Non-resonant Higgs boson pair production at the LHC

Olivier Bondu
on behalf of the ATLAS & CMS collaboration

CP3 - UC Louvain

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UCL Université catholique de Louvain

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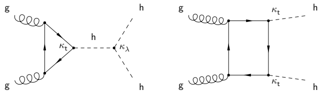
Motivation (1): access the scalar potential

hh production in the Standard Model

- **Direct access** to the **self-coupling λ**
  - SM scalar potential structure:
    $V(\mathrm{h}) = \frac{m_\mathrm{h}^2}{2}\mathrm{h}^2 + \lambda v \mathrm{h}^3 + \frac{\lambda}{4}\mathrm{h}^4$
- **Key property measurement** of h(125)
- Main production at LHC: **gluon fusion**



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

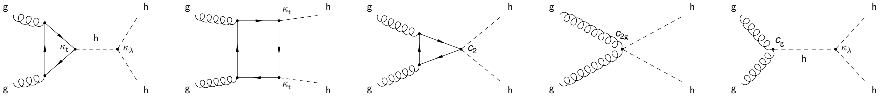
Major setback: **very low production cross-section**

- Strong destructive interference of the two main diagrams
- By (lack of) chance, SM is almost the most destructive case...

Motivation (2): Effective Field Theories

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

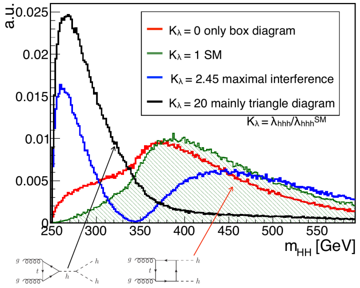
- Self-coupling λ predicted but (loosely) constrained experimentally
  - Experimental constraints of $O(n \times 10 - 100)$
- There exists other couplings in BSM scenarios:
  - $\kappa_\lambda = \lambda/\lambda_{SM}$, $\kappa_t = y_t/y_{t_{SM}}$, c_2, c_g, c_{2g} (1502.00539, 1410.3471, 1407.0281)
  - There exists alternatives (1607.05330) as well as indirect ways (1607.04251)
  - **Cross-section** can vary sensibly: $[10^{-1}, 10^4] \times \sigma(pp \to hh)^{SM}$
  - **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 $m_{\rm hh}$ spectrum
  - and somewhat in $\cos(\theta)^*$
  - Extensive discussions in a MITP TH-EXP workshop last year



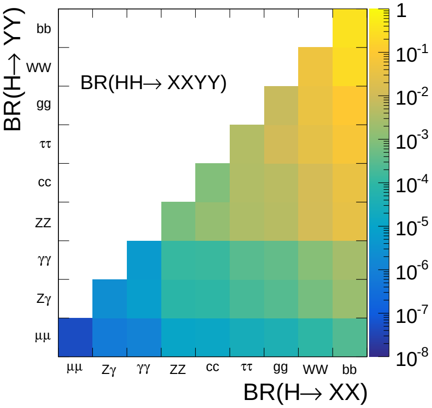
The cluster analysis (JHEP04(2016)126, LHCHXSWG report 4 pp 202-206)

- Exp. analyses **sensibility depend on the signal shape**
- **Cluster regions** of the parameter space with **similar kinematics**
- Define **benchmark points (BM)**: representative of a cluster
- Injection of the 12 benchmarks in the CMS full-sim MC prod.

