Searches for non-resonant HH production at CMS

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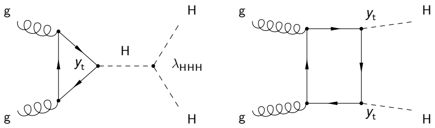
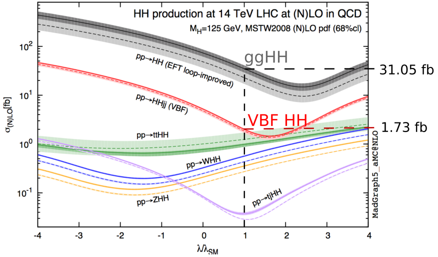
ggHH production diagrams at LO



HH production cross section vs λ/λ_{SM}

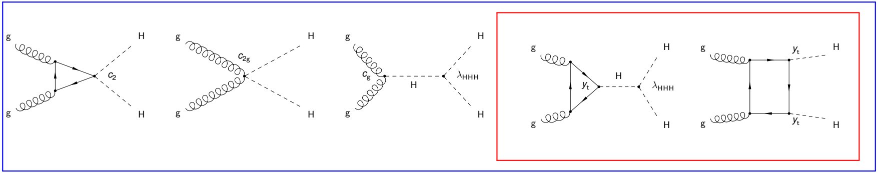


- HH production is sensitive to the **Higgs self-coupling** λ_{HHH}
- Contains information about the shape of the Higgs potential
- **SM Higgs pair production at LHC:**
  - **mainly happens in the gluon-gluon fusion mode**
  - small production cross-section due to destructive interference between triple coupling and the box diagrams σ_{ggHH}(13 TeV)=31.05 fb ($\sim$1000x smaller than σ_{ggH})
- BSM can significantly increase σ(HH) and changes the final state kinematics.

BSM

- In the EFT ggHH production is described by 5 diagrams

BSM **SM (k_λ=1, $\mathbf{k_t}$=1, $c_{2g} = c_g = c_2$=0)**



- 5 parameters controlling Higgs tree-level interactions: $\mathbf{k_\lambda}$, $\mathbf{k_t}$, $\mathbf{c_{2g}}$, $\mathbf{c_g}$, $\mathbf{c_2}$
- $\mathbf{c_{2g}}$, $\mathbf{c_g}$, $\mathbf{c_2}$ are not predicted in SM but could arise through BSM e.g. the mediation of new very heavy states (parametrized as contact terms)
- Each point in the 5D coupling phase space leads to different kinematics and cross sections

$$\mathcal{L}_\mathbf{h} = \frac{1}{2}\partial_\mu \mathbf{h} \partial^\mu \mathbf{h} - \frac{1}{2}\mathbf{m_h^2 h^2} - \mathbf{k_\lambda} \lambda_\mathbf{SM} \upsilon \mathbf{h^3} - \frac{\mathbf{m_t}}{\upsilon}(\upsilon + \mathbf{k_t h} + \frac{\mathbf{c_2}}{\upsilon}\mathbf{hh})(\mathbf{\bar{t}_L t_R} + \mathbf{h.c.}) + \frac{1}{4}\frac{\alpha_\mathbf{s}}{3\pi\upsilon}(\mathbf{c_g h} - \frac{\mathbf{c_{2g}}}{2\upsilon}\mathbf{hh})\mathbf{G}^{\mu\nu}\mathbf{G}_{\mu\nu}$$

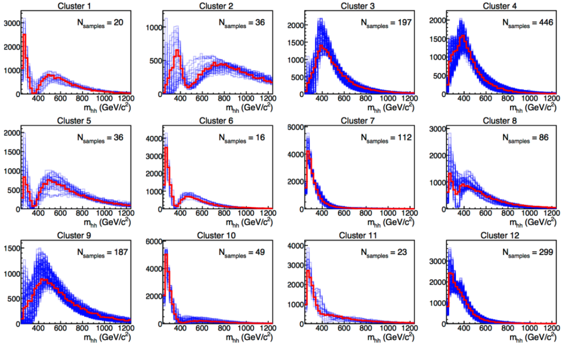
$k_\lambda = \lambda_{HHH}/\lambda_{HHHSM}$
$\lambda_{HHHSM} = m_H^2/(2v^2) = 0.129$

