hh

SangEun Lee

1st IUEP Mini-Workshop: Physics Opportunities at Future Colliders, **2018.10.05 (금) - 2018.10.07 (일)**

Chonnam National University

Acknowledgement

"Many of the materials from hh workshop @ Fermi-Lab".

"I'm a big pan of double higgs boson search, but my experience is on single Higgs boson."

What do we know about Higgs boson?

- Consistent with $J^{CP} = 0^{++}$
- Couplings to top, gauge bosons at 10-20% level
- Couplings to bottom, tau observed
- No evidence for coupling to 1st, 2nd generations
- Higgs-self coupling?

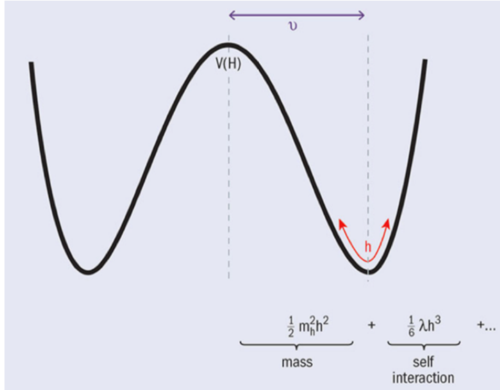
hh in Standard Model

Higgs potential

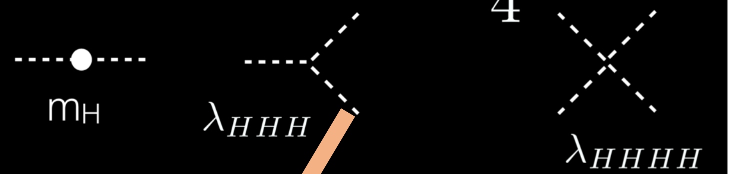
$V(\phi) = -\mu^2\phi^2 + \lambda^2\phi^4$

Reparameterization to consider the fluctuations around the minimum

$$\sqrt{\frac{\mu^2}{2\lambda}} \equiv \frac{v}{\sqrt{2}}$$



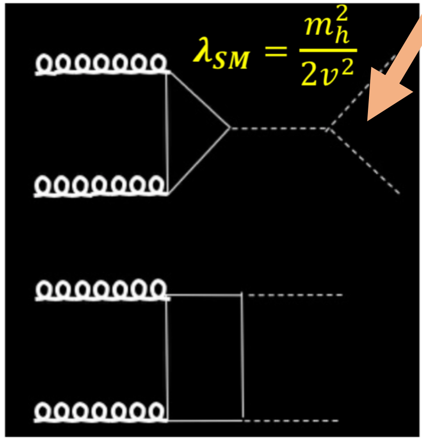
$$V(h) = \lambda v^2 h^2 + \lambda v h^3 + \frac{\lambda}{4} h^4$$



$$v^2 = (2G_F)^{-1/2}$$

$$\lambda = \frac{m_H^2}{\sqrt{2}} G_F$$

~1k di-Higgs boson event waiting to be discovered



- Destructive interference among two diagrams leads to a small cross section
  - $\sigma(gg \rightarrow HH)_{SM} = 33.53\ \text{fb}\ ^{+4.3\%}_{-6.0\%}(\text{scale}) \pm 5.9\%\ (\text{PDF})$
  - $\sigma(\text{VBF HH})_{SM} = 1.64\ ^{+0.05}_{-0.06}\ \text{fb}$

~ 1000 x less than H

- BSM contribution can modify the Higgs boson coupling parameters and enhance the HH cross section

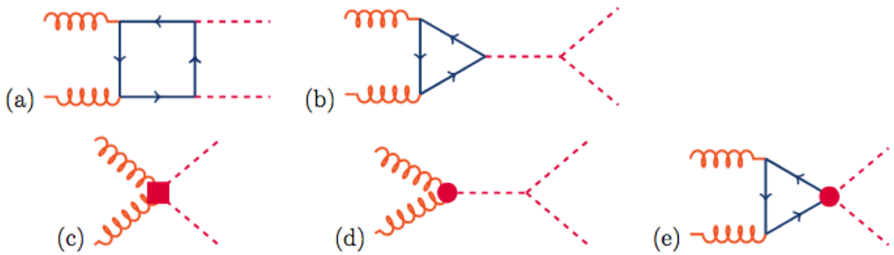
Di-Higgs non-resonant with BSM contribution

Extend the SM Lagrangian with dimension 4 and 6 operators in the framework of the EFT:

ggF HH production can be generally described by 5 parameters controlling the tree-level interactions of the Higgs boson:

$$\mathcal{L}_{\mathrm{H}} = \frac{1}{2}\partial_\mu \mathrm{H}\,\partial^\mu \mathrm{H} - \frac{1}{2}m_{\mathrm{H}}{}^2\mathrm{H}^2 - \kappa_\lambda\,\lambda_{\mathrm{SM}}\,v\,\mathrm{H}^3 - \frac{m_{\mathrm{t}}}{v}(v + \kappa_{\mathrm{t}}\,\mathrm{H} + \frac{c_2}{v}\mathrm{HH})\,(\bar{\mathrm{t}}_{\mathrm{L}}\mathrm{t}_{\mathrm{R}} + h.c.)$$
$$+\frac{1}{4}\frac{\alpha_S}{3\pi v}(c_{\mathrm{g}}\,\mathrm{H} - \frac{c_{2\mathrm{g}}}{2v}\,\mathrm{HH})\,G^{\mu\nu}G_{\mu\nu}\,.$$

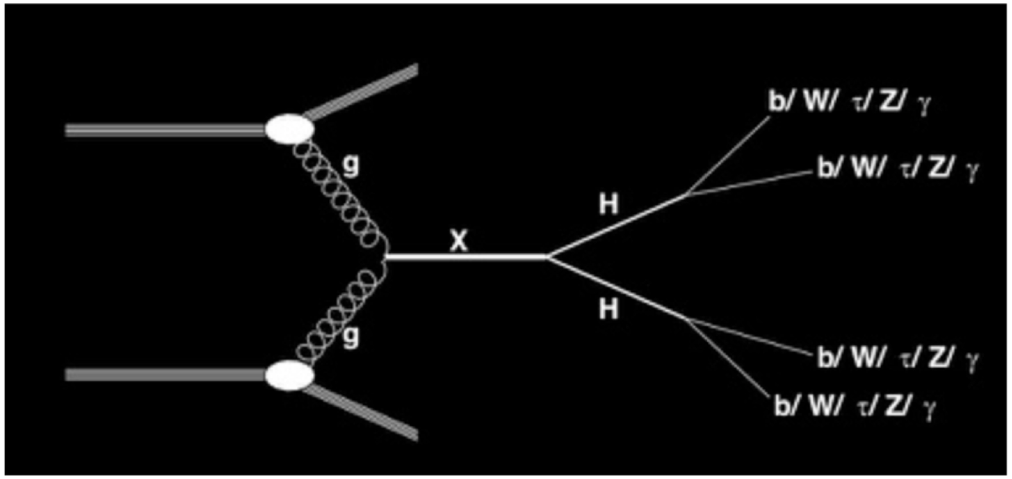
- c_{g}, $c_{2\mathrm{g}}$, c_2 for contact interactions not predicted by SM
- $\kappa_\lambda = \lambda_{\mathrm{HHH}}/\lambda_{\mathrm{SM}}$ and
- $\kappa_{\mathrm{t}} = y_{\mathrm{t}}/y_{\mathrm{SM}}$



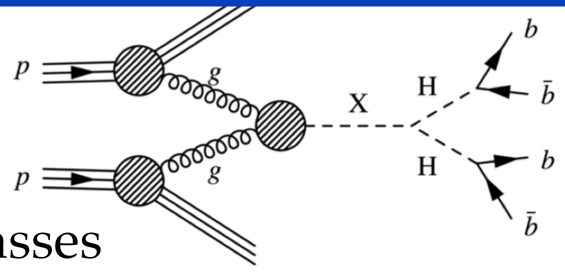
Diagrams (a) and (b) correspond to SM-like processes; (c), (d), and (e) to pure BSM effects

