Non-resonant Higgs boson pair production at CMS

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on behalf of the CMS collaboration

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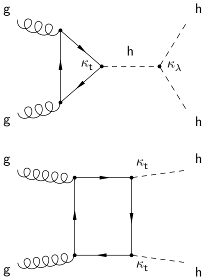
Motivation (1): access the scalar potential

hh production in the Standard Model

- **Direct access** to the **self-coupling λ**
  - SM scalar potential structure: $\mathcal{L}_h = \frac{1}{2}\partial_\mu h \partial^\mu h - \frac{1}{2}m_h^2 h^2 - \kappa_\lambda \lambda_{SM} v h^3 - \frac{m_t}{v}(v + \kappa_t h)(\bar{t}_L t_R + h.c.)$
- **Key property measurement** of h(125)
- Main production at LHC: **gluon fusion**



LHCHXSWG	$\sqrt{s}$ (TeV)	$\sigma_{NNLO+NNLL}$ (fb)
	8	10.16
m_h = 125 GeV	13	33.45
	14	39.56

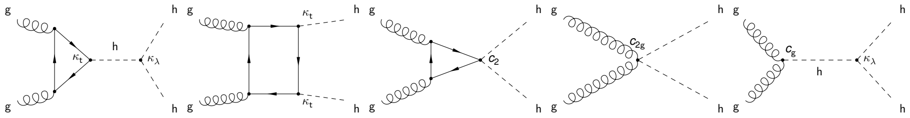
Major challenge: **very low production cross-section**

- Strong destructive interference of the two main diagrams
- By (lack of) chance, SM is almost the most destructive case...
- *Start* to be sensitive to SM at HL-LHC: **upgrade Strategy is decisive!**

Motivation (2): Effective Field Lagrangians

There is hope yet: we have some leeway...

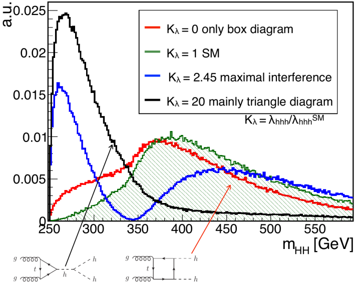
- Self-coupling λ predicted but (loosely) constrained experimentally
  - Experimental constraints of $O(n \times 10 - 100)$ on current data
- **There exists other couplings** in BSM scenarios:
  - $\kappa_\lambda = \lambda/\lambda_{\mathrm{SM}}$, $\kappa_{\mathrm{t}} = y_{\mathrm{t}}/y_{\mathrm{t}_{\mathrm{SM}}}$, c_2, c_{g}, $c_{2\mathrm{g}}$ (1502.00539, 1410.3471, 1407.0281)
  - There exists alternatives (1607.05330) as well as indirect ways (1607.04251)
  - **Cross-section** can vary sensibly: $[10^{-1}, 10^4] \times \sigma(\mathrm{pp} \to \mathrm{hh})^{SM}$
  - **Signal shape** can be significantly different from SM
- Model builders manage to accomodate deviations of O(1)... *we need to do better!*



Scan 5D parameter space: the clustering method

It is impractical to generate a 5D grid of signal samples

- LO generation and various theoretical arguments: most of the physics is contained in the m_{hh} spectrum
  - and somewhat in $\cos(\theta)^*_{hh}$
  - Extensive discussions in a MITP TH-EXP workshop (2015)



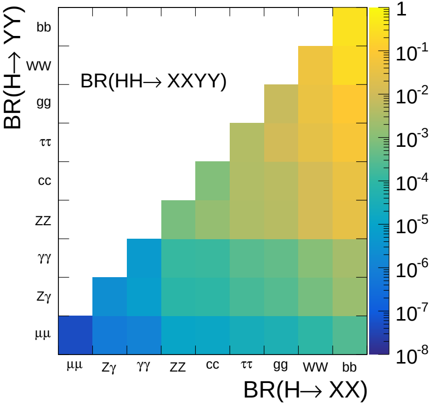
The cluster analysis (JHEP04(2016)126, LHCHXSWG report 4 pp 202-206)

- Exp. analyses **sensibility depend on the signal shape**
- **Cluster regions** of the parameter space with **similar kinematics**
  - Not necessarily adjoining regions!
- Define **benchmark points (BM)**: representative of a cluster
- Injection of the 12 benchmarks in the CMS full-sim MC prod.