$k_t = y_t/y_{tSM}$
$y_{tSM} = \sqrt{2}m_t/v \approx 1.0$, here v=246 GeV

BSM Benchmarks clustering

- Points in this parameter phase space can be clustered leading to similar kinematical distributions of final states
- 12 benchmarks were clustered (https://arxiv.org/pdf/1608.06578.pdf)
- Extract limit on the 12 benchmarks to explore EFT sensitivity
- Analytical reweighting implemented to reweight any MC sample to any other from the combination of $\mathbf{k_\lambda}$, $\mathbf{k_t}$, $\mathbf{c_{2g}}$, $\mathbf{c_g}$, $\mathbf{c_2}$

m(HH) distribution for 12 benchmarks



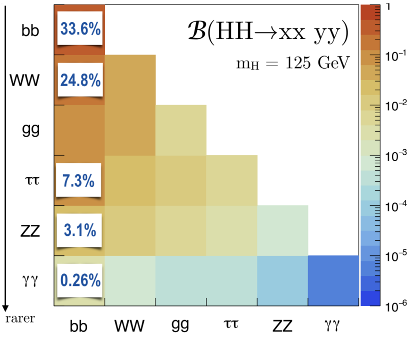
generator-level

12 kinematically representative points in the 5D parameters space

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

Explored final states

Rich set of final states accessible at the LHC

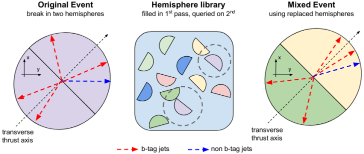


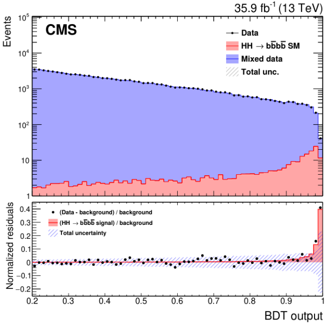
- **bbbb:** largest BR, large QCD and $t\bar{t}$ contamination
- **bbVV:** large BR, large $t\bar{t}$ contamination
- **bb$\tau\tau$:** sizeable BR, relatively small background
- **bb$\gamma\gamma$:** small BR, good $\sigma(m_{\gamma\gamma})$, relatively small background

HH→bbbb

- Final state with **4 identified b-jets**, paired into Higgs boson candidates
- Main challenge: **QCD multi-jet contamination**
- b-tag is crucial, used from trigger level (3 bjets)
- **BDT technique** optimised for SM HH signal
- Background model created with **hemisphere mixing technique** applied to signal region events and validated in data control regions
- Signal extraction from BDT output

Original dataset: bkgs and potentially a small signal fraction
Mixed dataset: new composed event that represent bkg-only





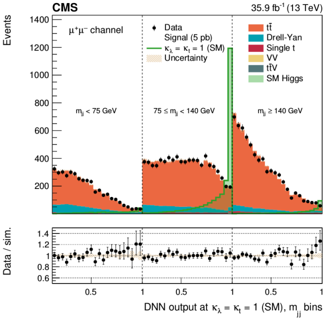
Result for RunII, 35.9 fb^{-1} (2016):

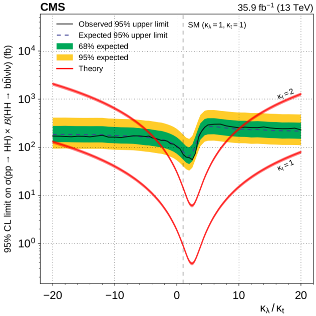
SM Obs(Exp) U.L.: 847 (419) fb
SM Obs(Exp) U.L.: 75 (37)$\times\sigma_{SM}$
BSM: -23 (-15) $< \kappa_\lambda <$ 30 (23)

JHEP 04 (2019) 112

HH→bbVV

- Event selection: **2 opposite charge leptons** (e^+e^-, $\mu^+\mu^-$, $e^\pm\mu^\mp$) and **2 b-jets**
- Events come from HH→bbWW^* →bb$l\nu l\nu$ and HH→bbZZ^* →bb$\nu\nu ll$ processes
- mass requirement (12 <m_{ll}<m_Z - 15 GeV) to suppress quarkonia resonances and Z boson background
- Large irreducible background from $t\bar{t}$ and Drell-Yan processes - **DNN to discriminate signal from background**
- Binned Maximum Likelihood fit performed over the DNN output distributions in 3 different m_{jj} regions and 3 channels (e^+e^-, $\mu^+\mu^-$, $e^\pm\mu^\mp$)





Result for RunII, 35.9 fb^{-1} (2016):

