Status and prospects for HH at the LHC

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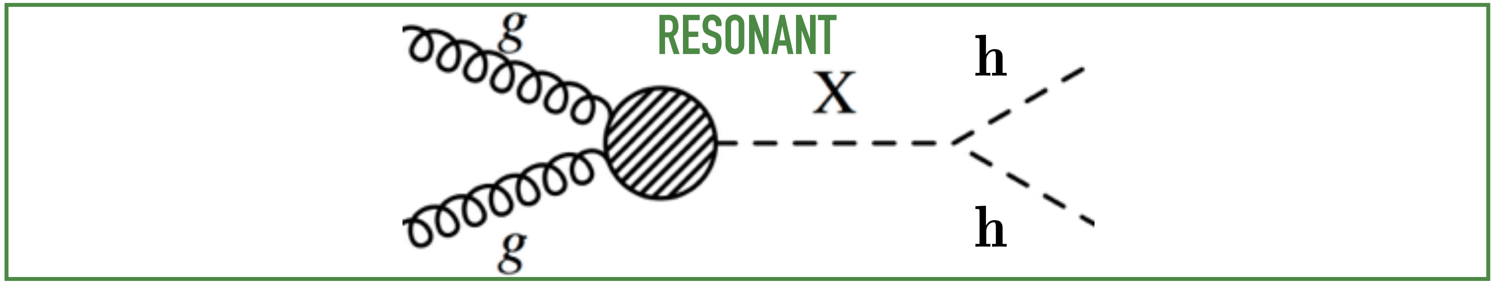
Status and prospects for HH at the LHC

- Di-Higgs productions in pp collisions
  - Mainly via gluon-gluon fusion GF but VBF can help at higher luminosities
  - GF has a small production cross section: 33.53fb at 13 TeV
- Direct measurement of the higgs self-coupling in SM
- Search for BSM effects
  - new resonances
  - Enhanced non resonant production
- Status of the search per decay channel
- Future prospects at HL-LHC

RESONANT

Higgs pair production: Resonant



Searches for new resonances decaying into a pair of Higgs are conducted: BSM models scenarios with SM di-Higgs final state

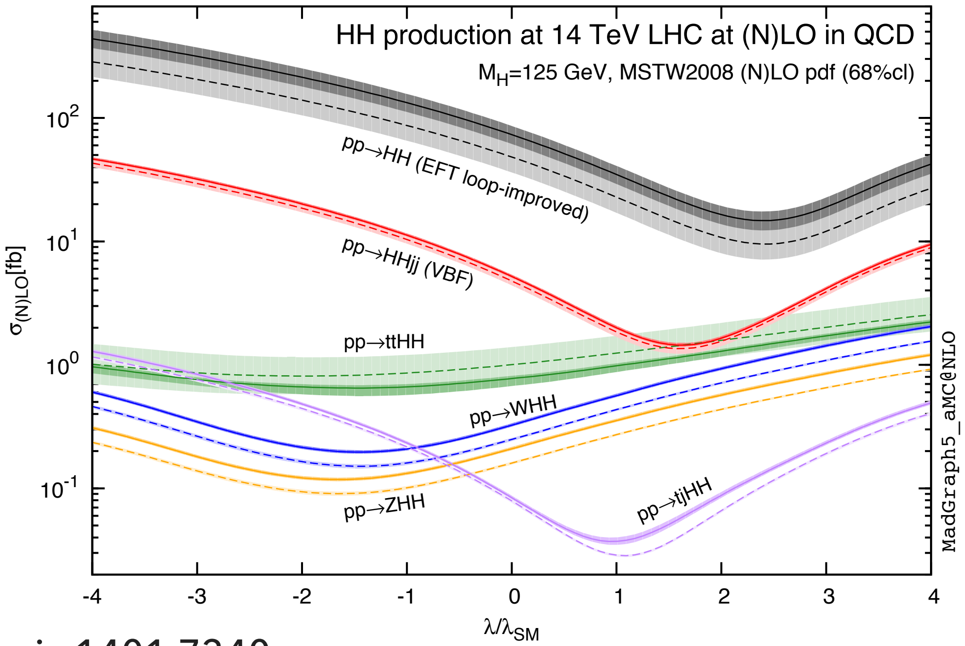
1. Higgs Singlet model (250-1000GeV)
    1. SM Higgs doublet ϕ_0 +real gauge singlet scalar S
    2. Physical fields h, H {h= $\phi_0 \cos\alpha$+S $\sin\alpha$, H= -$\phi_0 \sin\alpha$ +S $\cos\alpha$}
2. hMSSM (250-400 GeV)
    1. Two higgs doublets, resulting in 5 physical states: h, H, A, $H^{\pm}$
    2. Parametrization with two parameters: m_A and tanβ
    3. if $M_{SUSY} \gg$ 1TeV low tanβ could produce h with m_h=125GeV
3. Warped Extra Dim
    1. Two fields: Radion(spin 0) [1] and KK-Graviton(spin 2) [2]that could decay to hh(if M_X>250 GeV)

[1]https://arxiv.org/abs/0705.3844

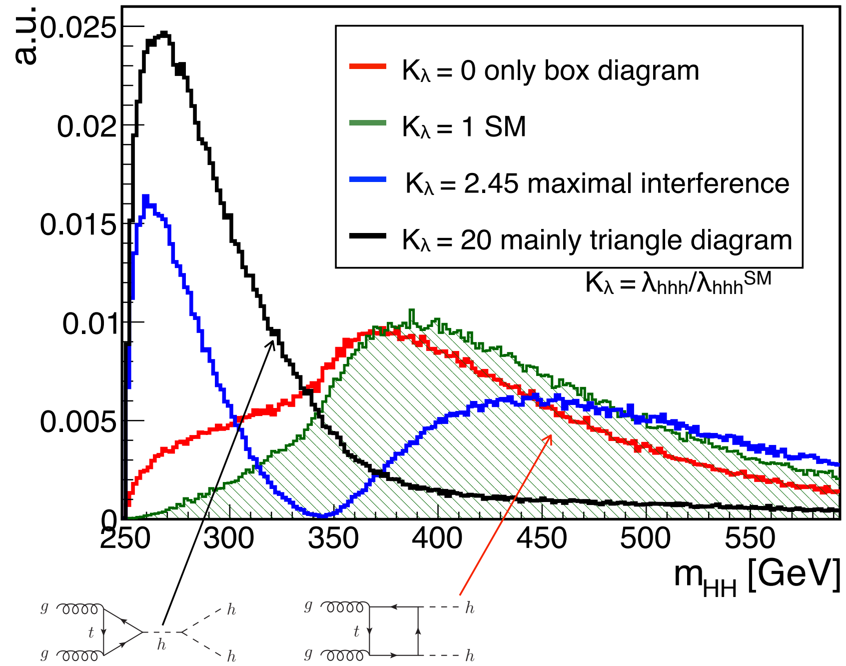
[2]https://arxiv.org/abs/hep-ph/0701186

Higgs Pair Production: Non resonant

1. Double Higgs production is the direct way to measure the higgs self coupling (trilinear): λ_{hhh}
2. The ATLAS and CMS detectors sensitivity at LHC-Run2 is not expected to suffice for this measurement
3. But BSM predictions using non-SM values for λ_{hhh} show an enhancement of the non-resonant di-Higgs production, hence a possiblity for λ_{hhh} measurement.
4. VBF contribution could also enhance the sensitivity and reduce the limits.



arxiv 1401.7340



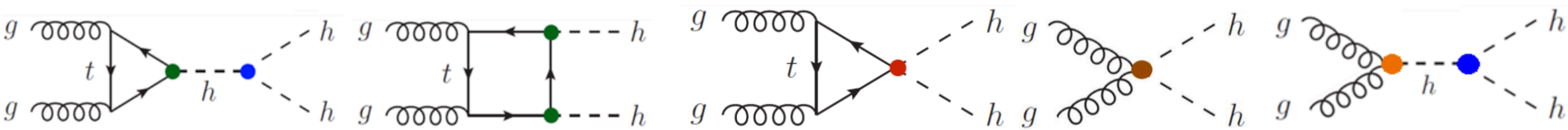
Higgs pair production: Non resonant

Beyond standard model BSM effect are EFT modeled with dim-6 opetrators[1]

The process 5 parameters Lagrangian is the following, where the parameters are λ_{hhh}, y_T, c_2, c_g, c_{2g}

$$\mathcal{L}_h = \frac{1}{2}\partial_\mu h \partial^\mu h - \frac{1}{2} m_h^2 h^2 - \kappa_\lambda \lambda_{SM} v h^3 - \frac{m_t}{v}\left(v + \kappa_t h + \frac{c_2}{v} h h\right)(\bar{t}_L t_R + h.c.) + \frac{1}{4}\frac{\alpha_s}{3\pi v}\left(c_g h - \frac{c_{2g}}{2v} h h\right) G^{\mu\nu} G_{\mu\nu} .$$

Where:
$k_\lambda = \lambda_{HHH}/\lambda_{HHH}^{SM}$;
$k_t = y_T/y_T^{SM}$;
$\lambda_{SM} = m^2_H/(2v^2) = 0.129$.