Experimental signatures studied at CMS

Ultimate figure of merit: sensitivity

- **hh $\rightarrow$ b$\bar{\text{b}}$b$\bar{\text{b}}$**: $\mathcal{B} = 33.3\%$, fully reconstructible, large QCD background + combinatorics, dedicated trigger studies
- **hh $\rightarrow$ b$\bar{\text{b}}\tau^-\tau^+$**: $\mathcal{B} = 7.27\%$, fully reconstructible, large $t\bar{t}$ & QCD backgrounds
- **hh $\rightarrow$ b$\bar{\text{b}}$WW$(jj\ell\bar{\nu}_\ell)$**: $\mathcal{B} = 7.2\%$, irreducible $t\bar{t}$ background, $\not{E}_T$
- **hh $\rightarrow$ b$\bar{\text{b}}$WW$(\ell\bar{\nu}_\ell\bar{\ell}\nu_\ell)$**: $\mathcal{B} = 1.23\%$, good triggers, irreducible $t\bar{t}$ background, $\not{E}_T$
- **hh $\rightarrow$ b$\bar{\text{b}}\gamma\gamma$**: $\mathcal{B} = 0.26\%$, excellent trigger thresholds and acceptance, relatively low background



The Higgs boson was discovered in 2012. Since 2014, many hh experimental studies:

- **1 papers** and **1 conference note** on 8 TeV data
- **5 conference notes** on 13 TeV data
- **1+2 conference notes** on HL-LHC projections at 13 and 14 TeV
- Not to mention many more results on resonant searches ...
- ... and similar activity on the ATLAS end

Very active area in experimental collaborations
(and growing community)

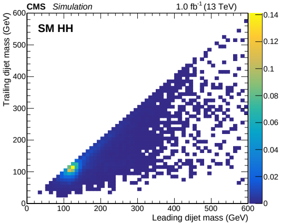
hh $\rightarrow b\bar{b}b\bar{b}$ analyses (1)

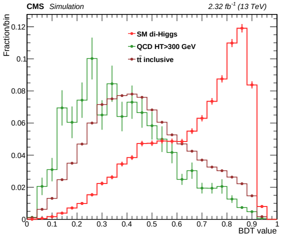
Key points

- **Largest BR: 33.9%**
- Fully hadronic final state: **HUGE QCD bkg**

Analysis Strategy

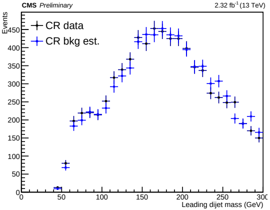
- **Set of multi-(b-)jets triggers**
- 4 b-tagged, resolved jets
- Jet pairs consistent with the Higgs mass
- Cut on kinematic BDT to improve S/B
- **Data-driven QCD background estimate**
- $t\bar{t}$, DY (SMHiggs) backgrounds estimated from simulation (10%)
- Signal region from m_h-m_h plane

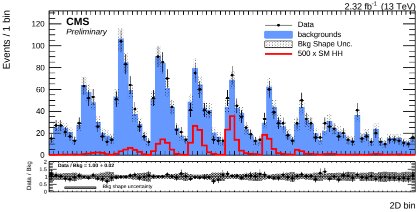




13 TeV: CMS-PAS-HIG-16-026 13 TeV HL-LHC: CMS-DP-2016-064

hh → $b\bar{b}b\bar{b}$ analyses (2)





QCD background prediction: hemisphere mixing

- Split data events into two hemispheres along thrust axis
- Assemble two half-events (criteria on jet variables, distance)
- **New independant dataset** with similar kinematics

- **Most sensitive result to date (ATLAS)**: important final state!

