Are two scalar bosons better than one? di-H(125) studies at CMS

a.k.a 'More bosons, more fun'

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CMS collaboration

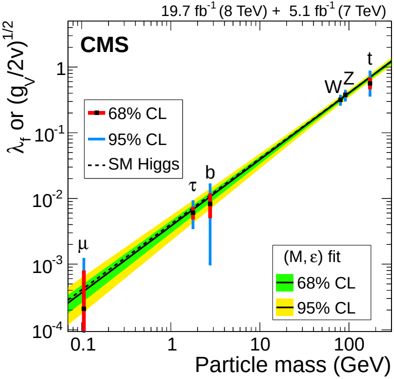
Fundamental interactions and IAP meeting
June 19th 2015

Why bother: we have found *a* BEH boson

- Observed by ATLAS & CMS in July 2012, **VERY** SM-like:
  - Mass in the expected range ($\approx 1\,\sigma$ away from EW fit)
  - Couplings match SM predictions, spin-parity favors 0^+
- **It is a BEH boson**, SM looks complete, so **what now?**

Moving forward: BSM still needed

- Final states with a scalar boson:
  - **Measurements in the scalar sector** (deviations? non-minimal?)
  - **Connection between the new boson and BSM physics**

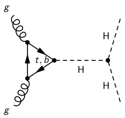


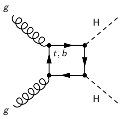
CMS-HIG-14-009 ; http://arxiv.org/abs/1412.8662

Di-H(125) final states: motivations

Context: the Standard Model

- Two diagrams dominating (λ and y_t)
- Intefere destructively almost perfectly
- $\sigma(ggHH) \approx 10(40)$ fb at 8(14) TeV





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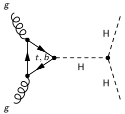

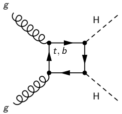

So then, why looking at these final states?

- **Self-coupling λ currently unconstrained** (prediction: $m_H^2 = \sqrt{2}\lambda / G_F$)
  - Shape of the potential responsible for EWSB
  - More freedom in Effective Field Theory (λ, y_t, c_{2t}, c_g, c_{2g}, ...)
- *Start* to be sensitive to SM at HL-LHC: **upgrade strategy is decisive!**

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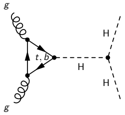

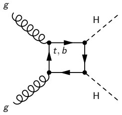

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- *Start* to be sensitive to SM at HL-LHC: **upgrade strategy is decisive!**
- **Many** BSM theories predict **resonant production** of HH
  - SUSY, extensions of the scalar sector (2HDM)
  - Warped Extra Dimension: radion (spin-0) or graviton (spin-2)
- m_X and σ can be considered as **free parameters**
  - $m_X \in [250; YYYY]$ GeV; $\sigma \in [10, 1000]$ fb for $\sqrt{s} = 8$ TeV

Resonant di-H(125) production

$$gg \rightarrow X \rightarrow HH$$

8 TeV searches

- Two Higgs Doublet Model (2HDM)
  - Multilepton and di-photon final states
- Warped Extra Dimension (WED)
  - **Final state with two b-quarks and two photons**
  - Final state with four b-quarks

Extended scalar sector (I): Two Higgs Doublet Model

Two Higgs Doublet Model (2HDM)

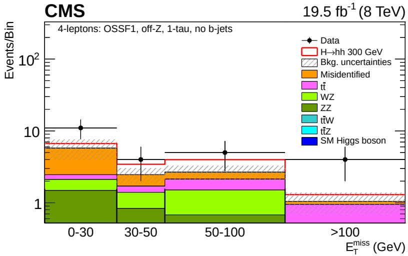
- Simplest extension compatible with gauge invariance of the minimal scalar sector
- 5 physical bosons:
  - 2 neutral CP-even scalars h and H
  - one neutral CP-odd pseudo-scalar A
  - 2 charged scalars $H^{\pm}$

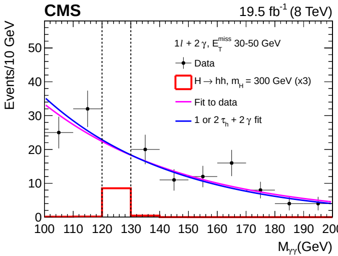
Phys. Rev.**D** 90 (2014) 112013: Search for $H \to hh$ and $A \to Zh$

- **Generic search with $h(125)$**: leptons and photons in the final state
- H in the range $[260, 360]$ GeV

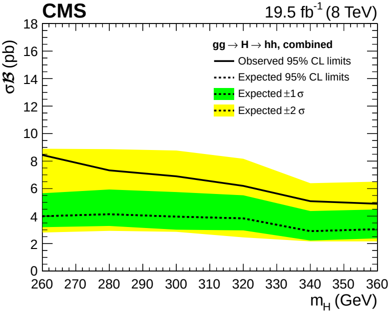
- **Cut and count search** based on dilepton and diphoton triggers
- Classification by N_l / OSSF pairs / off-on Z, N_τ, N_b, $\not{E}_T$
- **Very diverse background composition**

Extended scalar sector (II): search strategy





- Sensitivity comes mostly from decays of h to W and τ
- Multilepton final states: main bkg from Z+jets, VV+jets, tt, QCD
- Diphoton final states: bkg estimated in $m_{\gamma\gamma}$ sidebands

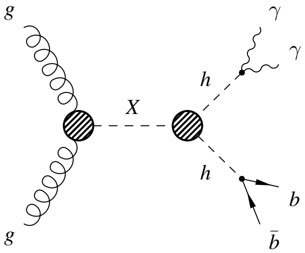


No significant deviation from expectations

Warped Extra Dimension: motivation

Benchmark model

- **WED models**: radion and (kk)graviton
  - These radion and graviton couple to h
  - σ depend on the scale Λ_R
  - Radion mass depends on ED stabilization mechanism (= model)
  - Graviton mass depends on the geometry of the ED
- Consider only **non-boosted regime** $m_X \in [270, 1100]$ **GeV**