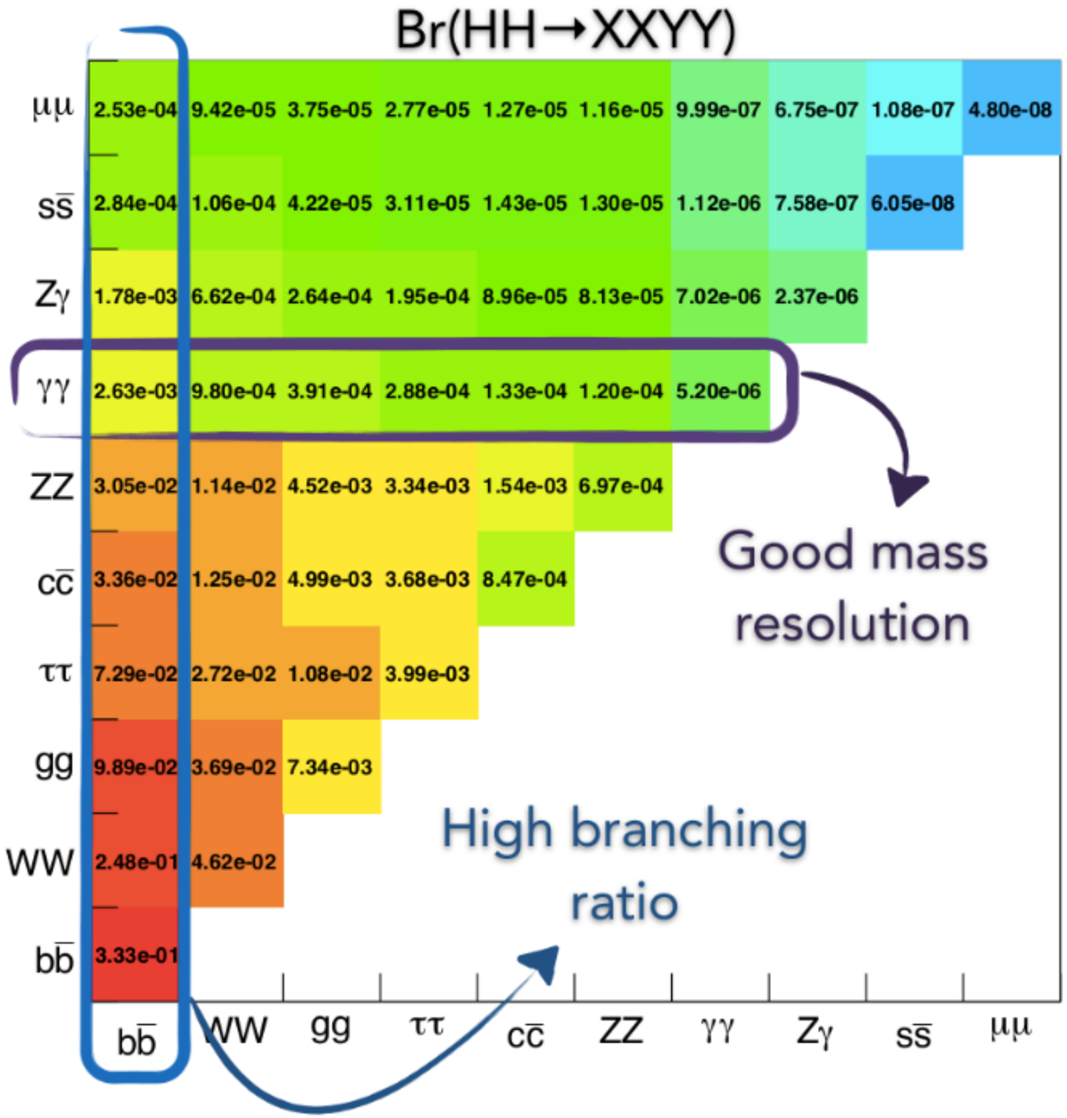
Tri-linear coupling | Yukawa interaction | ttHH interaction | Higgs-gluon contact interactions

The HH cross section and the final state kinematics vary in 5D phase space (over more than 1500 combinations: 12 benchmarks identified)[2]

[1]Phys.Rev.D91 (2015), n0.11, 115008
[2]JHEP04(2016)126

SEARCHES

Di-Higgs searches are performed looking at several final states



Among which:

1. bbbb: higher BR, High QCD/tt contamination
2. bbWW: high BR, large irreducible ttbackground
3. bb$\tau\tau$ relatively low bkg
4. bb$\gamma\gamma$ High purity, but very low BR
5. Other: $\gamma\gamma$WW*

NON-RESONANT RESONANT

GENERAL PROCEDURE: HH→$\gamma\gamma$bb

1. Reconstruct and select the 4 objets:

   -2b-tagged resolved jets+2 photons

   -with double photon trigger and MVA based vertex finding, selection on E_T, $m_{\gamma\gamma}$, m_{jj}, pT, $\Delta R(j,\gamma)>0.4$ and application of the jet energy regression for the b-tagged jets

2. Categorize the signal using the system invariant mass and MVA outputs:

   -classify the events according to BDT output in purity, trained on b-tagging variables, helicity angles, pT(jj)/m

   -for non resonant, categorize over the resolution improved 4-body mass $M_x = M(jj\gamma\gamma) - M(jj) - M(\gamma\gamma) + 250$, boundary $M_x = 350$GeV

3. Estimate the Background

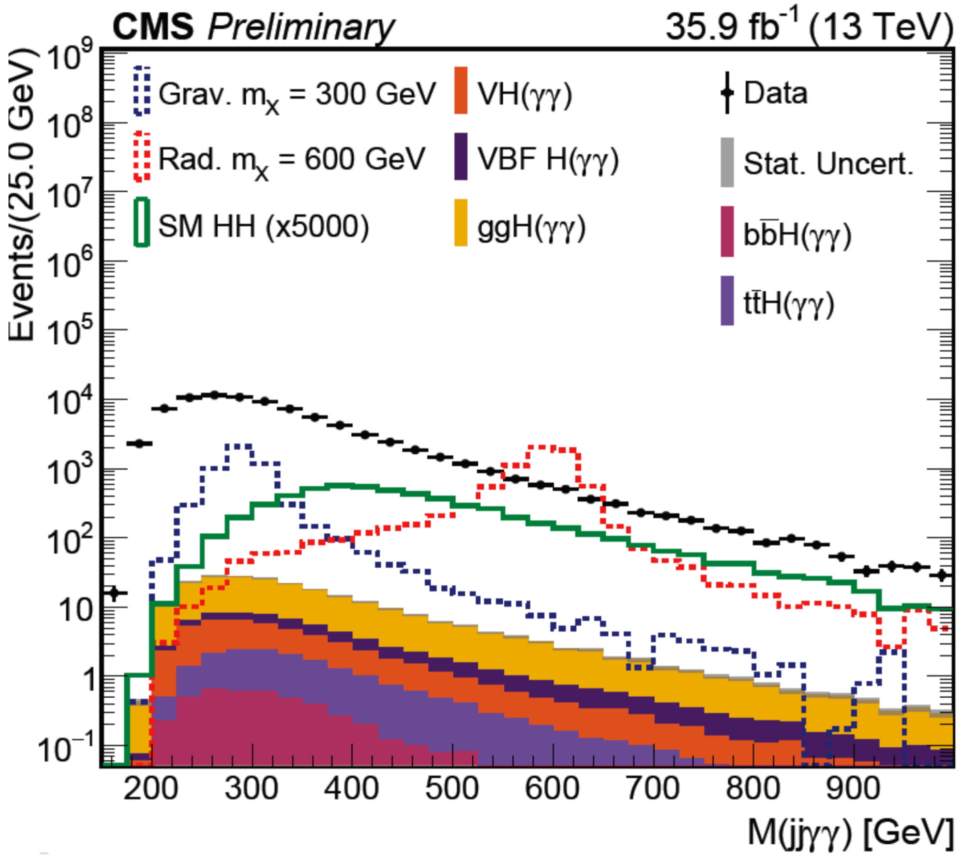
   - γ+jet from QCD (data driven), single H→$\gamma\gamma$, ttH, bbH, VH
   - fitted with Bernstein polynomials