$\sqrt{s}$ (TeV)	$\sigma^{SM} \times$ BR (fb)	95% CL upper limit on σ (pb) and $\sigma \times BR$ (fb)	obs.		(exp.)		$\mu_{hh}^{obs.}$ ($\mu_{hh}^{exp.}$) $\left(\frac{\sigma}{\sigma^{SM}}\right)$ if N/A	unc. on μ	significance	anomalous couplings
13	11.3	CMS-15	11.4	3880	(10.3)	(3490)	343 (308)		$< 1\sigma$	
13	11.3	HL-CMS					(7.0)	(2.5)	(0.39)	

Content in gray derived from public information

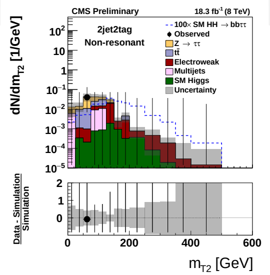
hh $\to b\bar{b}\tau^-\tau^+$ analyses (1)

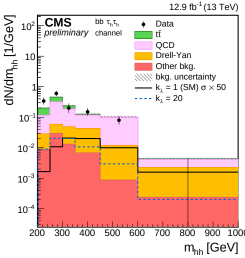
Key points

- **BR: 7.27%** (all tau decays)
- **Fully reconstructible final state**
- $t\bar{t}$ bkg dominating for $\tau_e\tau_h$,$\tau_\mu\tau_h$
- QCD, DY bkg dominating for $\tau_h\tau_h$

Analysis Strategy

- Single lepton and τ triggers
- τ ID (HPS, BDT, ...) with lepton veto
- **$\tau\tau$ system reco. (SVfit)**
- invariant mass windows
- QCD, fake τs from data
- DY $\to \tau\tau$ with embedding (for 8 TeV)
- $t\bar{t}$, others (W, t, VV, SMH) from MC



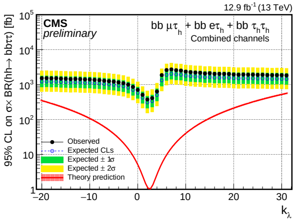


8 TeV: **13 TeV:** CMS-PAS-HIG-16-012, CMS-PAS-HIG-16-028 **13 TeV HL-LHC:** CMS-DP-2016-064 **14 TeV HL-LHC:** CMS-PAS-FTR-15-002

hh $\rightarrow b\bar{b}\tau^-\tau^+$ analyses (2)

5 analyses in CMS

analysis	channels	additional criteria	final discriminant
CMS 8 TeV	$\tau_h\tau_h$	kin. fit, $\Delta R(\tau,\tau) < 2$ 2jets{0,1,2}tag cat.	$mT2$ (1309.6318)
CMS-15 13 TeV	$\tau_e\tau_h$, $\tau_\mu\tau_h$, $\tau_h\tau_h$	cut on angular BDT	m_{hh}
CMS-16 13 TeV	$\tau_e\tau_h$, $\tau_\mu\tau_h$, $\tau_h\tau_h$	cut on angular BDT	m_{hh}
HL-CMS 13 TeV	extrapolation of **2015** analysis, upgrade scenarios studies		
HL-CMS 14 TeV	$\tau_\mu\tau_h$, $\tau_h\tau_h$		BDT ; $mT2$



$\sqrt{s}$ (TeV)	$\sigma^{\mathrm{SM}} \times$ BR (fb)	95% CL upper limit on σ (pb) and $\sigma \times BR$ (fb)	obs.		(exp.)		$\mu^{\mathrm{obs.}}_{\mathrm{hh}}$ ($\mu^{\mathrm{exp.}}_{\mathrm{hh}}$) $\left(\frac{\sigma}{\sigma^{\mathrm{SM}}}\right)$ if N/A	unc. on μ	significance	anomalous couplings
8	0.74	CMS	0.59	43	$(0.94^{+0.46}_{-0.24})$	(68)	53 (84)			
13	2.43	CMS-15	8.7	632	(7.2)	(523)	260 (215)			$\lvert\kappa_\lambda\rvert \lesssim 50$
		CMS-16	6.99	508	(5.78)	(420)	200 (170)			κ_λ, κ_t, BM
13	2.43	HL-CMS					(5.2 - 7.4)	(2.6 - 3.7)	(0.28 - 0.39)	
14	2.88	HL-CMS						(1.05)	(0.9)	

Content in gray derived from public information

- Very good sensitivity, and **sensitive to signal shape**
- **More data**: categories, variables, bkg estimates, ... **performance will improve**

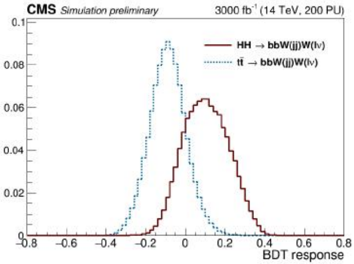
hh $\to b\bar{b}WW(jj\ell\bar{\nu}_\ell)$ analysis

Key points

- **BR: 7.2%**
- **Irreducible $t\bar{t}$** background
- Not fully reconstructible (1 d.o.f.)