CMS-PAS-HIG-13-032: dedicated resonant HH search

- **Gluon-fusion** production of a massive object X
- Object X decaying to a **pair of $h(125)$**
- hh (SM) decay to $b\bar{b}\gamma\gamma$:
  - Low BR $(0.26\,\%)$ - clean final state - low bkg - reconstruction of X

WED: H(bb)H($\gamma\gamma$) object selection

Photons

- $L = 19.7\,\text{fb}^{-1}$, $\sqrt{s_{pp}} = 8$ TeV
- **Inspired from $H \to \gamma\gamma$**
  - Diphoton trigger, cut based photon ID, ...
- Standard CMS vertex $\sum p_T^2$

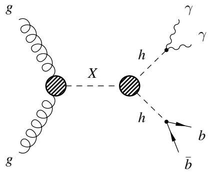
Jets

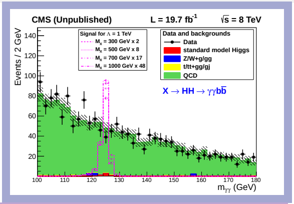
- Loose jet ID, PU rejection
- At least one b-tagged jet (CSV Medium WP, 60-70% efficiency)
- Hbb candidate : prefer b-tagged jets, max(p_T^{jj}) pair

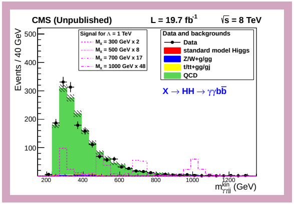
Photons	Jets	Events classification
tight photon identification $p_{T\gamma_1}/m_{\gamma\gamma} > 1/3$ $p_{T\gamma_2}/m_{\gamma\gamma} > 1/4$ $\lvert\eta_\gamma\rvert < 2.5$ $100 < m_{\gamma\gamma} < 180$ GeV	loose jet identification pileup rejection $p_{Tj} > 25$ GeV $\lvert\eta_j\rvert < 2.5$ at least 1 b–tagged jet	$\geq$2 b–tagged jets exactly 1 b–tagged jet

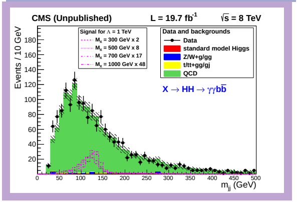
- Dominant background : QCD production of $\gamma\gamma jj$
  - **2 b-tagged jets : high-purity**
  - **1 b-tagged jet: medium purity**

WED: H(bb)H($\gamma\gamma$) signal extraction









Strategy: three invariant mass handles $m_{\gamma\gamma}$, $m_{\rm jj}$, $m_{\gamma\gamma\rm jj}$

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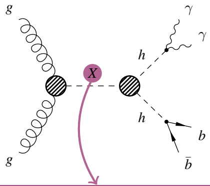

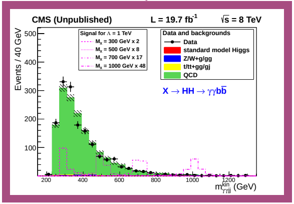

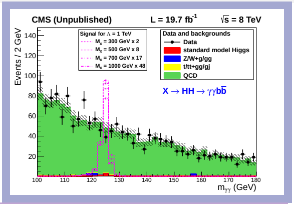

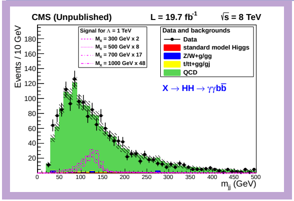

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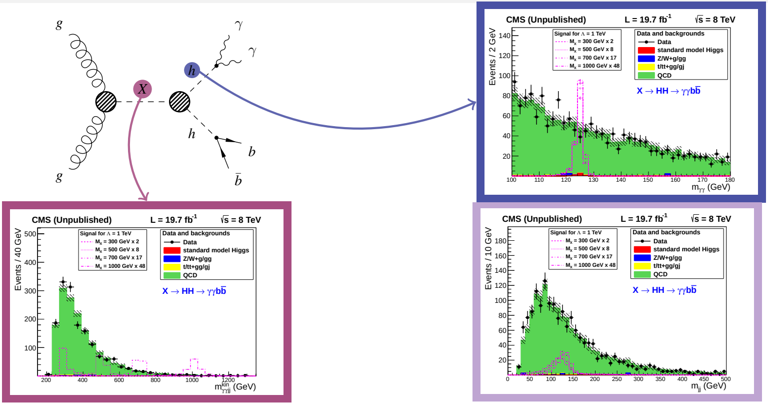

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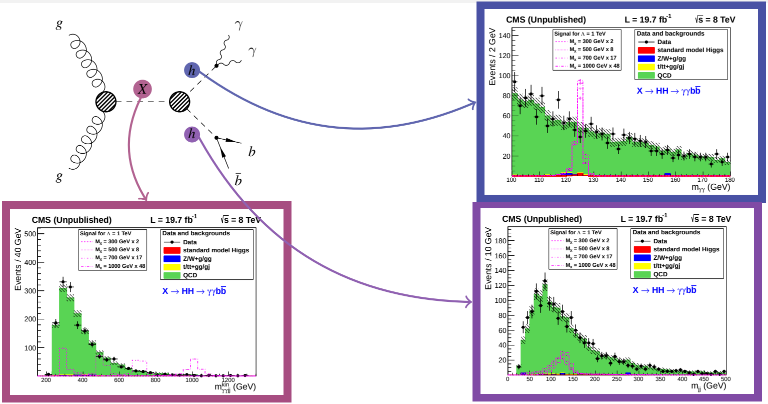