Di-Higgs resonant production

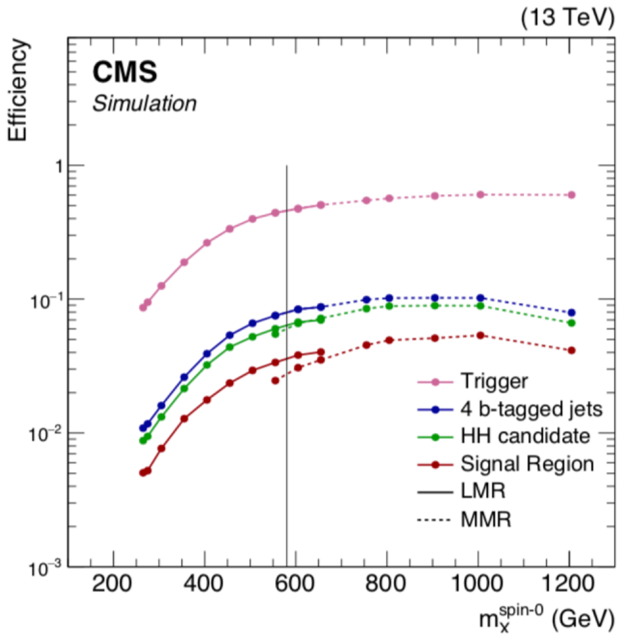
- Looking for a narrow resonance X with a mass m_X using the invariant mass spectrum m_{HH}.
  - One extra constraint w.r.t non-resonant
- Well-motivated signatures according to several scenarios:
  - Randall-Sundrum warped extra dimension ➔ spin-0 radion or spin-2 KK graviton
- Cross section is significantly enhanced on resonances (up to pb)

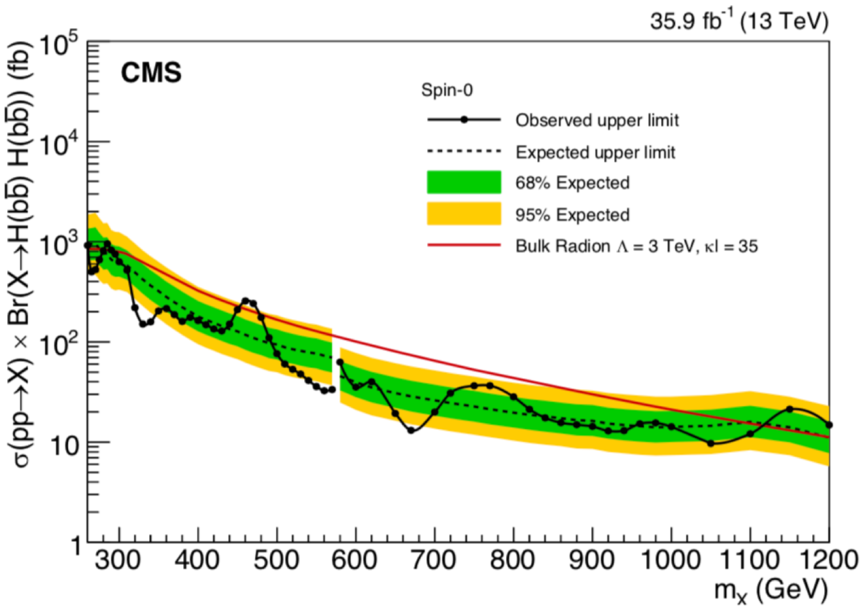


hh->4b resonant (Resolved Jet)



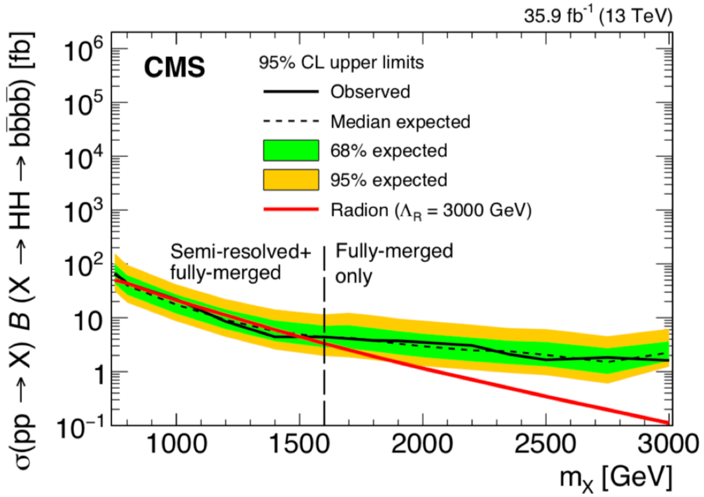
- The search covers low and medium mass regions
- Trigger the events using 4 jets (at least 3 should be b-tagged)
- Background estimation from sidebands of Higgs candidate masses
- Upper limits set on the cross section of bulk gravitions and Radions in the warped extradimensional models

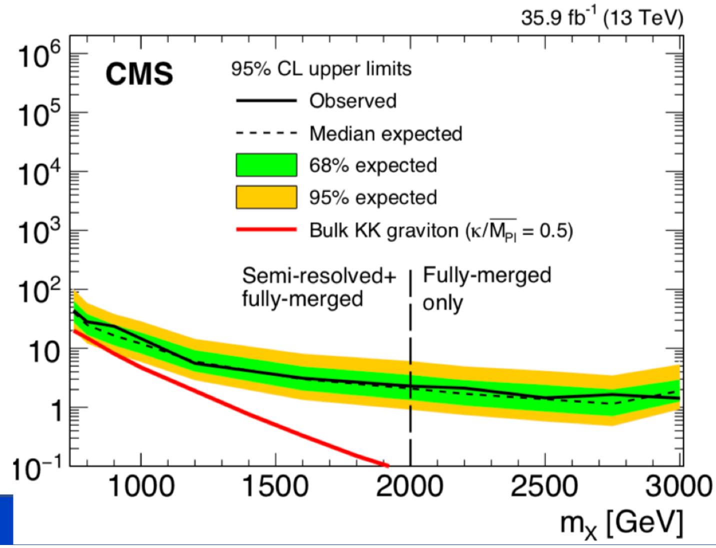




hh->4b resonant (fully- and semi-merged)

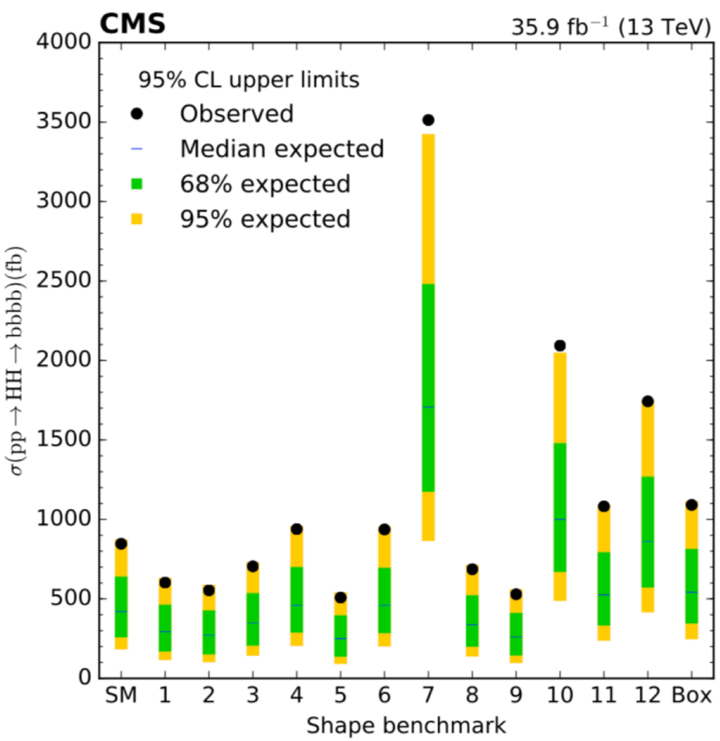
- Switch to boosted techniques for high masses
- Background estimated from sideband regions using misidentification rate of Higgs jets in QCD background
- Including semi-resolved events improve limits between 55-8% for the Radion in the mass range 750-1600 GeV
- Similar search for non resonant
  - Limit on 174 (119) obs. (exp.) times of SM Xs Br.

