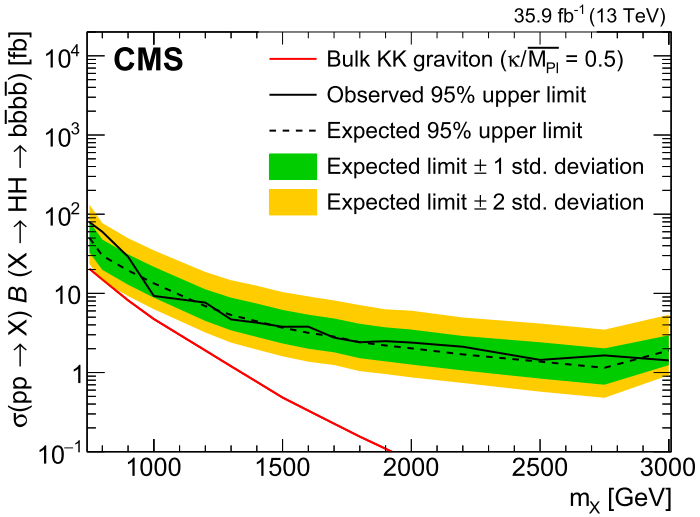


HH→bbbb (resonant)



NEW! JHEP08 (2018) 152
PLB 781 (2018) 244





Low mass Resolved

- At least 3 b-tagged jets
- Data-driven QCD estimation from sidebands of Higgs candidates masses

High mass Boosted + Semi-boosted

- 2 large-area jets or 1 large-area jet + 2 jets, passing b-tag or double-b discriminator
- QCD background measured from sidebands of AK8 jet mass and double-b discriminator

