Searches for Non-Resonant Double Higgs Production & Projections for the (HL-)LHC

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ATLAS EXPERIMENT

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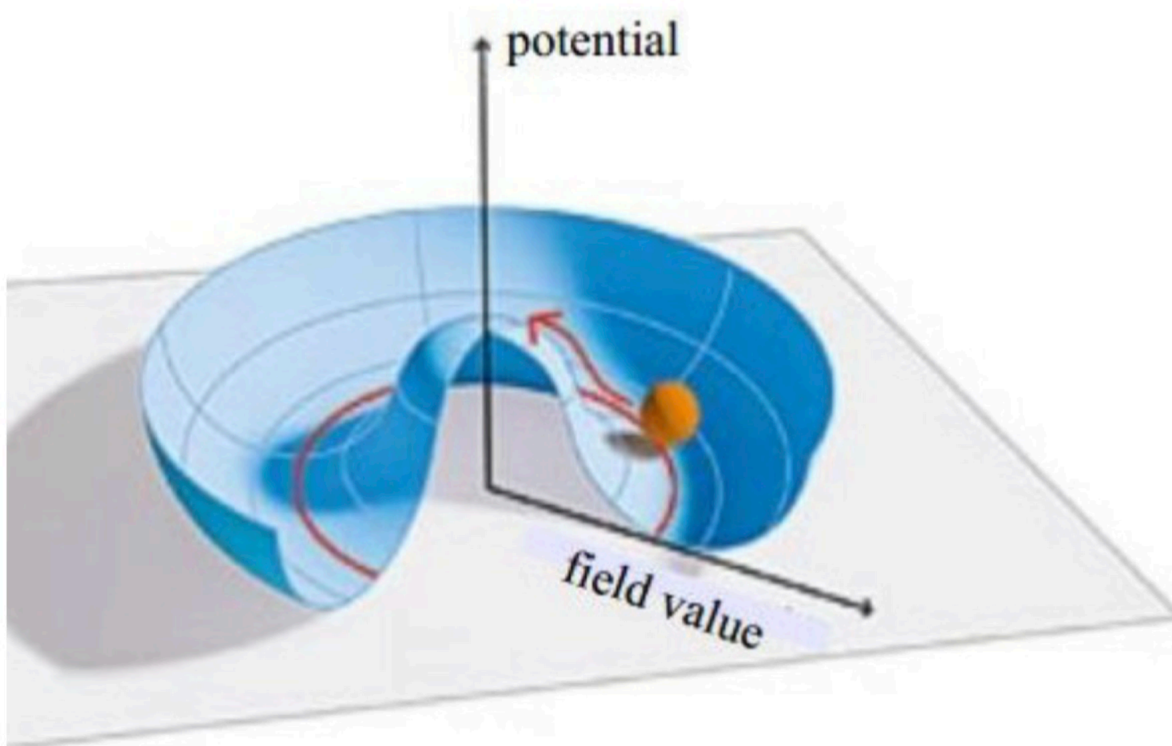
Enigmass
The enigma of mass

CMS
Compact Muon Solenoid

Introduction

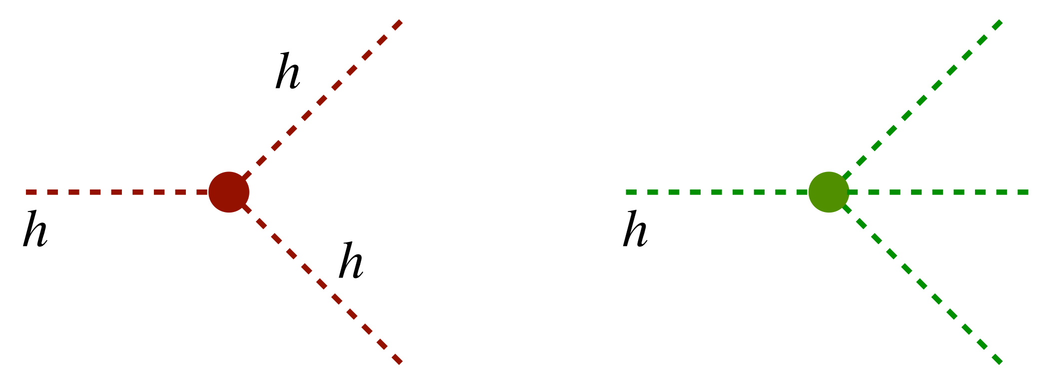
- In the Standard Model, the Higgs Field self-interaction generates the VeV
- Measurement of Higgs self-coupling is only method of experimentally reconstructing Higgs Potential
    - Constrains shape of Higgs Potential close to minimum



$$V(\Phi) = \mu^2\Phi^+\Phi + \eta(\Phi^+\Phi)^2$$

Expansion Around the Minimum

$$\frac{1}{2}m_H^2 + \sqrt{\frac{\eta}{2}}m_H h^3 + \frac{\eta}{4}h^4$$



- Measuring λ_{HHH} provides direct probe of Higgs potential
- Measuring $\kappa_\lambda = \lambda_{HHH}/\lambda_{HHH}^{SM}$ helps verify SM electroweak symmetry breaking
- Coupling constants could be changed by:
    - Existence of extended scalar sector
    - New dynamics at higher scales

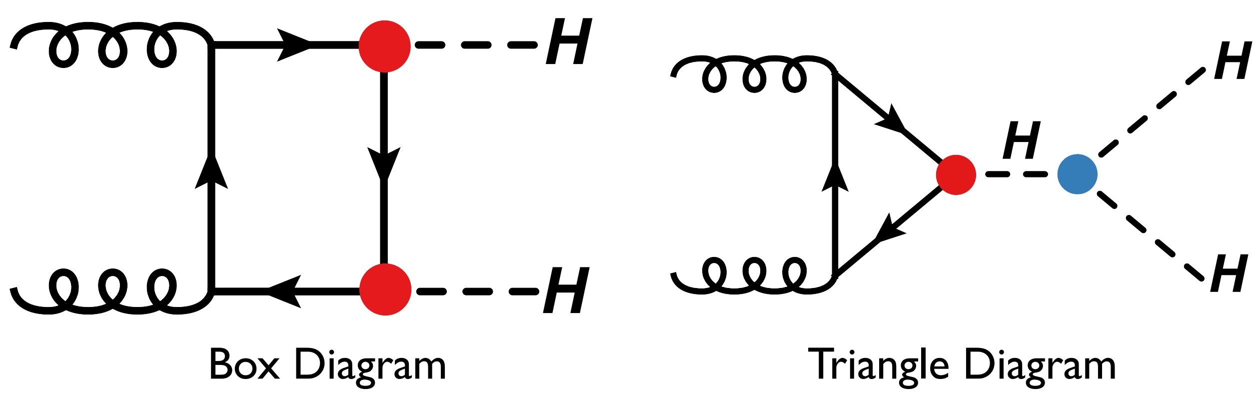
Higgs Boson Pair Production

- Measurement of κ_λ possible by studying HH production
- HH production cross-section at 13TeV is 31.05 fb

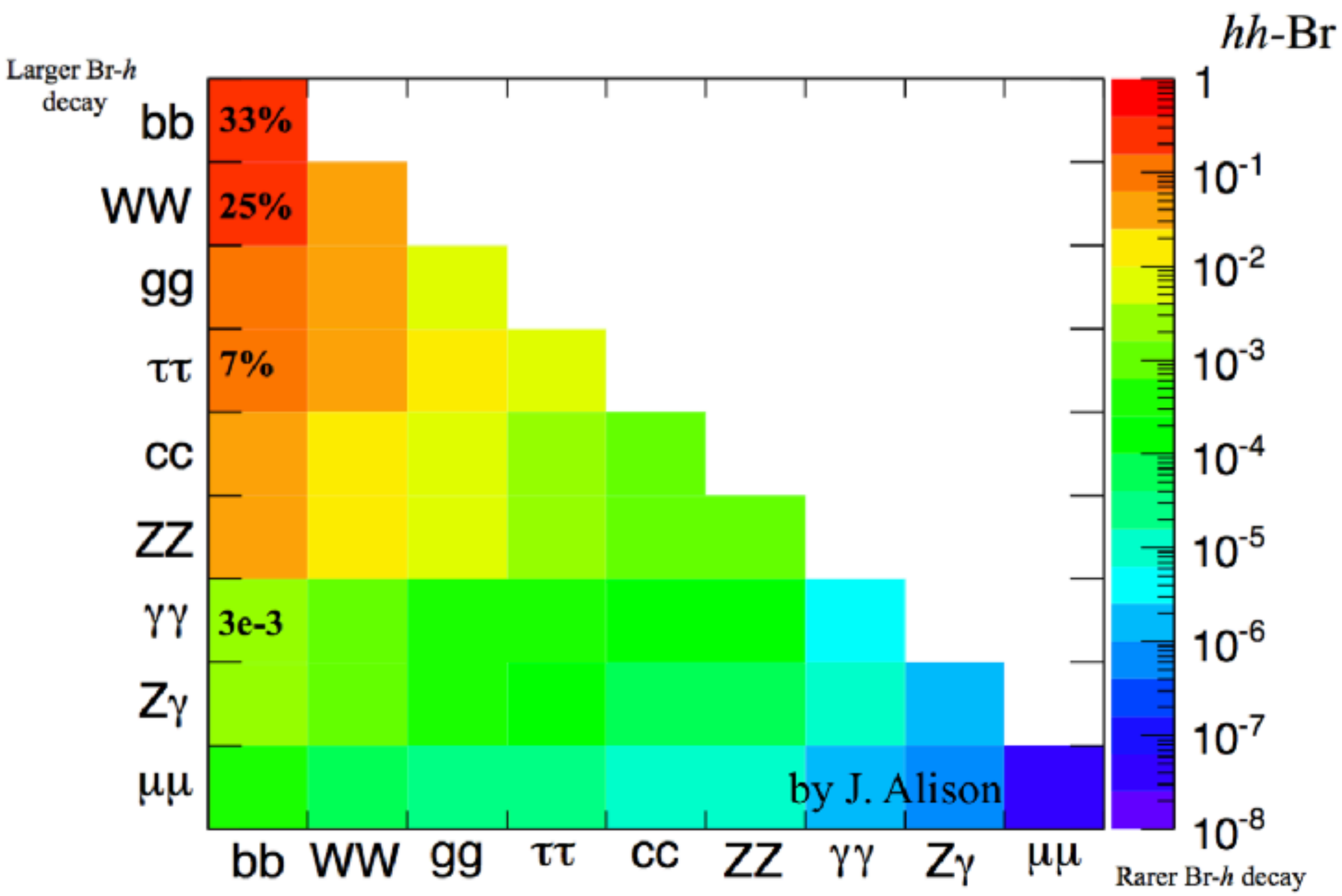
- Rich variety of final states available
  - $b\bar{b}\gamma\gamma$ has low branching ratio
  - $b\bar{b}\tau\tau$, $b\bar{b}b\bar{b}$ have high background
- Small cross-sections provide technical challenge

- ATLAS and CMS are investigating HH production
  - Results of searches for non-resonant production presented here
  - Presented results use 2015 and 2016 data

- Results extrapolated to show exciting prospects for future HL-LHC accelerator!



