Combination of searches for pairs of Higgs bosons with the ATLAS detector

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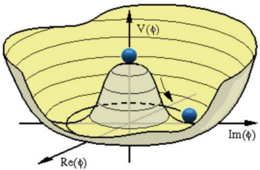
Partikeldagarna, Lund - October 16, 2018

Higgs potential

- Important to measure the shape of the Higgs potential

$$V(\phi) = -\frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4$$

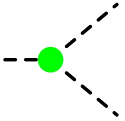


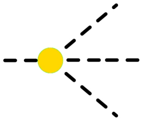
Expanding about minimum: $V(\phi) \to V(v+h)$

$$V = V_0 + \lambda v^2 h^2 + \lambda v h^3 + \frac{1}{4}\lambda h^4 + \ldots$$

$$= V_0 + \frac{1}{2}m_h^2 h^2 + \frac{m_h^2}{2v^2} v h^3 + \frac{1}{4}\frac{m_h^2}{2v^2} h^4 + \ldots$$

mass term | hh-production | hhh-production





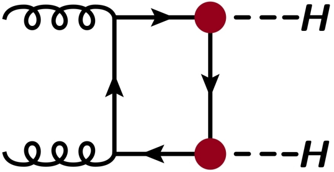
Standard Model (SM):

$$v = \frac{\mu}{\sqrt{\lambda}} = 246\,\mathrm{GeV}$$

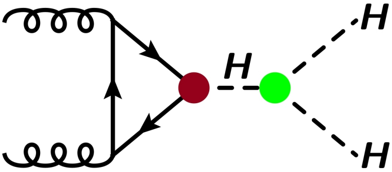
$$\lambda = \frac{m_h^2}{2v^2} \approx 0.13$$

Higgs boson pair production at the LHC

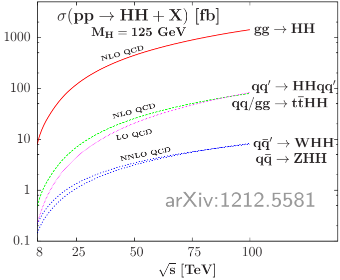
- SM Higgs boson pair production (gluon-gluon fusion - ggF):



Higgs-fermion Yukawa coupling



Higgs boson self-coupling



Small production cross-section:

$\sigma_{SM}^{ggF} = 33.41$ fb at $\sqrt{s} = 13$ TeV

– two massive final state particles

– destructive interference

Phys. Rev. Lett. 117 (2016) 012001

10.23731/CYRM-2017-002 LHCHXSWGHH

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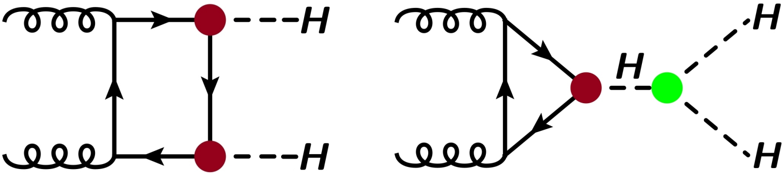

Higgs-fermion Yukawa coupling

Higgs boson self-coupling

- Potential non-resonant BSM enhancements
  (new couplings, modified Yukawa and/or self-couplings)

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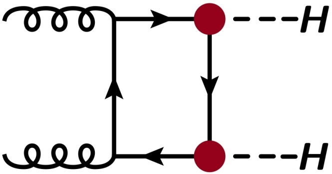
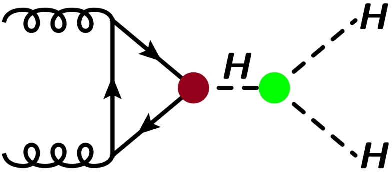


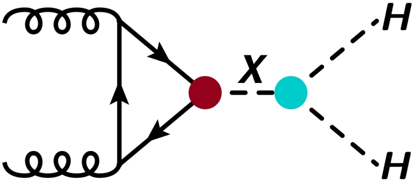
Higgs-fermion Yukawa coupling



Higgs boson self-coupling

- Potential non-resonant BSM enhancements
  (new couplings, modified Yukawa and/or self-couplings)

- Benchmark BSM resonance hypotheses:
  - Randall-Sundrum graviton $G \to HH$ (spin=2)
  - $S \to HH$ (spin=0)