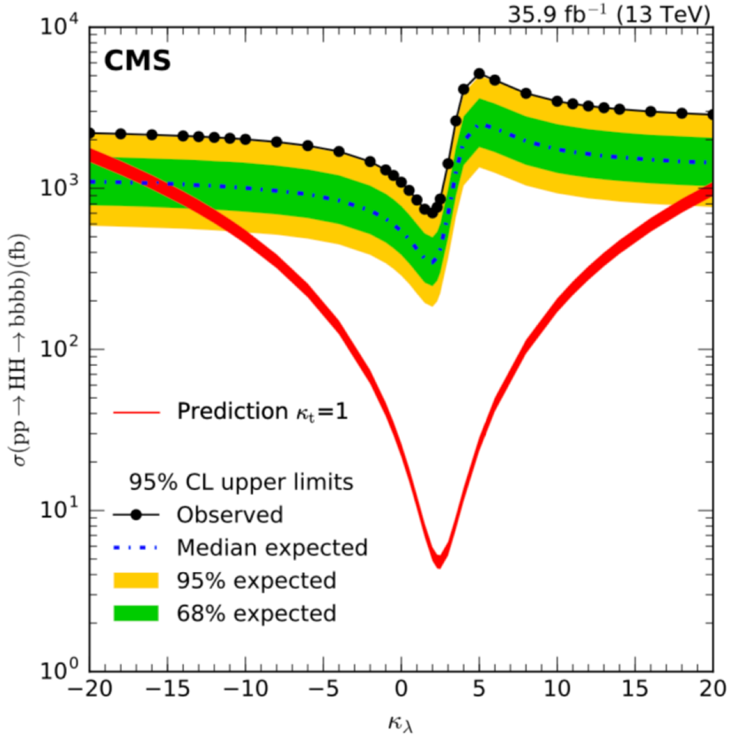




hh->4b non-resonant (resolved)

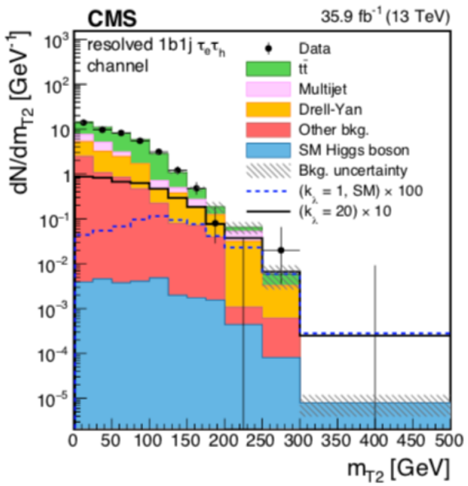
- Analysis optimized to be sensitive to the SM gg->hh->4b process
- Main background: QCD multijets. Reduced requiring 4 b jets and a BDT classifier
- Limits set on different shape benchmarks: SM, 12 BSM benchmarks

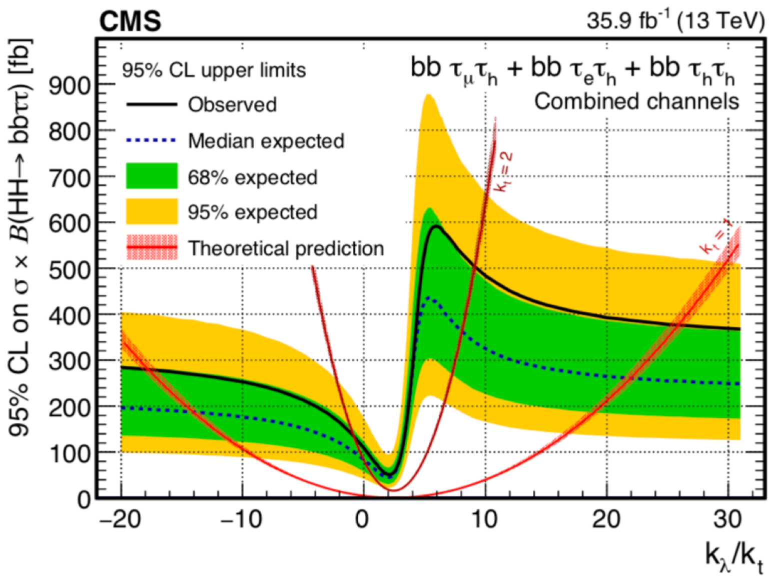


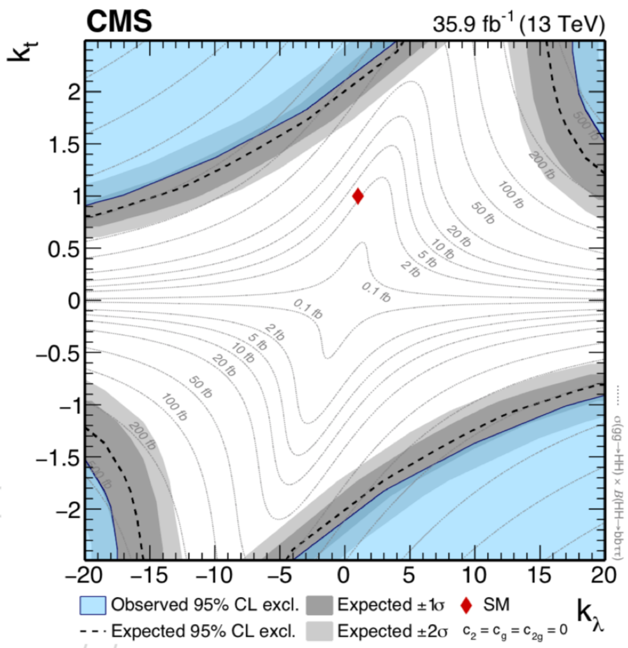


hh->bb tautau [non-resonant]

- Three different final states: bbtautau, bbmutau, bbetau
- The search also includes the cases where two b-jets are merged as a fat-jet as well
- Using m_2T as the observable
- The observed (expected) upper limit about 30 (25) times the prediction of the SM