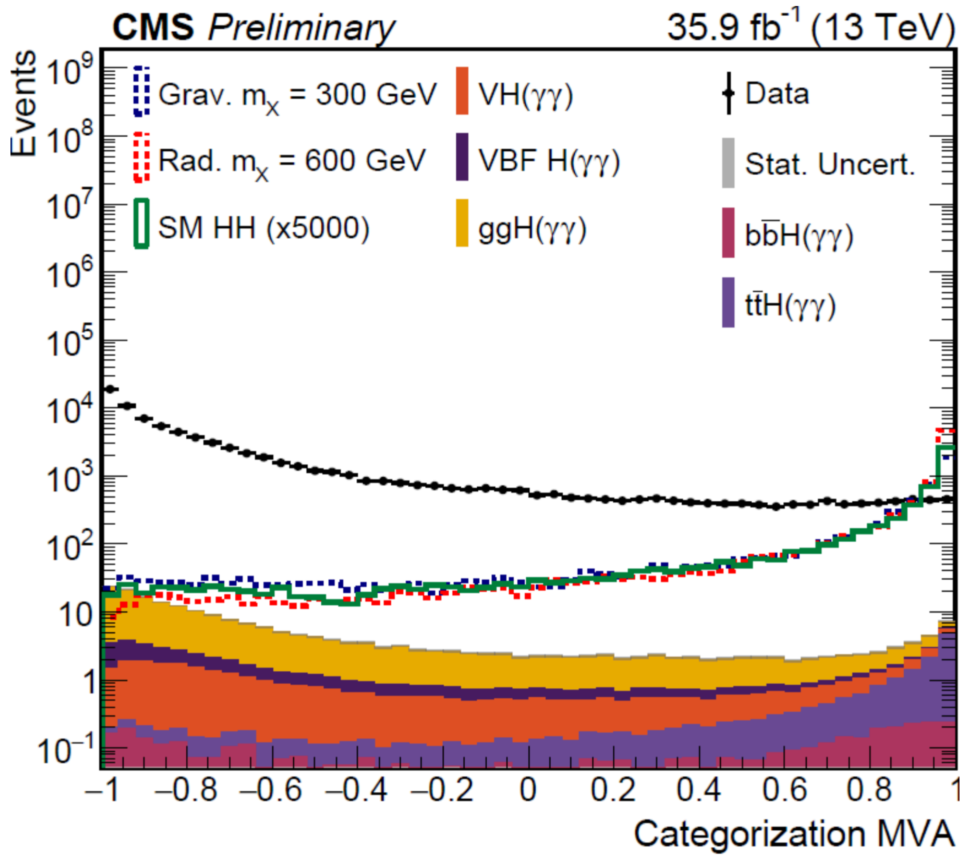
4. Extract the signal: in a 2D plane, simultaneously fitting $m_{\gamma\gamma}$ and m_{jj}

Results: HH→γγbb

NON-RESONANT | RESONANT

CMS-PAS-17-008



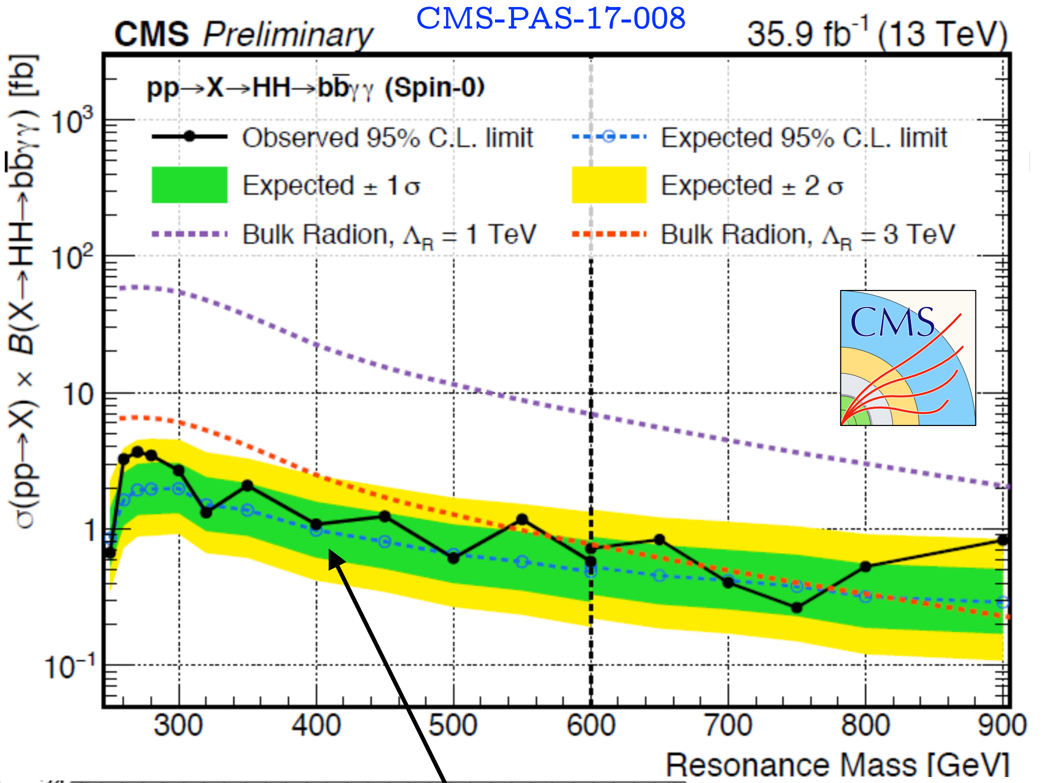


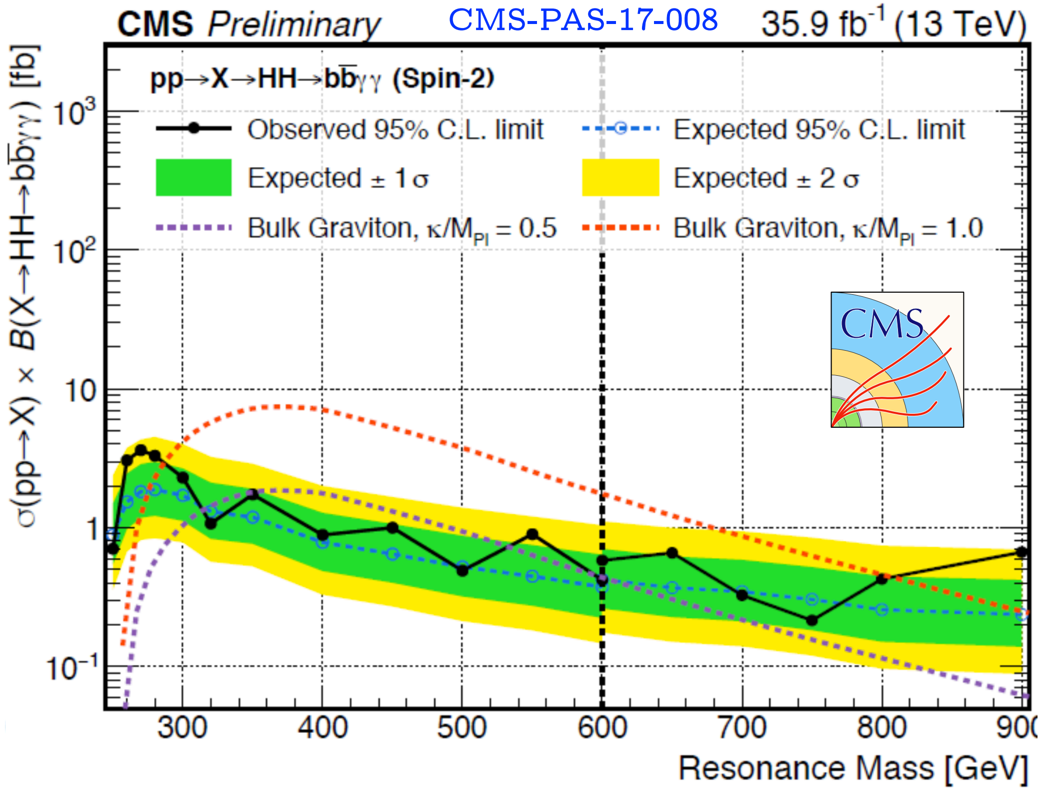
Results: HH→γγbb

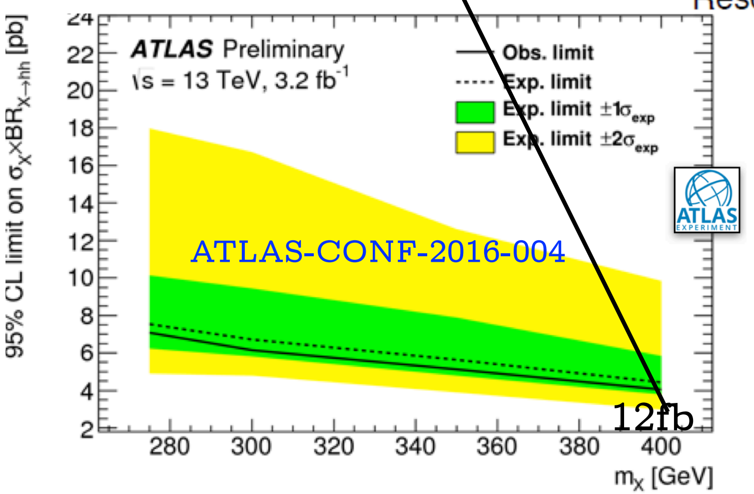
RESONANT

SPIN 0

SPIN 2







No signal excess in ATLAS nor CMS

From CMS results:

Limits set for $250 < m_X < 900$ GeV.