SM Obs(Exp) U.L.: 72 (81) fb

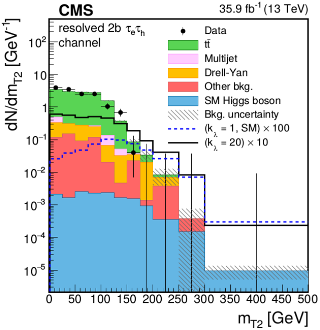
SM Obs(Exp) U.L.: 79 (89)$\times\sigma_{SM}$

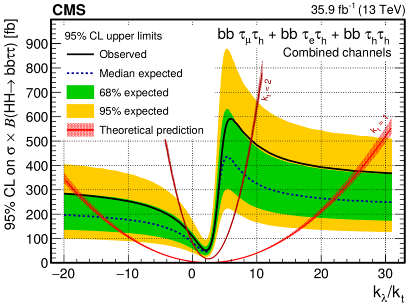
BSM: U.L. set as a function of k_λ/k_t

JHEP 01 (2018) 054

HH→bb$\tau\tau$

- Selected events with **1 isolated τ_{had}** with a **second lepton of opposite charge** (e, μ or τ_{had})
- Events categorized according to number (1/2) of b-jets
- Main background sources: $t\bar{t}$, Z/$\gamma^* \rightarrow ll$, QCD multi-jets (data-driven estimate)
- **BDT discriminant** trained on kinematic variables was used to reduce $t\bar{t}$ background in $e\tau_h$, $\mu\tau_h$ channels
- **Stranverse mass** m_{T2} (largest mass of the parent particle compatible with the kinematic constraints of the event) provide best separation between HH signal and background
- Binned Maximum Likelihood fit performed on the m_{T2} distributions, in the 3 final states





Result for RunII, 35.9 fb^{-1} (2016):

SM Obs(Exp) U.L.: 75.4 (61.0) fb

SM Obs(Exp) U.L.: 30 (25)$\times\sigma_{SM}$

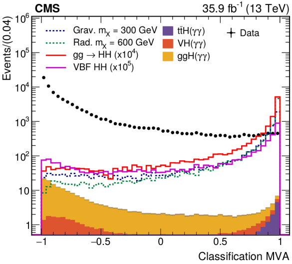
BSM: U.L. set as a function of k_λ/k_t

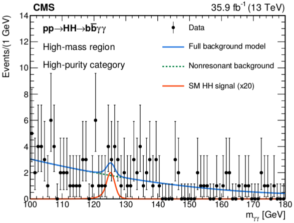
-18 (-14) $< \kappa_\lambda <$ 26 (22)

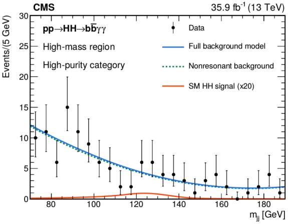
PLB 778 (2018) 101

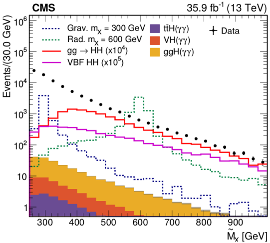
HH→bbγγ

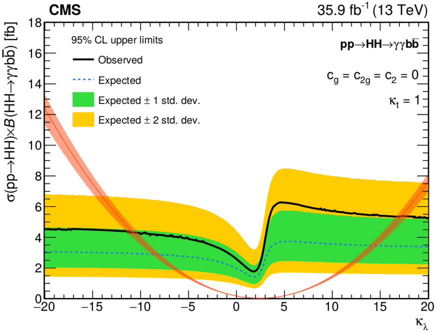
- **Most sensitive channel to SM HH**
- High bb branching ratio + **excellent γγ mass resolution**
- Main background is non-resonant $\gamma(\gamma)$ + jets and resonant Single Higgs
- Event categorisation in MVA and MX: $M_x = M(bb\gamma\gamma) - M(bb) - M(\gamma\gamma) + 2M_H$
- Signal extraction through **2D fit of M(γγ) vs M(bb)**











Result for RunII, 35.9 fb^{-1} (2016):

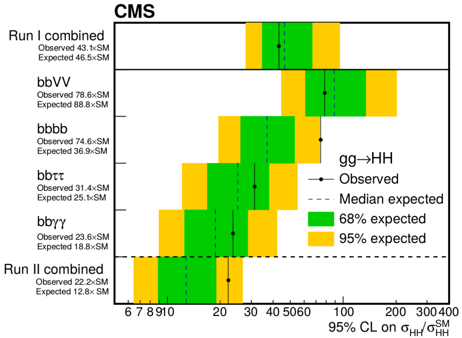
SM Obs(Exp) U.L.: 2.0 (1.6) fb

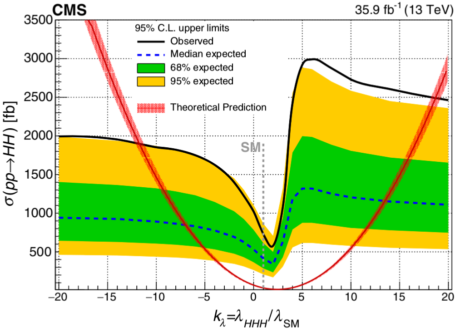
SM Obs(Exp) U.L.: 24 (9)$\times\sigma_{SM}$