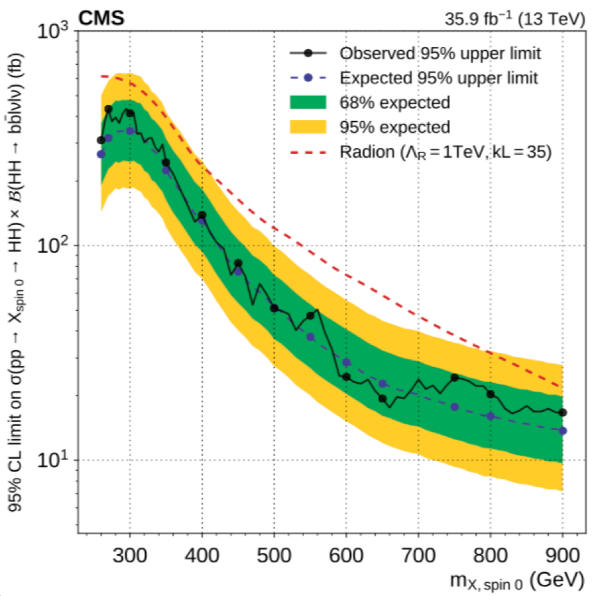


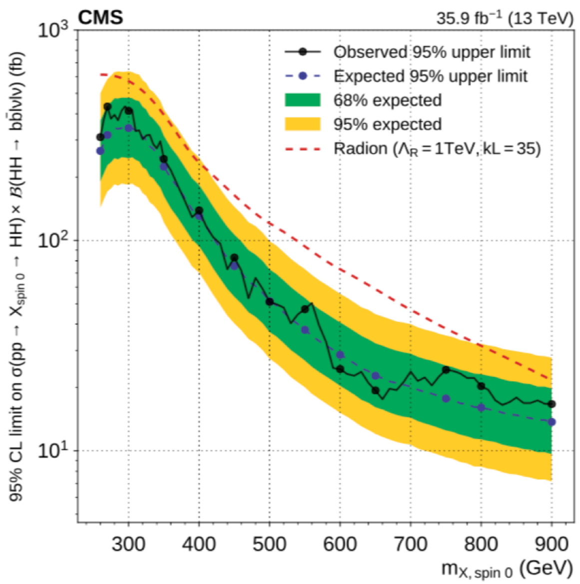




hh->bbllvv

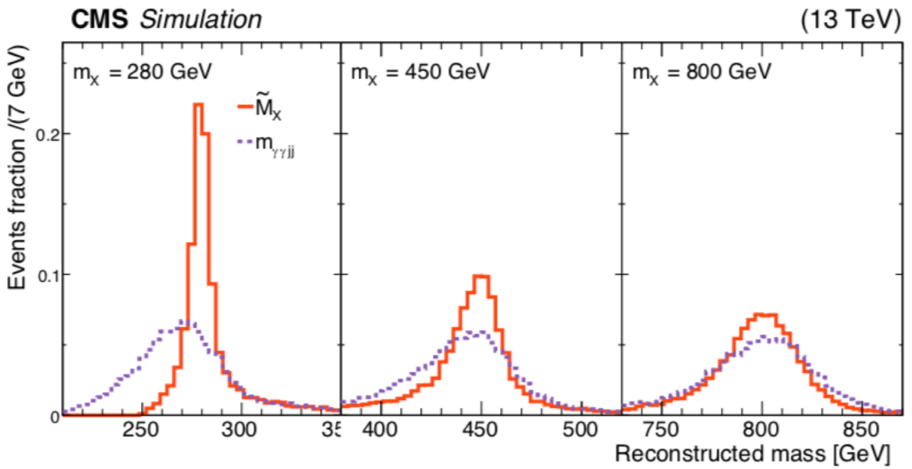
- Event categories: e+e-, mu+mu-, emu(OS) from Z(ll)Z(nunu), W(lnu)W(lnu)
- Exclude di-lepton events in case the mass is compatible with Z boson
- Neural network training used to improve signal-background sparation
- Upper limit on signal strength: obs(exp) = 79(89)XSM
- Large ttbar background limits the exclusion power at low masses

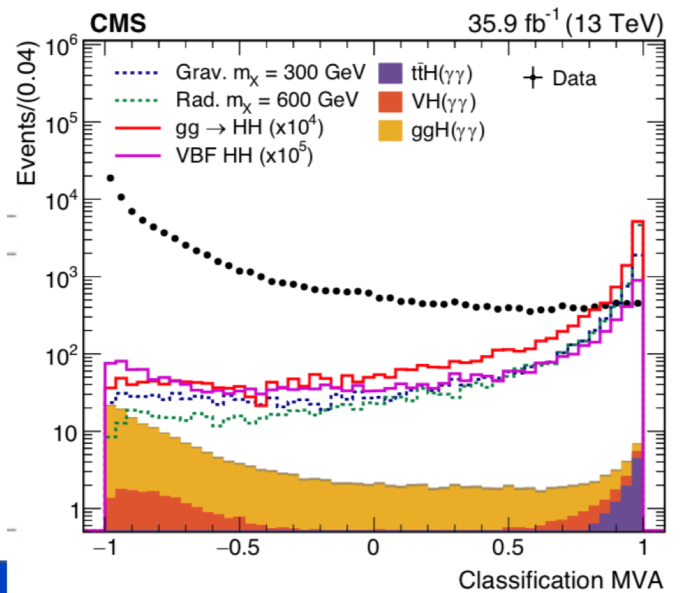




hh->bbgamgam

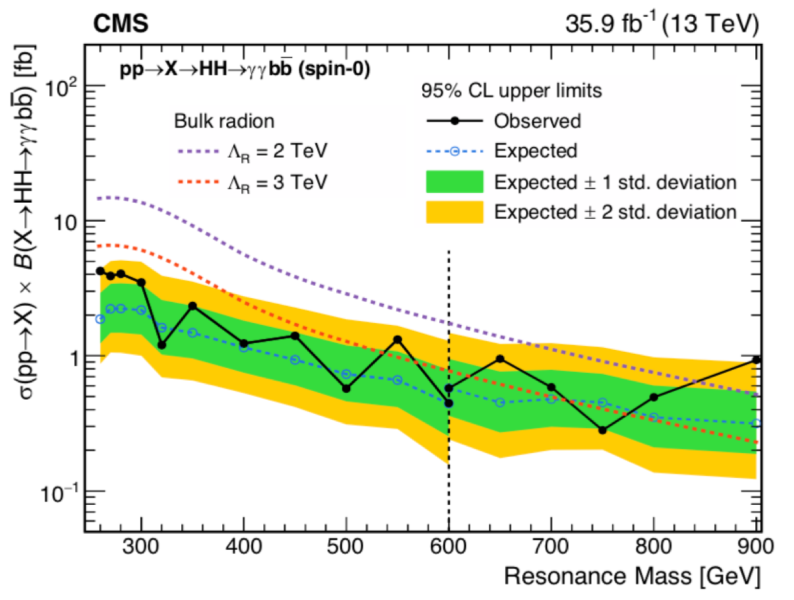
- Small BR(0.26%) but clean signature
- 2 photons + 2 b-tagged jets (2 photons trigger used)
- Resonant mass: $\widetilde{M}_X = M(jj\gamma\gamma) - M(jj) - M(\gamma\gamma) + 250$
- Categorization based on the MVA output and Mx mass
- Signal is searched for using a parametric fit to M(jj) and M(gamgam)

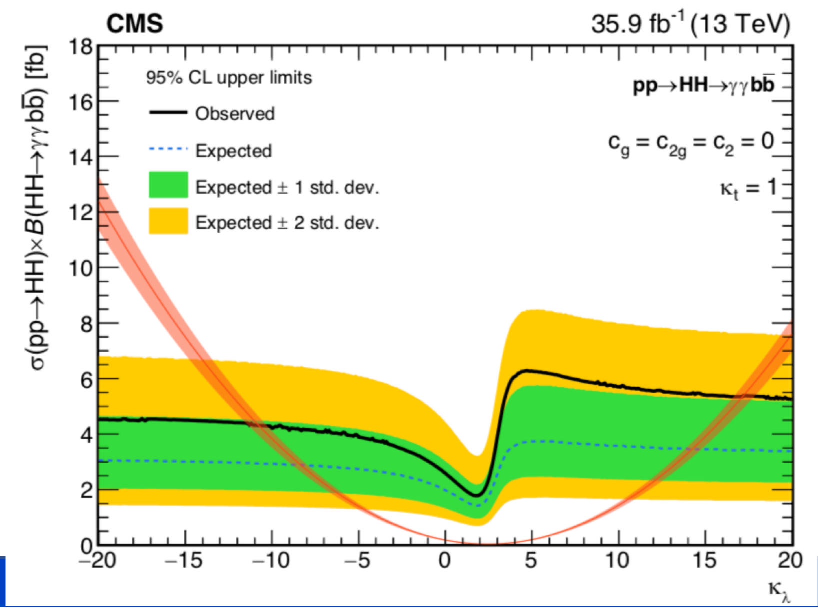




hh->bbgamgam

- Limits computed on the xs of bulk gravitons and radions in the warped extradimensional models
- Limit on SM xs of gg->hh->bbgamgam: obs (exp) 2 (1.6) fb
  - Corresponds to 24 (19) obs (exp) times to SM expectations
  - Including VBF hh production improves sensitivity by 1.3%
- Constraint on k_lambda between -11 and 17

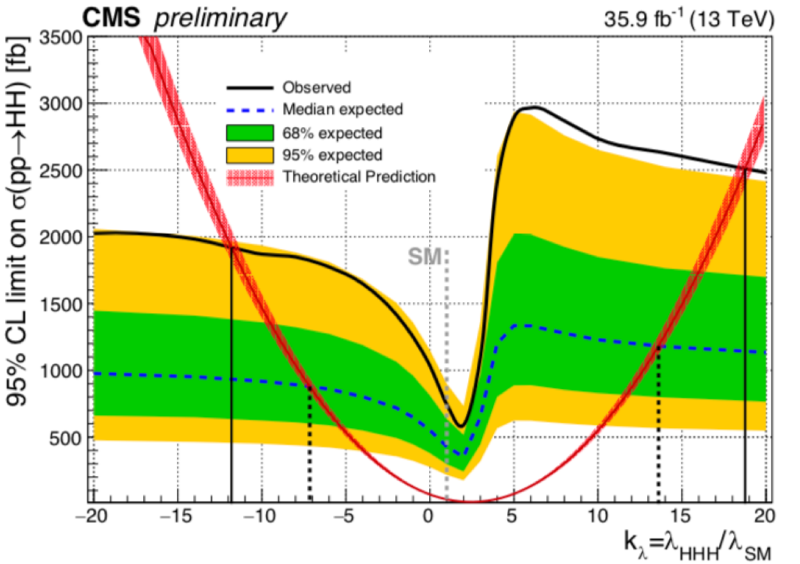


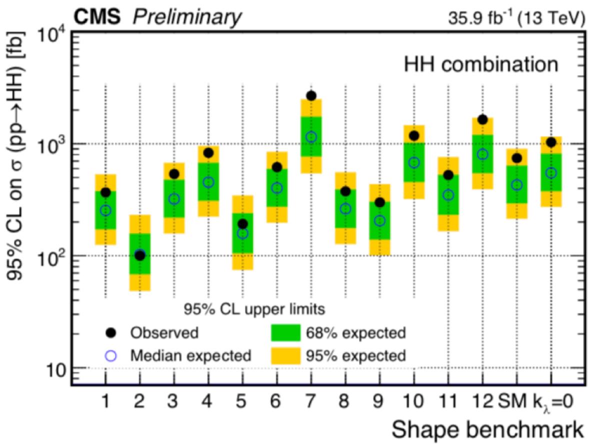


Combination of non-resonant

- Combined obs(exp) limit ~11(13) X SM
- Limits set on 12 BSM shape benchmarks, SM, and k_lambda=0
- Limit on k_lambda for k_t =1:
  - Observed: -11.8 ~ 18.8
  - Expected: -7.1 ~ 13.6
- Sensitivity to benchmarks with higher m_hh improved by including boosted topologies