Excluded any Radion for $\Lambda_R = 1$ TeV hypothesis

and $m_X < 550$ GeV for $\Lambda_R = 3$ TeV.

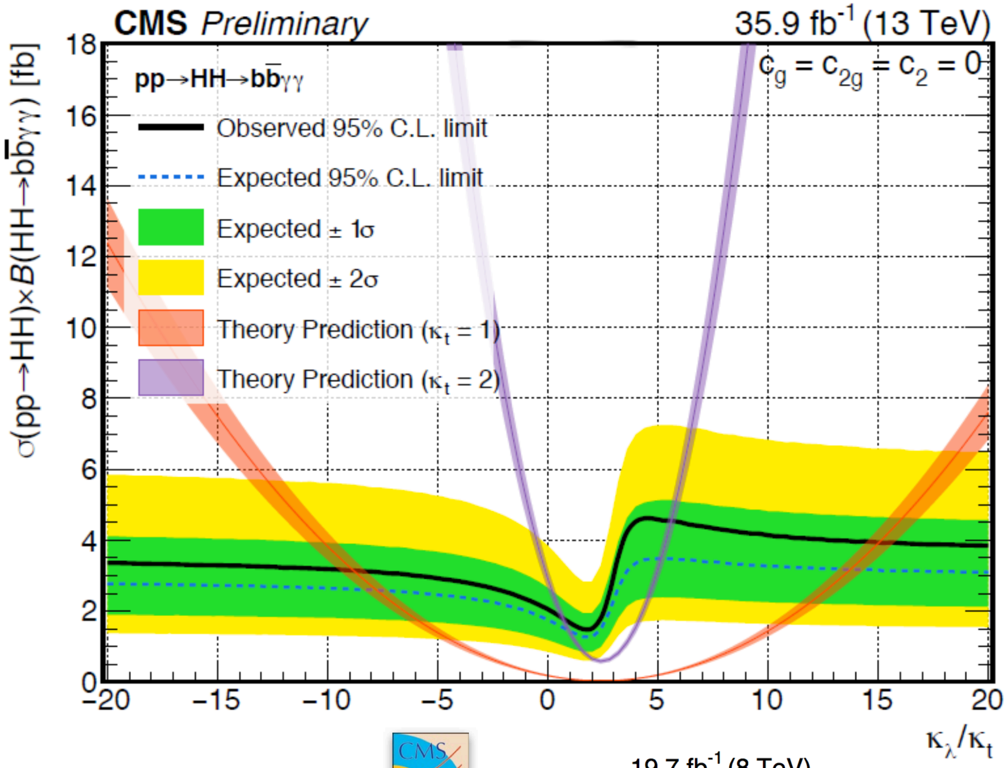
Exlusion for KK-Graviton in ranges

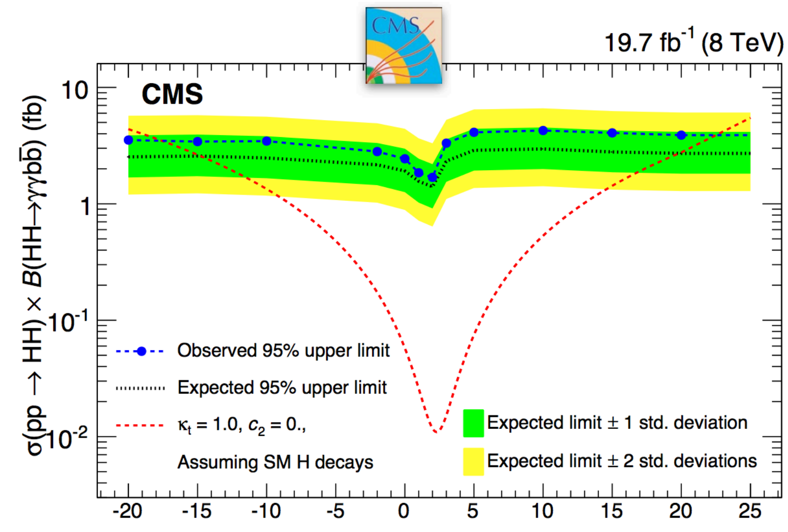
[280;900] GeV (k/M_{PI}=1.0) and [300;550] GeV (k/M_{PI}=0.5).

Results: HH→$\gamma\gamma$bb

NON-RESONANT

CMS-PAS-17-008





Run-1: Phys.Rev.D94,052012(2016) κ_λ

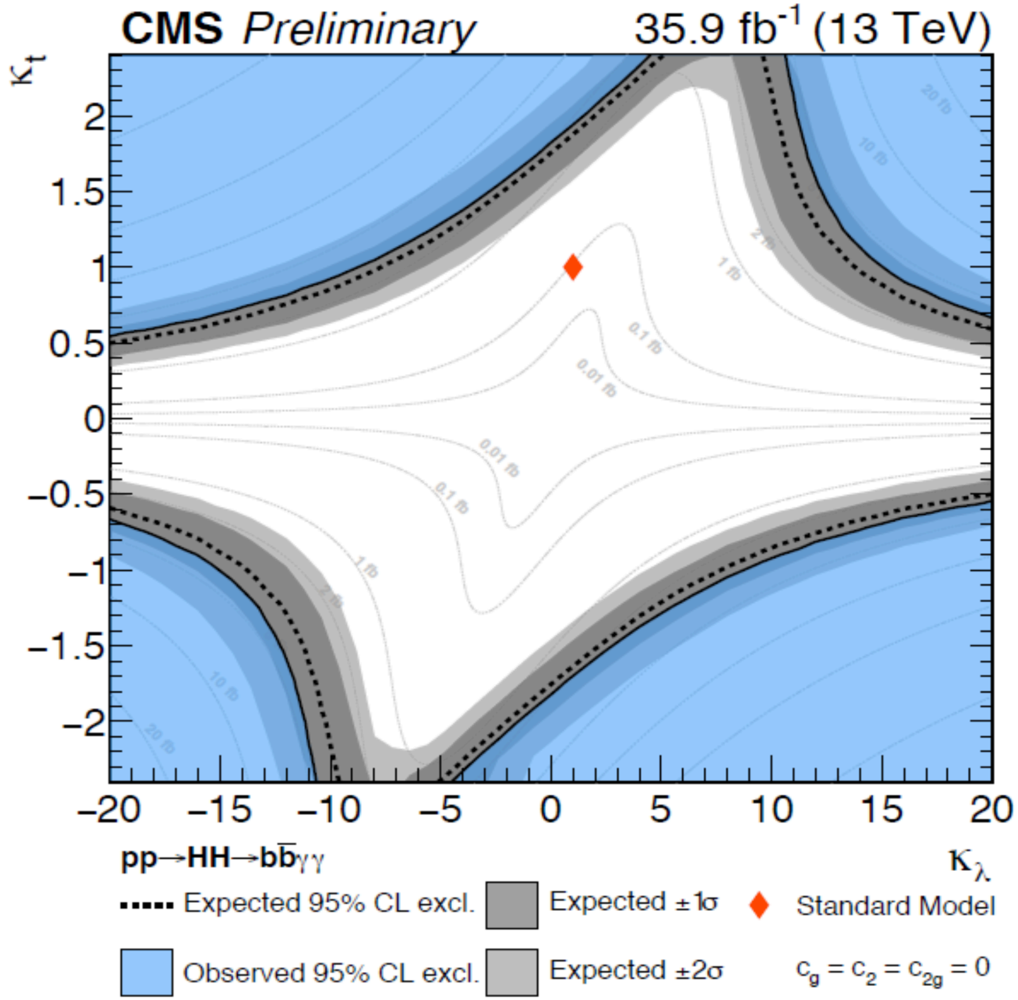
Limit on σ_{hh} :

1.67 (exp 1.44) fb

equal to 19.2 times σ^{SM}_{hh}

Limit as a function of k_λ/k_t .

k_t = 2 excluded with k_λ=1.



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$HH \to bb\tau\tau$

CMS-PAS-HIG-17-002

RESONANT

No signal excess.