In the SM, destructive interference lowers cross-section



Run 2: HH→$b\bar{b}b\bar{b}$

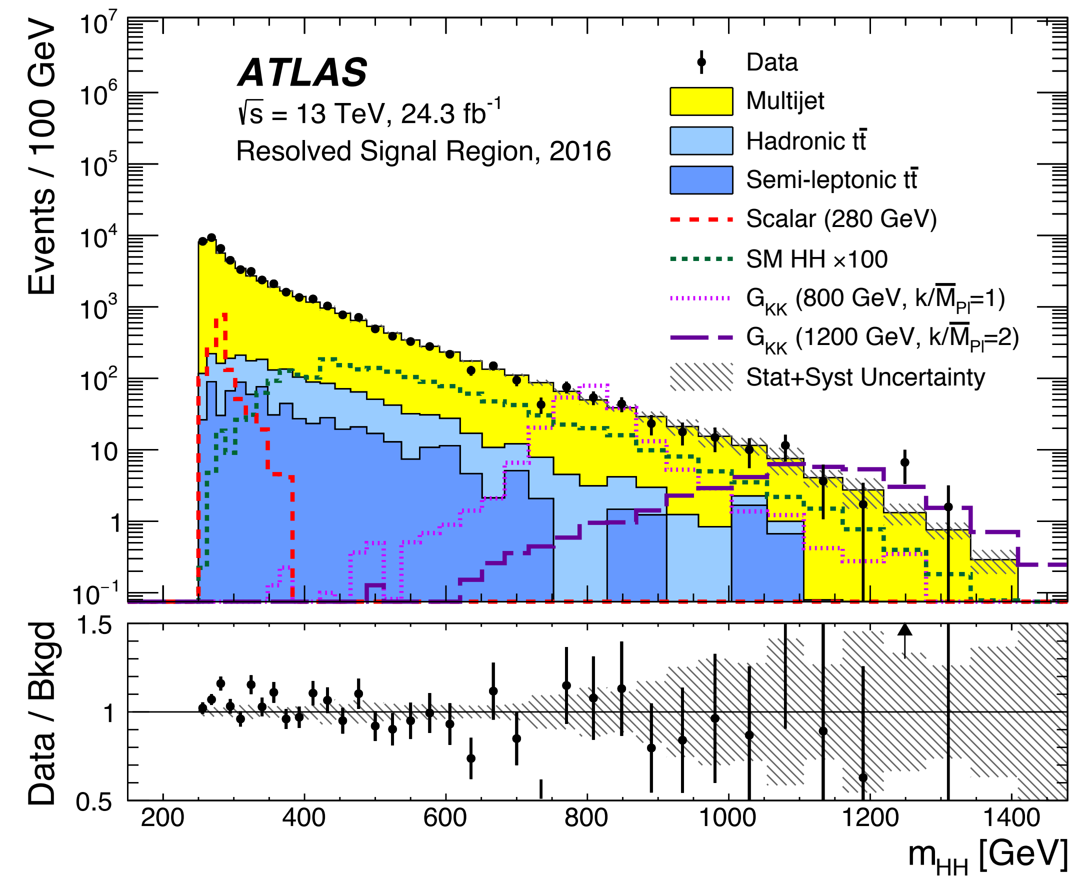
ATLAS: JHEP 01 (2019) 030, CMS: JHEP 04 (2019) 112

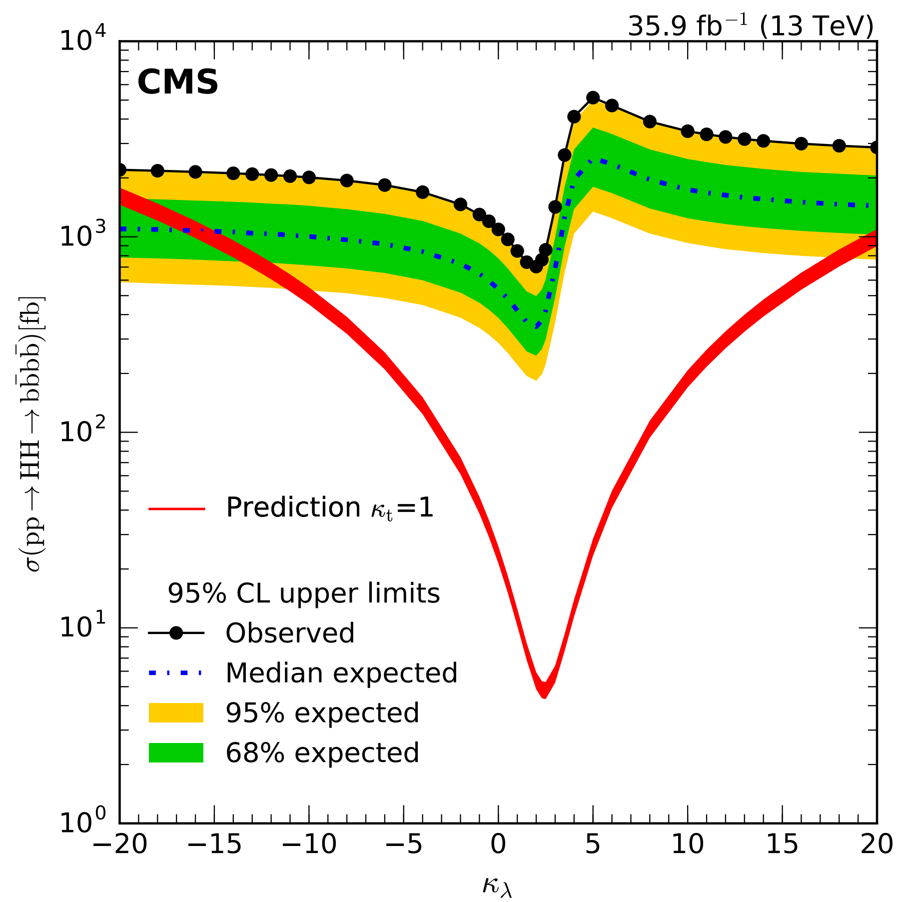
- Highest branching fraction but experimentally challenging
  - Irreducible multi-jet background dominates
  - Suffers from poor mass resolution
  - Multiple triggers combined to identify 4 jets

- ATLAS and CMS use similar approaches
- Searches use "resolved analysis"
  - All four b-jets can be reconstructed separately
  - B-jets combined to form H candidates
  - Multivariate methods used to identify signal amongst background

- HH production amplitude expressed in terms of:
  - Value of κ_λ
  - Top quark Yukawa coupling
- MC signal generated for multiple values of κ_λ
- Samples combined with appropriate weights
- Provides signal distribution for any arbitrary κ_λ value
- Possible to assess sensitivity as function of κ_λ

- Limits on non-resonant production at 95% CL:
  - ATLAS: 12.9 x SM (20.7 x SM) observed (expected)
  - CMS: 74.6 x SM (36.9 x SM) observed (expected)





Run 2: HH→$b\bar{b}\tau\tau$

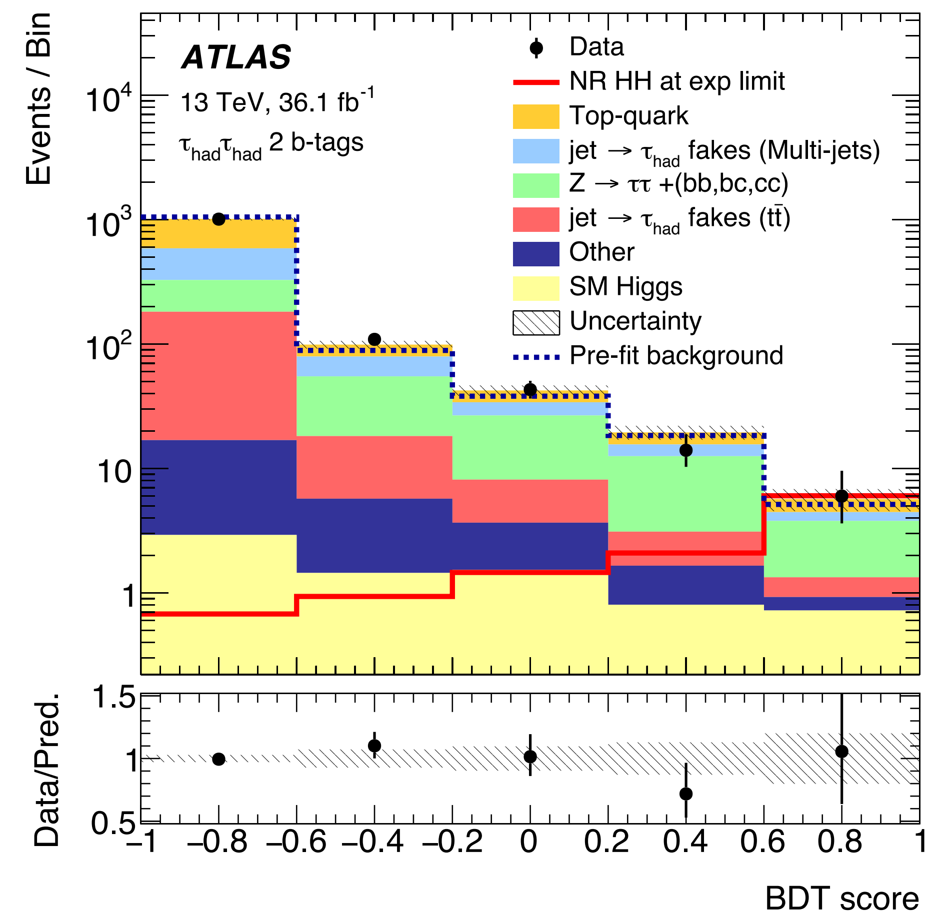
- Experimentally favourable due to 7.3% BR
  - Moderate background contamination
- Background dominated by $t\bar{t}$, QCD multi-jet, Z+heavy jets

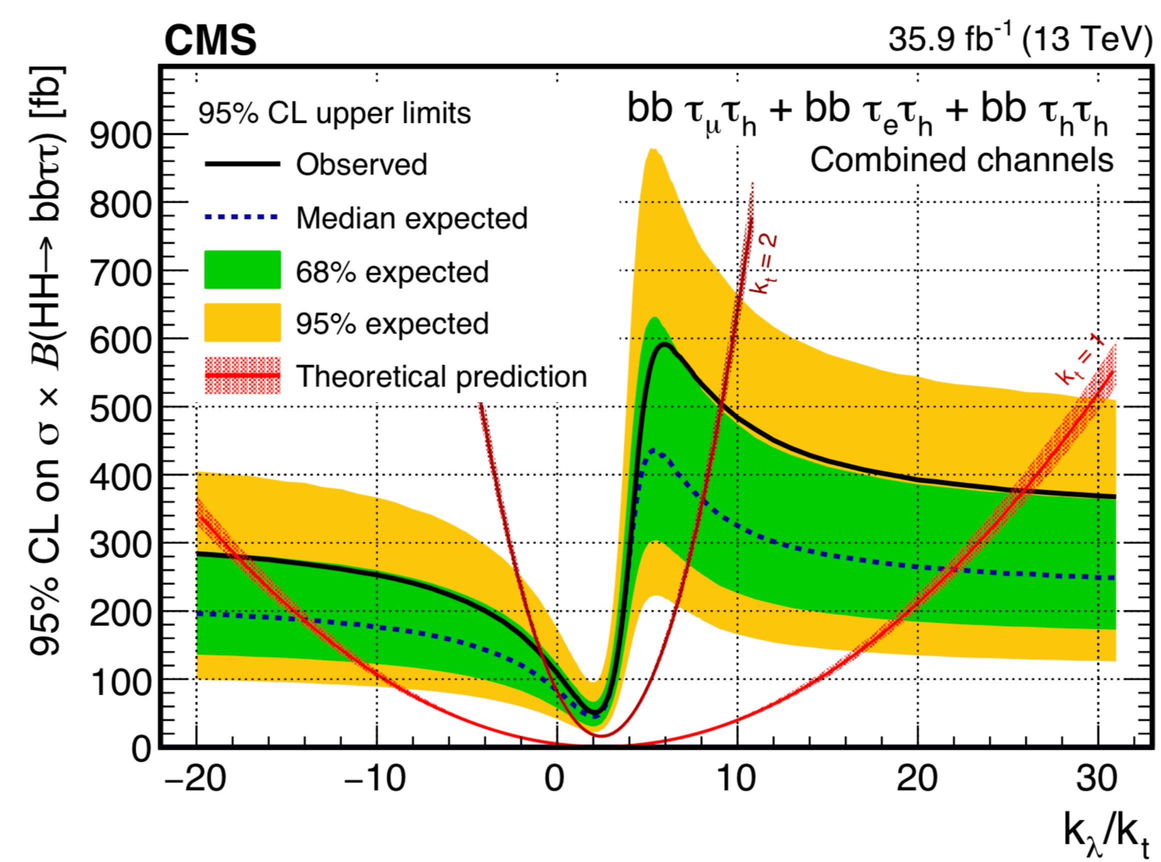
- ATLAS event selection uses three categories:
  - $\tau_{had}\tau_{had}$
  - Two $\tau_{lep}\tau_{had}$ categories (using different triggers)
- Kinematic variables used to train BDT for each category
- BDT scores used as final discriminant, boosts sensitivity