Resonant production

Di-Higgs final states

Di-Higgs decay modes and relative branching fractions:

	bb	WW	ττ	ZZ	γγ
bb	33%				
WW	25%	4.6%			
ττ	7.4%	2.5%	0.39%		
ZZ	3.1%	1.2%	0.34%	0.076%	
γγ	0.26%	0.10%	0.029%	0.013%	0.0005%

10.23731/CYRM-2017-002

Channels considered for this combination:

$HH \to b\bar{b}b\bar{b}$: the highest BR, large multijet background

$HH \to b\bar{b}\tau^+\tau^-$: relatively large BR, cleaner final state

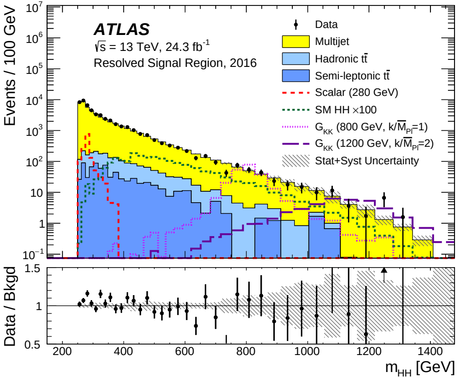
- $\tau_{\rm lep}\tau_{\rm had}$ (BR: 45.8%)
- $\tau_{\rm had}\tau_{\rm had}$ (BR: 41.9%)

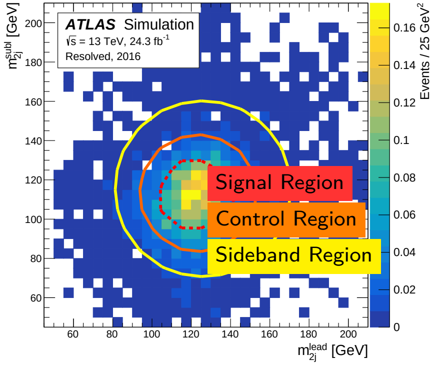
$HH \to b\bar{b}\gamma\gamma$: small BR, clean signal extraction due to a good $\gamma\gamma$ mass resolution

arXiv:1804.06174

(Resolved) $HH \to 4b$

- Background:
  $\sim 95\%$ multijet and $\sim 5\%$ $t\bar{t}$
- Data-driven estimation of the multijet background
  $\to 2b + nj$ $(n > 2)$ events model $4b$
- $t\bar{t}$ normalization from data





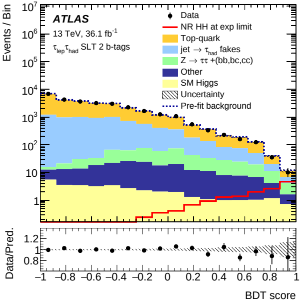
- Integrated luminosity (2015+2016): 27.5 fb^{-1}
- Final discriminant: m_{HH}

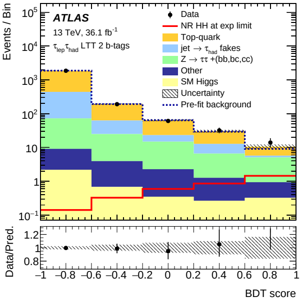
arXiv:1808.00336

$HH \to bb\tau\tau$

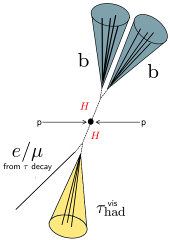
- A Boosted Decision Tree (BDT) classification is applied after preselection

SM $\tau_{lep}\tau_{had}$

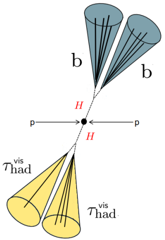




SM $\tau_{had}\tau_{had}$



- Jets$\to \tau_{had}$ fakes: data-driven (Fake Factor/Rate methods)
- $t\bar{t}$ and $Z + b\bar{b}$ normalization from data
- 3 signal regions ($\tau_{lep}\tau_{had}$ split into single e/μ trigger and $e/\mu + \tau$ trigger)
- BDT score used as a final discriminant