Analysis strategy

- Delphes study with upgraded CMS detector
- Large PU: **importance of combinatorics and jet tools**
- Numerous variables as input to a BDT
- Cut and count analysis



14 TeV HL-LHC: CMS-DP-2016-064

$\sqrt{s}$ (TeV)	$\sigma^{SM} \times$ BR (fb)	95% CL upper limit on σ (pb) and $\sigma \times BR$ (fb) obs.	(exp.)	$\mu_{hh}^{obs.}$ ($\mu_{hh}^{exp.}$) $\left(\frac{\sigma}{\sigma^{SM}}\right)$ if N/A	unc. on μ	significance	anomalous couplings
14	2.85			(5.3)	(2.8)		

Content in gray derived from public information

- **Promizing sensitivity**: to be pursued with data analysis ~~(?)~~ soon from ATLAS!

$hh \to b\bar{b}WW(\ell\bar{\nu}_\ell\bar{\ell}\nu_\ell)$ analyses

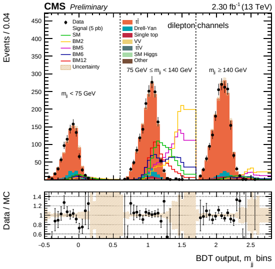
Key points

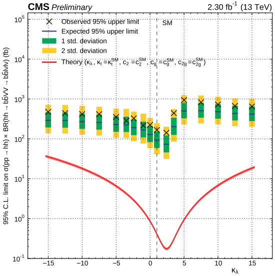
- **BR: 1.23%** (h $\to VV \to l\nu l\nu$ leg)
- **Irreducible $t\bar{t}$** background
- Not fully reconstructible (2 d.o.f.)

Strategy

- Kin. MVA (no m_{jj})
- 2D fit (13 TeV) – MVA-cut and count (14 TeV)
- Providing numerical **limits on 1459 points of the parameter space**

- **Same O(sensitivity)** as other final states





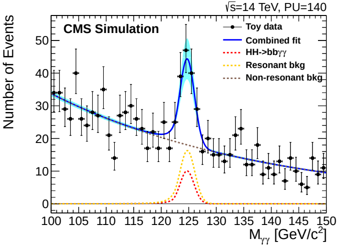
13 TeV: CMS-PAS-HIG-16-024, 13 TeV HL-LHC: CMS-DP-2016-064, 14 TeV HL-LHC: CMS-PAS-FTR-15-002

$\sqrt{s}$ (TeV)	$\sigma^{SM} \times$ BR (fb)		95% CL upper limit on σ (pb) and $\sigma \times BR$ (fb) obs.		(exp.)		$\mu_{hh}^{obs.}$ ($\mu_{hh}^{exp.}$) $\left(\frac{\sigma}{\sigma^{SM}}\right)$ if N/A	unc. on μ	significance	anomalous couplings
13	0.411	CMS-15	13.6	166.7	(7.5)	$(92.8^{+59.9}_{-33.4})$	$410\ (227^{+147}_{-82})$			κ_λ, κ_t, c_2, c_g, c_{2g}, BM
13	0.411	HL-CMS					(4.8)	(2.4)	(0.45)	
14	0.487	HL-CMS						1.6 - 5.4	$(\frac{s}{\sqrt{b}} \approx 0.60)$	

hh → $b\bar{b}\gamma\gamma$ analyses (1)

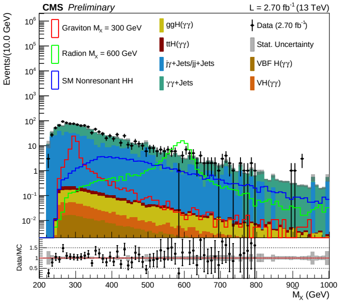
Key points

- **Lowest BR (0.26%)**
- fully reconstructible and clean final state - low background
- **Excellent sensitivity - stat. limited**