- CMS uses single b-jet and boosted categories
- Makes use of the "stransverse mass"
  - Largest mass of the parent particle compatible with kinematic constraints of event
  - Parent particle interpreted as top quark decaying to bottom quark and W-boson

$$m_{T2}\left(\underbrace{m_b, m_{b'}, \vec{b}_T, \vec{b'}_T}_{\text{b-jets}}, \vec{p}_T^{\,\Sigma}, \underbrace{m_c, m_{c'}}_{\text{leptons, neutrinos from top decay}}\right) = \min_{\vec{c}_T+\vec{c}_T'=\vec{p}_T^{\,\Sigma}} \left\{\max m_T, m'_T\right\}$$

- Limits on non-resonant production at 95% CL:
  - ATLAS: 12.7 x SM (14.8 x SM) observed (expected)
  - CMS: 31.4 x SM (25.1 x SM) observed (expected)





Run 2: $HH \to b\bar{b}\gamma\gamma$

ATLAS: JHEP 11 (2018) 040, CMS: PLB 788 (2018) 7

- Sensitive channel despite low branching fraction
  - Excellent di-photon mass resolution
  - Ability to fully reconstruct all final state objects
- Background dominated by non-resonant diphoton + jets

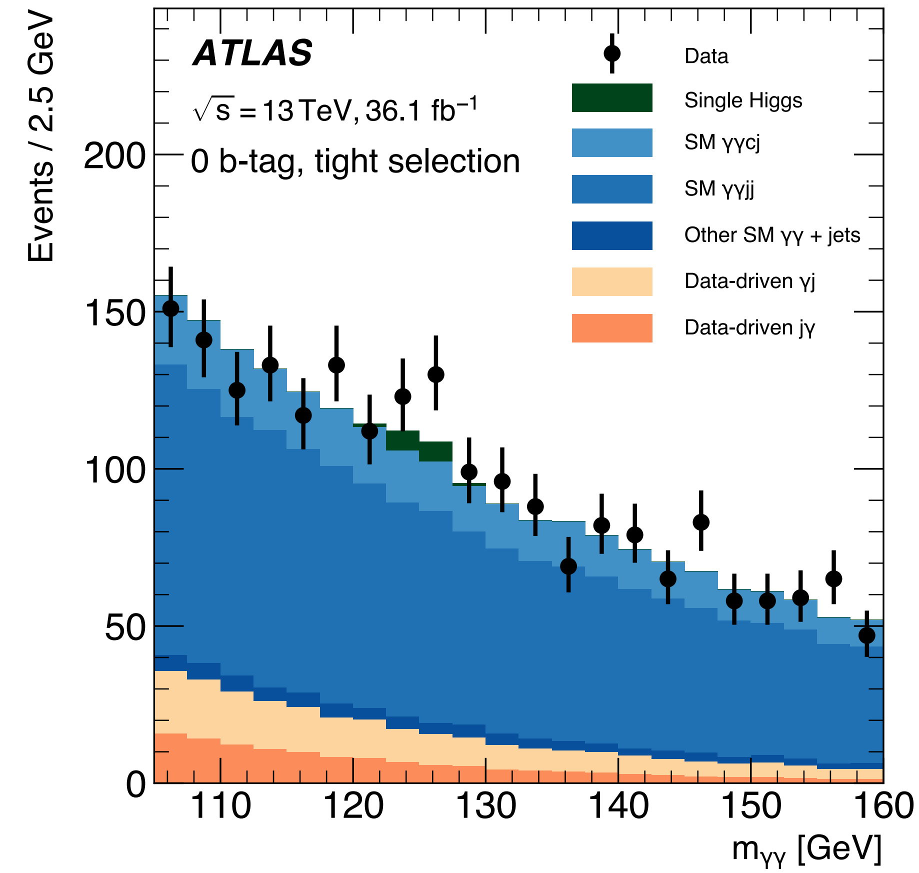
- ATLAS uses two sets of kinematic selections
- One for m_X < 500 GeV, optimised to search for
  - low mass resonances
  - non-SM values of Higgs self-coupling
- Tighter criteria for m_X > 500 GeV
  - Used for high mass resonances and κ_λ limits

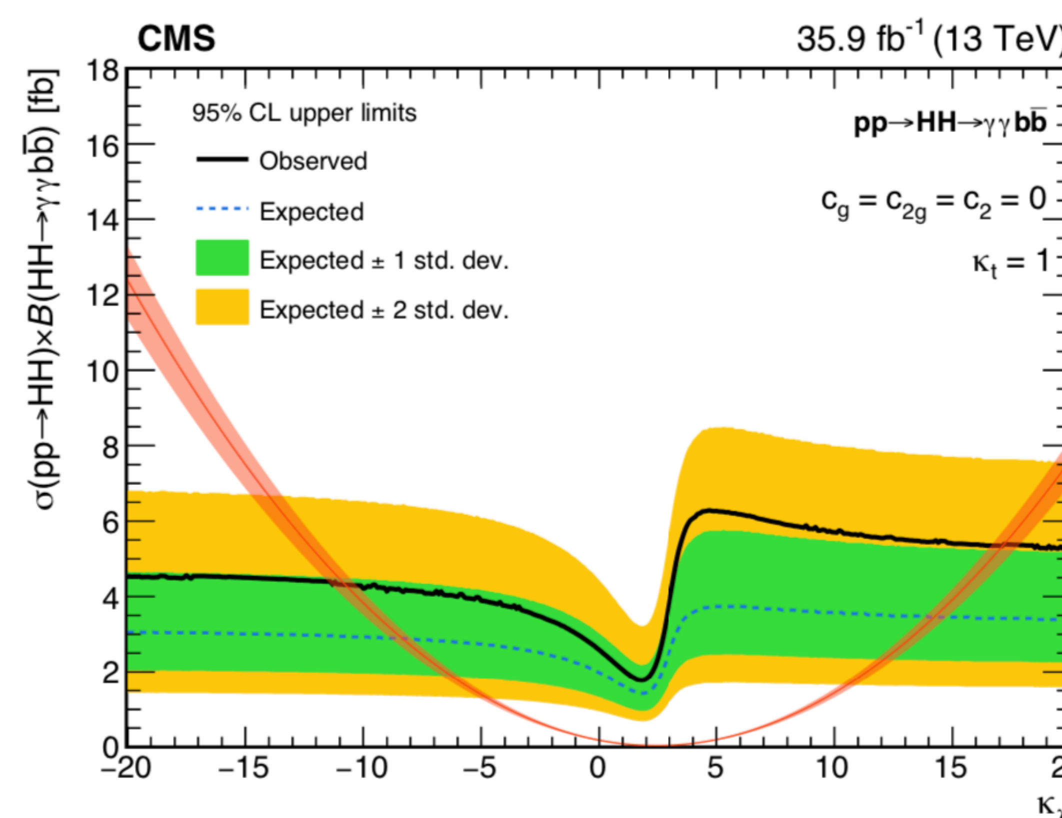
- CMS has introduced better estimate of m_{HH} than $m_{\gamma\gamma jj}$:

$$\widetilde{M}_X = m_{\gamma\gamma jj} - (m_{jj} - m_H) - (m_{\gamma\gamma} - m_H),$$

  - mitigates $m_{\gamma\gamma jj}$ dependency on dijet and diphoton energy resolutions

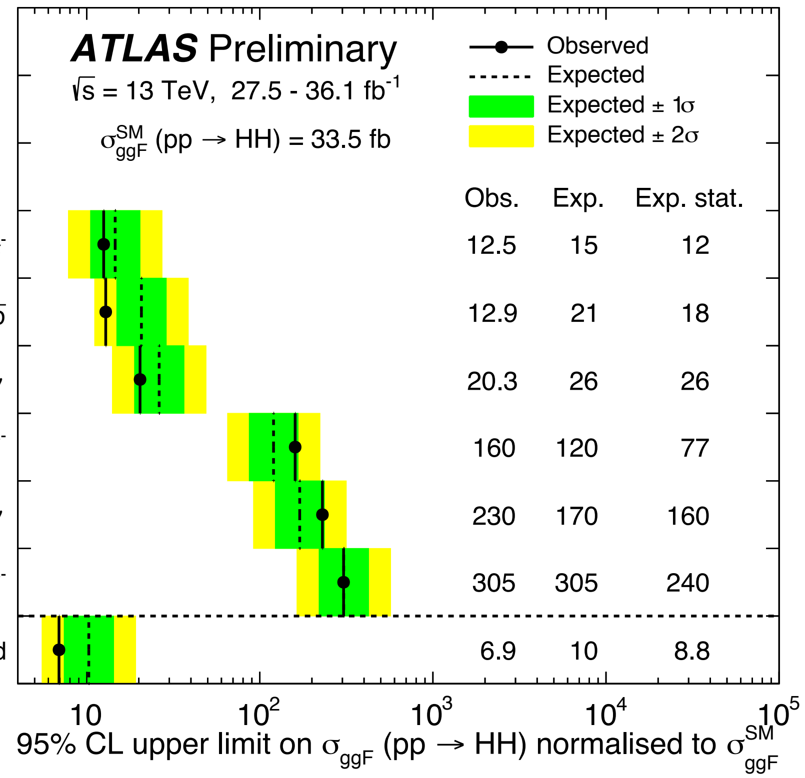
- Limits on non-resonant production at 95% CL:
  - ATLAS: 22 x SM (28 x SM) observed (expected)
  - CMS: 24 x SM (19 x SM) observed (expected)