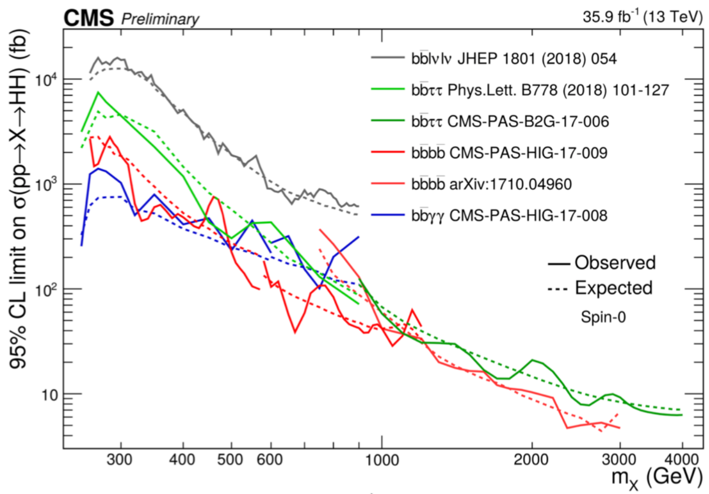
Final state	s/s_{SM} Obs(Exp)
$bb\gamma\gamma$	24 (19)
$bb\tau\tau$	31 (25)
$bbl^+l^-\nu\nu$	79 (89)
bbbb	75 (37)
Combined	22.2 (12.8)

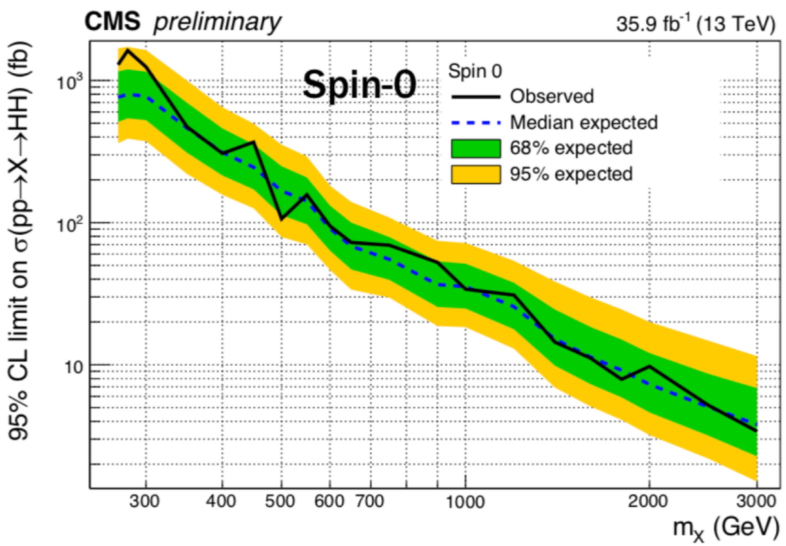


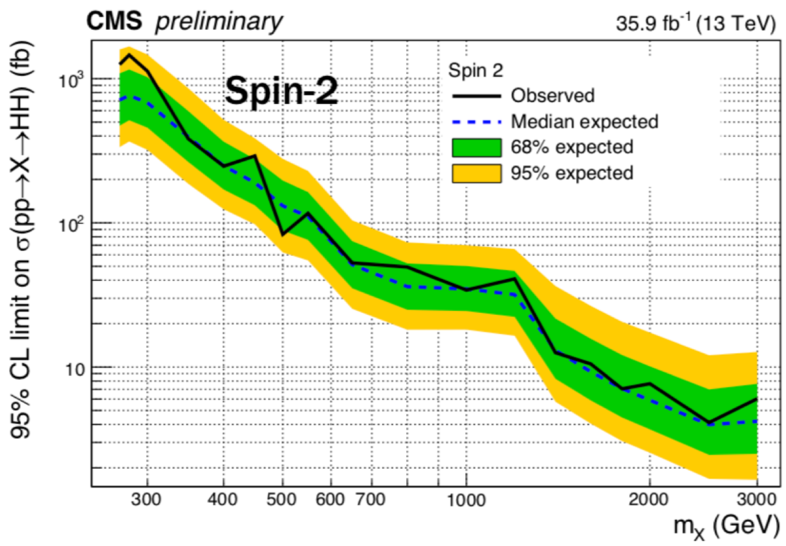


Combination of resonant

- Combination of several hh decay channels
- Interpretation in terms of spin-0 (radion) and spin-2 (bulk gravition) production cross section times the branching fraction to hh
- Narrow width approximation used

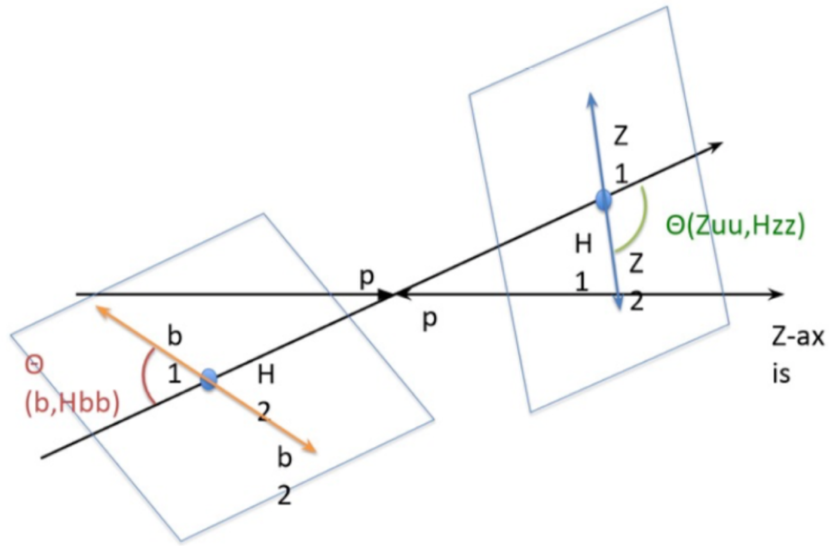






New search channels

- We have also started to explore new channels. [Less sensitive → More challenging]
- hh->bbZZ (in 3 channels)
  - bbllnunu
  - bbllll
  - bbllqq
  - Apart from kinematical distributions, some angular distributions are fed into the BDT
- hh → tautautautau
  - Clean signatures with either 1, 2 or 3 leptons
  - Dedicated effort to reconstruct ditau mass, consequently 4 tau system
  - Non-negligible contribution from WWtautau and WWWW