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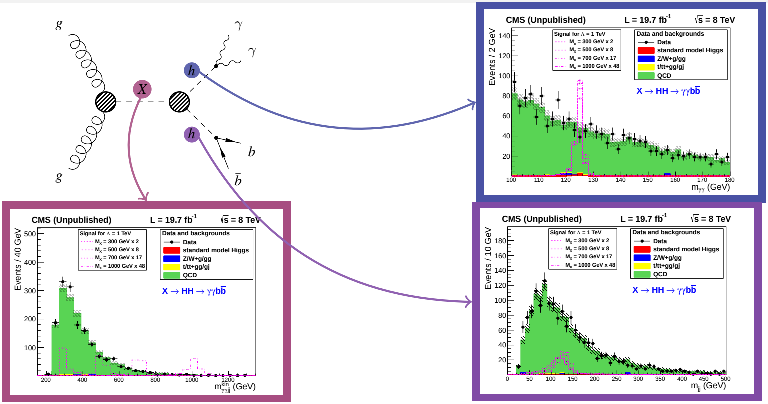

Strategy: three invariant mass handles $m_{\gamma\gamma}$, $m_{\rm jj}$, $m_{\gamma\gamma\rm jj}$

- $m_{\gamma\gamma\rm jj}$ ideal for limit extraction (direct handle on X)

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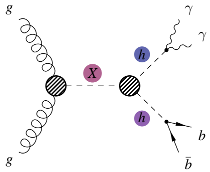

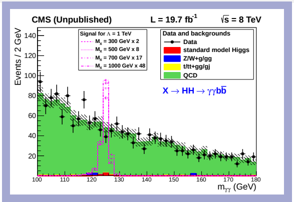

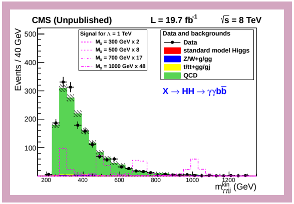

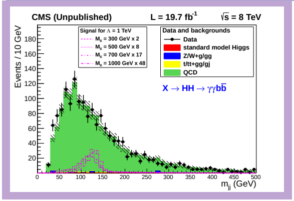

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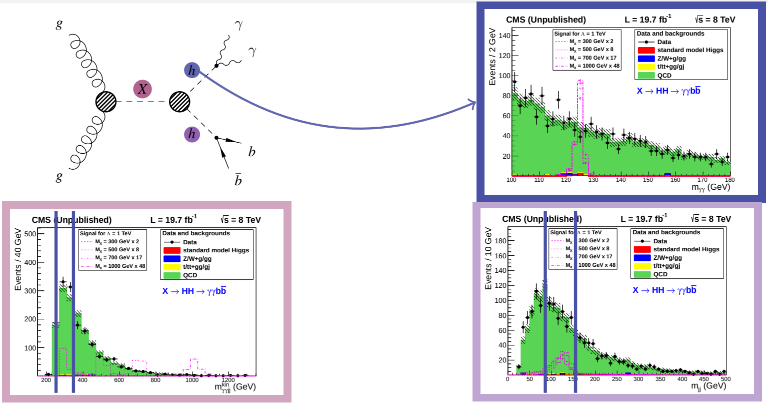
- $m_{\gamma\gamma\rm jj}$ ~~ideal~~ for limit extraction (direct handle on X) **kin. peak** (≈ 300 GeV)
- Split in **two regimes** for signal extraction:

WED: H(bb)H($\gamma\gamma$) signal extraction



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- Split in **two regimes** for signal extraction:
  - **Low mass** ($m_X \leq 400$ GeV): cut $m_{\gamma\gamma\rm jj}$ and $m_{\rm jj}$, **fit $m_{\gamma\gamma}$**

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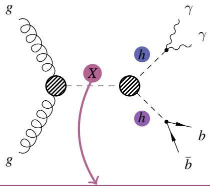

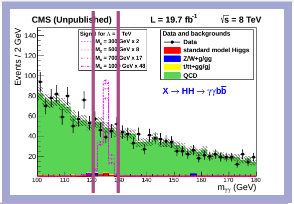

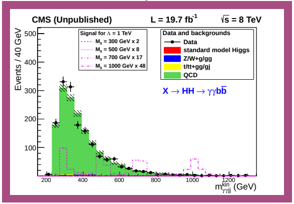

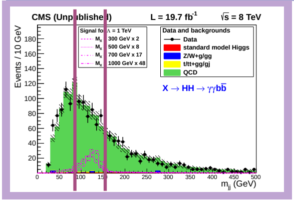

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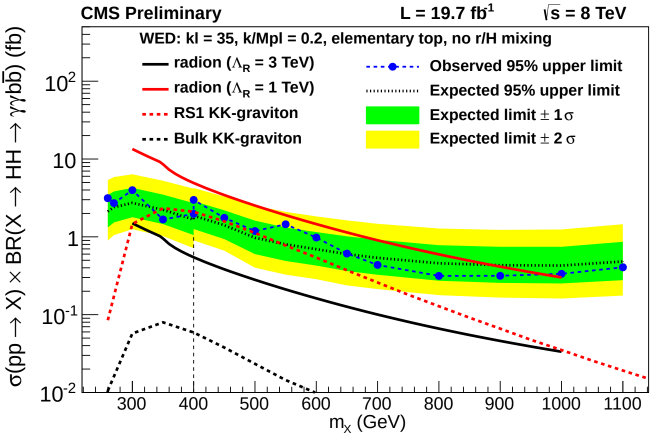
  - **Low mass** ($m_X \leq 400$ GeV): cut $m_{\gamma\gamma\rm jj}$ and $m_{\rm jj}$, **fit $m_{\gamma\gamma}$**
  - **High mass** ($m_X \geq 400$ GeV): cut $m_{\gamma\gamma}$ and $m_{\rm jj}$, **fit $m^{\rm kin.}_{\gamma\gamma\rm jj}$** (after kin. fit)