BSM: -11 (-8.0) $< \kappa_\lambda <$ 17 (14)

PLB 788 (2019) 7

Combination results for RunII (2016)





Combined SM 95% CL upper limit on σ(HH)

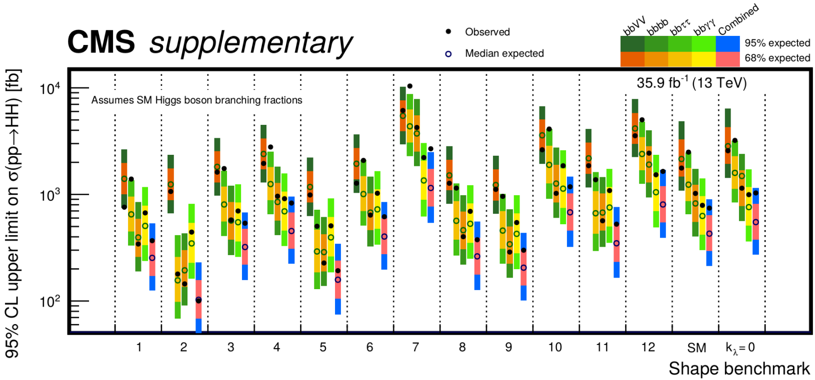
- Observed: **22.2**
- Expected: **12.8**

Constraint on κ_λ parameter:

- Observed: **-11.8** $< \kappa_\lambda <$ **18.8**
- Expected: **-7.1** $< \kappa_\lambda <$ **13.6**

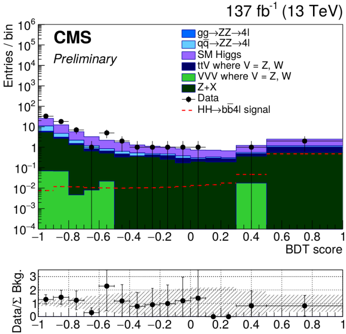
Phys. Rev. Lett. 122, 121803

Combination results for RunII (2016)

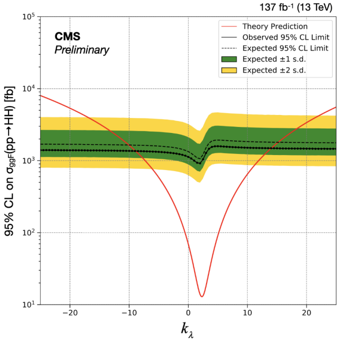


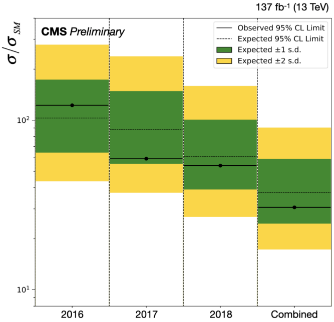
HH→bbZZ(4l) (NEW!)

- **First analysis that investigates the HH non-resonant production in bbZZ(4l) final state at the LHC**
- Select events with **two pairs of oppositely charged isolated leptons (4μ, 4e, and $2e2\mu$)** and at least **two jets**
- Single SM Higgs-boson production processes constitutes a main background
- Z+X background estimated from data
- **BDT used to discriminate** between signal and background events
- BDT trained in the SR: |m4l - 125|<10 GeV + number of jets $\geqslant 2$
- **BDT variables:**
  - p_T of the 4 leptons
  - ΔR between the H→4l and H→ $b\bar{b}$
  - p_T and b-tag score of the 2 selected jets
  - dijet invariant mass
- Different trainings for final states (bb4μ, bb4e, and bb$2e2\mu$)
- Signal extraction is performed through **multidimensional fit** to the BDT



HH→bbZZ(4l) (NEW!)