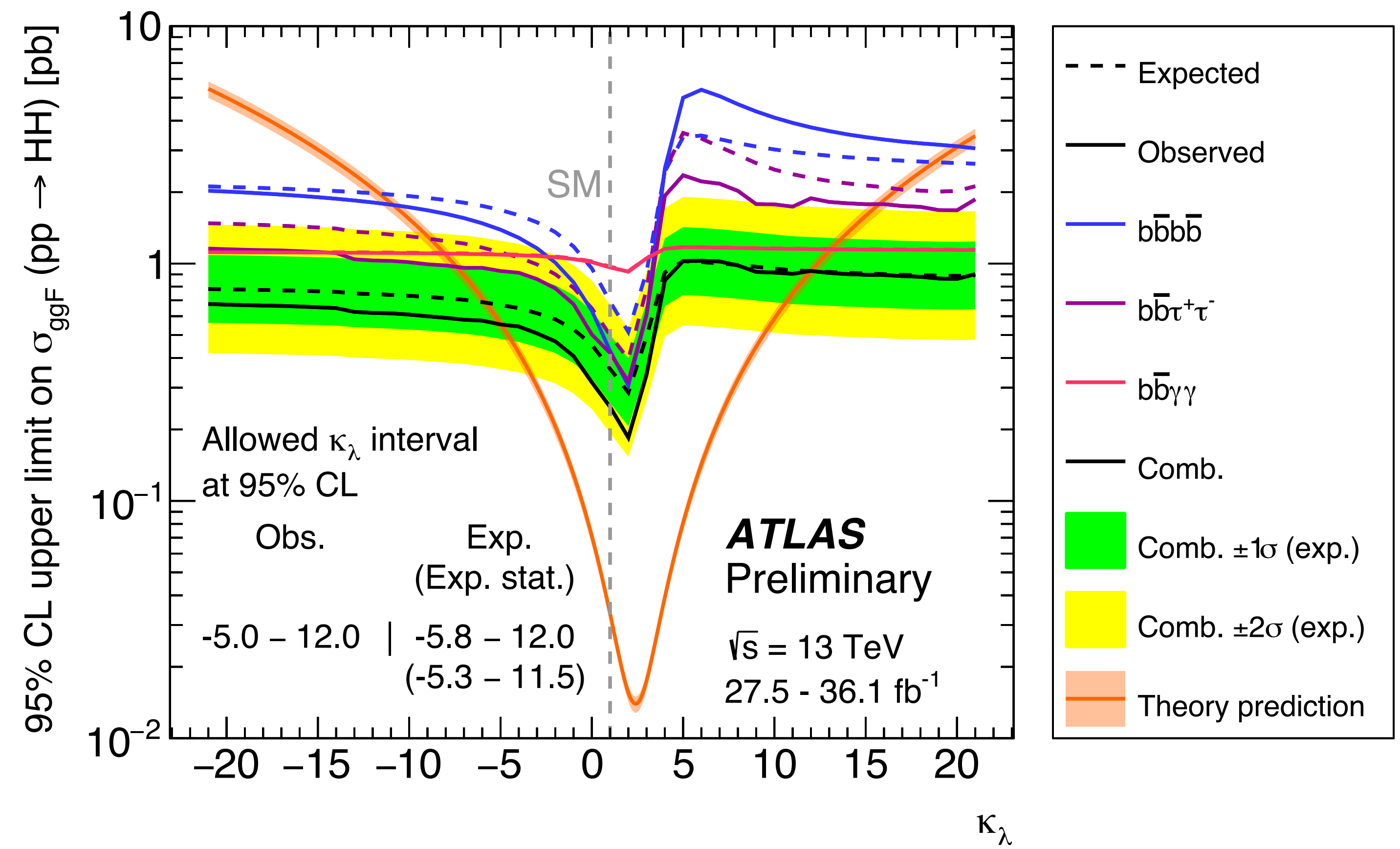




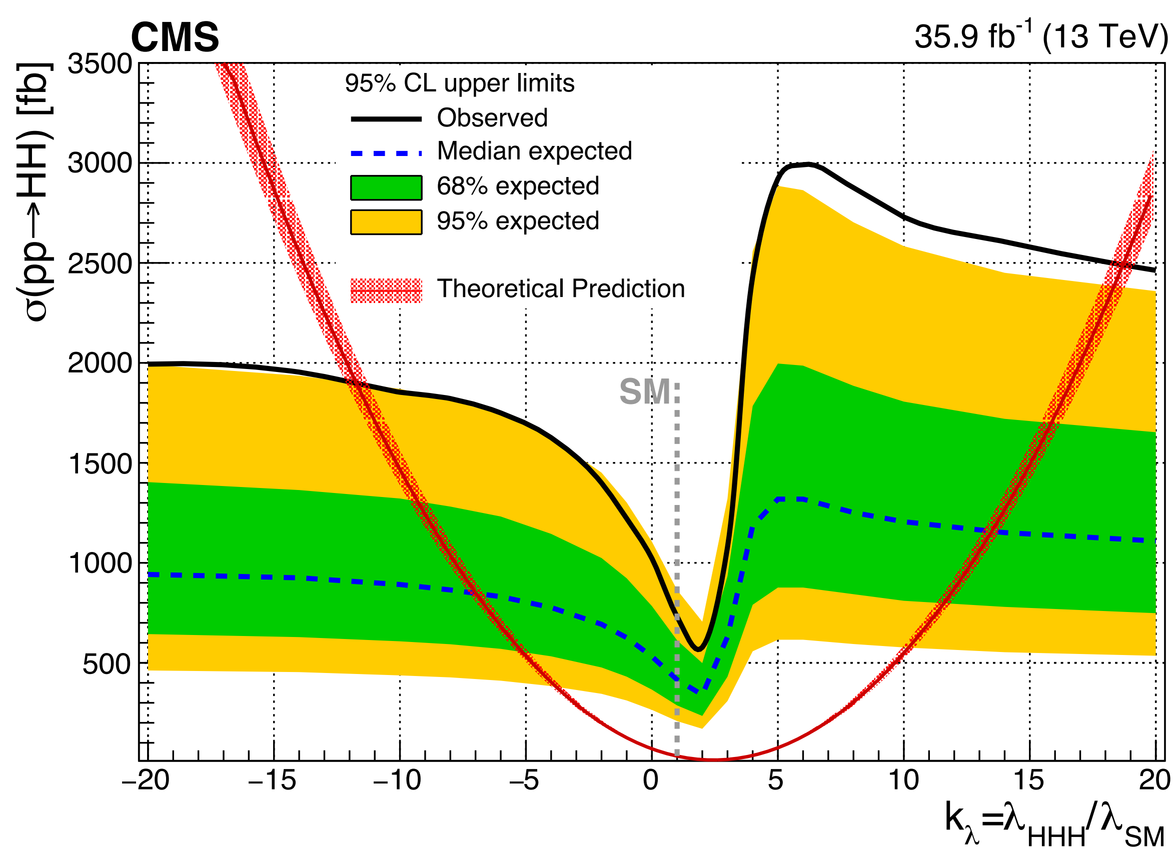
Run 2: Combination

ATLAS: ATLAS-HDBS-2018-58-002, CMS: PRL 122 (2019) 121803





- Combination of ATLAS results performed
- Constraints placed on κ_λ at 95% CL:
  - Observed: $-5.0 < \kappa_\lambda < 12.0$
  - Expected: $-5.8 < \kappa_\lambda < 12.0$



- Combination of CMS results performed
- Includes contributions from $b\bar{b}VV$ final states
- Constraints placed on κ_λ at 95% CL:
  - Observed: $-11.8 < \kappa_\lambda < 18.8$
  - Expected: $-7.1 < \kappa_\lambda < 13.6$

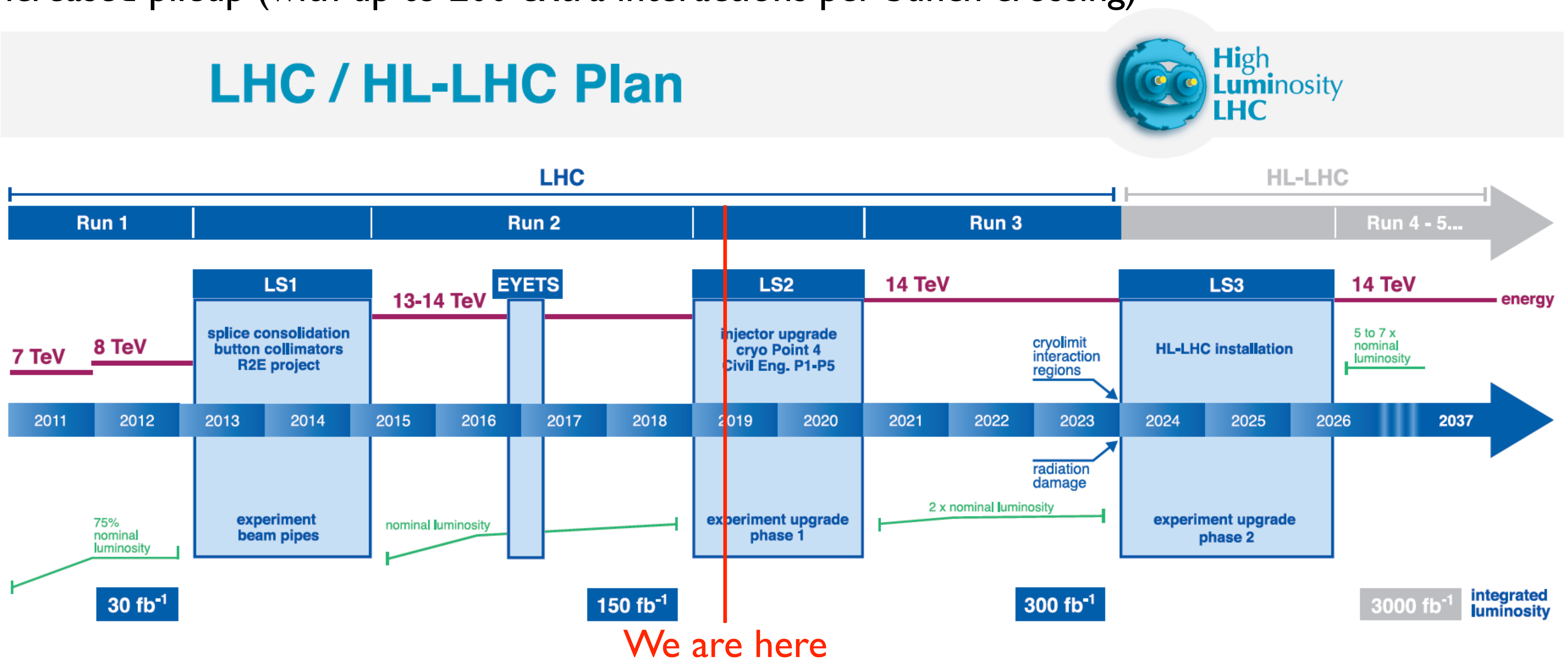
- Results statistically limited, will benefit from full Run 2 dataset!