WED: H(bb)H($\gamma\gamma$) limits



No significant deviation from expectations

- The analysis is observed to be statistics-limited
- **Improved analysis in progress** for paper publication

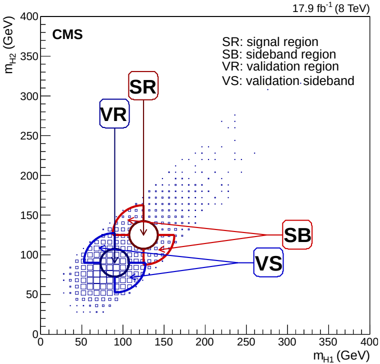
WED: H(bb)H(bb) object selection

arXiv:1503.04114

- **Branching ratio**: 33.3%
- **Trigger strategy**:
  - 4(2) jets with $p_T > 30(80)$ GeV
  - 2 CSV-b–tagged jets

Object selection: 4 jets

- $p_T > 40$ GeV and $|\eta| < 2.5$
- CMVA b–tag ($\epsilon_{\mathrm{(mis)tag}} = 75(3)\%$)
- Low Mass Region (≤ 440 GeV): 2 jets with $p_T > 90$ GeV
- High Mass Region (≥ 450 GeV): $\Delta R(jj) < 1.5$ ($p_{T_{jj}} > 300$ GeV if $m_X \in [740, 1100]$ GeV)
- **Combinatorics**: min $|m_{h1} - m_{h2}|$



Signal Region

- $\sqrt{\Delta m_{h1}^2 + \Delta m_{h2}^2} < 17.5$ GeV (with $\Delta m_{h1,2} = m_{h1,2} - 125$ GeV)
- Use kinematic fit (m_{jjjj} resolution)

WED: H(bb)H(bb) signal extraction

Signal extraction: fit to m_{jjjj}^{kin}

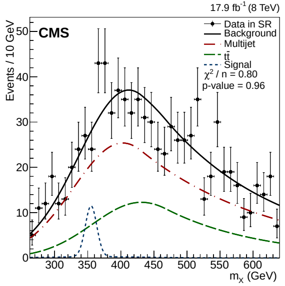
- **QCD multi-jet dominant** (data)
- $t\bar{t}$: 22 to 27% (mc)
- Z+jets, ZZ, ZH negligible

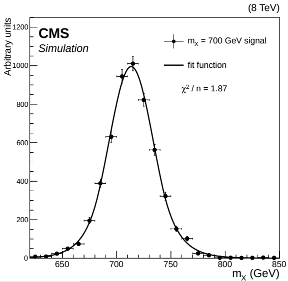
Background fit

- Gaussian extended with exp.
- **Shape determined in SB**
- VB → VR **validates** SB → SR
- **Validation** reversing 1 b–tag

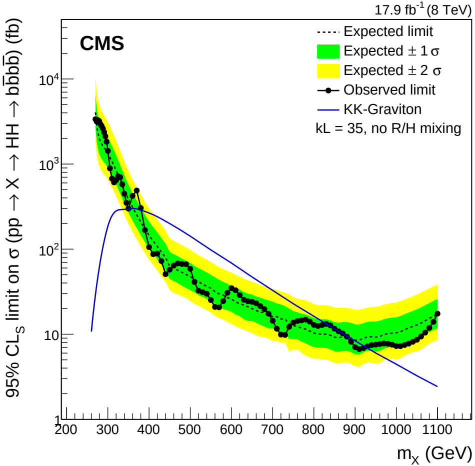
Signal model

- Gaussian extended with 2 exp.





WED: H(bb)H(bb) limits



No significant deviation from expectations (spin-0 or spin-2)

- Trigger efficiency critical for low mass
- Most powerful analysis for high mass

Non-resonant di-H(125) production

$$gg \rightarrow HH$$

14 TeV prospects ($\sigma_{SM} = 40.7$ fb)

- Standard Model benchmark
- Final states:
  - Two b-quarks and two photons
  - Two b-quarks and two tau leptons
  - **Two b-quarks and two W bosons decaying leptonically**

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8 TeV searches ($\sigma_{SM} = 9.96$ fb)

- Effective Field Theory (EFT) with dim. 6 operators:
  - Self-coupling λ
  - Top Yukawa coupling y_t
  - Anomalous ttHH coupling c_2
- Final state:
  - **Final state with two b-quarks and two photons**

Future studies: Motivation

- Of the future accelerator options currently under study, the Large Hadron Collider is the **only facility currently operating**.

Period		$\sqrt{s}$ (TeV)	$\int L$ (fb^{-1})	L (cm^{-2}s^{-1})	$< pu >$	BX (ns)
2009-2012	Run I	7 and 8	25	7×10^{33}	21	50
2013-2014	LS1	"Phase 1" upgrades				
2015-2017	Run II	13 (14?)	-	10^{34}	25	25
2018-2019	LS2	"Phase 1" upgrades				
$\approx$ 2021	Run III	-	300	-	50	-
2022-2023	LS3	"Phase 2" upgrades				
$\approx$ 2024	HL-LHC	-	3000	5×10^{34}	140	-

For HL-LHC (14 TeV, 3000 fb^{-1}) Technical Proposal Phase-II Upgrade

- $\sigma(pp \to HH) = 40.7$ fb: ≈ 120 k events produced

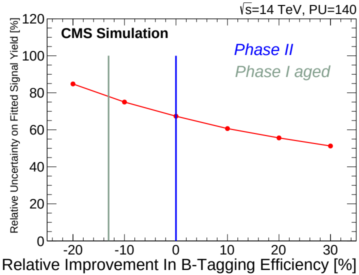
channel	Nevents
$b\bar{b}b\bar{b}$	$\approx$ 41 000
$jjVV$	$\approx$ 41 000
$b\bar{b}\tau\tau$	$\approx$ 9 000
$b\bar{b}\gamma\gamma$	$\approx$ 320