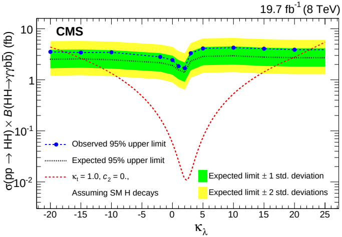
Analysis strategy

- Collect data with diphoton triggers
- Select 2 photons and 2 b-jets
- **Use $m_{\gamma\gamma}$ resolution:** fit ($m_{\gamma\gamma}$, m_{jj})
- $\gamma\gamma+$ jets , $\gamma+$ jets , multijets directly fit in data, single h from simulation
  - Account for possible background mismodeling



8 TeV: Phys. Rev. D 94 (2016) 052012 **13 TeV HL-LHC:** CMS-DP-2016-064 **14 TeV HL-LHC:** CMS-PAS-FTR-15-002

hh $\rightarrow$ $b\bar{b}\gamma\gamma$ analyses (2)



4 analyses in CMS

analysis	selection	tools	categories
CMS 8 TeV	$p_T^j > 25$ GeV	b-jet regr. ; $\lvert\cos\theta^*_{hh}\rvert$cut	b-tag, $m^{kin.}_{\gamma\gamma jj}$
CMS-15 13 TeV		b-jet regr. ; $m_{\gamma\gamma jj}$cut	b-tag
HL-CMS 13 TeV	Projection of CMS-15 13 TeV accounting high-pu ($\epsilon(\gamma\mathrm{ID})$, ϵ(vtx)) upgrade / aging scenarios studied		
HL-CMS 14 TeV	$p_T^j > 40$ GeV, lepton veto, ≤ 4 jets, angular cuts upgrade / aging scenarios studied		photon

$\sqrt{s}$ (TeV)	$\sigma^{SM} \times$ BR (fb)	95% CL upper limit on σ (pb) and $\sigma \times BR$ (fb)	obs.		(exp.)		$\mu^{obs.}_{hh}$ ($\mu^{exp.}_{hh}$) $\left(\frac{\sigma}{\sigma^{SM}}\right)$ if N/A	unc. on μ	significance	anomalous couplings
8	2.64×10^{-2}	CMS	0.71	1.85	(0.60)	(1.56)	74 (62^{+37}_{-22})			κ_λ, κ_t, c_2 $\kappa_\lambda \in [-17, 22.5]$
13	8.70×10^{-2}	CMS-15	3.04	7.90	(3.02)	(7.85)	$\approx$ 91 (90)			
13	8.70×10^{-2}	HL-CMS					(1.3)	(0.64)	(1.6)	
14	1.03×10^{-2}	HL-CMS						(0.67)	(1.6)	

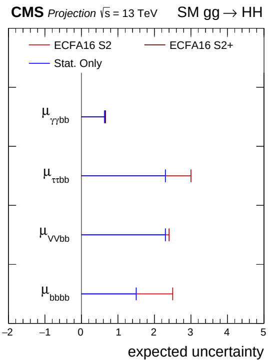
Content in gray derived from public information

- **Very similar analyses**
- Very good sensitivity and **sensitive to signal shape**, analyses are **stat. limited**,

Combinations: towards the end goal

L'union fait la force

- Not all (not any?) analyses has reached yet it's full maturity: **areas for improvements**
- Yet **all** final states have an expected sensitivity **within one order of magnitude**
- **The end game will be to combine them all**
- Even if the target seems far away yet, we might be lucky and BSM could be around the (hh-)corner...



$\sqrt{s}$ (TeV)	σ^{SM} (fb)	95% CL upper limit on σ (pb) obs.	(exp.)	$\mu_{hh}^{obs.}$ ($\mu_{hh}^{exp.}$) ($\frac{\sigma}{\sigma^{SM}}$) if N/A	unc. on μ	significance	anomalous couplings
8	10.16	ATLAS 0.69	(0.47)	70 (48)			
14	39.56	HL-CMS			(0.54)	(1.9)	