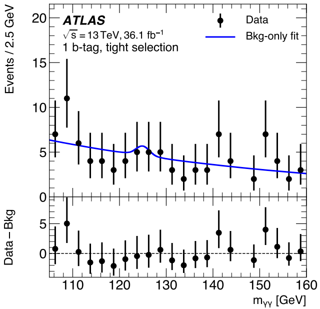


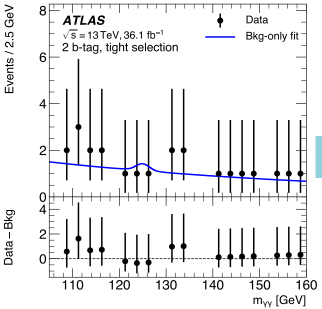
arXiv:1807.04873

$HH \rightarrow bb\gamma\gamma$

tight

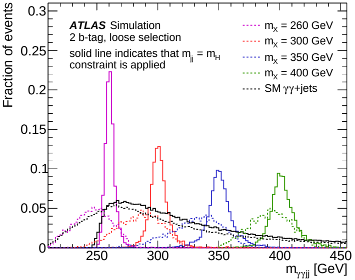
$1b$-tag





tight

$2b$-tags



- Data-driven methods used to estimate the continuum background
  double two-dimensional sideband method
- Unbinned maximum-likelihood fits to the data in the 1-tag and 2-tag regions
- Final discriminant: $m_{\gamma\gamma}$ (non-resonant), $m_{\gamma\gamma jj}$ (resonant)

Non-resonant SM HH production

The combination is realized by constructing a combined likelihood function that takes into account data, models and systematic uncertainties

Instrumental and luminosity uncertainties correlated across the channels

The acceptance and the background modeling uncertainties treated as uncorrelated

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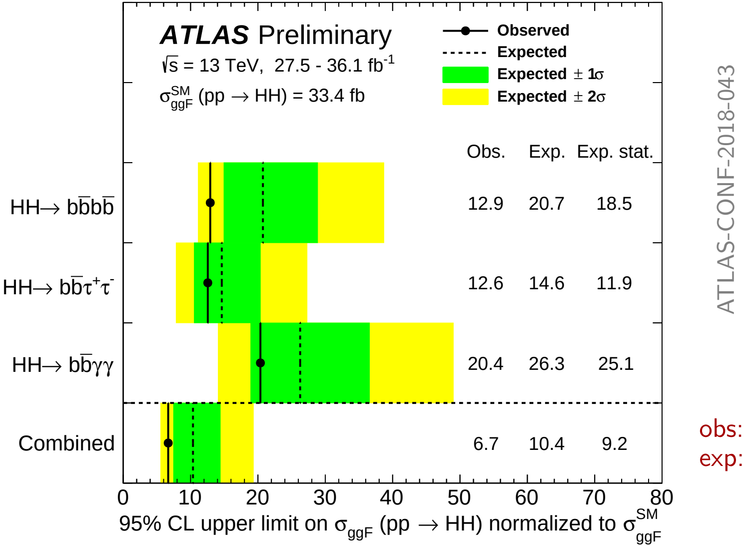
SM HH production, combined result



obs: 0.22 pb
exp: 0.35 pb

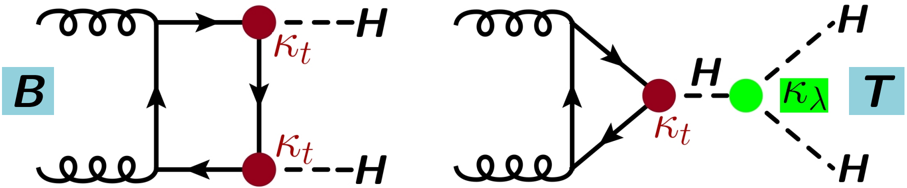
Run-1 ATLAS combination obs (exp): 70 (48) Phys. Rev. D 92, 092004

Trilinear Higgs self-coupling variations

Varied trilinear Higgs self-coupling

HH production modified

(using scale factors: $\kappa_t = g_{t\bar{t}H}/g^{SM}_{t\bar{t}H}$ and $\kappa_\lambda = \lambda_{HHH}/\lambda^{SM}_{HHH}$)



$$A(\kappa_t, \kappa_\lambda) = \kappa_t^2 B + \kappa_t \kappa_\lambda T$$

Varied trilinear Higgs self-coupling

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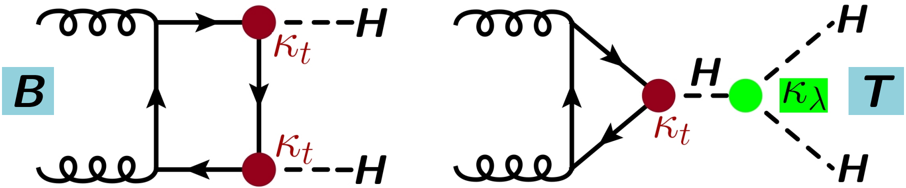

$$A(\kappa_t, \kappa_\lambda) = \kappa_t^2 B + \kappa_t \kappa_\lambda T$$

$A(1,0) = B \qquad A(1,1) = B + T \qquad A(1,2) = B + 2T$

Express $|B|^2$, $|T|^2$ and $(BT^* + TB^*)$ in terms of $|A(1,0)|^2$, $|A(1,1)|^2$ and $|A(1,2)|^2$,