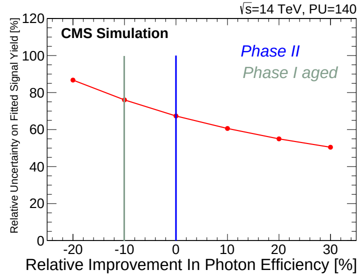
Future studies: H(bb)H($\gamma\gamma$)

Analysis strategy

- **Object performance tuned to Phase II**
- 2 tight photons, 2 b–tagged jets, lepton veto
- $\Delta R(bb) < 2.$, $\Delta R(\gamma\gamma) < 2.$, $\Delta R(b\gamma) > 1.5$
- categories: EBEB, !EBEB
- 2D fit $(m_{\gamma\gamma}, m_{jj})$

- Upgrade strategy and future **performance have a direct impact** on the final physics reach!



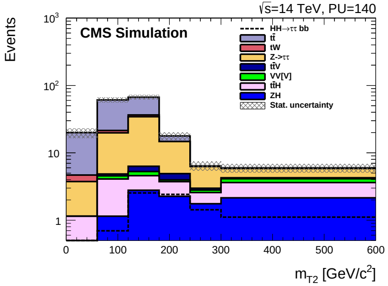


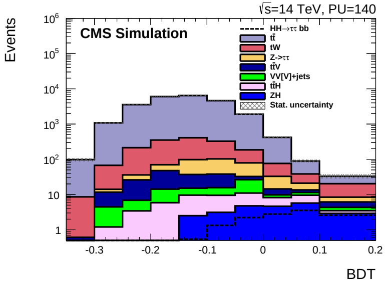
Future studies: H(bb)H($\tau\tau$)

$HH \to b\bar{b}\tau\tau$ (BR = 7.29%)

- **Phase II object performance**
- $\tau_h\tau_h$ and $\tau_h\tau_\mu$ final states
- Dominating backgrounds: $t\bar{t}$, Z+jets, ZH, $t\bar{t}$H
- 2 b–tagged jets and 2 taus
- SVFIT $m_{\tau\tau}$ reconstruction
- $\tau_h\tau_h$: fit on m_{T2}
- $\tau_h\tau_\mu$: BDT on m_{T2}, m, p_T, ΔR of bb, $\tau\tau$ and HH systems

- Expected significance of 0.9 σ (105% uncertainty on μ)
- **Estimates rely on triggering on tracks at L1** (alternative: sensitivity reduced by 40%)



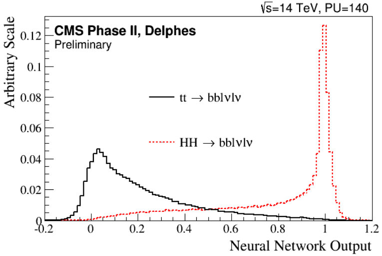


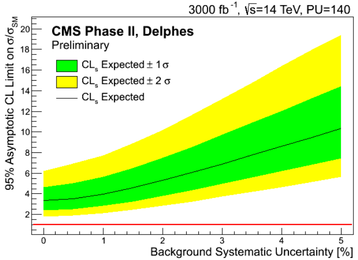
Future studies: H(bb)H(WW)

$HH \to b\bar{b}W(l\nu)W(l\nu)$ (BR = 1.22%)

- **Phase II object performance (Delphes)**
- 2 CSVM jets $p_T > 30$ GeV
- 2 leptons, $p_T(\mu(e)) > 20(25)$ GeV
- MET > 20 GeV
- NN: Variables: m_{ll}, m_{jj}, $\Delta R(ll)$, $\Delta R(jj)$, $\Delta R(jl)$, MET, $\Delta\phi(ll, jj)$, $p_T(jj)$, m_T
- **Dominating background: $t\bar{t}$**

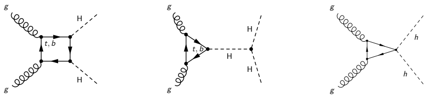
- Challenging measurement! But very promising sensitivity
- **Run II analysis** preparation just starting





Final cut: 3875 bkg events, 37.1 signal events

Preparing Run II: non-resonant H(bb)H($\gamma\gamma$) @ 8TeV



y_t $\quad$ y_t, λ $\quad$ c_2

Benchmark for aHH

- Parameters can vary for ggHH process: λ, y_t, c_2
- **Scan of shapes and σ**
  - Private MG5 samples

$(\kappa_\lambda = \lambda/\lambda_{\text{SM}}, c_2)$	$\sigma^{LO}/\sigma^{LO}_{SM}$, $\kappa_t = y_t/y_{tSM}$ = .5	1.	1.2
(1 , 2)	38	29	23
(1 ,-2)	42	51	59
(1 , 0)		SM	
(20, 2)	125	39	305
(20,-2)	12	250	61

CMS Analysis currently in finalization on 8 TeV data

- Shape and normalization evaluated on full-sim samples
- ATLAS expected sensitivity at 1 pb ($\approx 100 \times \sigma_{SM}$)
- **Current data already sensitive** to anomalous scenarios!
  - Scan of the anomalous parameter space