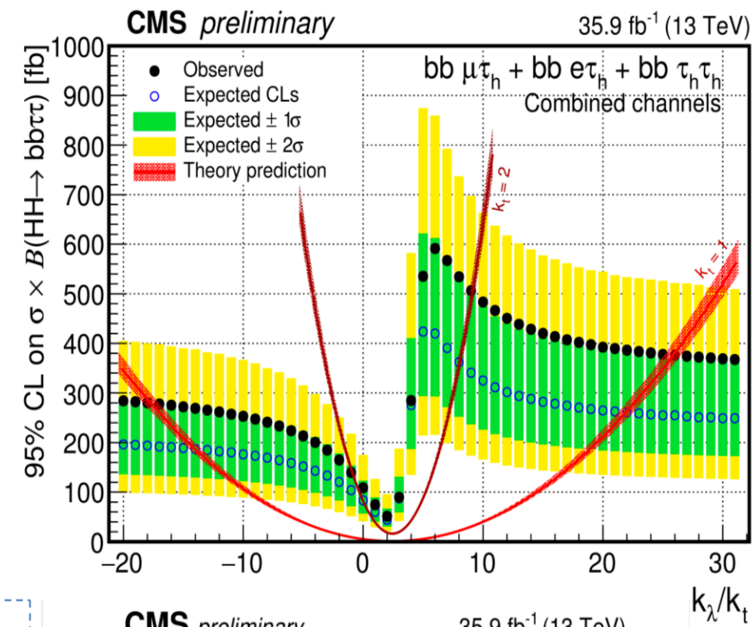
Model independent limits set for $250 < m_X < 900$ GeV.

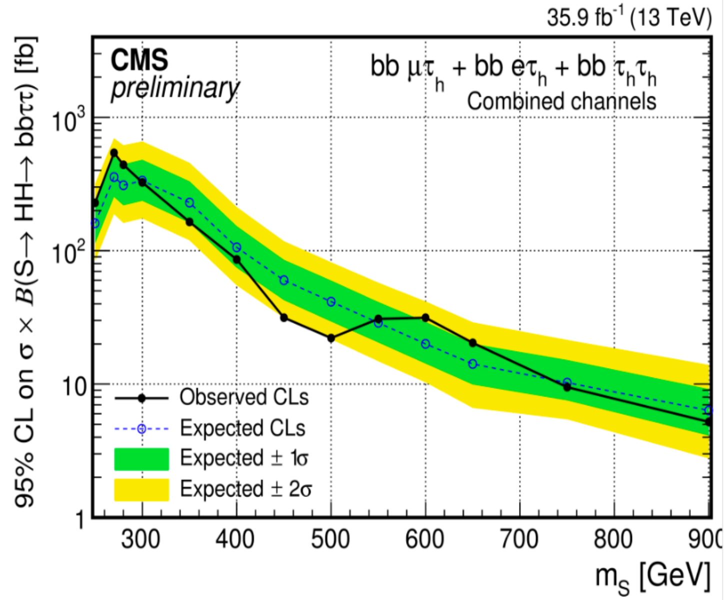
Interpreted in MSSM scenarios with HH prod parametrized as a function of m_A and tanβ.

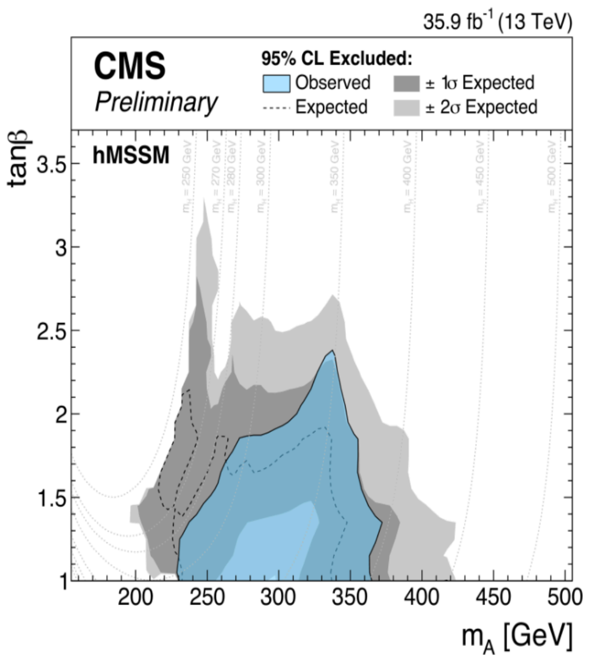
NON-RESONANT

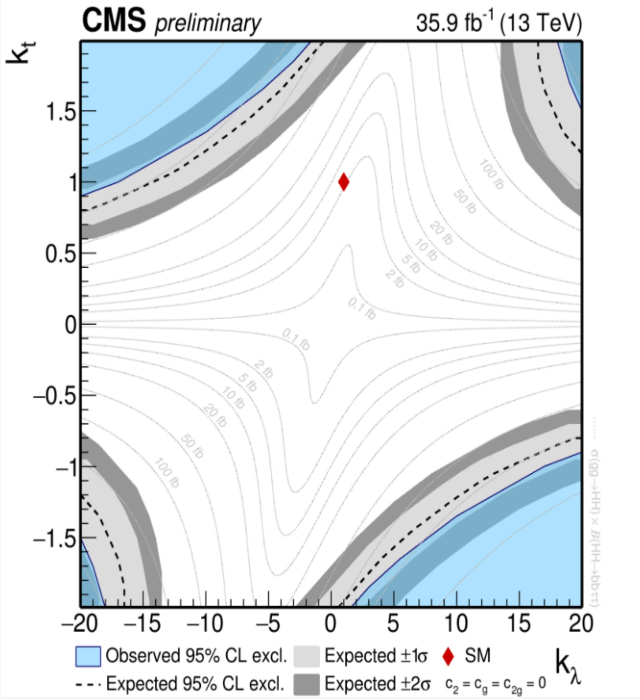
Limit on σ_{hh} :
25 (exp 28) times σ^{SM}_{hh}

Limit as a function of k_λ k_t (BSM).







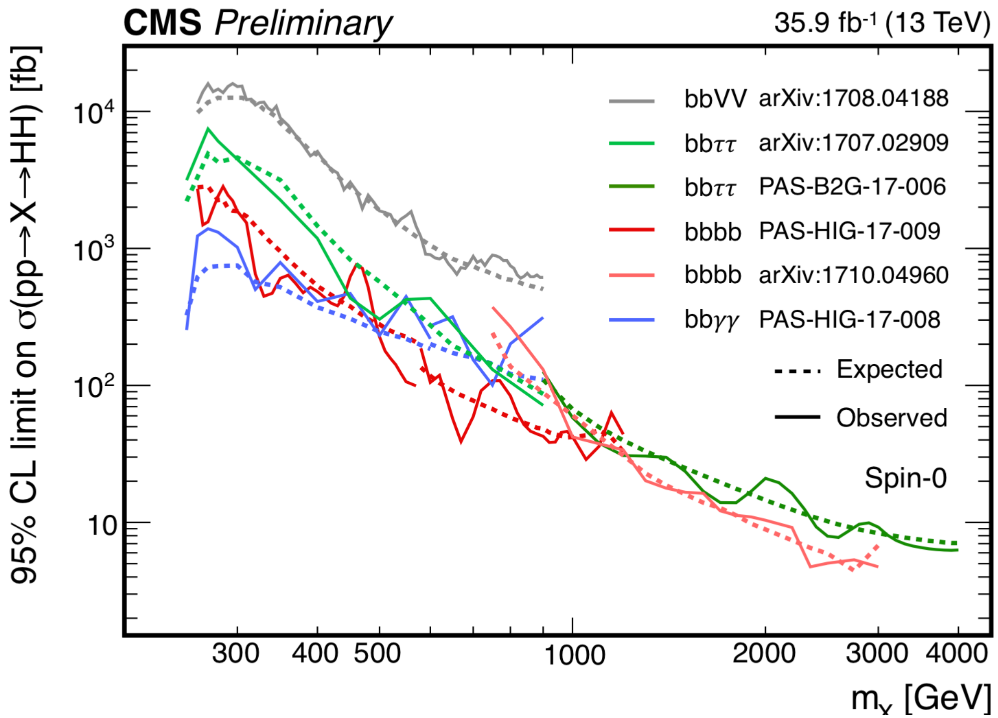


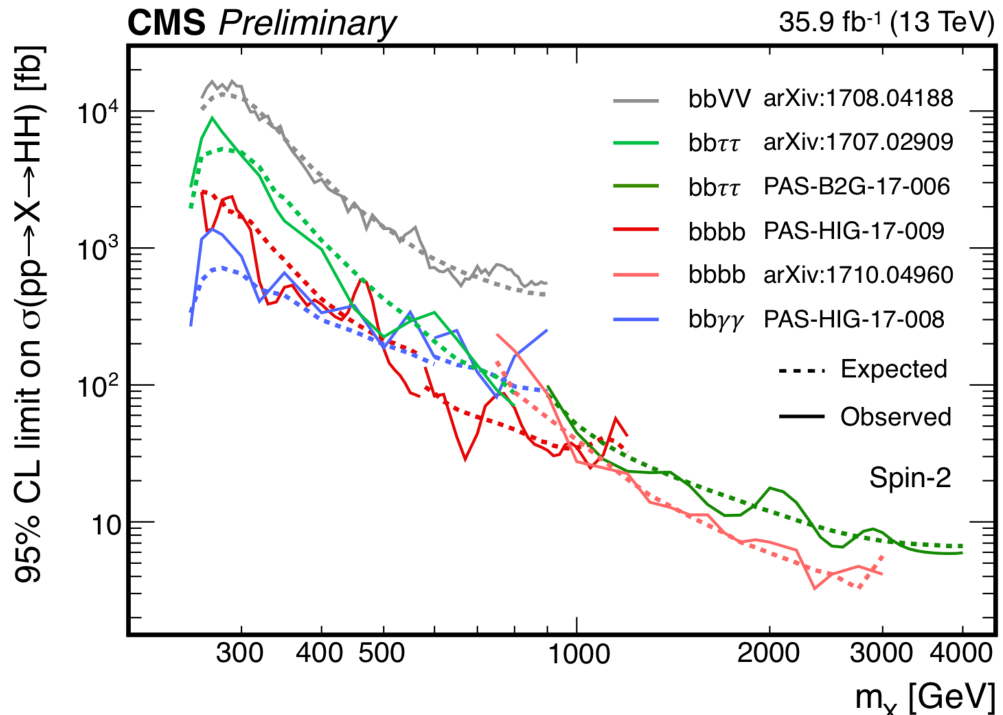
HH Run2 summary

RESONANT

SPIN 0

SPIN 2





2b2γ channel is the best at low mass. Lowest BR.