The High-Luminosity LHC

- Various upgrades to be made to LHC and its detectors in coming years
- Phase 1 currently being implemented in Long Shutdown 2 (maintenance + upgrades)
- Phase 2 begins after Run 3, will see transition from LHC to High-Luminosity LHC (HL-LHC)

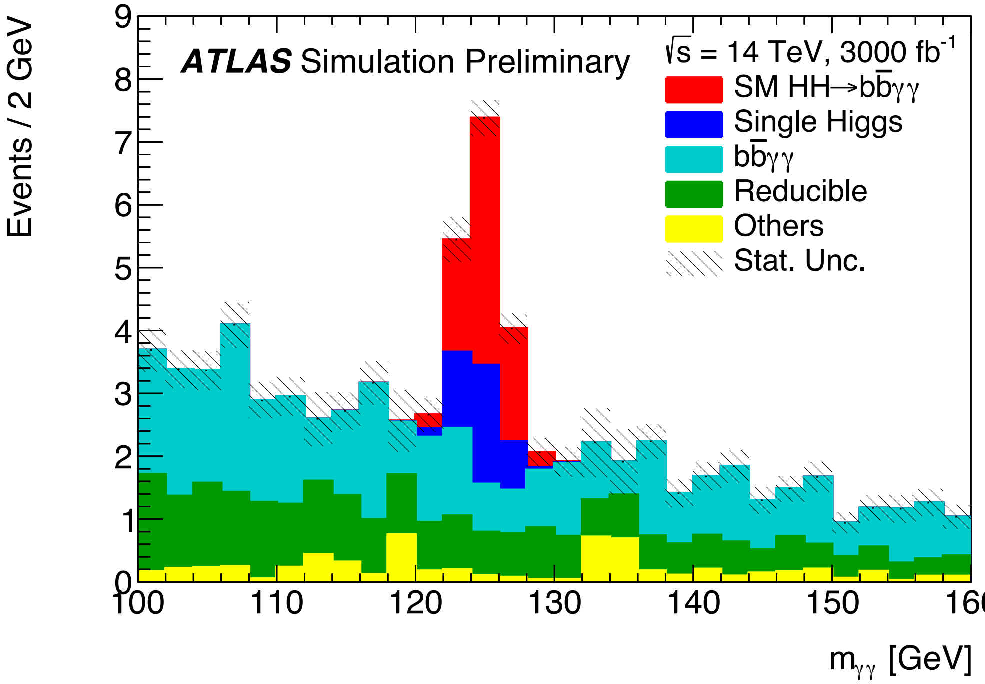
- The HL-LHC will:
  - increase peak luminosity to 5-7.5×10^{34} $cm^{-2}s^{-1}$
  - provide at least 3000 fb^{-1} of data at 14 TeV
  - allow precision measurements of Higgs couplings and differential cross-sections
  - provide access to rare decays and probes for New Physics

- Detector designs and reconstruction algorithms will be improved to handle challenging conditions
  - increased pileup (with up to 200 extra interactions per bunch crossing)



ATLAS HH Prospects at HL-LHC

- Recent Run2 $b\bar{b}b\bar{b}$ and $b\bar{b}\tau\tau$ results extrapolated to HL-LHC
  - Signals normalised to 14 TeV cross-section and luminosity
  - Background yields scaled to 3000 fb^{-1}
- Truth-level MC samples used for $b\bar{b}\gamma\gamma$ analysis
  - Parametric functions emulate expected detector response
  - Boosted decision tree used for event selection
  - Shape of m_{HH} used to extract κ_λ
- Several realistic assumptions made:
  - Experimental and theory uncertainties reduced by factor 2
  - Same detector performance as 2015-16

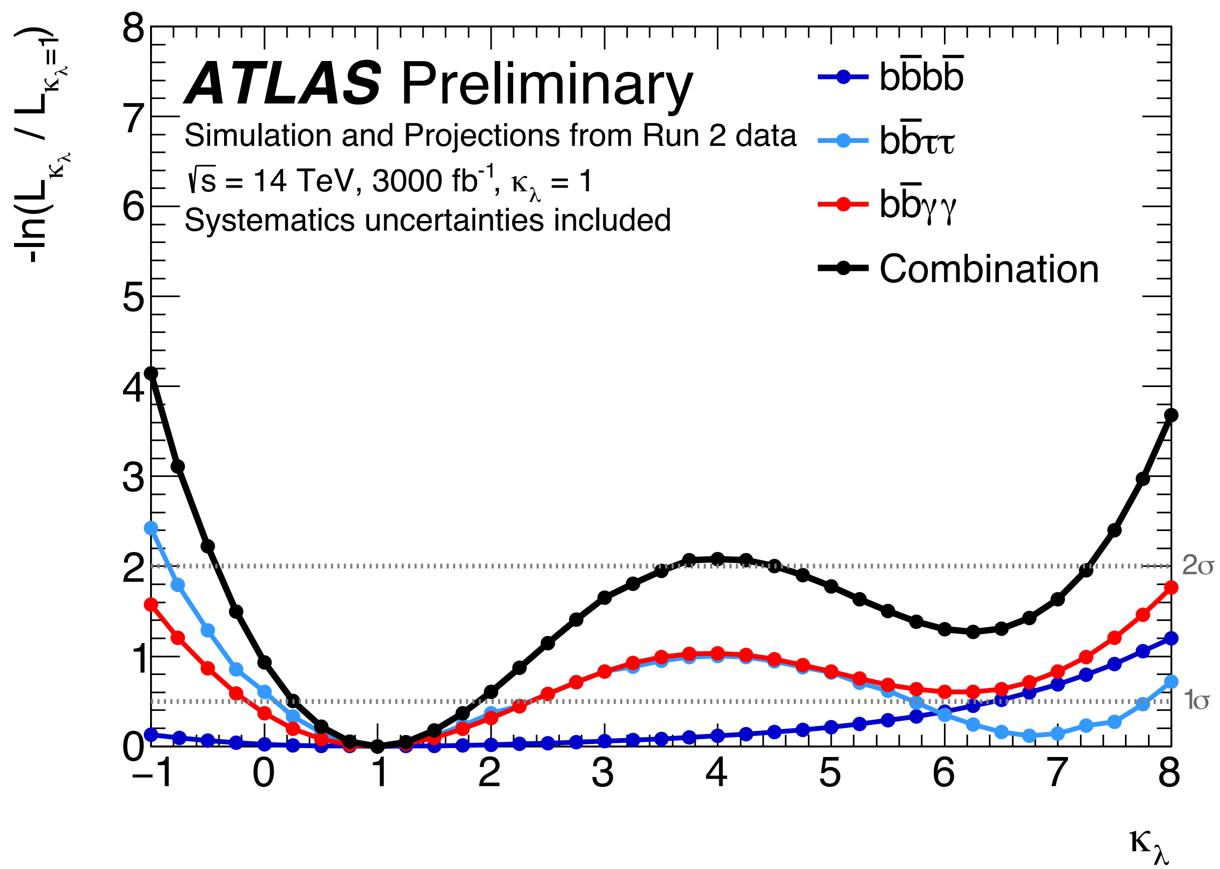


Significance of channels and combination

Channel	Statistical-only	Statistical + Systematic
$HH \to b\bar{b}b\bar{b}$	1.4	0.61
$HH \to b\bar{b}\tau^+\tau^-$	2.5	2.1
$HH \to b\bar{b}\gamma\gamma$	2.1	2.0
Combined	3.5	3.0

Constraints on κ_λ after combination

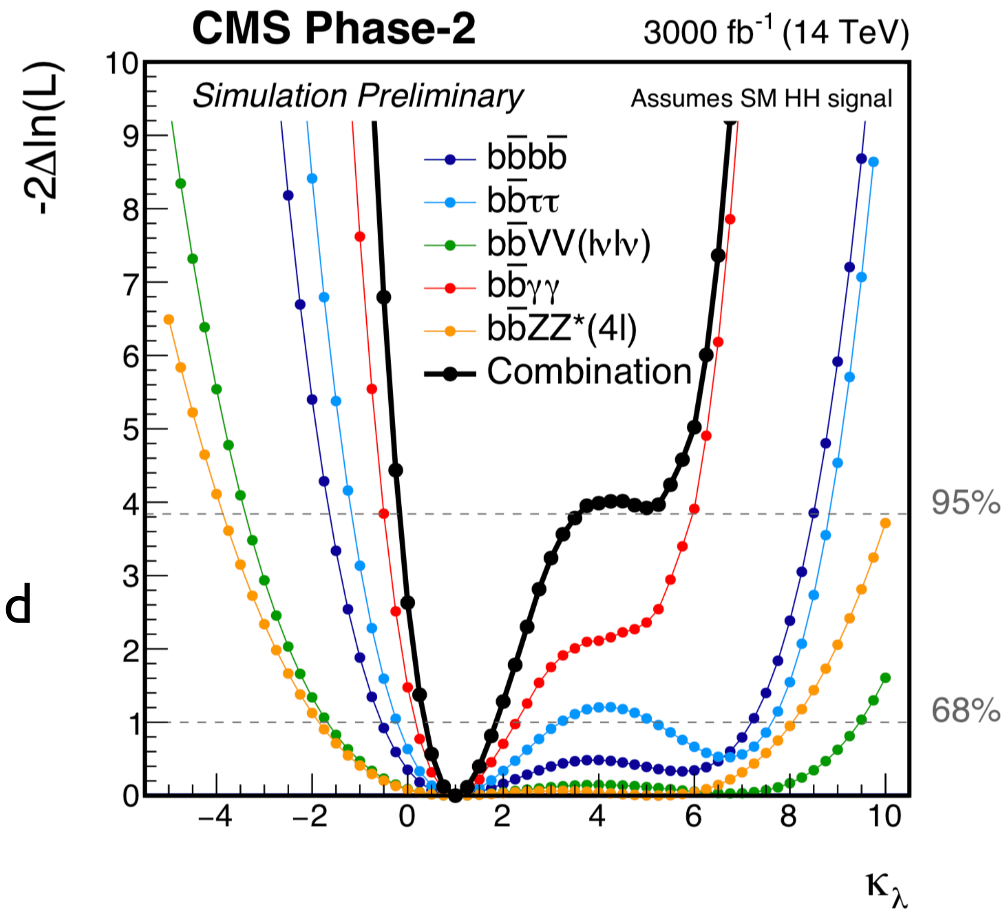
Scenario	1σ CI	2σ CI
No systematic uncertainties	$-0.1 < \kappa_\lambda < 2.4$	$-1.1 < \kappa_\lambda < 8.1$
Systematic uncertainties included	$-0.2 < \kappa_\lambda < 2.5$	$-1.4 < \kappa_\lambda < 8.2$



CMS HH Prospects at HL-LHC

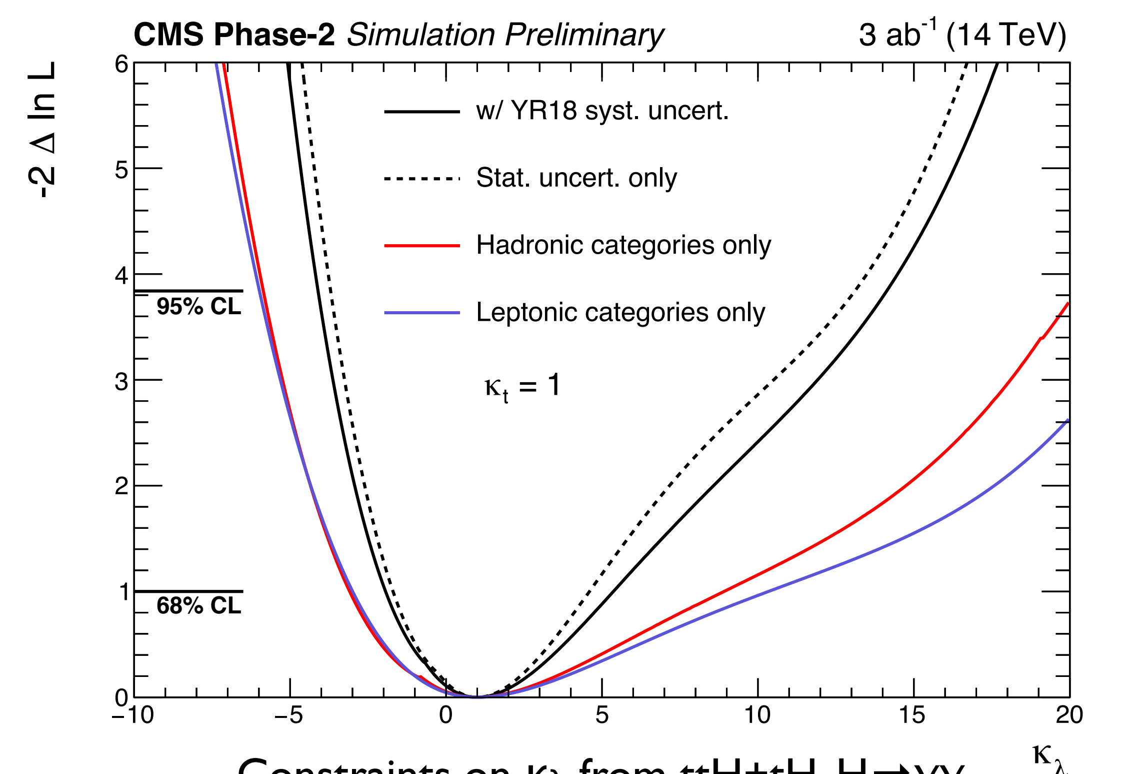
- MC studies use parametric functions to model detector response
- HH→$b\bar{b}b\bar{b}$
  - Similar strategy to Run 2, with 1- and 2- b-tag categories
- HH→$b\bar{b}\tau\tau$
  - Only $\mu\tau_h$, $e\tau_h$ and $\tau_h\tau_h$ final states considered (88% total BR)
  - State-of the art machine learning techniques used
  - Ten deep neural networks
- HH→$b\bar{b}\gamma\gamma$
  - Uses multivariate kinematic discriminant to suppress background
- HH→$b\bar{b}$VV channels suffer from irreducible $t\bar{t}$ background