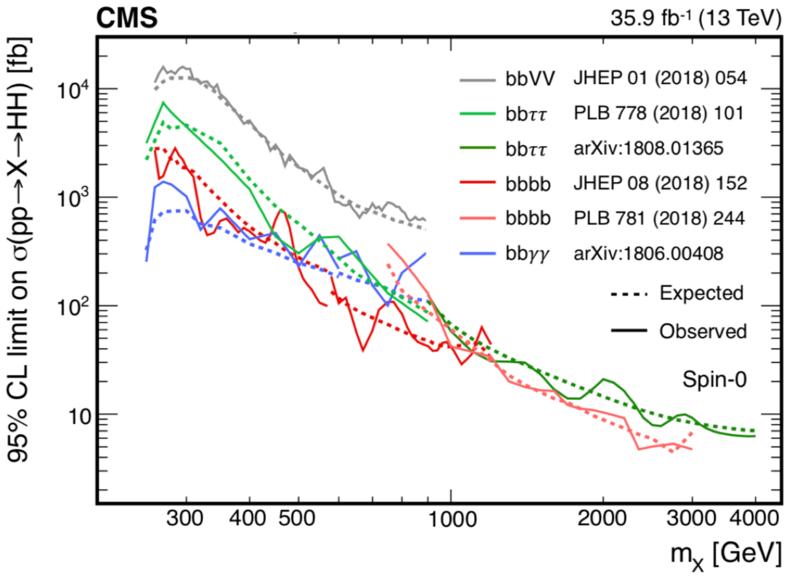


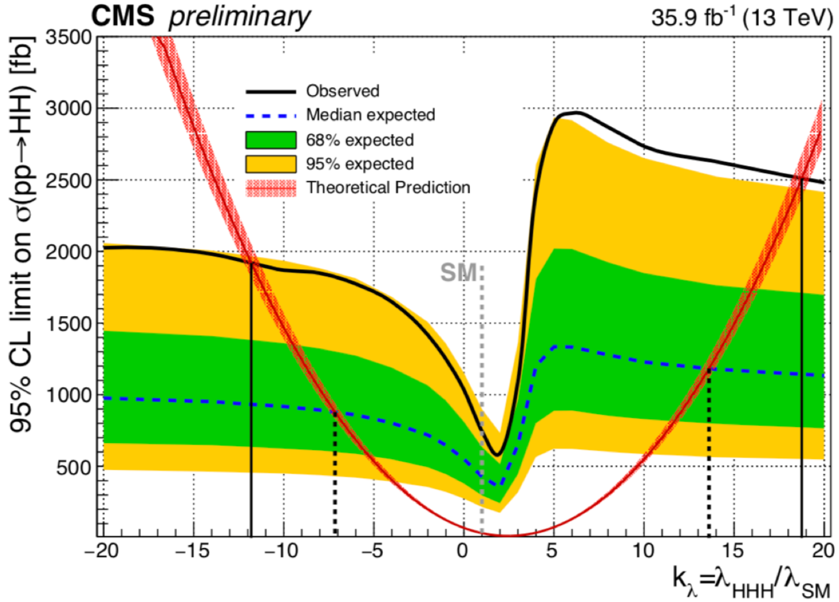
Summary

- CMS has conducted extensive searches for diHiggs production for all sensitive channels, in large mass ranges and for both resonant and non-resonant modes
- All results consistent with SM backgrounds so far
- Combined observed (expected) limit ~22 (13) X SM
- New search channels are being investigated
- We are now switching toward processing rest of run2 data (the next goal is run2 legacy analyses)

Back-Up

CMS Results (2016 data)





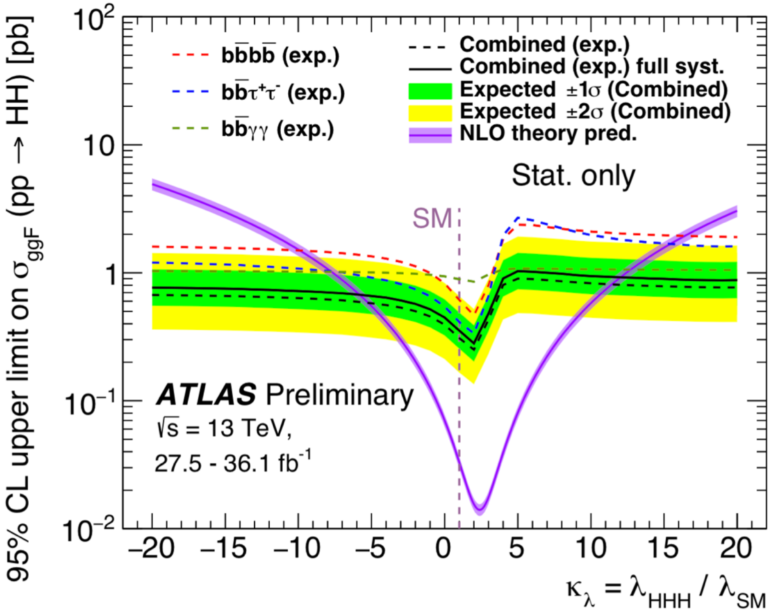
Report on bbbb, bbrr, bbWW, bbtautau

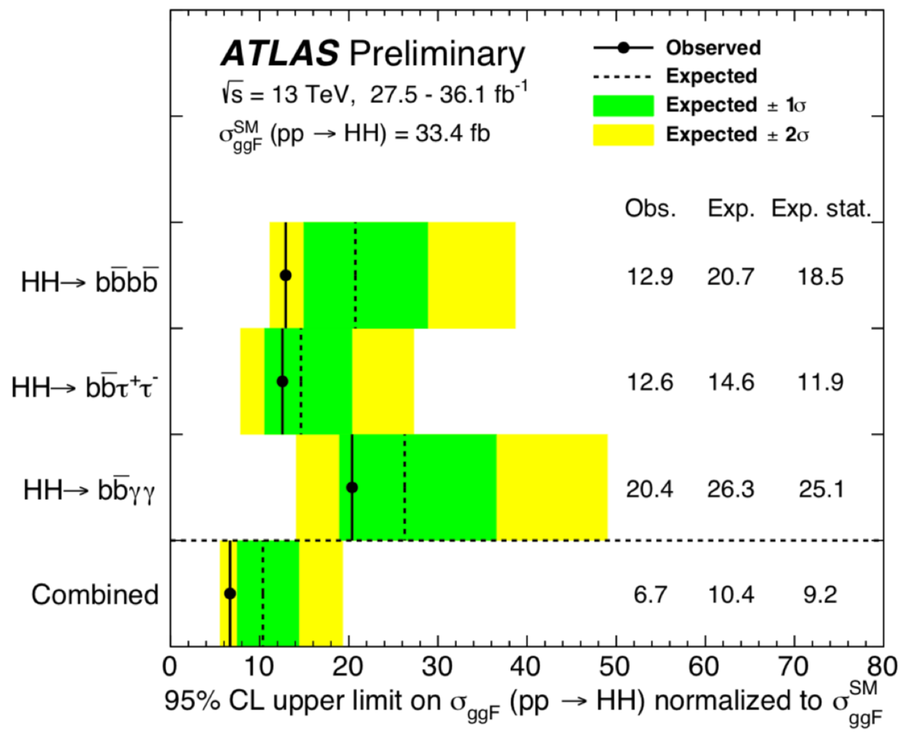
Constraint on $k_\lambda = \lambda_{HHH} / \lambda_{HHH}^{SM}$

Observed : $-11.8 < k_\lambda < 18.8$

Expected : $-7.1 < k_\lambda < 13.6$

ATLAS (2016)





~20% better than CMS: longer time spent in analysis optimisation

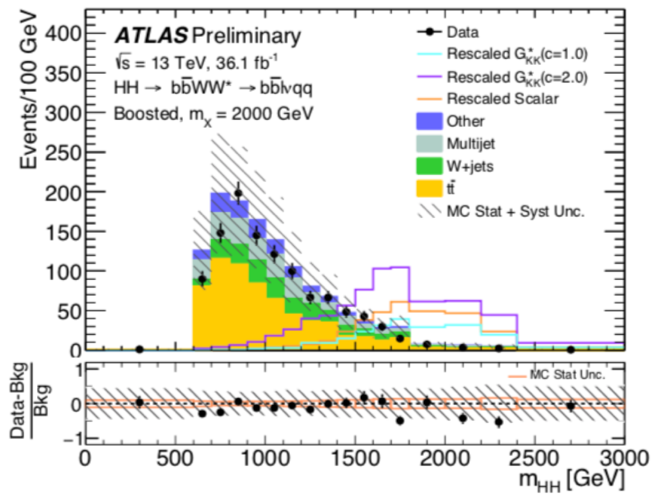
Expected -5.8 < k_λ < 12, observed -5.0 < k_λ < 12.1