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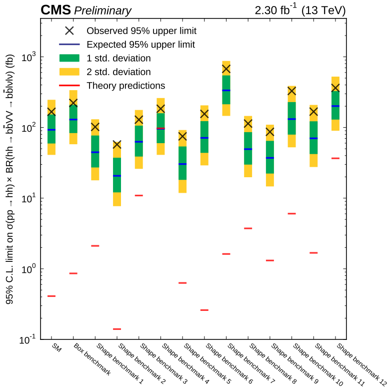
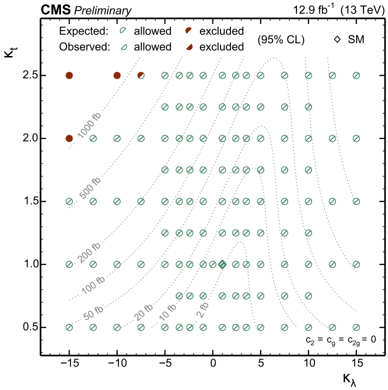
8 TeV: Phys. Rev. D 92 (2015) 092004 **14 TeV HL-LHC:** CMS-PAS-FTR-15-002

Studying BSM: scanning shapes & parameter space





Beyond the Higgs self-coupling λ

- **Anomalous couplings studied** ($hh \to b\bar{b}\gamma\gamma$, $hh \to b\bar{b}\tau^-\tau^+$, $hh \to b\bar{b}WW(\ell\bar{\nu}_\ell\bar{\ell}\nu_\ell)$)
- **Shape benchmarks investigated** ($hh \to b\bar{b}\tau^-\tau^+$, $hh \to b\bar{b}WW(\ell\bar{\nu}_\ell\bar{\ell}\nu_\ell)$)
- SM is a particular case, **care is necessary to not miss BSM!**

8 TeV: Phys. Rev. D 94 (2016) 052012 **13 TeV:** CMS-PAS-HIG-16-012, CMS-PAS-HIG-16-028, CMS-PAS-HIG-16-024

Conclusion

Where we are

- **SM hh production is out of reach for the short term**
- **Experimental effort to make sure all interesting final states are considered**, combination is likely the best answer
- Start **probing anomalous couplings**, BSM could be around the hh-corner

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Where we are going:

- **More final states!**
  - ATLAS: has results on hh $\rightarrow \gamma\gamma$WW$(jj\ell\bar{\nu}_\ell)$, working on hh $\rightarrow$ b$\bar{\text{b}}$WW$(jj\ell\bar{\nu}_\ell)$
  - CMS: working on hh $\rightarrow \gamma\gamma\gamma\gamma$, hh $\rightarrow$ b$\bar{\text{b}}$ZZ
- **More production modes!** next stop: VBF ($\approx$ 10% of the total production)
- **4-20 times more data**: $\approx$ 40 fb-1 to analyse! (for the *very* short term!)
- **With more data comes improved analyses**, we can do better than our own extrapolations: categorisation, data-driven bkg estimates, ...

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Stay tuned! More Higgses, more fun!

BACKUP

References

hh $\to$ b$\bar{\text{b}}$b$\bar{\text{b}}$

8 TeV: Phys. Rev. D 92 (2015) 092004,
Eur. Phys. J. C 75 (2015) 412
13 TeV: Phys. Rev. D 94 (2016) 052002,
ATLAS-CONF-2016-049, CMS-PAS-HIG-16-026
13 TeV HL-LHC: CMS-DP-2016-064
14 TeV HL-LHC: ATL-PHYS-PUB-2016-024

hh $\to$ b$\bar{\text{b}}\tau^-\tau^+$

8 TeV: Phys. Rev. D 92 (2015) 092004,
CMS-PAS-HIG-15-013
13 TeV: CMS-PAS-HIG-16-012,
CMS-PAS-HIG-16-028
13 TeV HL-LHC: CMS-DP-2016-064
14 TeV HL-LHC: ATL-PHYS-PUB-2015-046,
CMS-PAS-FTR-15-002

hh $\to$ b$\bar{\text{b}}$WW$(jj\ell\bar{\nu}_\ell)$

14 TeV HL-LHC: CMS-DP-2016-064

hh $\to$ b$\bar{\text{b}}$WW$(\ell\bar{\nu}_\ell\bar{\ell}\nu_\ell)$

13 TeV: CMS-PAS-HIG-16-024
13 TeV HL-LHC: CMS-DP-2016-064
14 TeV HL-LHC: CMS-PAS-FTR-15-002

hh $\to$ b$\bar{\text{b}}\gamma\gamma$

8 TeV: Phys. Rev. D 94 (2016) 052012,
Phys. Rev. Lett. 114 (2015) 081802,
Phys. Rev. D 92 (2015) 092004
13 TeV: CMS-PAS-HIG-16-032,
ATLAS-CONF-2016-004
13 TeV HL-LHC: CMS-DP-2016-064
14 TeV HL-LHC: CMS-PAS-FTR-15-002,
ATL-PHYS-PUB-2014-019