Channel	Significance		95% CL limit on $\sigma_{HH}/\sigma_{HH}^{SM}$	
	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	0.77	0.71



- Combination places constraints on κ_λ:
  - $0.35 < \kappa_\lambda < 1.9$ at 68% CL, $-0.18 < \kappa_\lambda < 3.6$ at 95% CL

- Complimentary study on ttH+tH, H→γγ
  - Measurement of differential cross-section constrains κ_λ
  - $-1.9 < \kappa_\lambda < 5.3$ at 68% CL, $-4.1 < \kappa_\lambda < 14.1$ at 95% CL



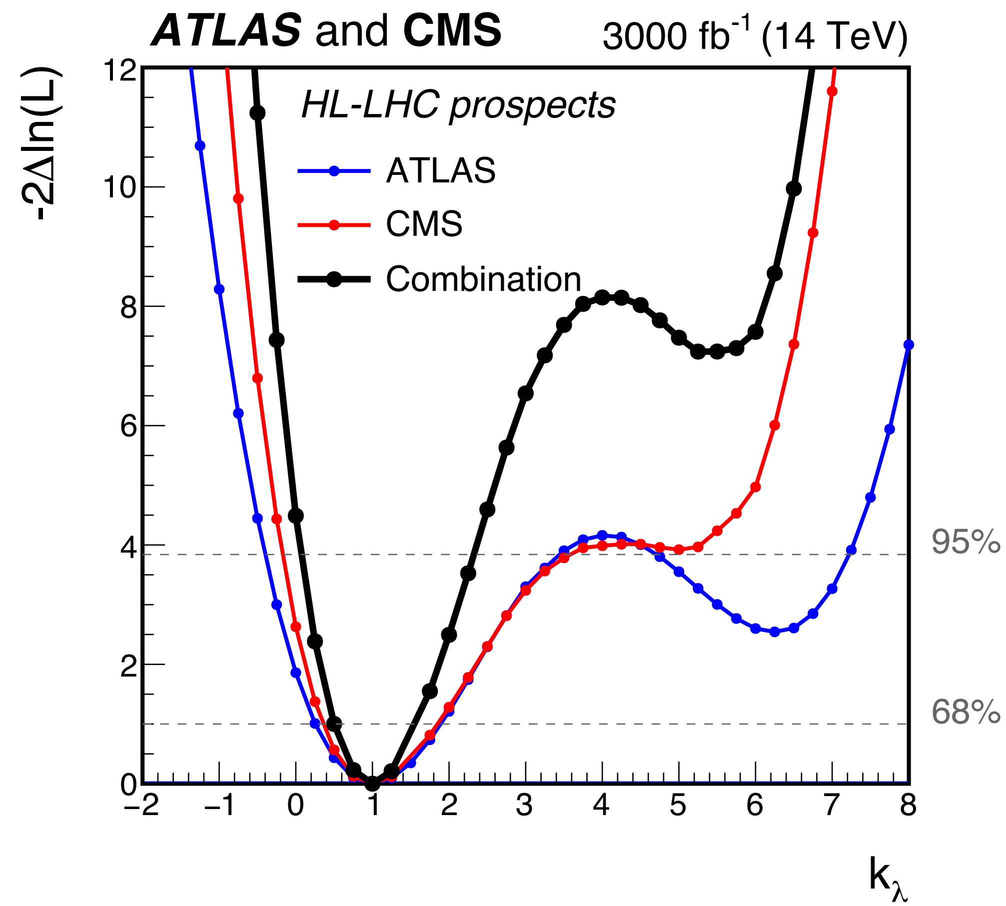
Constraints on κ_λ from ttH+tH, H→γγ

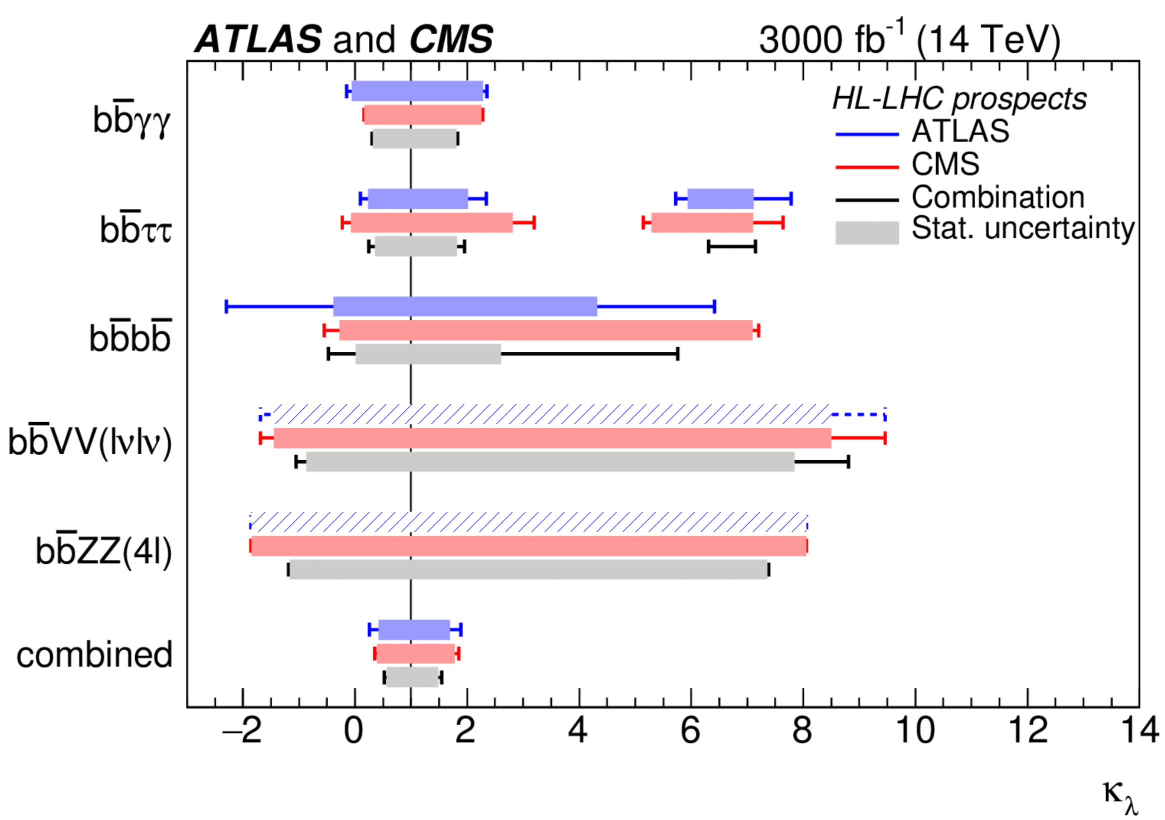
HH Prospects: Combinations

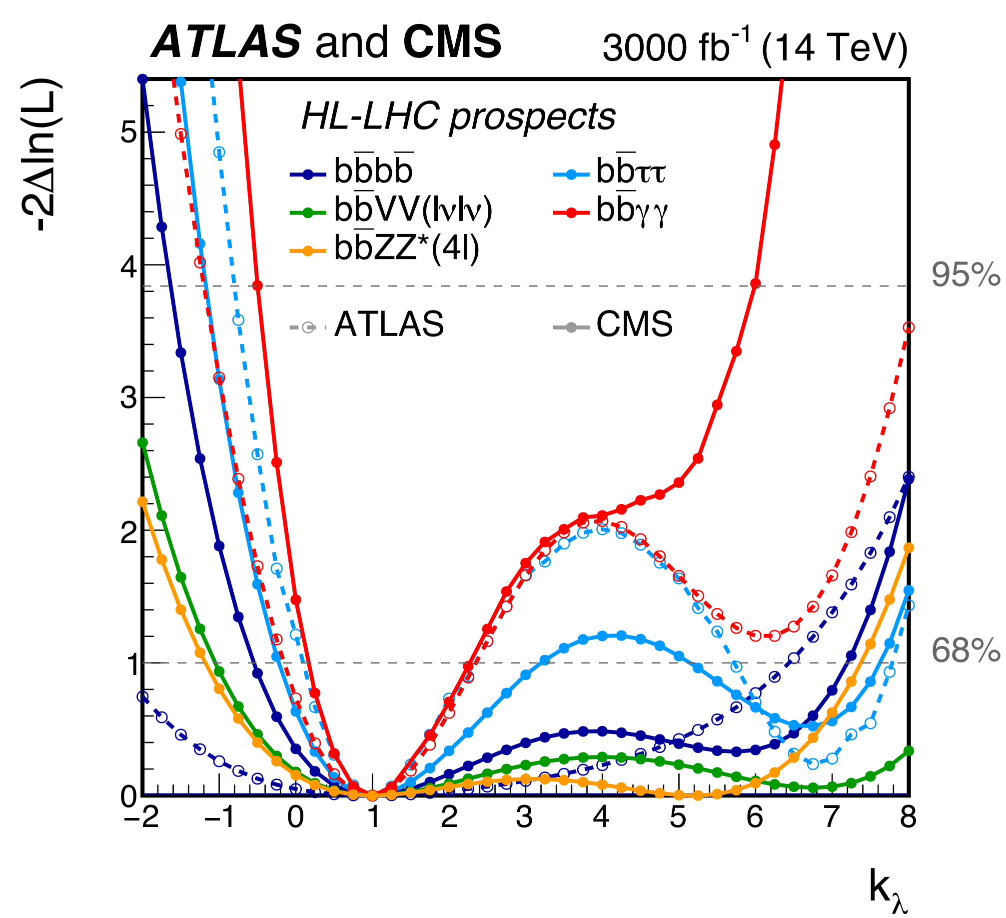
CERN-LPCC-2018-04

- Combining 3 channels from ATLAS yields
  - 3σ for statistical+systematics
  - 3.5σ for statistical only
- Combining 5 channels from CMS yields:
  - 2.6σ for statistical+systematics
  - 2.8σ for statistical only

- Combining ATLAS and CMS results
  - Channels treated as uncorrelated
  - Total sensitivity increases to 4σ significance
  - $\kappa_\lambda = \lambda_{HHH}/\lambda_{HHH}^{SM}$ to be measured as $1.0^{+0.5}_{-0.5}$
  - Second minimum excluded at 99.4% CL