Result for full Run II, 137 fb^{-1}:

BSM: -9 (-10.5) $< \kappa_\lambda <$ 14 (15.5)

	UL @95% CL Obs (Exp) $\times\sigma_{SM}$
2016	122 (102)
2017	59 (88)
2018	53 (61)
Comb	**30 (37)**

Summary

- CMS searches for HH production presented
- We studied several final states: bbbb, bbVV, bb$\tau\tau$, bb$\gamma\gamma$, bbZZ(4l)
- Searches not yet sensitive to SM production, but limits from combinations increasingly stringent
- Various BSM scenarios tested
- Preliminary CMS result for full RunII (137 fb^{-1}) for HH$\rightarrow$bbZZ(4l) channel presented
- Full RunII results for several final states ongoing - coming soon
- Important to combine different channels and experiments
- New data will be collected in RunIII and HL-LHC

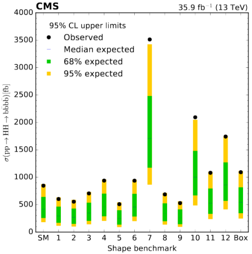
BACKUP

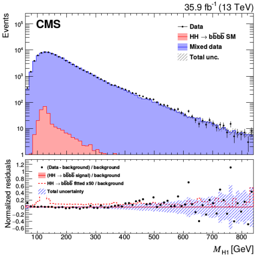
List of BDT input variables

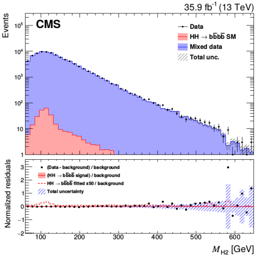
HH system	H candidates	Jet variables
M_{X}, M_{HH},	M_{H_1}, M_{H_2}	$p_{\mathrm{T}_\mathrm{j}}^{(i=1\text{–}4)}$, $\eta_\mathrm{j}^{(i=1\text{–}4)}$,
$p_{\mathrm{T}}^{\mathrm{H}_1\mathrm{H}_2}$	$p_{\mathrm{T}}^{\mathrm{H}_1}$, $p_{\mathrm{T}}^{\mathrm{H}_2}$	$H_{\mathrm{T}}^{\mathrm{rest}}$, H_{T}
$\cos\theta^*_{\mathrm{H}_1\mathrm{H}_2-\mathrm{H}_1}$	$\cos\theta^*_{\mathrm{H}_1-\mathrm{j}_1}$	$CMVA_3$, $CMVA_4$
	$\Delta R_{\mathrm{jj}}^{\mathrm{H}_1}$, $\Delta R_{\mathrm{jj}}^{\mathrm{H}_2}$, $\Delta\phi_{\mathrm{jj}}^{\mathrm{H}_1}$, $\Delta\phi_{\mathrm{jj}}^{\mathrm{H}_2}$	

Systematic uncertainties

Source	Affects	Exp. limit variation
Bkg. shape	bkg.	30%
Bkg. norm.	bkg.	8.6%
b tagging eff.	sig	2.8%
Pileup	sig	<0.01%
Jet energy res.	sig	<0.01%
Jet energy scale	sig	<0.01%
Int. luminosity	sig	<0.01%
Trigger eff.	sig	<0.01%
μ_{F} and μ_{R} scales	sig	<0.01%
PDF	sig	<0.01%