Experimental signatures

Ultimate figure of merit: sensitivity

- $\mathbf{hh \rightarrow b\bar{b}b\bar{b}}$: $\mathrm{BR} = 33.3\%$, fully reconstructible, but large QCD background + combinatorics and trigger thresholds
- $\mathbf{hh \rightarrow b\bar{b}\tau^-\tau^+}$: $\mathrm{BR} = 7.27\%$, fully reconstructible, large $t\bar{t}$ QCD backgrounds
- $\mathbf{hh \rightarrow b\bar{b}WW(jj\ell\bar{\nu}_\ell)}$: $\mathrm{BR} = 7.2\%$, irreducible $t\bar{t}$ background, $\not{E}_T$
- $\mathbf{hh \rightarrow b\bar{b}WW(\ell\bar{\nu}_\ell\bar{\ell}\nu_\ell)}$: $\mathrm{BR} = 1.23\%$, good triggers, irreducible $t\bar{t}$ background, $\not{E}_T$
- $\mathbf{hh \rightarrow b\bar{b}\gamma\gamma}$: $\mathrm{BR} = 0.26\%$, excellent trigger thresholds and acceptance, relatively low background
- $\mathbf{hh \rightarrow \gamma\gamma WW(jj\ell\bar{\nu}_\ell)}$: $\mathrm{BR} = 0.10\%$, excellent trigger thresholds, relatively low background



List of LHC HH analyses

	SM-like		anomalous couplings	
	ATLAS	CMS	ATLAS	CMS
Run I - 8 TeV				
$hh \to b\bar{b}\gamma\gamma$	20 fb-1 (Phys. Rev. Lett. 114 (2015) 081802)	19.7 fb-1 Phys. Rev. D 94 (2016) 052012	XX	19.7 fb-1 Phys. Rev. D 94 (2016) 052012, κ_λ, c_2, κ_t
$hh \to b\bar{b}\tau^-\tau^+$	20.3 fb-1 (Phys. Rev. D 92 (2015) 092004)	18.3 fb-1 CMS-PAS-HIG-15-013	XX	XX
$hh \to b\bar{b}b\bar{b}$	19.5 fb-1 (Eur. Phys. J. C 75 (2015) 412)	XX	XX	XX
$hh \to \gamma\gamma WW(jj\ell\bar{\nu}_\ell)$	20.3 fb-1 (Phys. Rev. D 92 (2015) 092004)	XX	XX	XX
combination	20.3 fb-1 (Phys. Rev. D 92 (2015) 092004)	XX	XX	XX
Run II - 13 TeV				
$hh \to b\bar{b}\gamma\gamma$	3.2 fb-1 (ATLAS-CONF-2016-004)	2.70 fb-1 (CMS-PAS-HIG-16-032)	XX	XX
$hh \to b\bar{b}\tau^-\tau^+$(ICHEP16)	XX	12.9 fb-1 (CMS-PAS-HIG-16-028)	XX	12.9 fb-1 (CMS-PAS-HIG-16-028), κ_λ, κ_t, BM
$hh \to b\bar{b}\tau^-\tau^+$(Moriond16)	XX	2.7 fb-1 (CMS-PAS-HIG-16-012)	XX	2.7 fb-1 (CMS-PAS-HIG-16-012), κ_λ
$hh \to b\bar{b}b\bar{b}$(ICHEP16)	13.3 fb-1 (ATLAS-CONF-2016-049)	XX	XX	XX
$hh \to b\bar{b}b\bar{b}$(Moriond16)	3.2 fb-1 (Phys. Rev. D 94 (2016) 052002)	2.32 fb-1 (CMS-PAS-HIG-16-026)	XX	XX
$hh \to b\bar{b}WW(\ell\bar{\nu}_\ell\bar{\ell}\nu_\ell)$	XX	2.30 fb-1 (CMS-PAS-HIG-16-024)	XX	2.30 fb-1 (CMS-PAS-HIG-16-024), κ_λ, κ_t, c_g, c_{2g}, c_2, BM
$hh \to \gamma\gamma WW(jj\ell\bar{\nu}_\ell)$	13.3 fb-1 (ATLAS-CONF-2016-071)	XX	XX	XX
13 TeV projections				
$hh \to b\bar{b}\gamma\gamma$	XX	3000 fb-1 (CMS-DP-2016-064)	XX	XX
$hh \to b\bar{b}\tau^-\tau^+$	XX	3000 fb-1 (CMS-DP-2016-064)	XX	XX
$hh \to b\bar{b}b\bar{b}$	XX	3000 fb-1 (CMS-DP-2016-064)	XX	XX
$hh \to b\bar{b}WW(\ell\bar{\nu}_\ell\bar{\ell}\nu_\ell)$	XX	3000 fb-1 (CMS-DP-2016-064)	XX	XX
14 TeV projections				
$t\bar{t}hh$	3000 fb-1 (ATL-PHYS-PUB-2016-023)	XX	XX	XX
$hh \to b\bar{b}\gamma\gamma$	3000 fb-1 (ATL-PHYS-PUB-2014-019)	3000 fb-1 (CMS-PAS-FTR-15-002)	3000 fb-1 (ATL-PHYS-PUB-2014-019), κ_λ	XX
$hh \to b\bar{b}\tau^-\tau^+$	3000 fb-1 (ATL-PHYS-PUB-2015-046)	3000 fb-1 (CMS-PAS-FTR-15-002)	3000 fb-1 (ATL-PHYS-PUB-2015-046), κ_λ	XX
$hh \to b\bar{b}b\bar{b}$	3000 fb-1 (ATL-PHYS-PUB-2016-024)	XX	3000 fb-1 (ATL-PHYS-PUB-2016-024), κ_λ	XX
$hh \to b\bar{b}WW(\ell\bar{\nu}_\ell\bar{\ell}\nu_\ell)$	XX	3000 fb-1 (CMS-PAS-FTR-15-002)	XX	XX
$hh \to b\bar{b}WW(jj\ell\bar{\nu}_\ell)$	XX	3000 fb-1 (CMS-DP-2016-064)	XX	XX
combination	XX	3000 fb-1 (CMS-PAS-FTR-15-002)	XX	XX