Varied trilinear Higgs self-coupling

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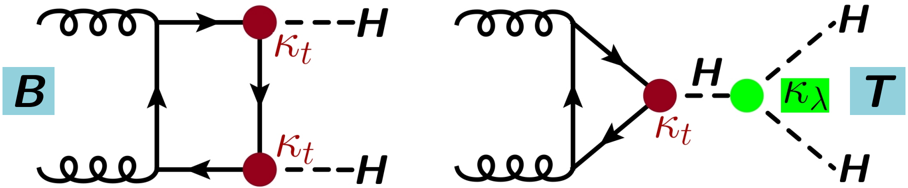

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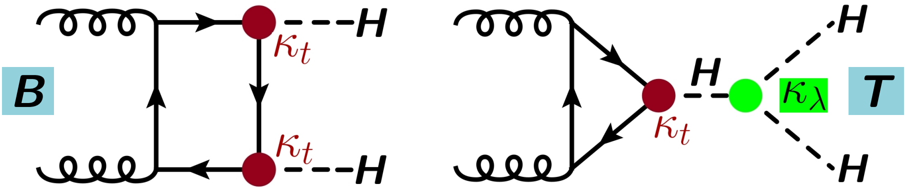
$$|A(\kappa_t, \kappa_\lambda)|^2 = a(\kappa_t, \kappa_\lambda)|A(1,0)|^2 + b(\kappa_t, \kappa_\lambda)|A(1,1)|^2 + c(\kappa_t, \kappa_\lambda)|A(1,2)|^2$$

Varied trilinear Higgs self-coupling

HH production modified

(using scale factors: $\kappa_t = g_{t\bar{t}H}/g^{SM}_{t\bar{t}H}$ and $\kappa_\lambda = \lambda_{HHH}/\lambda^{SM}_{HHH}$)



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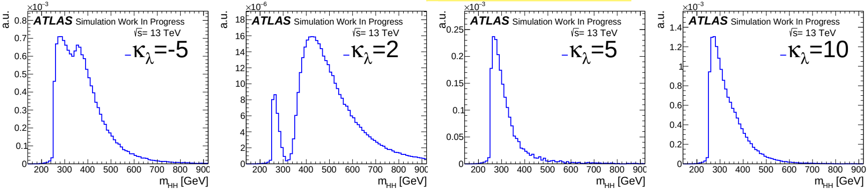
Any $(\kappa_t, \kappa_\lambda)$ combination at LO can be obtained from a **linear combination** of some 3 $(\kappa_t \neq 0, \kappa_\lambda)$ samples!

Trilinear Higgs self-coupling scan strategy

1 $m_{HH}^{\kappa_\lambda = x}$, for $x = \{-20, -19, ..., 20\}$, at generator level, at LO

obtained using the linear combination :



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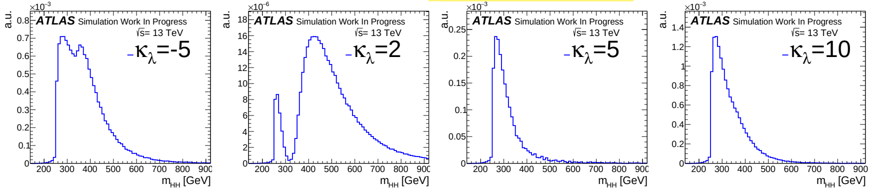
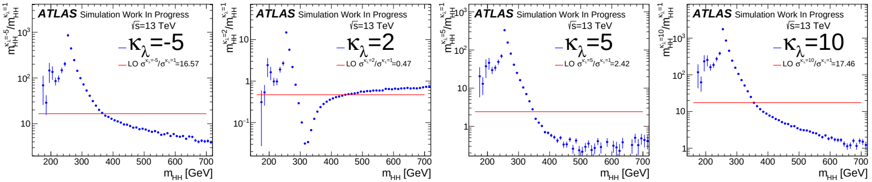