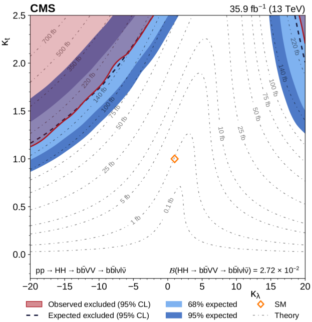




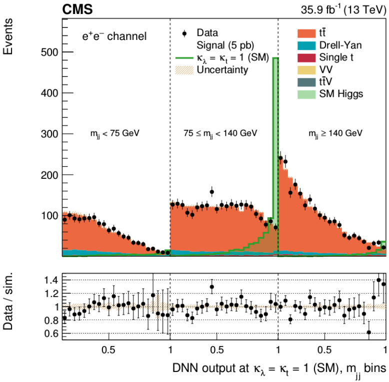
HH→bbVV

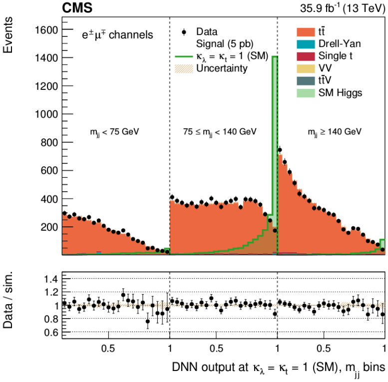
Systematic uncertainties

Source	Background yield variation	Signal yield variation
Electron identification and isolation	2.0–3.2%	1.9–2.9%
Jet b tagging (heavy-flavour jets)	2.5%	2.5–2.7%
Integrated luminosity	2.5%	2.5%
Trigger efficiency	0.5–1.4%	0.4–1.4%
Pileup	0.3–1.4%	0.3–1.5%
Muon identification	0.4–0.8%	0.4–0.7%
PDFs	0.6–0.7%	1.0–1.4%
Jet b tagging (light-flavour jets)	0.3%	0.3–0.4%
Muon isolation	0.2–0.3%	0.1–0.2%
Jet energy scale	<0.1–0.3%	0.7–1.0%
Jet energy resolution	0.1%	<0.1%
Affecting only $t\bar{t}$ (85.1–95.7% of the total bkg.)		
μ_R and μ_F scales	12.8–12.9%	
$t\bar{t}$ cross section	5.2%	
Simulated sample size	<0.1%	
Affecting only DY in $e^{\pm}\mu^{\mp}$ channel (0.9% of the total bkg.)		
μ_R and μ_F scales	24.6–24.7%	
Simulated sample size	7.7–11.6%	
DY cross section	4.9%	
Affecting only DY estimate from data in same-flavour events (7.1–10.7% of the total bkg.)		
Simulated sample size	18.8–19.0%	
Normalisation	5.0%	
Affecting only single top quark (2.5–2.9% of the total bkg.)		
Single t cross section	7.0%	
Simulated sample size	<0.1–1.0%	
μ_R and μ_F scales	<0.1–0.2%	
Affecting only signal	SM signal	m_X = 400 GeV
μ_R and μ_F scales	24.2%	4.6–4.7%
Simulated sample size	<0.1%	<0.1%



The variables used as input are: $m_{\ell\ell}$, $\Delta R_{\ell\ell}$, ΔR_{jj}, $\Delta\phi(\ell\ell, jj)$ (defined as the $\Delta\phi$ between the dijet and the dilepton systems), $p_T^{\ell\ell}$, p_T^{jj}, $\min(\Delta R_{j\ell})$, and $m_T = \sqrt{2 p_T^{\ell\ell} p_T^{\text{miss}}[1 - \cos\Delta\phi(\ell\ell, \vec{p}_T^{\text{miss}})]}$.

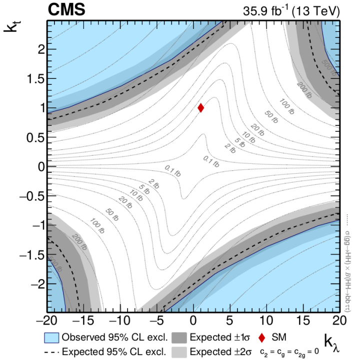




HH→bb$\tau\tau$

Systematic uncertainties

Systematic uncertainty	Value	Processes
Luminosity	2.5%	all but multijet, $Z/\gamma^* \rightarrow \ell\ell$
Lepton trigger and reconstruction	2–6%	all but multijet
τ energy scale	3–10%	all but multijet
Jet energy scale	2–4%	all but multijet
b tag efficiency	2–6%	all but multijet
Background cross section	1–10%	all but multijet, $Z/\gamma^* \rightarrow \ell\ell$
$Z/\gamma^* \rightarrow \ell\ell$ SF uncertainty	0.1–2.5%	$Z/\gamma^* \rightarrow \ell\ell$
Multijet normalization	5–30%	multijet
Scale unc.	+4.3%/−6.0%	signals
Theory unc.	5.9%	signals



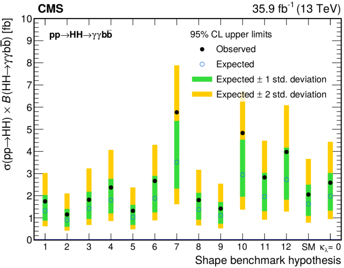
HH→bb$\gamma\gamma$

Definition of high-purity category (HPC) and medium-purity category (MPC)

Analysis	Region	Classification MVA	$\tilde{M}_X$
Nonresonant	High-mass	HPC: MVA $>$ 0.97 MPC: 0.6 $<$ MVA $<$ 0.97	$\tilde{M}_X > 350\,\text{GeV}$
	Low-mass	HPC: MVA $>$ 0.985 MPC: 0.6 $<$ MVA $<$ 0.985	$\tilde{M}_X < 350\,\text{GeV}$

Summary of systematic uncertainties.