Conclusions

Preparing Run II: overview

Run I results being finalized

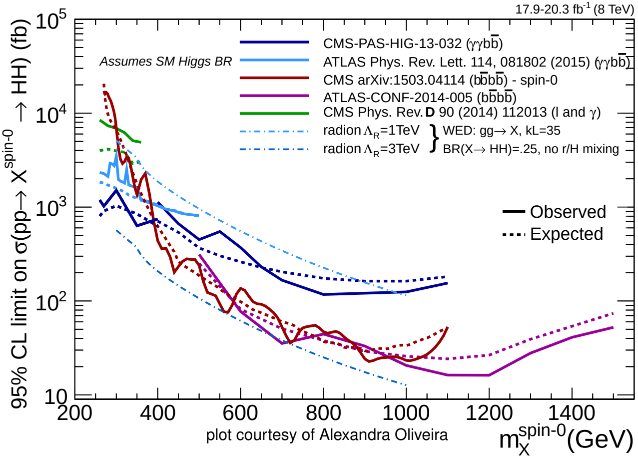
- H(bb)H($\gamma\gamma$) paper: improved low mass, first non-resonant study
- H(bb)H($\tau\tau$) papers: low mass (MSSM), high mass, non-resonant
- H(bb)H(bb) paper

Ramping up efforts for Run II

- **All final states plan to continue** to Run II
  - H(bb)H(WW) joining the game!
- Should reach 8 TeV-like sensitivity around 2-5 fb^{-1}
  - **first access to VBF during 2015?** (both res. / non-res.)
- Harmonization of MC plans (both res. / non-res.) across final states

Exciting times ahead!

Conclusion



- Searches for two scalar bosons are gearing up
  - Nine (9) LHC public results in the past year!

    Looking forward to more data during LHC Run II!

BACKUP

Future studies: H(bb)H($\gamma\gamma$)

Process / Selection Stage	HH	ZH	$t\bar{t}H$	$b\bar{b}H$	$\gamma\gamma$+jets	γ+jets	jets	$t\bar{t}$
Object Selection & Fit Mass Window	22.8	29.6	178	6.3	2891	1616	292	113
Kinematic Selection	14.6	14.6	3.3	2.0	128	96.9	20	20
Mass Windows	9.9	3.3	1.5	0.8	8.5	6.3	1.1	1.1

Table 3: The expected event yields of the signal and background processes for 3000 fb^{-1} of integrated luminosity are shown at various stages of the cut-based selection for the both photons in the barrel region. Mass window cuts are 120 GeV to 130 GeV for $M_{\gamma\gamma}$ and 105 GeV to 145 GeV for M_{bb}. A large fit mass window, 100 GeV to 150 GeV for $M_{\gamma\gamma}$ and 70 GeV to 200 GeV for M_{bb}, is used for the likelihood fit analysis. The statistical uncertainties on the yields are of the order of percent or smaller.

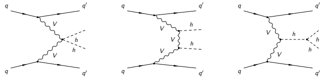
Non-resonant scalar pair production in VBF

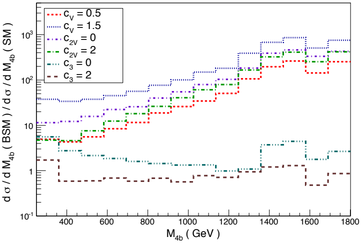
O. Bondu, A. Oliveira, R. Contino,
M. Gouzevitch, A. Massironi, J. Rojo

Proceedings : *Les Houches 2013: Physics@TeV Colliders NP WG Report* (arXiv:1405.1617)

O. Bondu et al. "Strong Double Higgs Production at the LHC in the 4b and 2b2W Final States"

- **Effective coupling modifiers**:
  - $c_{2V} g^{SM}_{hhVV} hhVV,\ c_V g^{SM}_{hVV} hVV,\ c_3 g^{SM}_{hhh} hhh$
- Sensitive to strong interactions of a composite scalar boson
- Parton level analysis of $4b$ and $2b2W$ final states, with irreducible backgrounds





Model	Final state	Cross section [fb]	N_{ev} ($\mathcal{L} = 3$ ab^{-1})
SM (no cut)	*hhjj*	0.83	2500
SM	*hhjj*	0.12	360
SM		0.049	150
$c_V = 0.5$		0.54	1600
$c_V = 1.5$		2.72	8100
$c_{2V} = 0$	$hhjj \to 4bjj$	1.23	3700
$c_{2V} = 2$		0.78	2300
$c_3 = 0$		0.14	420
$c_3 = 2$		0.042	130

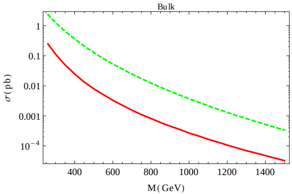
Resonant scalar pair production in VBF

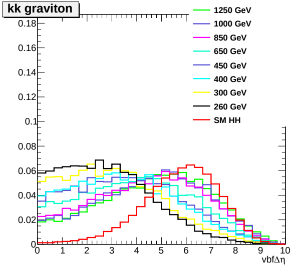
A. Belyaev, O. Bondu, A. Massironi,
A. Oliveira, R. Rosenfeld, V. Sanz

Proceedings : *Les Houches 2013: Physics@TeV Colliders NP WG Report* (arXiv:1405.1617)

A. Belyaev et al. "Resonant Higgs Pair Production in Vector Boson Fusion at the LHC"

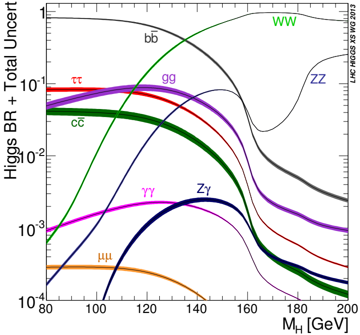
- **Vector boson fusion production of a (kk)-Graviton (spin 2)**
  - Sensitive to new physics couplings / gauge bosons polarized longitudinally
- Decay into two scalar bosons
- Partonic analysis of the $b\bar{b}b\bar{b}$ final state
- Only irreducible backgrounds studied





	$pp \to G(HH)jj$ σ (pb)	$\sigma \times$eff. (pb)	Nevents (3000/fb)	$S/\sqrt{B}$
1450 GeV	6.91E-06	8.17E-07	2.45E+00	7.74E-06
1050 GeV	7.87E-05	9.13E-06	2.74E+01	8.66E-05
650 GeV	1.28E-03	1.40E-04	4.20E+02	1.33E-03
400 GeV	1.41E-02	1.20E-03	3.60E+03	1.14E-02
300 GeV	1.55E-02	6.42E-04	1.93E+03	6.09E-03