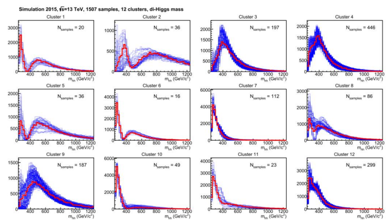
bbbb channel has recently improved (NEW) and is competitive with 2b2 at low mass and shows best sensitivity at high mass

2b2τ channel improved at high mass with better trigger efficiency.

2b2W channel is limited by large irreducible tt background.

HH Run2 summary

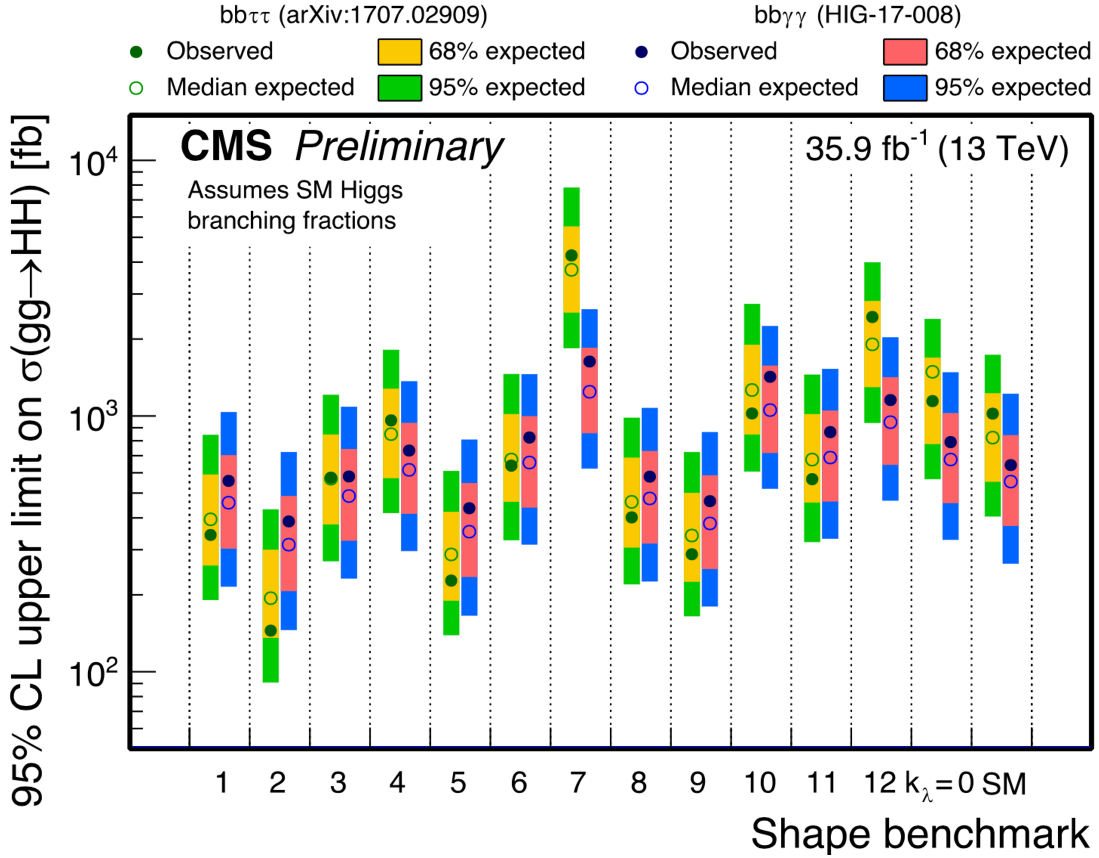
NON-RESONANT



Run2 95 % C.L. limits on $\mu=\sigma/\sigma_{SM}$

Observed/(Expected)

final state	ATLAS	CMS
$bb\gamma\gamma$	117(161) (3fb^{-1})	19(17) (36fb^{-1})
$bb\tau\tau$		28(25) (36fb^{-1})
$bb\upsilon\upsilon$		79(89) (36fb^{-1})
bbbb	29(38) (13fb^{-1})	342(308) (2.3fb^{-1})
$WW\gamma\gamma$	747(386) (13fb^{-1})	



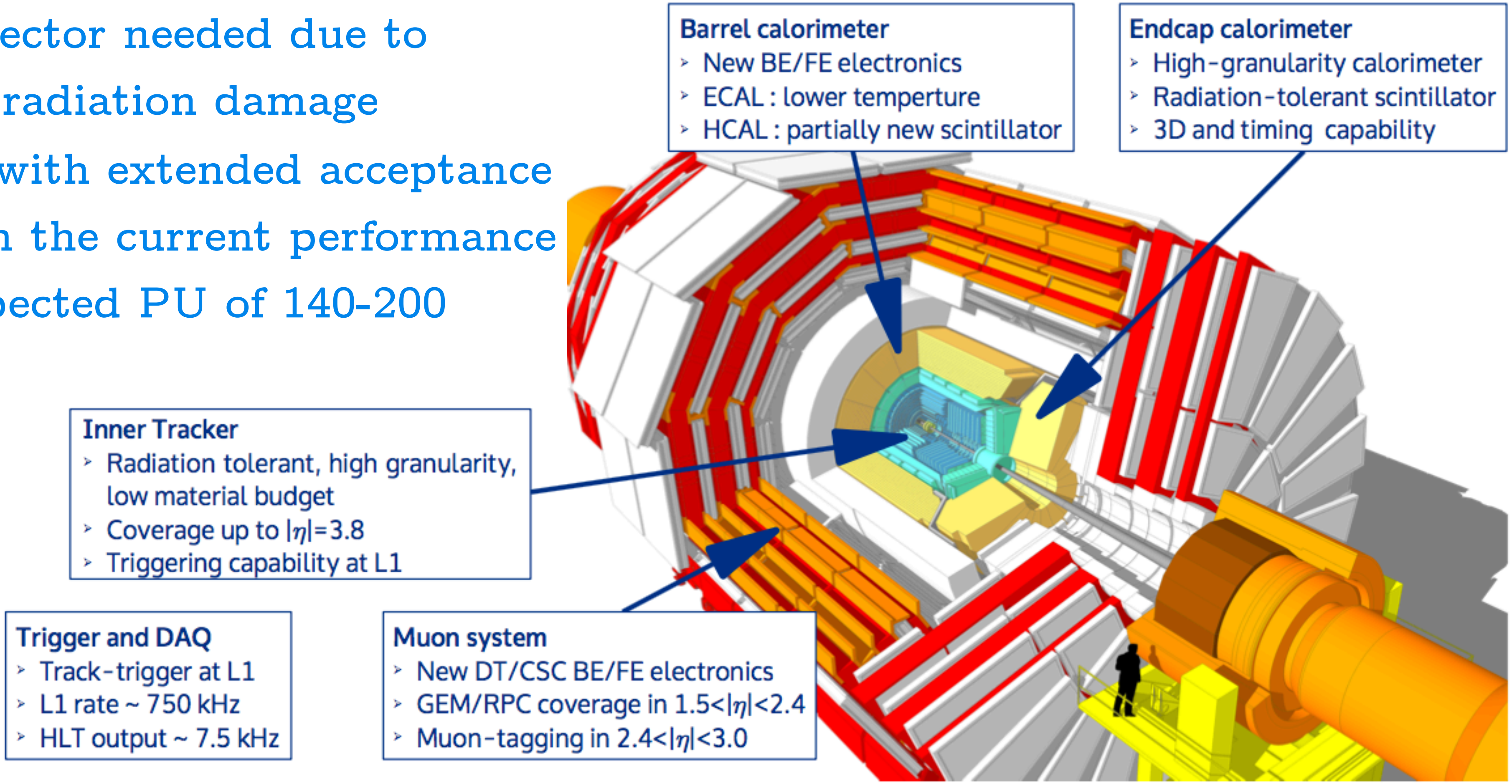
CMS provides also limits in benchmarks (slide 5) that describe typical topologies possible in 5D EFT space.