Higgs boson was discovered in 2012. Since 2014...

- **4 papers** and **1 conference note** on 8 TeV data
- **1 paper** and **8 conference notes** on 13 TeV data
- **1+6 conference notes** on HL-LHC projections at 13 and 14 TeV
- Not to mention many more results on resonant searches
  - see Souvik Das' talk (CMS) as well as BaoJia Tong's talk (ATLAS))

Very active area in experimental collaborations
(and growing community)

I apologize for the large tables:
not all informations are provided on public documents
for a proper apple-to-apple comparison of everything...

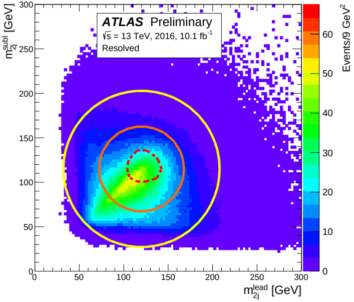
hh → $b\bar{b}b\bar{b}$ analyses (1)

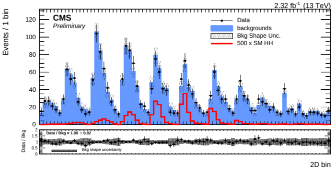
Key points

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

Analysis Strategy

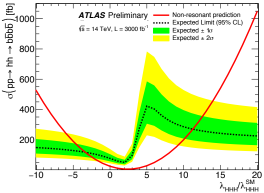
- **Set of multi-(b-)jets triggers**
- 4 b-tagged, resolved jets
- consistent pairs with the Higgs mass
- **Data-driven QCD background estimate**
- $t\bar{t}$, DY (SMHiggs) backgrounds estimated from simulation (10%)
  - yields from data in some cases
- Signal region from mh-mh plane (ellipse, X_{hh})





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 → $b\bar{b}b\bar{b}$ analyses (2)



Analysis	QCD bkg.	misc.	final discriminant
ATLAS 8 TeV ATLAS-15 13 TeV ATLAS-15+16 13 TeV HL-ATLAS 14 TeV	2btag CR & iter. kin. corrections	veto w/ n_{jets} and χ^2 trigger, bkg. unc., $\int L$, min p_T^j studies	cut-and-count m_{jjjj}
CMS-15 13 TeV HL-CMS 13 TeV	data-driven hemisphere mixing	cut on BDT(kin., angles)	binned (m_{jj}, m_{jj})