2 Weights, binned in m_{HH}, obtained as: $m_{HH}^{\kappa_\lambda=x}|_{\text{bin }i}/m_{HH}^{\kappa_\lambda=1}|_{\text{bin }i}$



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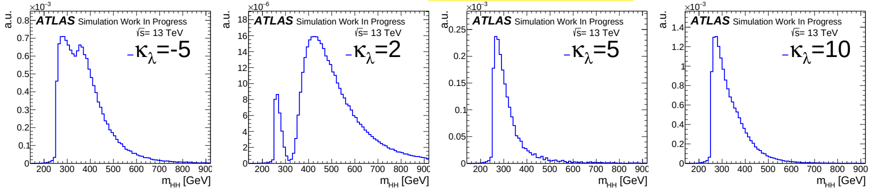

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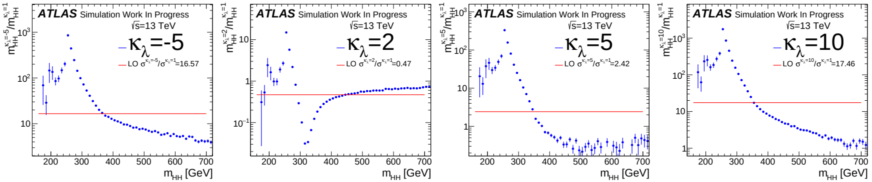


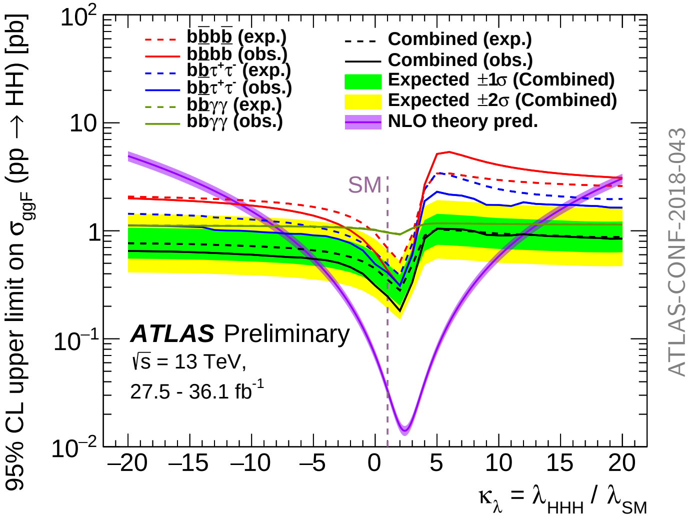
3 These weights are applied to the fully reconstructed NLO SM sample to obtain any κ_λ point, assuming that the LO to NLO factorization does not depend on κ_λ

Limits on the cross-section as a function of κ_λ

$4b$
$bb\tau\tau$
$bb\gamma\gamma$
combination

dashed: expected

solid: observed



The scale factor κ_λ is observed (expected) to be constrained in the range:

$$-5.0 < \kappa_\lambda < 12.1 \; (-5.8 < \kappa_\lambda < 12.0)$$

Resonant HH production

(combination in the mass range: 260-1000 GeV)

Differences compared to the SM HH search:

$bb\gamma\gamma$:

looser selection below 500 GeV

final discriminant: $m_{\gamma\gamma jj}$

$b\bar{b}\tau\tau$:

dedicated BDTs

$b\bar{b}b\bar{b}$:

boosted analysis for signal masses > 800 GeV

(combined with the resolved)