For the trilinear coupling more integrated luminosity is needed : What can we expect at HL-LHC?

HH at HL-LHC

HL-LHC upgrade CMS detector

1. Phase-2 LHC: up to $3000 fb^{-1}$ ($L_{inst}=5x10^{34}\ cm^{-2}\ s^{-1}$)
2. New detector needed due to Phase-1 radiation damage
3. Will be with extended acceptance
4. Maintain the current performance with expected PU of 140-200

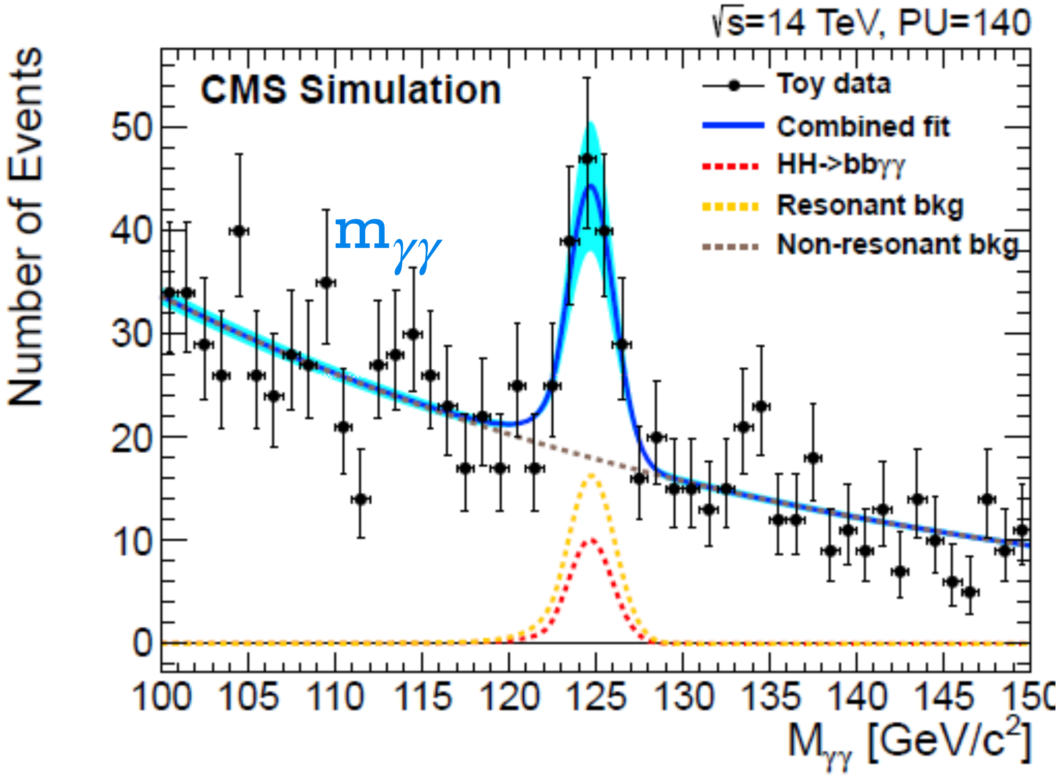


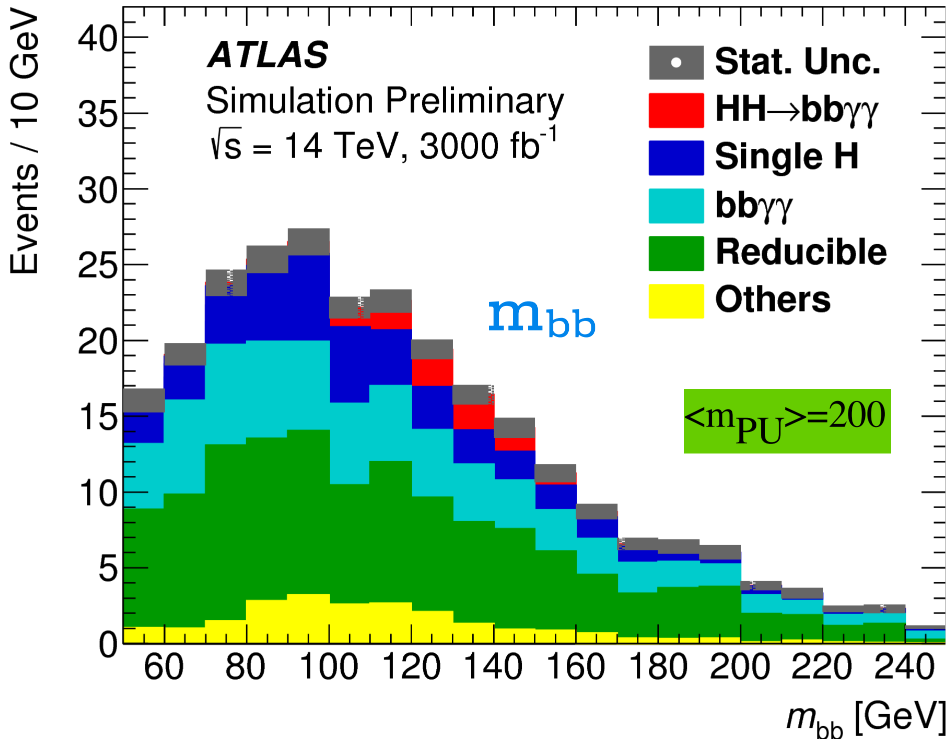
Phase-2 HH → $bb\gamma\gamma$

SM NON-RESONANT

CMS-PAS-FTR-16-002

ATL-PHYS-PUB-2017-001





Extrapolation from Run2 analysis/data (CMS-PAS-HIG-16-032)

2D fit of $m(\gamma\gamma)$ – $m(bb)$ distributions

Syst. uncertainty:S2+ scenario (backup slide)