- cfr. expectation of -7.1 < k_λ < 13.6 for CMS

Recent Results

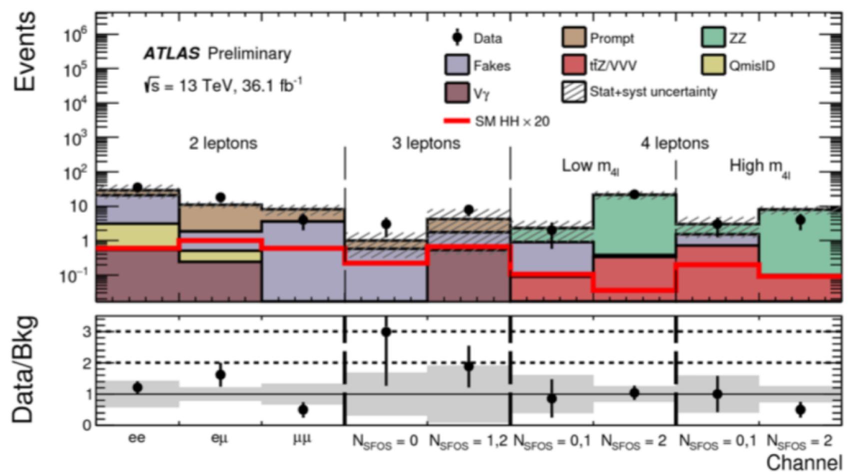
bbWW

- WW->lnuqq
- Resolved and boosted analyses
  - Cut and count (resolved) and mhh shape (boosted) analyses
- Both exp. and obs. About 300 x sigma_HH^SM
- Lnulnu and qqqq (boosted) in the pipeline



WWWW

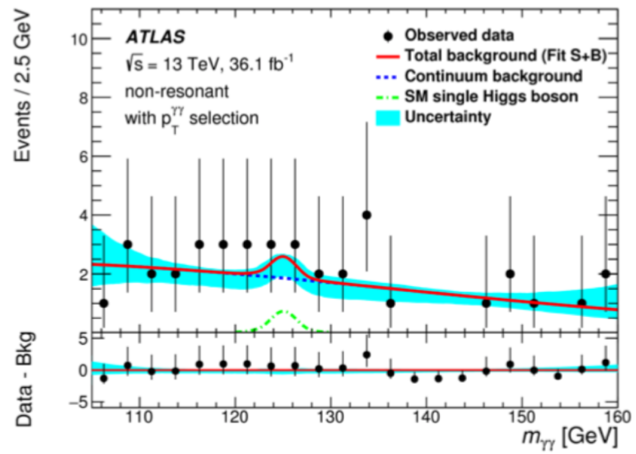
- 2 same-sign l + 3l + 4l
- Cut and count analysis
- Resonant X->HH and X->SS
- Obs (Exp) 160 (110) x sigma_HH^SM



New signatures

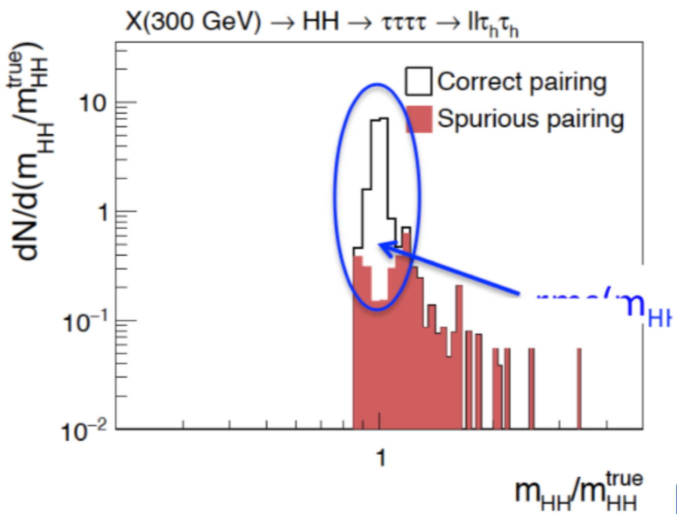
WWgamgam

- WW->lnuqq
- Fit to the m_gamgam spectrum
- Obs (exp) 230 (160) x sigma_HH^SM

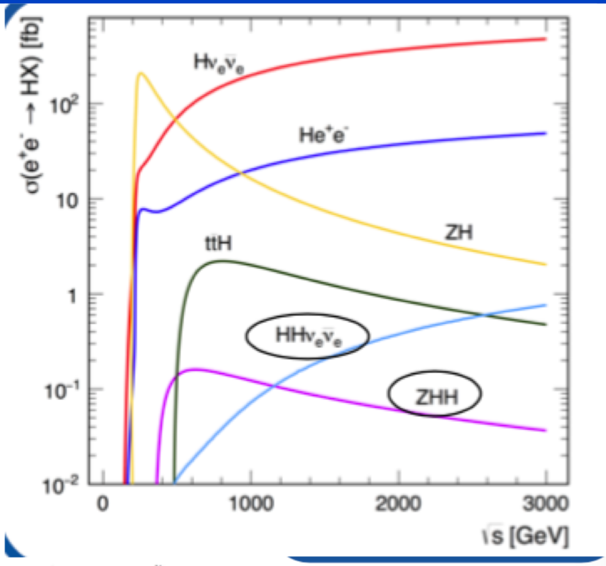


tautautautau

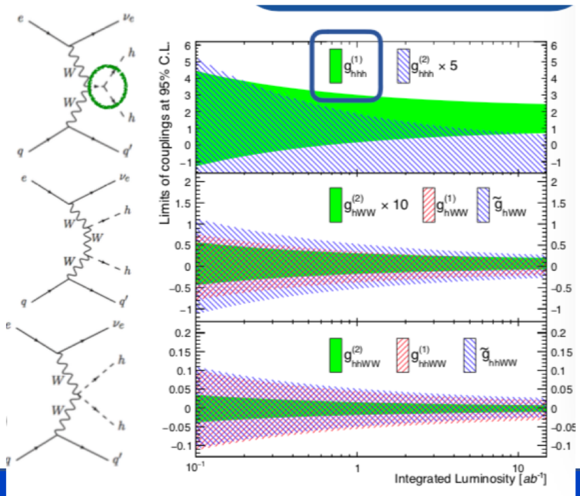
- In preparation in CMS
- Dedicated mass reconstruction with extended SVFit
  - 6%-20% depending on correct tautautautau pairing
- Important to understand overlap/interplay with WWWW/WWtautau



hh at future colliders



- Need high energy to access HH
  - ILC only from second stage @ 500 GeV
- Bbbb as the golden channel
  - Sigma Ramda ~27% @ ILC 500 GeV, 4/ab
  - Sigma Ramda ~13% @ CLIC, 1.4 TeV, 2.5/ab + 3 TeV, 5/ab

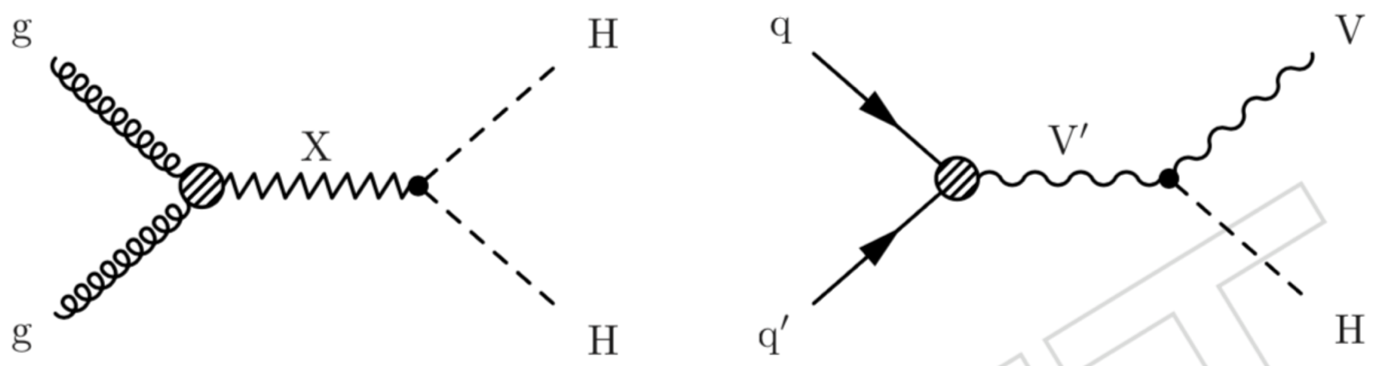


- HH: excellent case for HL-LHC
  - Important goal for the YR5
- FC—hh: sigma(100 TeV) = 30 x sigma(14TeV)
  - Sigma Ramda ~27% @ ILC 500 GeV, 4/ab
  - Sigma Ramda ~13% @ CLIC, 1.4 TeV, 2.5/ab + 3 TeV, 5/ab

Back-Up

The WED models have an extra spatial dimension compactified between two branes, with the region between (called the bulk) warped via an exponential metric κl, κ being the warp factor and l the coordinate of the extra spatial dimension [12]. The reduced Planck scale ($\overline{M_{\mathrm{Pl}}} \equiv M_{\mathrm{Pl}}/8\pi$, M_{Pl} being the Planck scale) is considered a fundamental scale. The free parameters of the model are $\kappa/\overline{M_{\mathrm{Pl}}}$ and the ultraviolet cutoff of the theory $\Lambda_{\mathrm{R}} \equiv \sqrt{6}\mathrm{e}^{-\kappa l}\overline{M_{\mathrm{Pl}}}$ [6]. In pp collisions at the LHC, the graviton and the radion are produced primarily through gluon-gluon fusion and are predicted to decay to HH [13].