Randall-Sundrum graviton model in the backup

Scalar resonance

$4b$

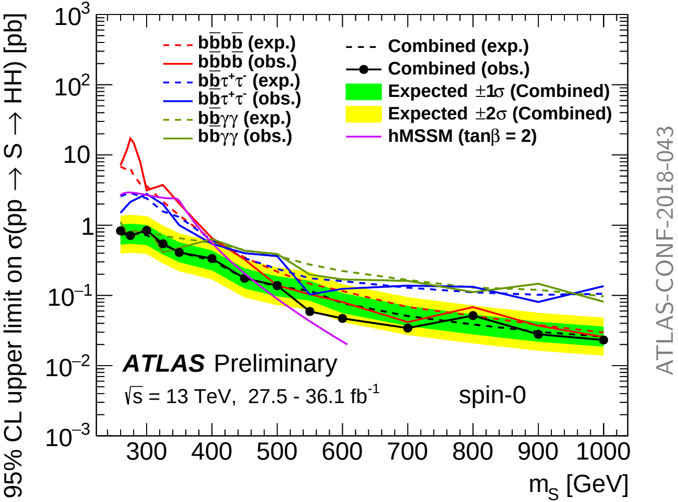
$bb\tau\tau$

$bb\gamma\gamma$

combination

dashed: expected

solid: observed



hMSSM, narrow width CP-even scalar ($\tan\beta = 2$)*: $m_S < 462$ GeV at 95% CL excluded

*$\tan\beta = 2$: ratio of the vacuum expectation values of the two Higgs doublets

Conclusion

- A statistical combination of searches for non-resonant and resonant production of Higgs boson pairs for the most sensitive channels is presented.
- Using up to 36.1 fb^{-1} of pp collision data recorded with the ATLAS detector.
- The observed (expected) 95% CL exclusion upper limit on the SM Higgs boson pair production is set to 6.7 (10.4) times the SM prediction.
- The observed (expected) exclusion limit as a function of the Higgs self-coupling scale factor, κ_λ, allows to constrain values in the range: $-5.0 < \kappa_\lambda < 12.1$ $(-5.8 < \kappa_\lambda < 12.0)$ at 95% CL.
- The exclusion limits are set on the production cross-section of heavy spin-0 and spin-2 resonances decaying into a pair of Higgs bosons, in the mass range 260-1000 GeV.
- No significant data excess is found after the combination.

Thank you for your attention!

backup slides

Differences compared to the SM HH search

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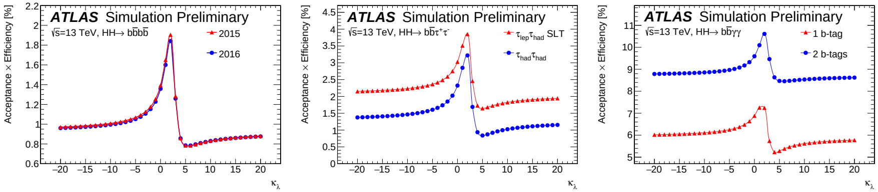
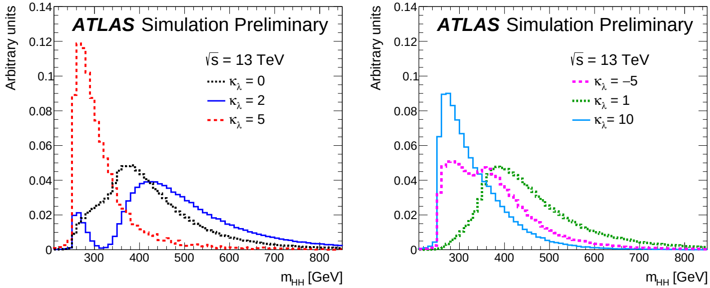
- Acceptance changes significantly as a function of κ_λ:



variations of the m_{HH} spectrum with κ_λ:



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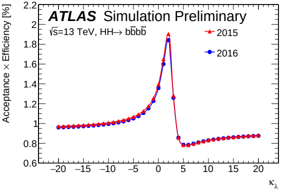
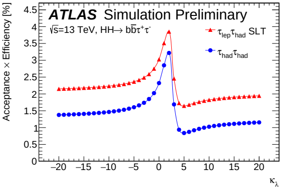
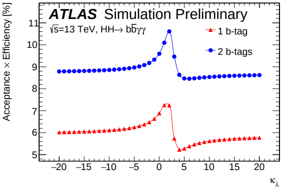
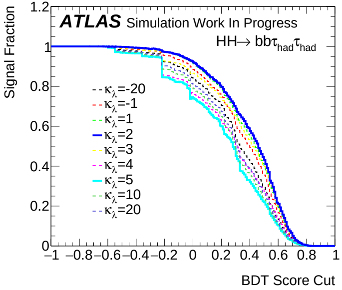






- Looser $bb\gamma\gamma$ selection (softer p_T for large κ_λ)
- $bb\tau\tau$: a dedicated BDT, trained on $\kappa_\lambda = 20$ signal is used since it performs good for all κ_λ points.
- The shape of $bb\gamma\gamma$ discriminant ($m_{\gamma\gamma}$) remains independent of κ_λ, while an additional loss in sensitivity is observed for $bb\tau\tau$ and $4b$ analyses for large $|\kappa_\lambda|$.