→ Significance : 1.43 σ

Smearing function approach

Cut and count method

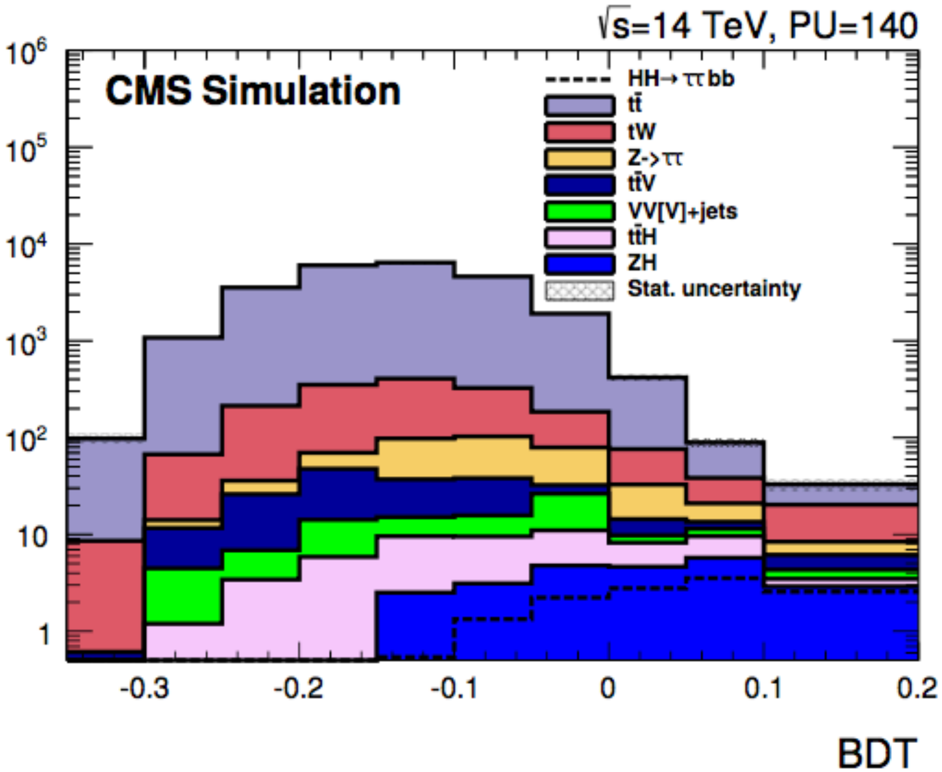
2.9 % signal efficiency

→ Significance : 1.05 σ

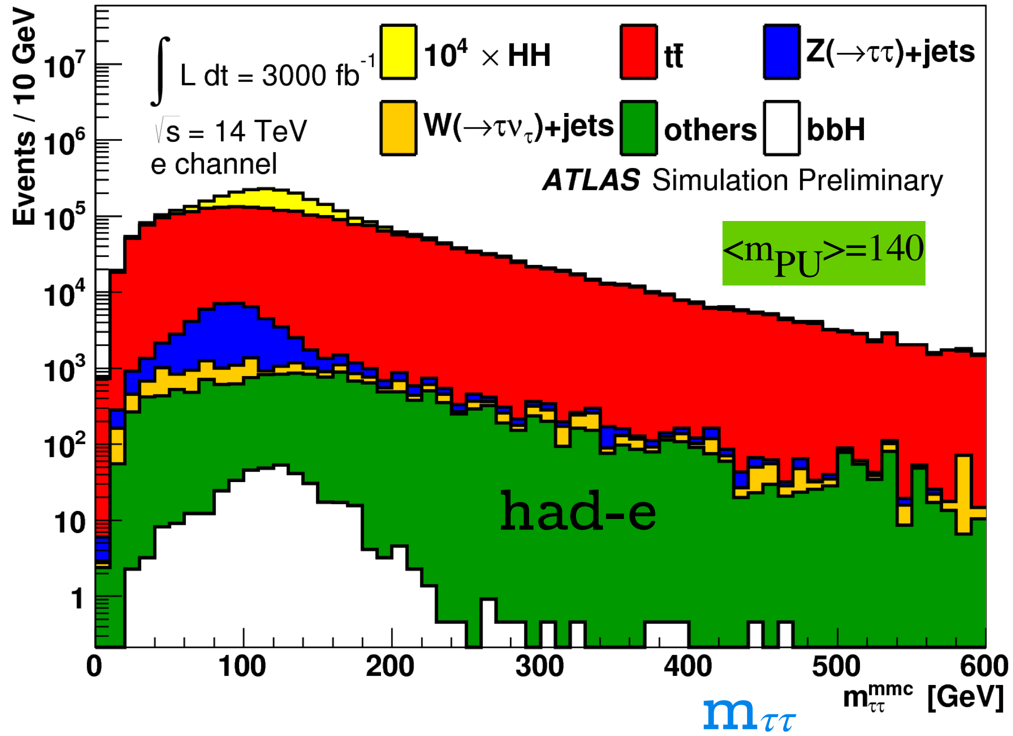
Phase-2 HH → $bb\tau\tau$

SM NON-RESONANT

CMS-PAS-FTR-16-002



ATL-PHYS-PUB-2015-048



Reduced uncertainty on tt shape (< lower jet → τ fake rate)

- Multijet bkg. from data → negligible stat. uncertainty

Lepton (incl. τ) uncertainties as of 2015

→ Significance : 0.39 σ

Main background had-e/μ :tt

had-had:Z→$\tau\tau$+jets+tt

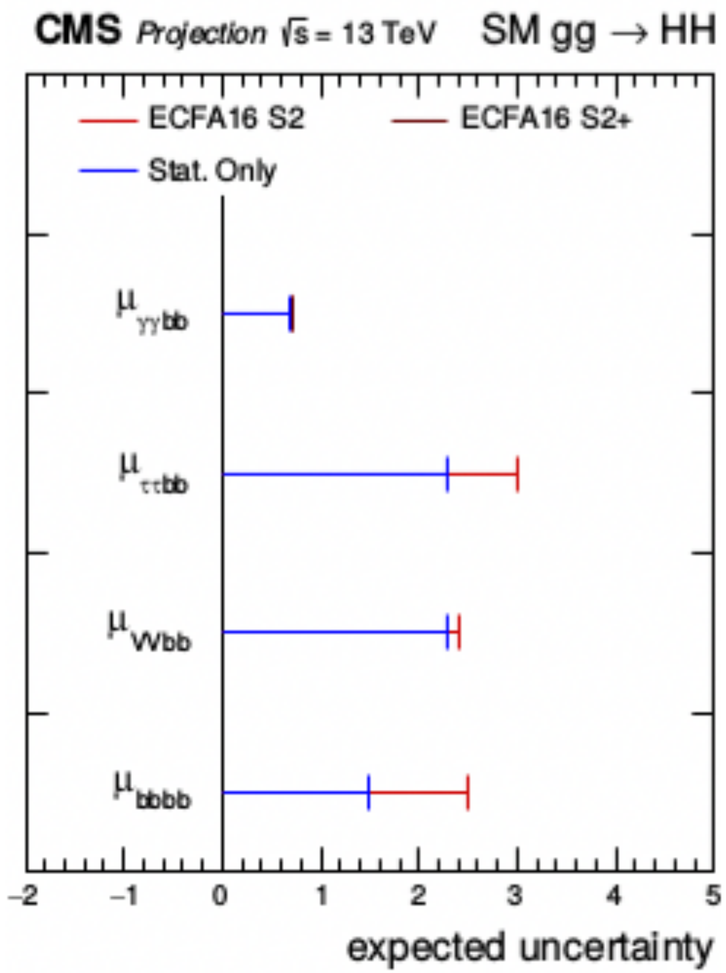
smearing function approach

→ Significance : 0.6 σ

Expected HH results at HL-LHC

SM NON-RESONANT

HH final state	ATLAS Signficance	CMS Significance
$bb\gamma\gamma$	1.05 σ	1.43 σ
$bb\tau\tau$	0.6 σ	0.39 σ
$bb\upsilon\upsilon$		0.39 σ
bbbb		0.45 σ



-Observation with $3ab^{-1}$ will be challenging even with combination of the different final states

-Additional HH production processes such as VBF and ttHH would be helpful

-Improvements in the analysis techniques are also expected

Spares

Extrapolation of Run II analyses

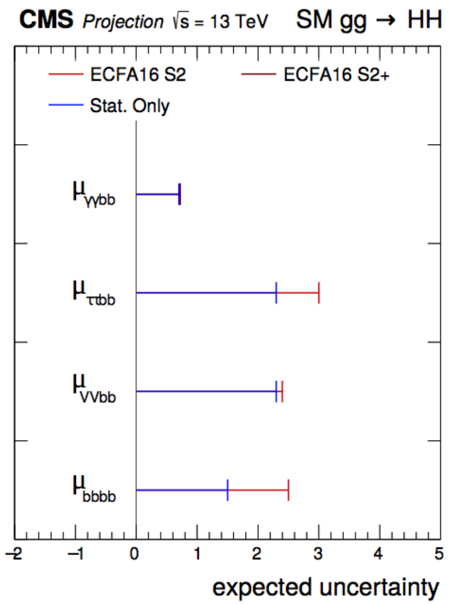
- Results on 2015 data @ 13 TeV (2.3 - 2.7 fb^{-1}) → projected to L_{int}=3000 fb^{-1}
- 13 → 14 TeV : σ_{HH} increase by 18 % – scale backgrounds by same factor (pessimistic)
- Increased acceptance not taken into account (pessimistic)
- Different scenarios assumed for systematic uncertainties :

1) « **Stat. only** » : scale yields with L_{int}; neglect systematics

2) « **ECFA16 S2** » :
- Theory uncertainties reduced by 50 %
- Experimental systematics reduced with luminosity

→ lower limit depending on upgraded detector performances

3) « **ECFA16 S2+** » ($b\bar{b}\gamma\gamma$ only) :
- S2 + Impact of <PU>=200 and detector upgrades on photon performance (efficiency, resolution, fake rate) explicitly taken into account



Assumptions on photon reconstruction :
- Majority of signal photons in Barrel
  → Efficiencies & energy resolution similar to current detector
- Vertex finding degradation due to PU mitigated by timing capabilities
  → Maintain $M_{\gamma\gamma}$ resolution

Results in agreement with dedicated study
- $t\bar{t}H$ background not explicitly rejected here

Assumptions :
- Reduced uncertainty on $t\bar{t}$ shape (< lower jet → τ fake rate)
- Multijet bkg. from data → negligible stat. uncertainty
- Lepton (incl. τ) uncertainties as of 2015

Differences with dedicated study :
- Multijet bkg. not explicitly rejected
- Signal extraction less aggressive

Channel	Median expected limits in μ_r		Z-value		Uncertainty as fraction of $\mu_r = 1$	
	ECFA 16 S2	Stat. Only	ECFA 16 S2	Stat. Only	ECFA 16 S2	Stat. Only
gg → HH → γγbb (S2+)	1.44	1.37	1.43	1.47	0.72	0.71
gg → HH → ττbb	5.2	3.9	0.39	0.53	2.6	1.9
gg → HH → VVbb(lνlν)	4.8	4.6	0.45	0.47	2.4	2.3
gg → HH → bbbb	7.0	2.9	0.39	0.67	2.5	1.5

Assumptions :
- Main background : QCD multijet est. from data
  → Stat. uncertainty only (scaled with L)
- Other backgrounds : uncertainties as of 2015

Assumptions :
- Main backgrounds ($t\bar{t}$, Z+jets) est. from data
  → Stat. uncertainty only (scaled with L)

Results in agreement with dedicated study