Heavy resonances that decay to HH, VV, or VH, where H denotes the Higgs boson, and V denotes a W or Z boson, are motivated by theories beyond the standard model (SM) that address the large difference between the electroweak and gravitational scales. These heavy particles arise as Kaluza–Klein (KK) excitations of spin-0 radions [1–3], and as spin-2 gravitons predicted in models based on Randall–Sundrum warped extra dimensions [4, 5], with the gravitons propagating in the entire five-dimensional bulk [6–8]. Heavy spin-1 W′ and Z′ particles that decay to VV and VH are also postulated in composite Higgs models [9–12], little Higgs models [13, 14], and in the sequential SM (SSM) [15]. The models containing new spin-1 states are generalized in the heavy vector triplet (HVT) framework [16]. All of the new hypothetical particles with spins of 0, 1, or 2 can be produced at the CERN LHC, via the processes depicted in the Feynman diagrams of Fig. 1.



The bulk graviton model has two free parameters: the mass of the first KK excitation of the spin-2 boson, denoted as the KK bulk graviton, and the ratio $\tilde{k} \equiv k/\overline{M}_{\mathrm{Pl}}$, where k is the unknown curvature scale of the extra dimension and $\overline{M}_{\mathrm{Pl}} \equiv M_{\mathrm{Pl}}/\sqrt{8\pi}$ is the reduced Planck mass. Searches for radions in this model can be described in terms of the radion mass and the ultraviolet cutoff of the theory Λ_{R} [17]. The HVT model is formulated in terms of four parameters: the mass of the new vector bosons, their coupling coefficient to fermions c_{F}, their coupling coefficient to the Higgs boson and longitudinally-polarized SM vector bosons c_{H}, and the strength of the new vector boson interaction g_{V}. In the HVT framework two scenarios are

Models with a warped extra dimension (WED), as proposed by Randall and Sundrum [7], are among those BSM scenarios that predict the existence of resonances with large couplings to the SM Higgs boson, such as the spin-0 radion [9–11] and the spin-2 first Kaluza–Klein (KK) excitation of the graviton [12–14]. The WED models postulate an additional spatial dimension l compactified between two four-dimensional hypersurfaces known as the branes, with the region between, the bulk, warped by an exponential metric κl, where κ is the warp factor [15]. A value of $\kappa l \sim 35$ fixes the mass hierarchy between the Planck scale M_{Pl} and the electroweak scale [7]. One of the parameters of the model is $\kappa / \overline{M_{\mathrm{Pl}}}$, where $\overline{M_{\mathrm{Pl}}} \equiv M_{\mathrm{Pl}} / \sqrt{8\pi}$. The ultraviolet cutoff scale of the model $\Lambda_{\mathrm{R}} \equiv \sqrt{6} \mathrm{e}^{-\kappa \mathrm{l}} \overline{M_{\mathrm{Pl}}}$ [9] is another parameter, and is expected to be near the TeV scale.

In the absence of new resonances coupling to the Higgs boson, the gluon fusion Higgs boson pair production subprocess can still be enhanced by BSM contributions to the coupling parameters of the Higgs boson and the SM fields [16]. The SM production rate of HH through gluon fusion is determined by the Yukawa coupling of the Higgs boson to the top quark $y_{\mathrm{t}}^{\mathrm{SM}}$ and the Higgs boson self-coupling $\lambda_{\mathrm{HH}}^{\mathrm{SM}} = m_{\mathrm{H}}^2/2v^2$. Here, $m_{\mathrm{H}} = 125\,\mathrm{GeV}$ is the Higgs boson mass [17, 18] and $v = 246\,\mathrm{GeV}$ is the vacuum expectation value of the Higgs field. Deviations from the SM values of these two coupling parameters can be expressed as $\kappa_\lambda \equiv \lambda_{\mathrm{HH}}/\lambda_{\mathrm{HH}}^{\mathrm{SM}}$ and $\kappa_{\mathrm{t}} \equiv y_{\mathrm{t}}/y_{\mathrm{t}}^{\mathrm{SM}}$, respectively. Depending on the BSM scenario, other couplings not present in the SM may also exist and can be described by dimension-6 operators in the framework of an effective field theory by the Lagrangian [19]:

$$\begin{aligned}\mathcal{L}_{\mathrm{H}} =& \frac{1}{2}\partial_\mu \mathrm{H}\partial^\mu \mathrm{H} - \frac{1}{2}m_{\mathrm{H}}^2\mathrm{H}^2 - \kappa_\lambda\,\lambda_{\mathrm{HH}}^{\mathrm{SM}} v\,\mathrm{H}^3 - \frac{m_{\mathrm{t}}}{v}(v + \kappa_{\mathrm{t}}\,\mathrm{H} + \frac{c_2}{v}\,\mathrm{HH})\,(\bar{\mathrm{t}}_{\mathrm{L}}\mathrm{t}_{\mathrm{R}} + h.c.)\\ &+ \frac{1}{4}\frac{\alpha_s}{3\pi v}(c_{\mathrm{g}}\,\mathrm{H} - \frac{c_{2\mathrm{g}}}{2v}\,\mathrm{HH})\,G^{\mu\nu}G_{\mu\nu}\,.\end{aligned}$$

The anomalous couplings and the corresponding parameters in this Lagrangian are: the contact interaction between a pair of Higgs bosons and a pair of top quarks (c_2), the interaction between the Higgs boson and the gluon (c_g), and the interaction between a pair of Higgs bosons and a pair of gluons (c_{2g}). The couplings with CP-violation and the interactions of the Higgs boson with light SM and BSM particles are not considered. The Lagrangian models the effects of BSM scenarios with a scale that is beyond the direct LHC reach. This five-parameter space of BSM Higgs couplings has constraints from measurements of single Higgs boson production and other theoretical considerations [20, 21].

published by the CMS Collaboration [36], in which two large-area jets are used to reconstruct the highly Lorentz-boosted Higgs bosons ("fully-merged" event topology). A similar search, focusing on a lower range of m_X, was also performed by CMS [37], using events with four separate b quark jets. The configuration of a Higgs boson candidate as one large-area jet or as two separate smaller jets is dependent on the momentum of the Higgs boson [38].

In this paper, we improve upon the CMS search for high mass resonance ($750 \leq m_X \leq 3000$ GeV) decaying to HH $\rightarrow$ b$\bar{b}$b$\bar{b}$ [36] by using "semi-resolved" events, i.e. those containing exactly one highly Lorentz-boosted Higgs boson while the other Higgs boson is required to have a lower boost. The more boosted Higgs boson is reconstructed using a large-area jet and the other is reconstructed from two separate b quark jets. The inclusion of the semi-resolved events leads to a significant improvement in the search sensitivity for resonances with $750 \leq m_X \leq 2000$ GeV.

radions decaying to boosted W and Z bosons [74]. The "N-subjettiness" algorithm [75] is used on the AK8-PUPPI jet constituents, to compute the variables τ_N, which quantify the degree to which a jet contains N subjets. A selection on the ratio $\tau_{21} \equiv \tau_2/\tau_1 < 0.55$ is required for all AK8 jets to be H tagged, which has a jet p_T-dependent efficiency of 50%–70%. The selection