hh $\to \gamma\gamma$WW$(jj\ell\bar{\nu}_\ell)$

8 TeV: Phys. Rev. D 92 (2015) 092004
13 TeV: ATLAS-CONF-2016-071

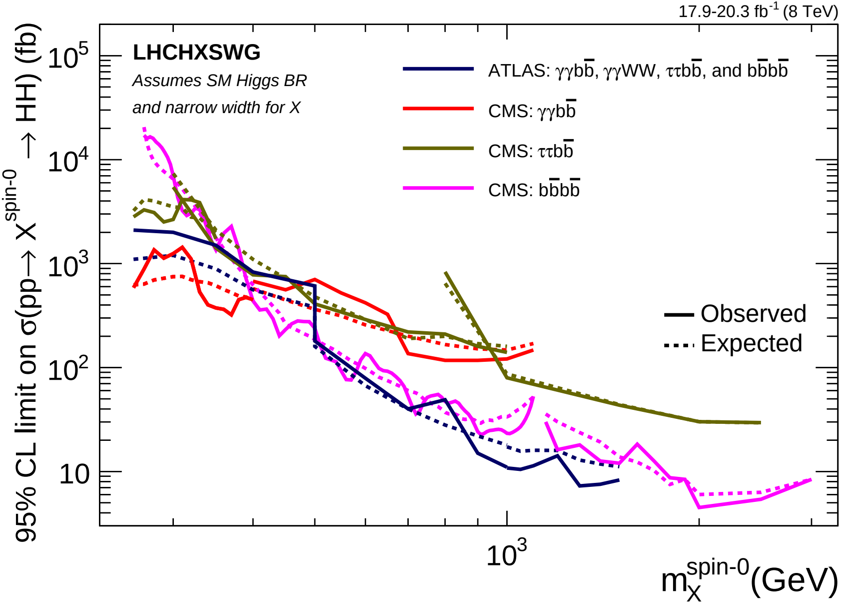
Combinations

8 TeV: Phys. Rev. D 92 (2015) 092004
14 TeV HL-LHC: CMS-PAS-FTR-15-002

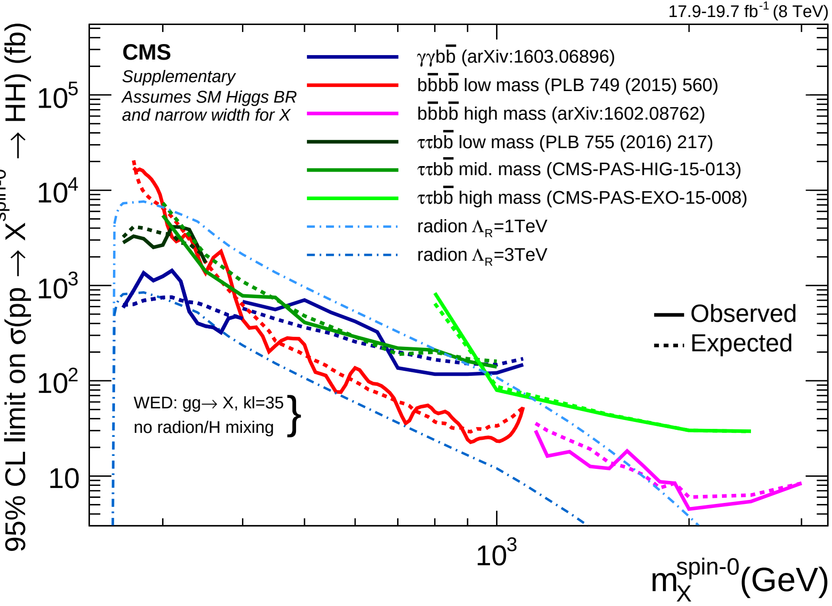
t$\bar{\text{t}}$hh

14 TeV HL-LHC: ATL-PHYS-PUB-2016-023

State of the art on resonant searches (I)



State of the art on resonant searches (II)



State of the art on resonant searches (III)