Outlook

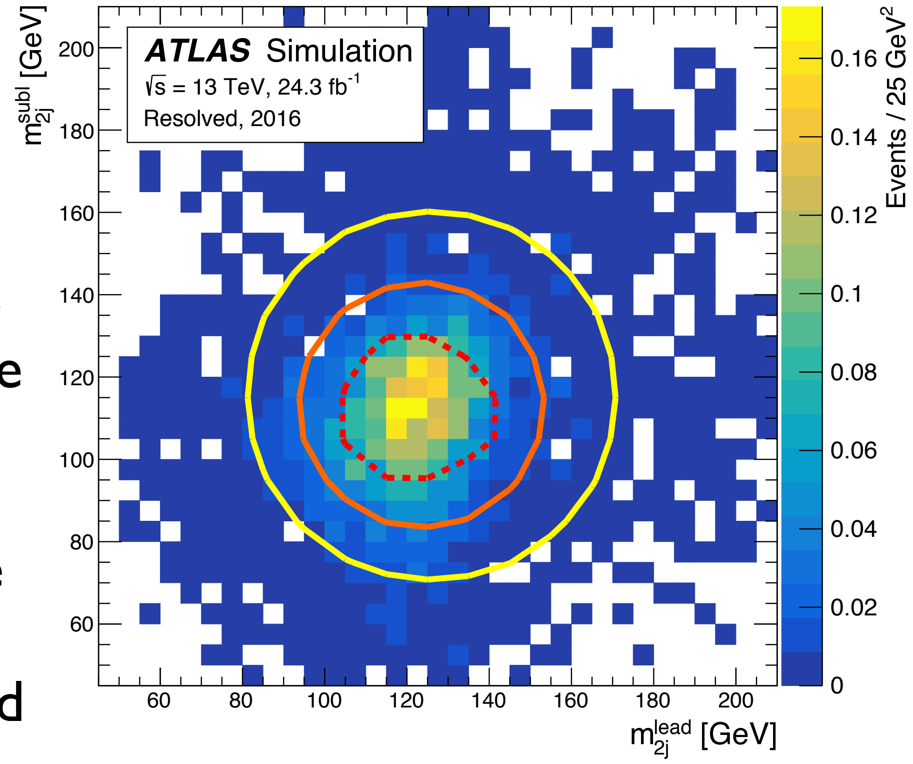
- First Run 2 results have been published using ~36 fb^{-1} of data recorded in 2015 and 2016
- Not yet sensitive to SM Higgs Boson pair production
- For non-resonant SM HH production, best limits on κ_λ at 95% CL are:
  - ATLAS observed (expected) = $-5.0 < \kappa_\lambda < 12.1$ ($-5.8 < \kappa_\lambda < 12.0$)
  - CMS observed (expected) = $-11.8 < \kappa_\lambda < 18.8$ ($-7.1 < \kappa_\lambda < 13.6$)
- Ongoing effort to process full Run 2 dataset with 150 fb^{-1} of data recorded from 2015-2018

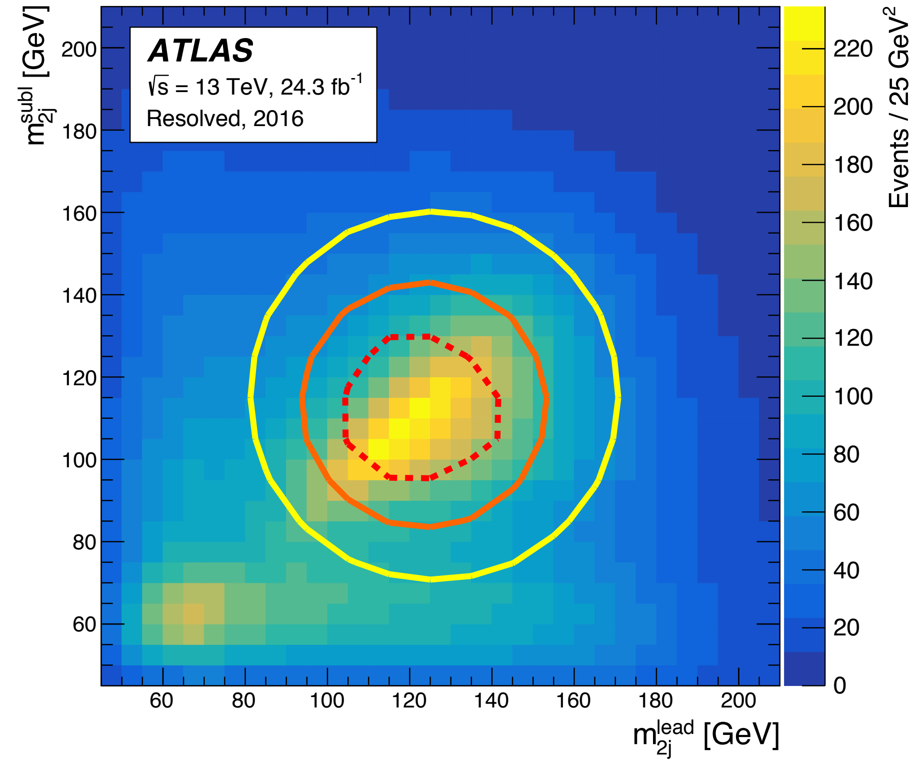
- Prospects for the HL-LHC have been assessed by both ATLAS and CMS
  - Di-Higgs studies will fully benefit from the increased integrated luminosity
  - With existing analysis tools:
    - Individual detectors capable of achieving 3σ significance
    - Combining results from ATLAS and CMS brings 4σ significance!
    - Di-Higgs observation in SM case is close
    - Assuming SM case, κ_λ could be measured with 50% precision!
  - Reaching expected performances and systematic uncertainty levels will be challenging
  - Potential for improvement thanks to future Run 2 and Run 3 analyses

Backup

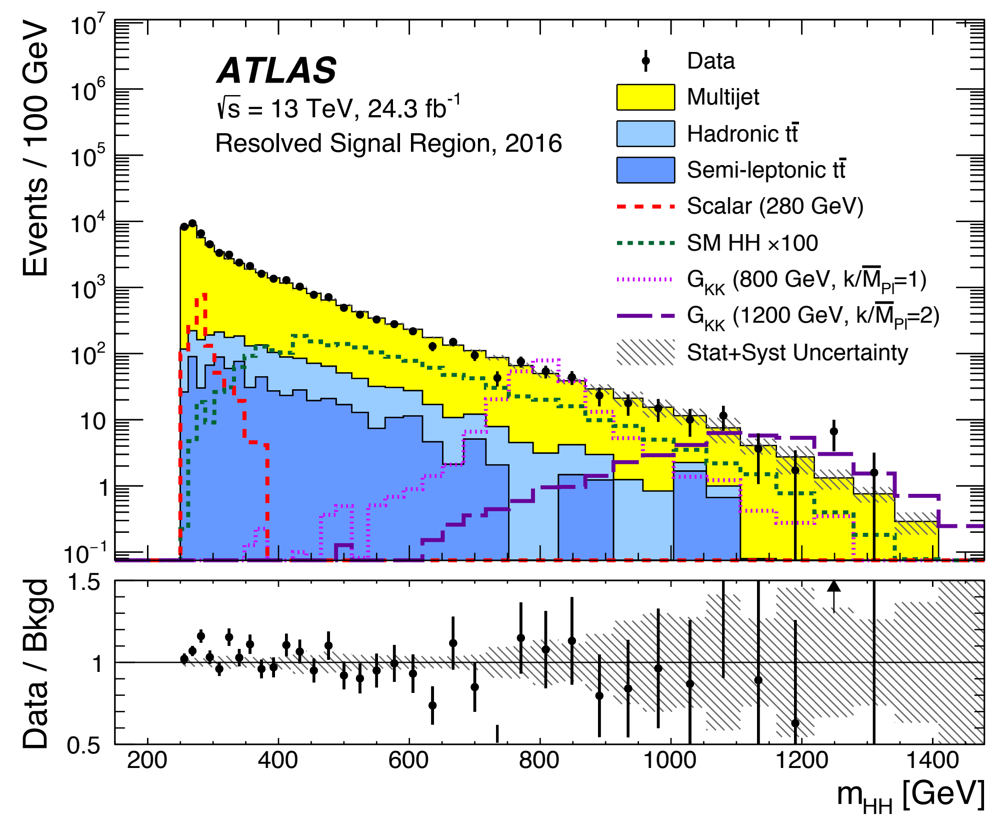
ATLAS Run 2 HH→$b\bar{b}b\bar{b}$

- Higgs boson candidate mass-plane regions. Signal region is inside the inner (red) dashed curve, control region is outside the signal region and within the intermediate (orange) circle, the sideband is outside the control region and within the outer (yellow) circle. (Left) shows the SM non-resonant HH process, and (Right) shows the estimated multijet background,



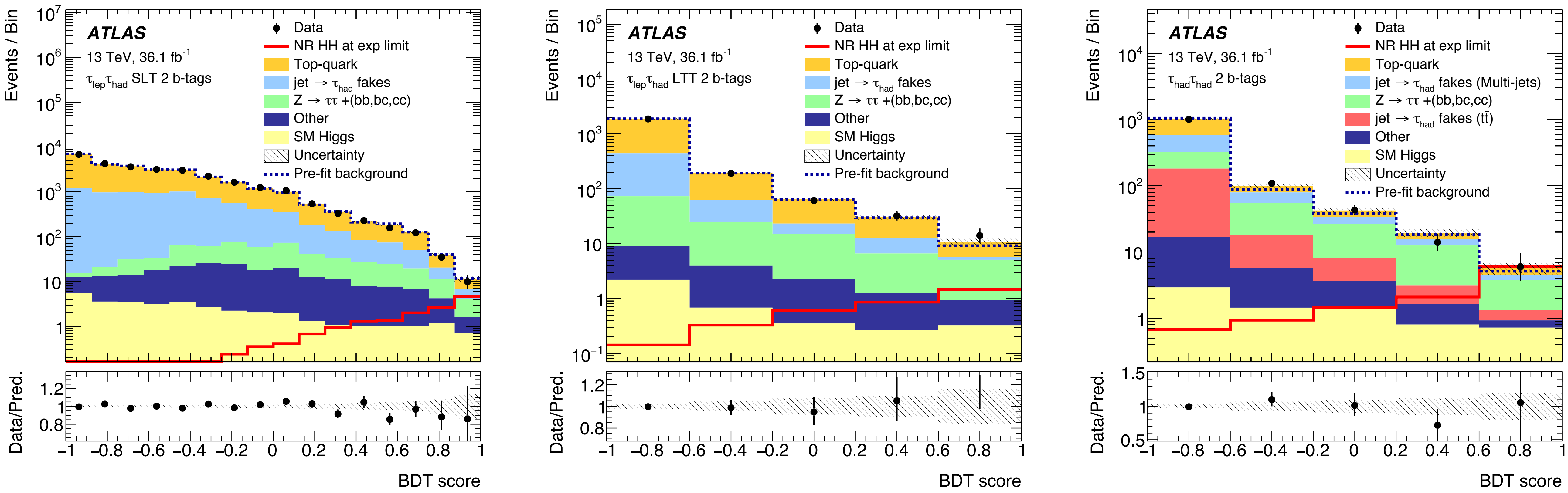


- Distributions of m_{4j} in the signal region of the resolved analysis for 2016 data, compared to the predicted backgrounds. The hatched bands represent the combined statistical and systematic uncertainties in the total background estimates. The expected signal distributions of GKK resonances with masses of 800 and 1200 GeV, a 280 GeV scalar sample and SM non-resonant HH production (×100) are also shown. The scalar sample is normalized to a cross section times branching ratio of 2.7 pb.