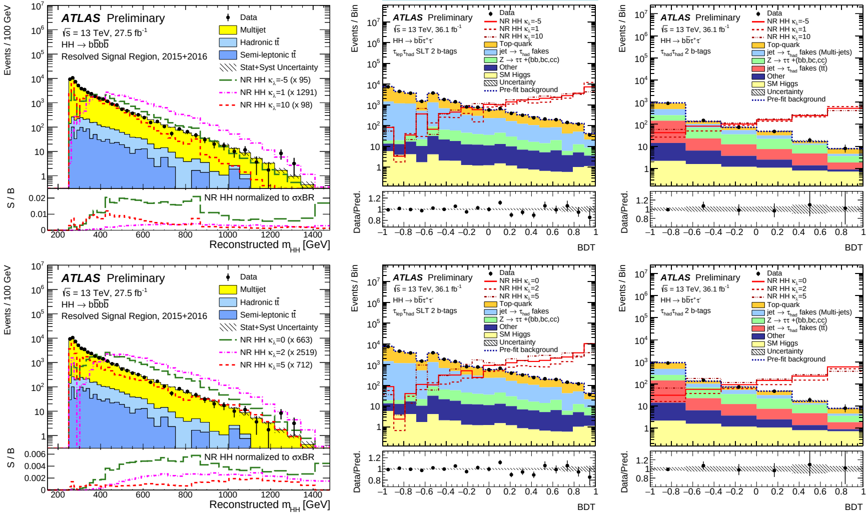


Differences compared to the SM HH search

$HH \to b\bar{b}b\bar{b}$ | $HH \to b\bar{b}\tau_{\rm lep}\tau_{\rm had}$ | $HH \to b\bar{b}\tau_{\rm had}\tau_{\rm had}$

$\kappa_\lambda = \{-5, 1, 10\}$

$\kappa_\lambda = \{0, 2, 5\}$



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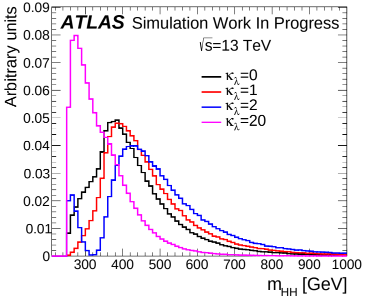
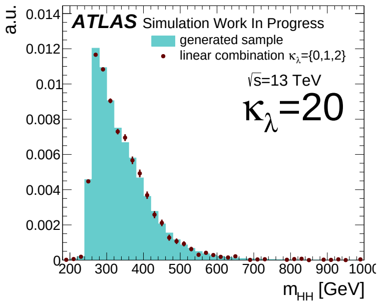
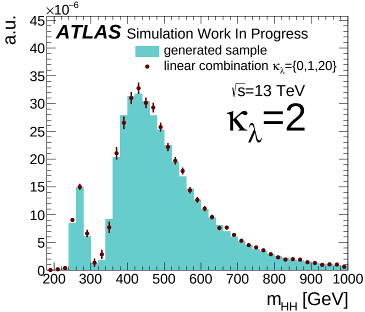
Linear combination

- Showing generator level m_{HH} for: $\kappa_\lambda = \{0, 1, 2, 20\}$ (other parameters fixed to the SM)
- Different bases tested for linear combination (e.g. $\kappa_\lambda = \{0, 1, 2\}$ vs $\kappa_\lambda = \{0, 1, 20\}$)
- Remaining sample used for validation (very good closure at generator level)







Full systematic uncertainty vs data stat-only

$4b$

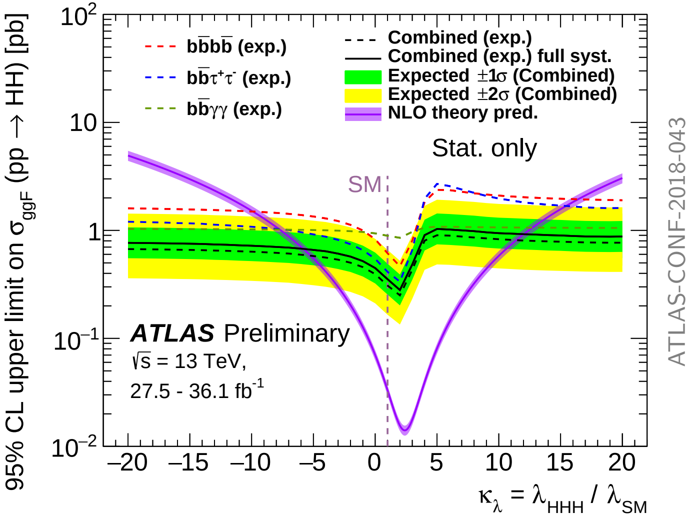
$bb\tau\tau$

$bb\gamma\gamma$

combination

solid: expected full syst.