Sources of systematic uncertainties	Type	Value (%)
Integrated luminosity	Normalization	2.5
Photon related uncertainties		
Diphoton selection (with trigger uncertainties and PES)	Normalization	2.0
Photon identification	Normalization	1.0
PES ($\frac{\Delta m_{\gamma\gamma}}{m_{\gamma\gamma}}$)	Shape	0.5
PER ($\frac{\Delta\sigma_{\gamma\gamma}}{\sigma_{\gamma\gamma}}$)	Shape	5.0
Jet related uncertainties		
Dijet selection (JES+JER)	Normalization	0.5
JES ($\frac{\Delta m_{jj}}{m_{jj}}$)	Shape	1.0
JER ($\frac{\Delta\sigma_{jj}}{\sigma_{jj}}$)	Shape	5.0
Resonant analysis specific uncertainties		
Mass window selection (JES+JER)	Normalization	3.0
Classification MVA – b tagging (HPC)	Normalization	10–19
Classification MVA – b tagging (MPC)	Normalization	3–9
Nonresonant analysis specific uncertainties		
$\tilde{M}_X$ Classification	Normalization	0.5
Classification MVA – b tagging (HPC)	Normalization	10–19
Classification MVA – b tagging (MPC)	Normalization	3–9
Theoretical uncertainties in the SM single-Higgs boson production		
QCD missing orders (ggH, VBF H , VH, t$\bar{\text{t}}$H)	Normalization	0.4–5.8
PDF and α_S uncertainties (ggH, VBF H , VH, t$\bar{\text{t}}$H)	Normalization	1.6–3.6
Theoretical uncertainty b$\bar{\text{b}}$H	Normalization	20
Theoretical uncertainties in the SM HH boson production		
QCD missing orders	Normalization	4.3–6
PDF and α_S uncertainties	Normalization	3.1
m_t effects	Normalization	5



HH→bbZZ(4l) (NEW!)

Physics object selection criteria

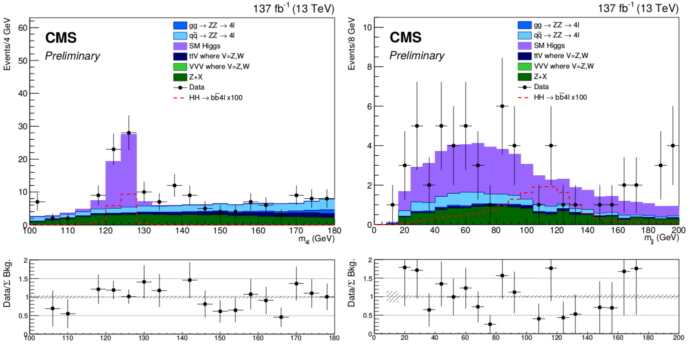
Electrons
$p_T^e > 7\,\mathrm{GeV}$ $\quad |\eta^e| < 2.5$
$d_{xy} < 0.5\,\mathrm{cm}$ $\quad d_z < 1\,\mathrm{cm}$
$|SIP_{3D}| < 4$
Muons
Global or Tracker Muon
Discard Standalone Muon tracks if reconstructed in muon system only
Discard muons with muonBestTrackType==2 even if they are globa or tracker muons
$p_T > 5\,\mathrm{GeV}$ $\quad |\eta^\mu| < 2.4$
$d_{xy} < 0.5\,\mathrm{cm}$ $\quad d_z < 1\,\mathrm{cm}$
$|SIP_{3D}| < 4$
PF muon ID if $p_T < 200$ GeV, PF muon ID or High-p_T muon ID (Table 11) if $p_T > 200$ GeV
$\mathcal{I}^{\mu}_{PF} < 0.35$
FSR photons
$p_T^{fl} > 2\,\mathrm{GeV}$ $\quad |\eta^\gamma| < 2.4$
$\mathcal{I}^{\gamma}_{PF} < 1.8$
$\Delta R(\ell,\gamma) < 0.5$ $\quad \frac{\Delta R(\ell,\gamma)}{(p_T^\gamma)^2} < 0.012\,\mathrm{GeV}^{-2}$
Jets
$p_T^{jet} > 20\,\mathrm{GeV}$ $\quad |\eta^{jet}| < 2.4$
$\Delta R(\ell/\gamma, \mathrm{jet}) > 0.3$
Cut-based jet ID (tight WP)
Jet pileup ID (tight WP)

Selections:

- Z candidates are built as lepton pairs:
  - Same flavour ($\mu^+\mu^-$,e^+e^-)
  - $12 < m_{ll(\gamma)} < 120$ GeV
- ZZ (non-overlapping Z candidates pairs):
  - $\Delta R > 0.02$ for each of the 4 leptons
  - $p_T(l1) > 20$ GeV, $p_T(l2) > 10$ GeV
  - $m_{ll} > 4$ GeV for lepton pairs
  - $m_{Z1} > 40$ GeV
  - discard 4μ and 4e candidates where the alternative combination Z_aZ_b satisfy $|$m(Z_a)-m$(Z)|<|$m(Z_1)-m$(Z)|$ and m(Z_b)<12 GeV
  - $115 < m_{4l} < 135$ GeV$/c^2$
- di-Jets:
  - $\Delta R > 0.3$; $p_T > 20$ GeV
  - two jets with the highest b-tagging score

HH→bbZZ(4l) (NEW!)

Reconstruced invariant masses of H→4l and H→bb, after full selection (full RunII)



HH→bbZZ(4l) (NEW!)

Theory uncertainties	
PDF set and α_s HH $\rightarrow 4\ell$b	3.0%
QCD scale HH $\rightarrow 4\ell$b	2.2 – 5%
m_{top} unc HH $\rightarrow 4\ell$b	2.6%
PDF set ggH	1.8%
α_s ggH	2.59 – 2.62%
QCD scale ggH	4.27 – 6.49%
PDF set and α_s VBFH	2.1%
QCD scale VBFH	0.3 – 0.4%
PDF set and α_s ZH	1.6%
QCD scale ZH	2.7 – 3.5%
PDF set and α_s WH	1.3%
QCD scale WH	0.5%
PDF set and α_s bbH	3.2%
QCD scale bbH	4.6 – 6.7%
PDF set and α_s ttH	3.6%
QCD scale ttH	6.0 – 9.2%
PDF set and α_s qqZZ	3.1 – 3.4%
QCD scale qqZZ	3.2 – 4.2%
Electroweak correction qqZZ	0.1%
PDF set and α_s ttW	25 – 37.5%
QCD scale ttW	3 – 4%
PDF set and α_s ttZ	7 – 14%
QCD scale ttZ	2 – 3%
PDF set and α_s VVV	2 – 17%
QCD scale VVV	3%
PDF set and α_s ggZZ	3.2%
QCD scale ggZZ	4.6 – 6.7%
Electroweak correction ggZZ	10.0%

Experimental uncertainties			
type	2016	2017	2018
Luminosity	2.6%	2.3%	2.5%
Leptons ID and reco eff	1.6 – 15.5%	1.1 – 12.1%	1.0 – 11%
b tagging SF	shape	shape	shape
JEC	shape	shape	shape
JER	shape	shape	shape
Z+X uncertainties	30 – 41%	30 – 38%	30 – 37%

Perspectives for HH searches

Getting closer to the observation of SM Higgs pair production:

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

- the single analyses are constantly improving
- full RunII statistics: $\sim$137 fb^{-1}

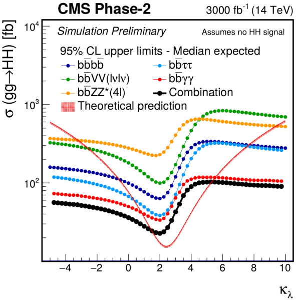
Projected sensitivity of the combination of the 5 existing analyses (PU=200, L=3000 fb^{-1})

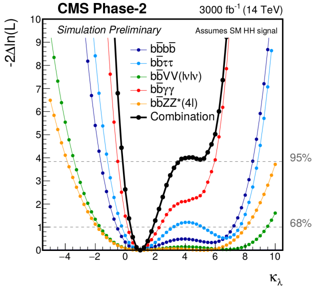
Channel	Significance		95% CL limit on $\sigma_{\mathrm{HH}}/\sigma_{\mathrm{HH}}^{\mathrm{SM}}$	
	Stat. + syst.	Stat. only	Stat. + syst.	Stat. only
bbbb	0.95	1.2	2.1	1.6
bb$\tau\tau$	1.4	1.6	1.4	1.3
bbWW($\ell\nu\ell\nu$)	0.56	0.59	3.5	3.3
bb$\gamma\gamma$	1.8	1.8	1.1	1.1
bbZZ($\ell\ell\ell\ell$)	0.37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

Projected constraints on κ_λ:

$$0.35 < \kappa_\lambda < 1.9 \text{ at } 68\% \text{ CL}$$
$$-0.18 < \kappa_\lambda < 3.6 \text{ at } 95\% \text{ CL}$$

CMS-PAS-FTR-18-019





See Sandhya Jain talk!