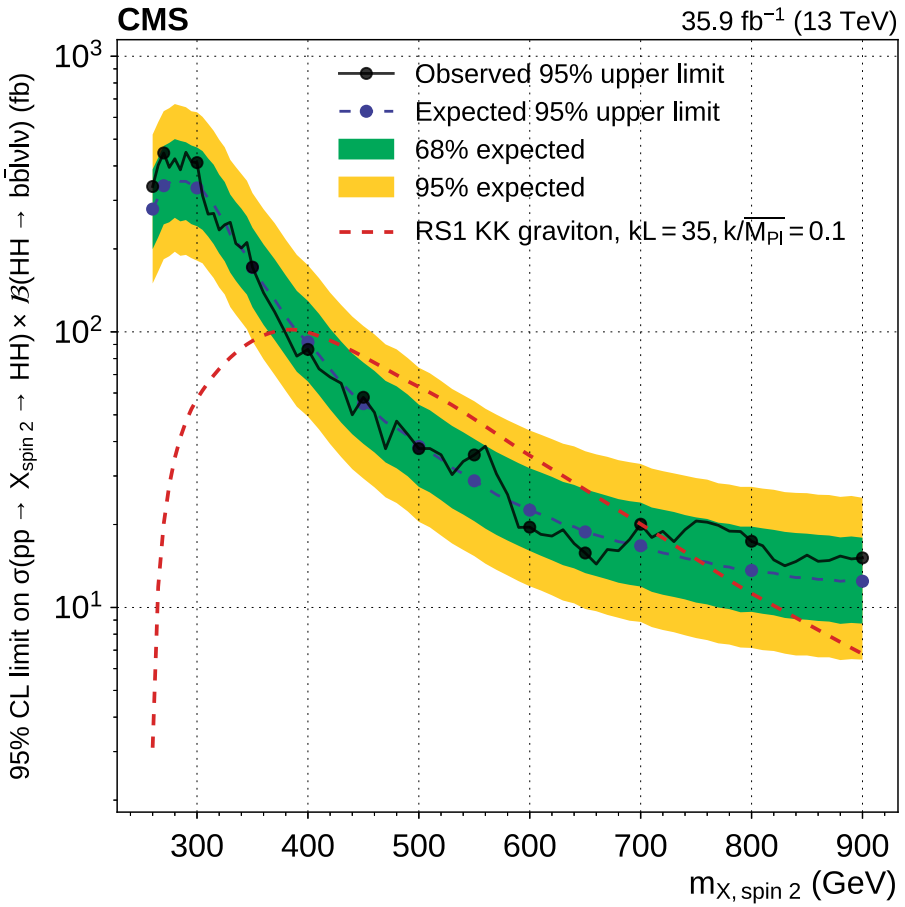
Excluded mass ranges

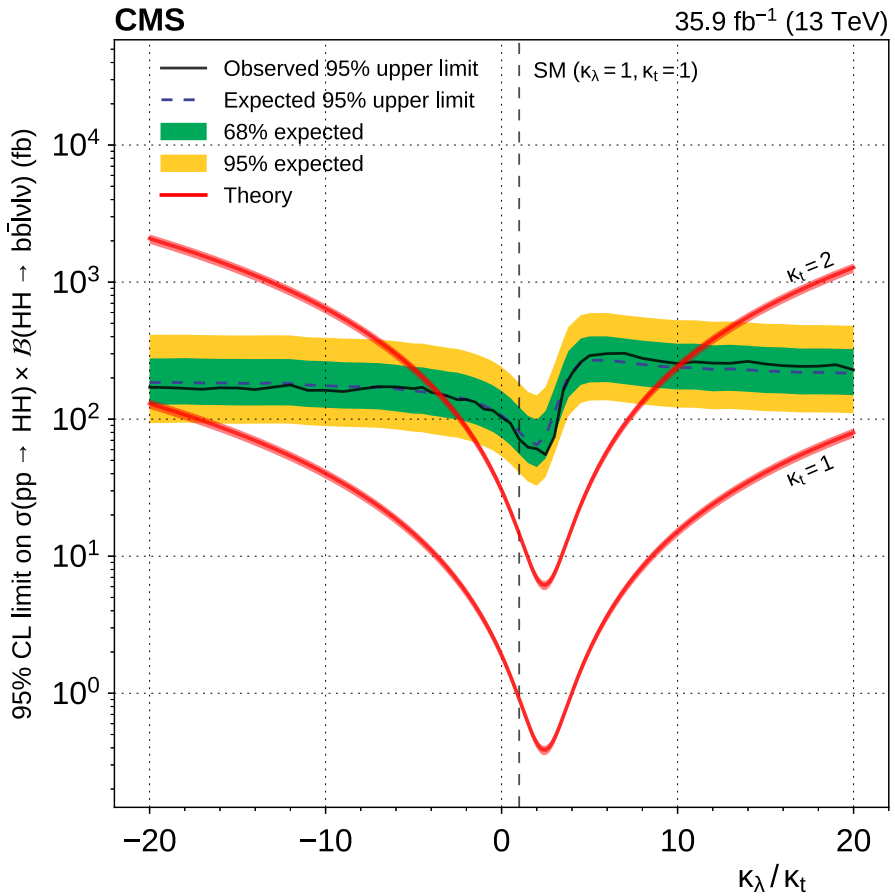
Radion: 260-280 GeV; 300-450 GeV; 480-1120 GeV; no exclusion in high mass region

Graviton: 320-450 GeV; 480-720 GeV; no exclusion in high mass region

HH→bbVV

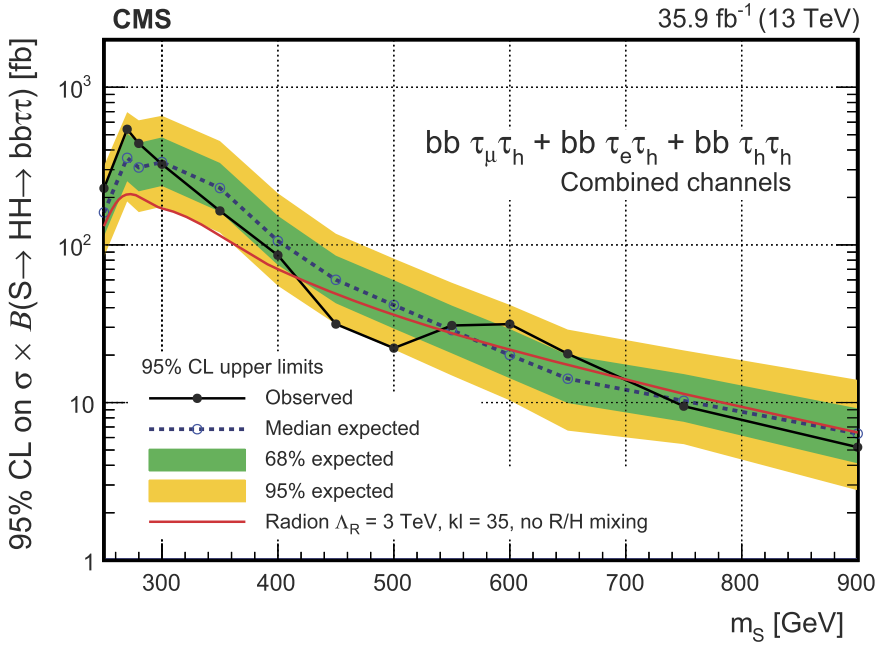
JHEP 01 (2018) 054

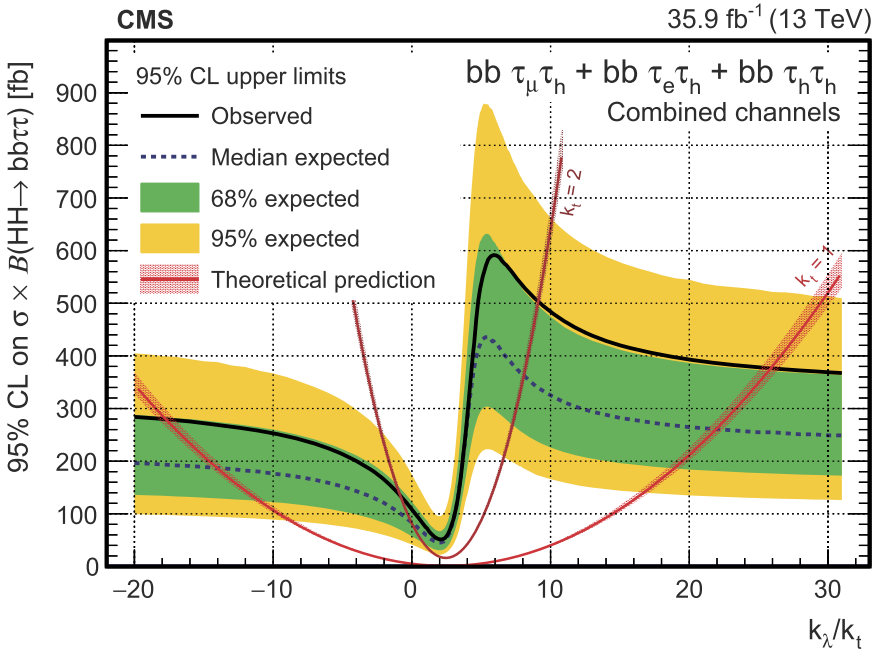




HH→bbττ

PLB 778 (2018) 101





HH→bbγγ

NEW! PLB 788 (2019) 7