dashed: expected stat-only



Stat. only limits for the individual channels and the combination

Allowed intervals for κ_λ

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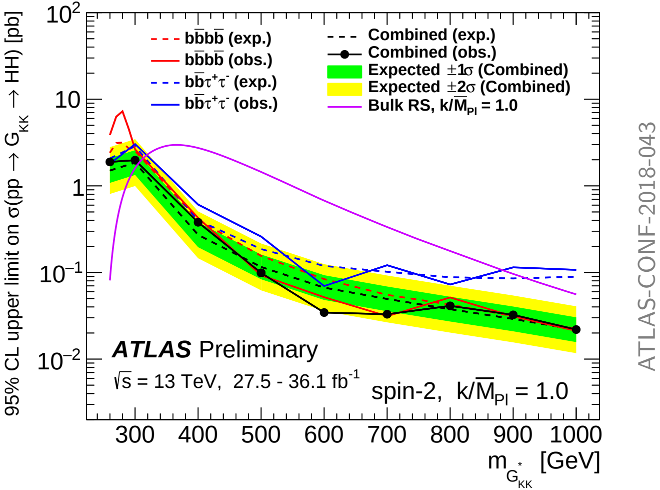
Search channel	Allowed κ_λ interval at 95% CL		
	obs.	exp.	exp. stat.
$HH \to b\bar{b}b\bar{b}$	-10.9 – 20.1	-11.6 – 18.7	-9.9 – 16.4
$HH \to b\bar{b}\tau^+\tau^-$	-7.3 – 15.7	-8.8 – 16.7	-7.8 – 15.4
$HH \to b\bar{b}\gamma\gamma$	-8.1 – 13.2	-8.2 – 13.2	-7.7 – 12.7
Combination	-5.0 – 12.1	-5.8 – 12.0	-5.2 – 11.4

Randall-Sundrum graviton model

$4b$
$bb\tau\tau$
combination

dashed: expected

solid: observed



$(k/\bar{M}_{Pl} = 1)^* \; 307 < m_G < 1362$ GeV** at 95% CL

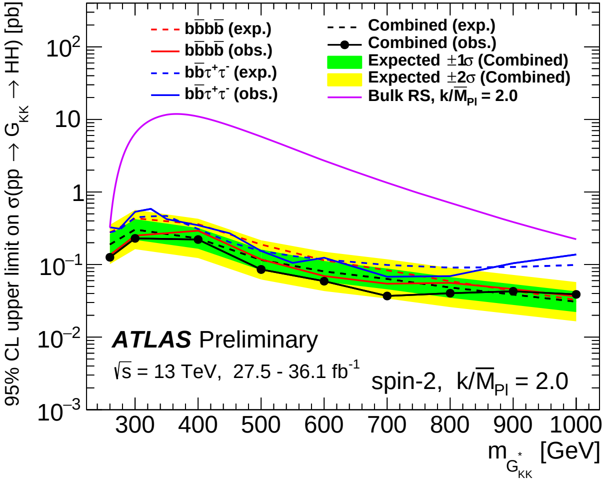
$^*k$: curvature of the warped extra dimension, $\bar{M}_{Pl}$: the effective four-dimensional Planck scale
**the upper limit on the mass comes from $4b$ only

Randall-Sundrum graviton model

$4b$
$bb\tau\tau$
combination

dashed: expected

solid: observed



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$(k/\bar{\mathrm{M}}_{\mathrm{Pl}} = 2)^{*}\ m_G < 1744$ GeV** at 95% CL

$^{*}k$: curvature of the warped extra dimension, $\bar{\mathrm{M}}_{\mathrm{Pl}}$: the effective four-dimensional Planck scale
**the upper limit on the mass comes from $4b$ only

Randall-Sundrum graviton model, 4b

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