$\sqrt{s}$ (TeV)	$\sigma^{\text{SM}} \times$ BR (fb)	95% CL upper limit on σ (pb) and $\sigma \times BR$ (fb)	obs.		(exp.)		$\mu_{hh}^{\text{obs.}}$ ($\mu_{hh}^{\text{exp.}}$) $\left(\frac{\sigma}{\sigma^{\text{SM}}}\right)$ if N/A	unc. on μ	significance	anomalous couplings
8	3.45	ATLAS	0.62	202	(0.62)	(210)	63 (63)			
13	11.3	ATLAS-15	3.6	1220				36 (N/A)		
		ATLAS-15+16	0.97	330			29 (N/A)			
		CMS-15	11.4	3880	(10.3)	(3490)	343 (308)		$< 1\sigma$	
13	11.3	HL-CMS					(7.0)	(2.5)	(0.39)	
14	13.4	HL-ATLAS					(1.5 - 5.2)			$(\kappa_\lambda \in [-3.5; 0.2, 7; 11])$

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- Trigger, preselection, bkg estimation, signal extraction: **different strategies**
- **Most sensitive result to date (ATLAS)**: important final state!

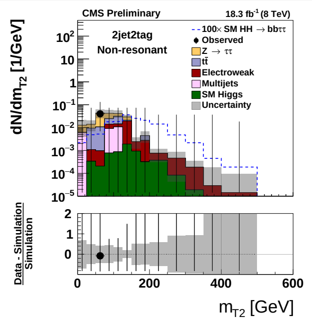
$hh \to b\bar{b}\tau^-\tau^+$ analyses (1)

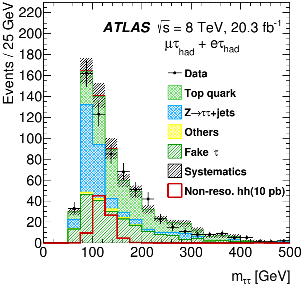
Key points

- **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. (MMC, 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



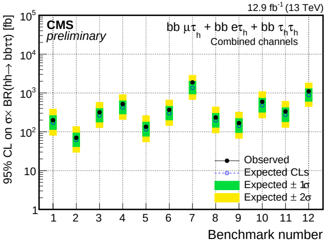


8 TeV: Phys. Rev. D 92 (2015) 092004, CMS-PAS-HIG-15-013 **13 TeV:** CMS-PAS-HIG-16-012, CMS-PAS-HIG-16-028 **13 TeV HL-LHC:** CMS-DP-2016-064 **14 TeV HL-LHC:** ATL-PHYS-PUB-2015-046, CMS-PAS-FTR-15-002

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

Key differences

analysis	channels	additional criteria	final discriminant
ATLAS 8 TeV	$\tau_e\tau_h$, $\tau_\mu\tau_h$	$n_b < 3$, $m_T^{l\nu} < 60 GeV$, angular cuts (m_W, m_t) elliptic cut	$m_{\tau\tau}$
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-ATLAS 14 TeV	$\tau_l\tau_l$, $\tau_e\tau_h$, $\tau_\mu\tau_h$, $\tau_h\tau_h$	p_T^h, $mT2$, angles, m_T, $\chi^2_{t\bar{t}}$	cut-based
HL-CMS 14 TeV	$\tau_\mu\tau_h$, $\tau_h\tau_h$		BDT ; $mT2$



$\sqrt{s}$ (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
8	0.74	ATLAS	1.6	116	(1.3)	(94)	160 (130)			
		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-ATLAS					(4.3)		(0.60)	$(\kappa_\lambda \in [-4, 12])$
		HL-CMS						(1.05)	(0.9)	

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

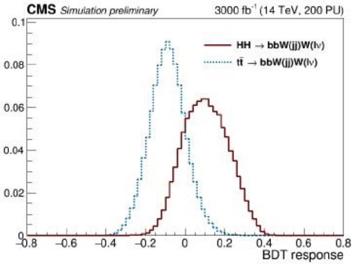
$hh \to b\bar{b}WW(jj\ell\bar{\nu}_\ell)$ analysis

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)		

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- **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

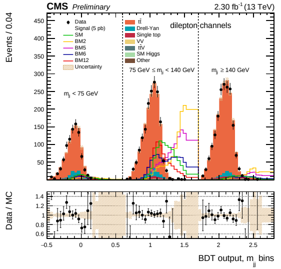
Key points

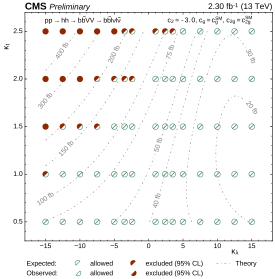
- **BR: 1.23%** (h $\to VV \to l\nu l\nu$ leg)
- **Irreducible $t\bar{t}$** background
- Not fully reconstructible (2 d.o.f.)