Comments on other channels



channel	frequency(%)
$h(b\bar{b},c\bar{c},gg)h(b\bar{b},c\bar{c},gg)$	47.86
$h(b\bar{b})h(b\bar{b})$	33.30
$h(b\bar{b},c\bar{c},gg)h(VV^{*})$	33.40
$h(b\bar{b})h(\tau^{+}\tau^{-})$	7.29
$h(VV^{*})h(VV^{*})$	5.83
$h(l^{+}l^{-})h(VV^{*})$	3.06
$h(l^{+}l^{-})h(l^{+}l^{-})$	0.40
$h(b\bar{b},c\bar{c},gg)h(\gamma\gamma)$	0.32
$h(b\bar{b})h(\gamma\gamma)$	0.26
$h(b\bar{b},c\bar{c},gg)h(\mu^{+}\mu^{-})$	0.03
$h(l^{+}l^{-})h(\gamma\gamma)$	0.03

For HL-LHC ($\sqrt{s} = 14$ TeV, $\int L = 3000$ fb^{-1})

- $\sigma(pp \to HH) = 33.86$ fb: ≈ 100 k events produced

channel	Nevents
$b\bar{b}b\bar{b}$	$\approx$ 34 000
$jjVV$	$\approx$ 34 000
$b\bar{b}\tau\tau$	$\approx$ 7 400
$b\bar{b}\gamma\gamma$	$\approx$ 260

Extended scalar sector (II): search strategy

	$h \to WW^*$	$h \to ZZ^*$	$h \to \tau\tau$	$h \to bb$	$h \to \gamma\gamma$
$h \to WW^*$	☑	☑	☑	☐	☑
$h \to ZZ^*$	-	☑	☑	☑	☑
$h \to \tau\tau$	-	-	☑	☐	☑
$h \to bb$	-	-	-	☐	☐
$h \to \gamma\gamma$	-	-	-	-	☐

Leptons	Photons	OSSF pairs	Hadronic τ	b-tag
4	0	0, 1 or 2	0 or 1	0 or 1
3	0	0 or 1	0 or 1	0 or 1
2	2	0 or 1	0	-
1	2	-	0	-
1	2	-	1	-
0	2	-	1 or 2	-

hh final state	Search channels
WW^*WW^* $WW^*\tau\tau$ $\tau\tau\tau\tau$ $ZZ^*\tau\tau$ ZZ^*bb	$3-4$ leptons ($\leq 1\tau_h$), OSSF pair off-Z or no OSSF pair in bins of $\not{E}_T$ and b-tag
$\gamma\gamma WW^*$ $\gamma\gamma ZZ^*$ $\gamma\gamma\tau\tau$	2γ ($M_{\gamma\gamma}$ within scalar bin) + $\geq$ 1 leptons($\leq$ 2 τ_h),in bins of $\not{E}_T$

- Sensitivity comes mostly from decays of h to W bosons and taus:
  - Channels without OSSF pair (reduces DY)
  - Channels with OSSF pair but the invariant mass of the pair is off-Z
  - Channels with SS pairs (very low SM bkg)

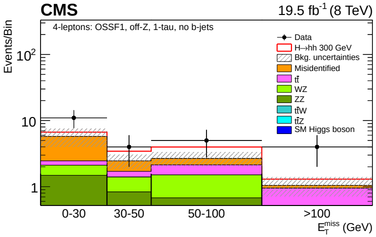
Extended scalar sector (III): background estimation

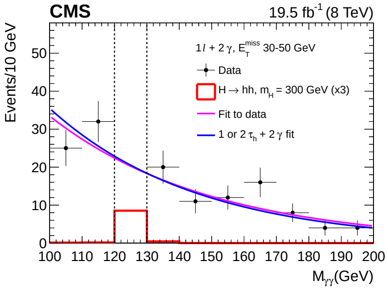
Multileptons final states

- Main backgrounds from Z+jets, VV+jets, tt, QCD, ...:
  - Non-prompt 3^{rd} lepton in $Z+$ jets, $WW+$ jets : data control sample
  - $t\bar{t}$, diboson backgounds : (validated) MC simulation
  - Asymmetric γ conversions : data control sample

Diphoton final states

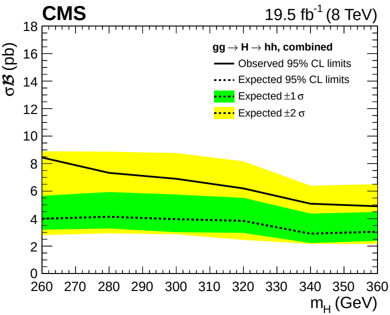
- Background evaluated in $m_{\gamma\gamma}$ sidebands ($\notin [120, 130]$ GeV) in $1-2\tau_h$, 2γ and $\not{E}_T < 30$ GeV





Extended scalar sector (IV): model-independent limits

- Limits combining lepton and photon channels
- Excess in $3(e/\mu) + \tau_h$ off-Z channels with no b-tags:
  - obs. (exp.) [3 $\not{E}_T$ bins]
    - $11(5.1 \pm 1.7)$
    - $4(2.4 \pm 0.5)$
    - $5(2.6 \pm 0.6)$
- p-values:
  - local $= 1.5\,\%$
  - global, sum of $\not{E}_T$ bins: $46\,\%$
  - global, all three $\not{E}_T$ bins: $5\,\%$