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





$\sqrt{s}$ (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	$(\frac{s}{\sqrt{b}} \approx 0.60)$	

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

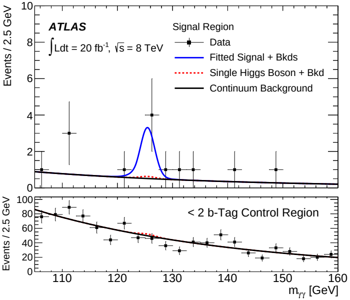
hh → $b\bar{b}\gamma\gamma$ analyses (1)

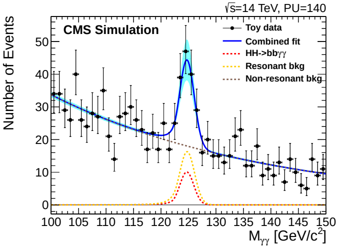
Key points

- **Lowe 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**
- $\gamma\gamma+$ jets , $\gamma+$ jets , multijets directly fit in data, single h from simulation
  - Account for possible background mismodeling





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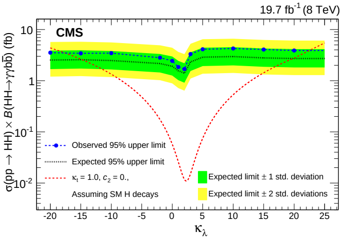
14 TeV HL-LHC: CMS-PAS-FTR-15-002, ATL-PHYS-PUB-2014-019

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



Key differences

analysis	selection	tools	categories	signal extraction
ATLAS 8 TeV	$p_T^j > 55, 35$ GeV	m_h/m_{jj} scaling	b-tag	fit $m_{\gamma\gamma}$
CMS 8 TeV	$p_T^j > 25$ GeV	b-jet regr. ; $\lvert\cos\theta^*_{hh}\rvert$cut	b-tag, $m^{kin.}_{\gamma\gamma jj}$	fit ($m_{\gamma\gamma}$, m_{jj})
ATLAS-15 13 TeV	Similar to ATLAS 8 TeV			
CMS-15 13 TeV		b-jet regr. ; $m_{\gamma\gamma jj}$cut	b-tag	fit ($m_{\gamma\gamma}$, m_{jj})
HL-CMS 13 TeV	Projection of CMS-15 13 TeV accounting high-pu ($\epsilon(\gamma\mathrm{ID})$, $\epsilon(\mathrm{vtx})$) upgrade / aging scenarios studied			
HL-ATLAS 14 TeV	angular cuts, ≤ 6 jets, lepton veto, $p_T^{\gamma\gamma}, p_T^{bb} > 110$ GeV		photon	cut/count(?)
HL-CMS 14 TeV	$p_T^j > 40$ GeV, lepton veto, ≤ 4 jets, angular cuts upgrade / aging scenarios studied		photon	fit ($m_{\gamma\gamma}$, m_{jj})

$\sqrt{s}$ (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}	ATLAS	2.2	5.72	($1.0^{+0.5}_{-0.2}$)	(2.60)	220 (100)		2.4σ	
		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}	ATLAS-15	3.9	10.1	($5.4^{+2.8}_{-1.0}$)	(14.0)	$\approx$ 116 (161)			
		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-ATLAS					(1.4)			($\kappa_\lambda \in [-1.3, 8.7]$)
		HL-CMS						(0.67)	(1.6)	

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- **Very similar analyses**
- Very good sensitivity and **sensitive to signal shape**, analyses are **stat. limited**,
- More on (CMS) hh $\to b\bar{b}\gamma\gamma$ analyses in Rafael Teixeira De Lima talk