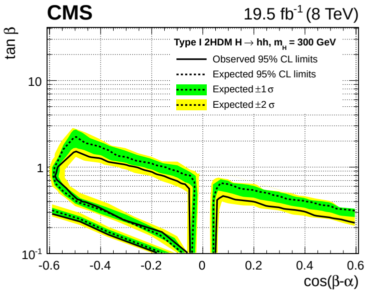


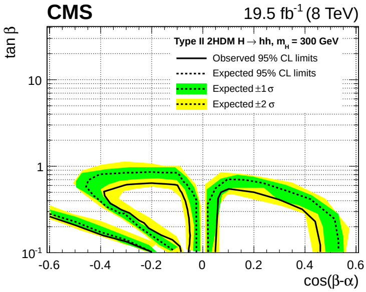
No significant deviation from expectations

Extended scalar sector (V): limits in 2HDM space

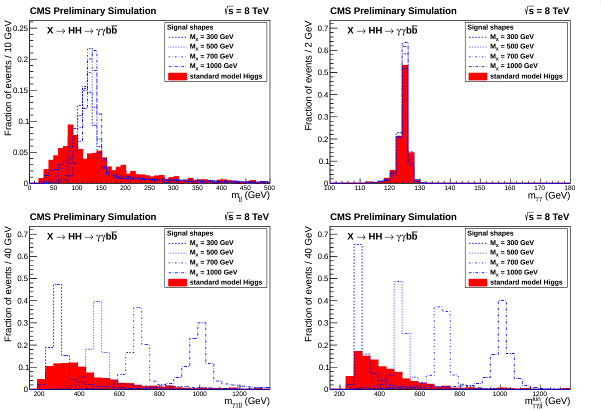
- Recast $\sigma \times BR$ limits in 2HDM Type I and Type II parameter space:
  - α (mixing $H - h$)
  - β (relative contribution of each doublet to EWSB)

1	2HDM I	2HDM II
hVV	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
hQu	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
hQd	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
hLe	$\cos\alpha\sin\beta$	$\sin\alpha\cos\beta$
HVV	$\cos(\beta-\alpha)$	$\cos(\beta-\alpha)$
HQu	$\sin\alpha\sin\beta$	$\sin\alpha\sin\beta$
HQd	$\sin\alpha\sin\beta$	$\cos\alpha\sin\beta$
HLe	$\sin\alpha\sin\beta$	$\cos\alpha\sin\beta$
AVV	0	0
AQu	$\cot\beta$	$\cot\beta$
AQd	$-\cot\beta$	$\tan\beta$
ALe	$-\cot\beta$	$\tan\beta$





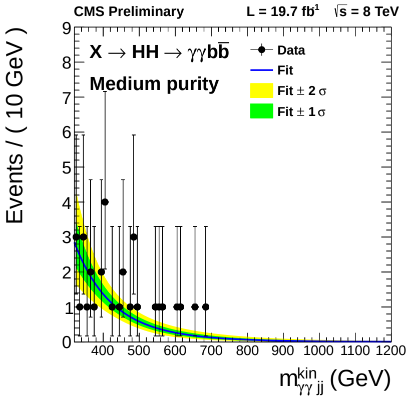
Signal shapes

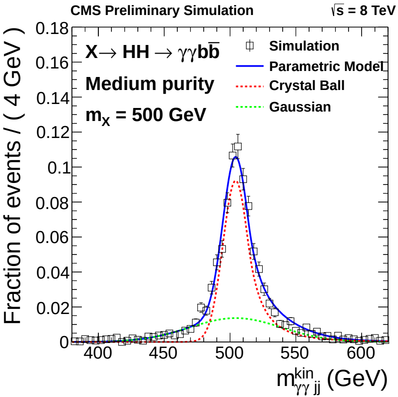


Kinematic fit

- Once the jj system is selected, constraint that m_{jj} compatible with $m_H = 125$ GeV
- This constraint takes into account the experimental jet resolutions
- Improves notably the 4-body mass spectrum resolution for signal
- Shuffle events around for background

WED: H(bb)H($\gamma\gamma$) bkg & signal modeling





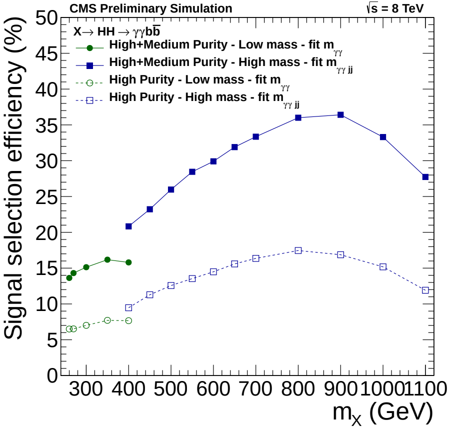
Bias studies

- Function choice for background estimation :
  - **Negligible bias on signal strength** for a variety of 'truth' background functional shapes
  - Power-law for both low and high mass

Selection cuts, efficiency and yields

m_X	$m_{\gamma\gamma jj}$ selection
260	$[225, 280]$
270	$[225, 295]$
300	$[255, 330]$
350	$[310, 395]$
400	$[370, 440]$
	m_{jj} selection
all masses	$[85, 155]$

Sample	High-purity	Medium-purity
di-Higgs resonance (300 GeV, Λ_R=1 TeV)	18.73	21.66
$ggH(\to \gamma\gamma)$	0.02	0.19
VBF ($H \to \gamma\gamma$)	0.00	0.04
$VH(\to \gamma\gamma)$	0.01	0.08
$t\bar{t}H \to \gamma\gamma$	0.10	0.15
data	21	230



Additional scalar-boson-like states in $h \to \gamma\gamma$ search

- Ancillary result from SM $H \to \gamma\gamma$ search hep-ex/1407.0558 : **substract the observed state**
  - Search for **additional $H \to \gamma\gamma$ states** in $[110, 150] \setminus [120, 130]$ GeV
  - Search for near and mass degenerate states in $[120, 130]$ GeV ($m_H + \Delta m_H$ with μx and $\mu(1-x)$ strength)