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

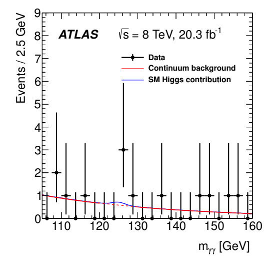
Key points

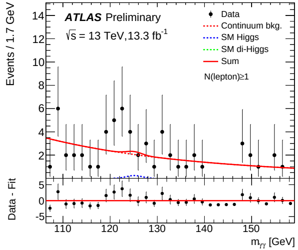
- **Lowest BR: 0.10%**
- **à la hh $\to$ b$\bar{\text{b}}\gamma\gamma$**: low BR, good trigger and selection eff., low bkg
- $\gamma\gamma$ continuum ($W\gamma\gamma+$ jets) bkg.

Strategy

- h $\to \gamma\gamma$ triggers
- 2 tight γ, 1 medium l, 0 b-tag jet
- **Fit $m_{\gamma\gamma}$ to estimate continuum bkg**
- Cut on $m_{\gamma\gamma}$ and count

- **Stat. limited**: more data coming!





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

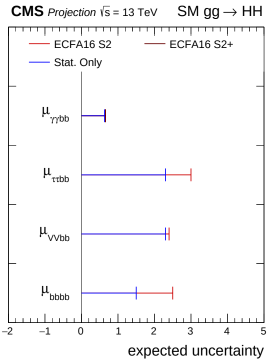
$\sqrt{s}$ (TeV)	$\sigma^{\text{SM}} \times$ BR (fb)	95% CL upper limit on σ (pb) and $\sigma \times BR$ (fb)	obs.		(exp.)		$\mu_{\text{hh}}^{\text{obs.}}$ ($\mu_{\text{hh}}^{\text{exp.}}$) $\left(\frac{\sigma}{\sigma^{\text{SM}}}\right)$ if N/A	unc. on μ	significance	anomalous couplings
8	0.010	ATLAS	11	11	(6.7)	(6.7)	1150 (680)			
13	0.033	ATLAS-16	25.0	25.0	12.9	(12.9)	757 (390)			

Content in gray is not official

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 in each experiment**
- 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)	

Content in gray is not official

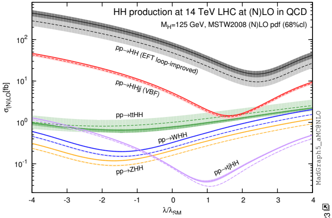
Bonus track: what about $t\bar{t}hh$?

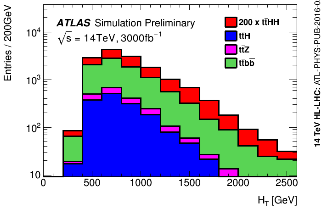
Key points

- **$t\bar{t}hh \rightarrow bl\nu bjj(b\bar{b}b\bar{b})$**
- low background, no loops in LO diagrams
- **Very low stat.**, combinatorics

Strategy

- Single lepton triggers, ≥ 7 jets, 1 lepton, $\geq 5-6$ b-tagged jets
- Discriminant variable: $< \eta(b_i, b_j) >$ ($\frac{\sum_{jets} p_T}{\sum_{jets} E}$, $H_B = \sum_{b-jets} p_T$ also studied)
- Jets combinatorics via χ^2 or scalar sums
- cut and count





$\sqrt{s}$ (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
14	0.33	HL-ATLAS			(0.35)	

Content in gray is not official

- **No hope of a stand-alone discovery** (/ not much contribution to total hh rate)

Conclusion

Where we are

- **SM hh production is out of reach for the short term**
- **Experimental effort to make sure all interesting final state 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: hh $\rightarrow$ b$\bar{\text{b}}$WW($jj\ell\bar{\nu}_\ell$)
  - CMS: 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**: 40 fb-1 to analyse! (for the 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 $\to$ $b\bar{b}b\bar{b}$

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

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

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

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

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

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

$t\bar{t}$hh

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