ATLAS Run 2 HH→$b\bar{b}\tau\tau$

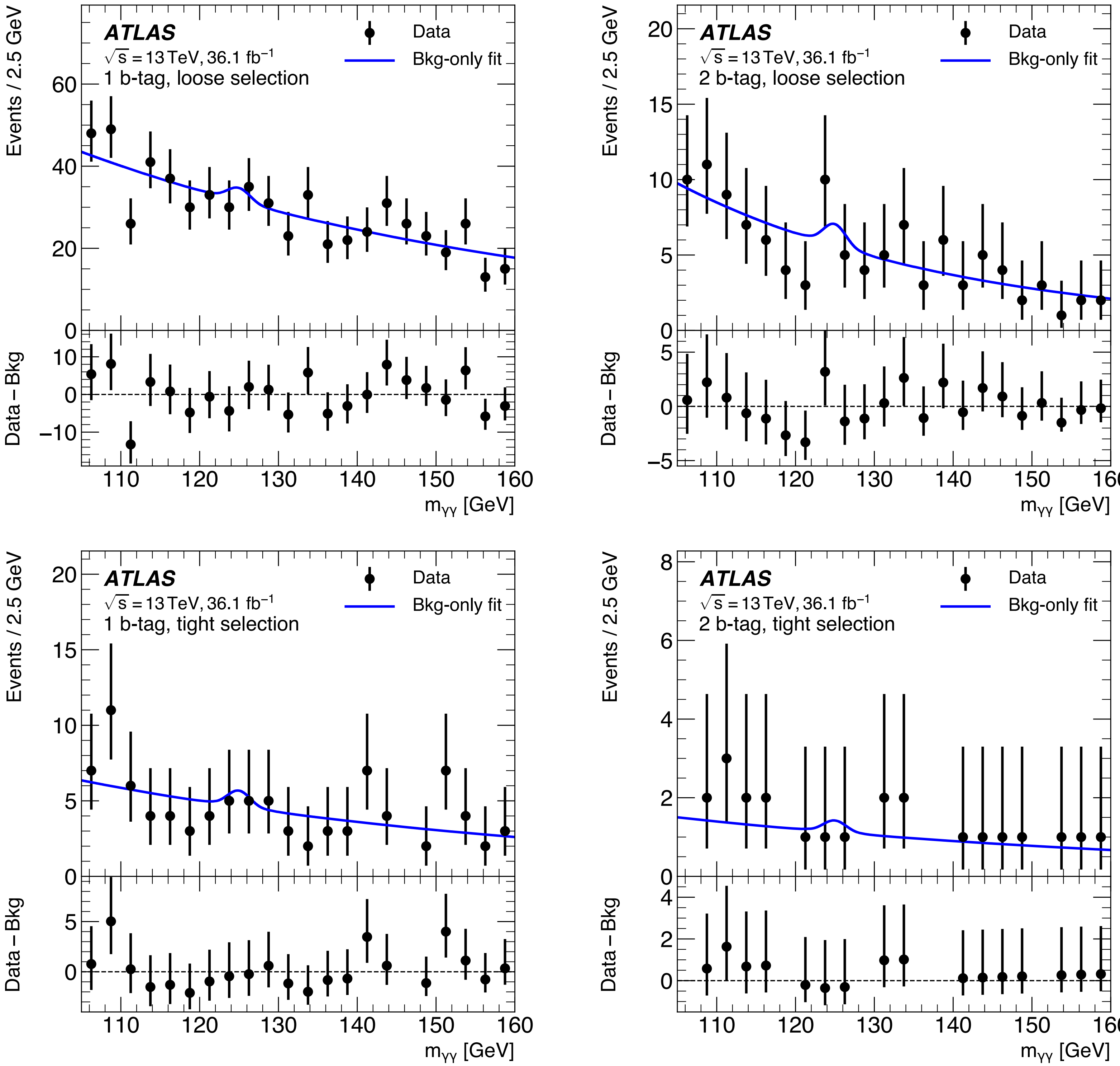
- Distributions of the BDT score for non-resonant HH signal
- Shown after fit to background-only hypothesis, signal scaled to approximately the expected limit

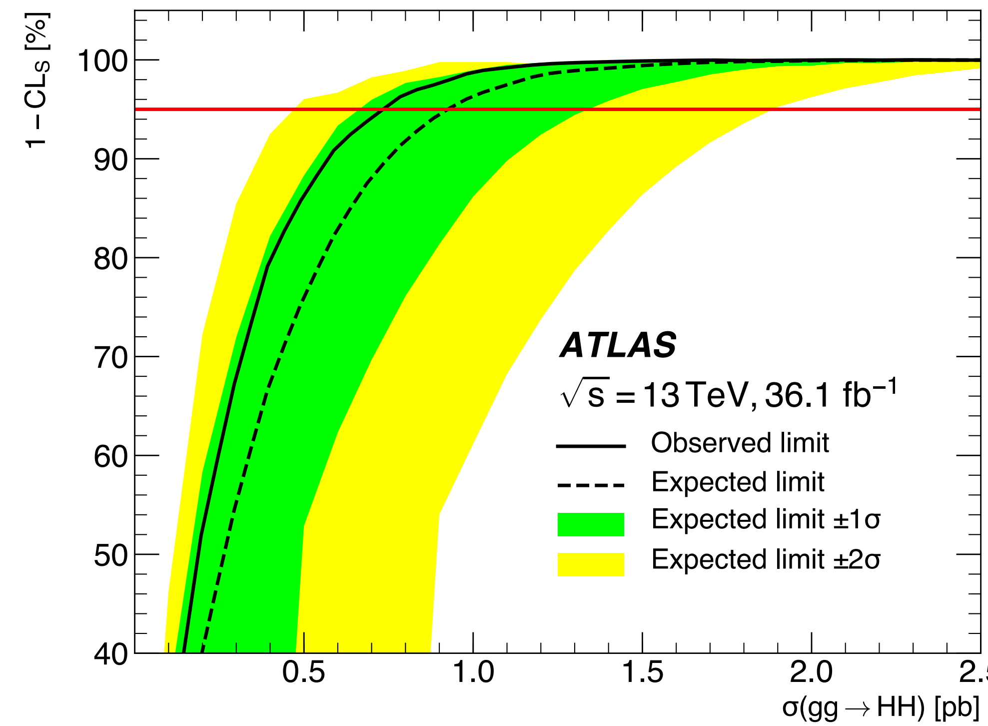


- Observed and expected upper limits on the production cross-section times the HH→ bbττ branching ratio for non-resonant HH at 95% CL, and their ratios to the SM prediction.

		Observed	-1σ	Expected	$+1\sigma$
$\tau_{\rm lep}\tau_{\rm had}$	$\sigma(HH \to bb\tau\tau)$ [fb]	57	49.9	69	96
	$\sigma/\sigma_{\rm SM}$	23.5	20.5	28.4	39.5
$\tau_{\rm had}\tau_{\rm had}$	$\sigma(HH \to bb\tau\tau)$ [fb]	40.0	30.6	42.4	59
	$\sigma/\sigma_{\rm SM}$	16.4	12.5	17.4	24.2
Combination	$\sigma(HH \to bb\tau\tau)$ [fb]	30.9	26.0	36.1	50
	$\sigma/\sigma_{\rm SM}$	12.7	10.7	14.8	20.6

ATLAS Run 2 HH→b$\bar{b}$γγ





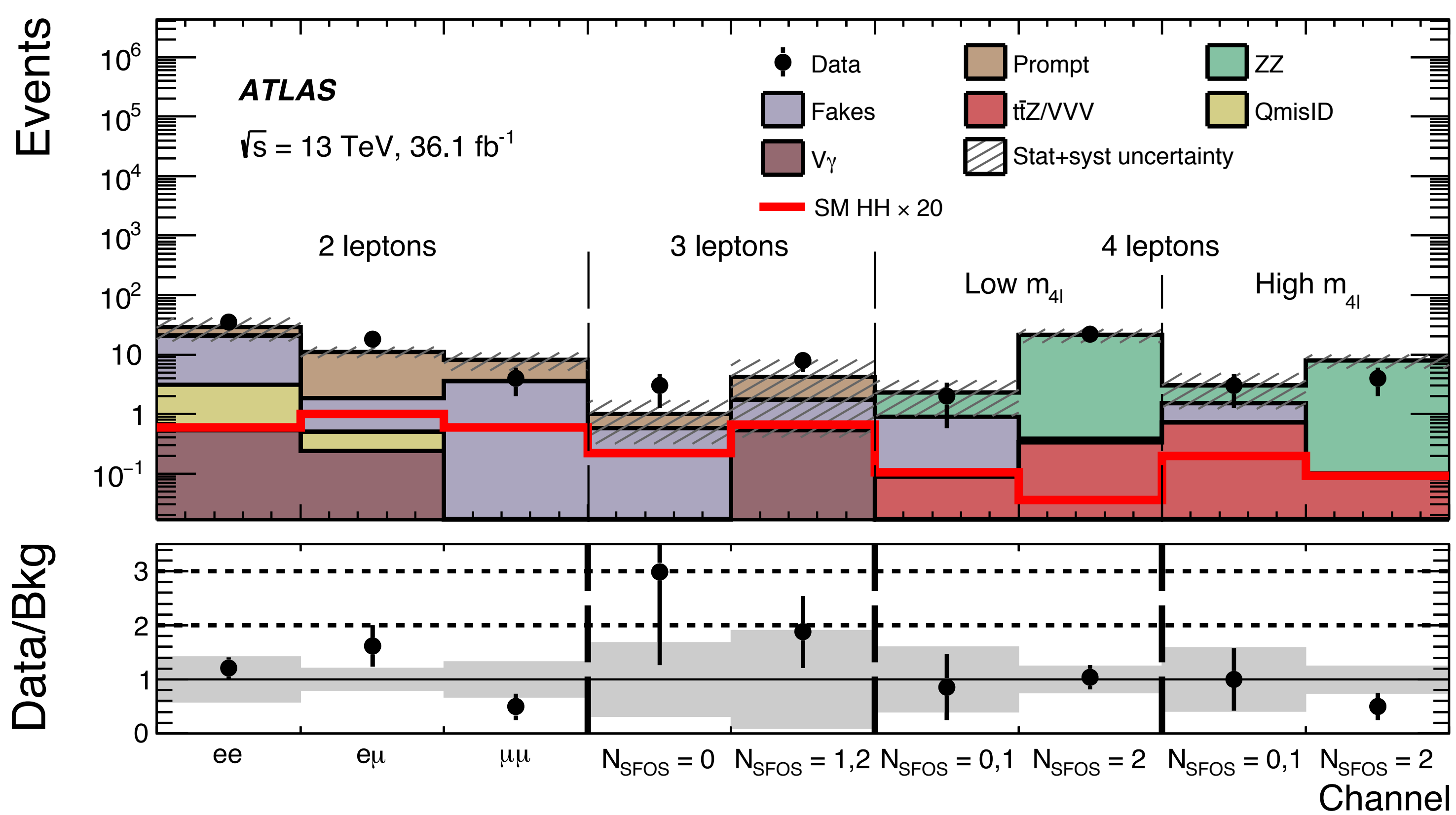
- The expected and observed 95% CL limits on the non-resonant production cross-section σgg → HH for the SM-optimised limit using the tight selection

- For the non-resonant analysis, data (black points) are compared with the background-only fit (blue solid line) for mγγ in the 1-tag (left) and 2-tag (right) categories with the loose (top) and tight (bottom) selections. Both the continuum γγ background and the background from single Higgs boson production are considered. The lower panel shows the residuals between the data and the best-fit background.

ATLAS Run 2 HH→WW*WW*

CERN-EP-2018-227

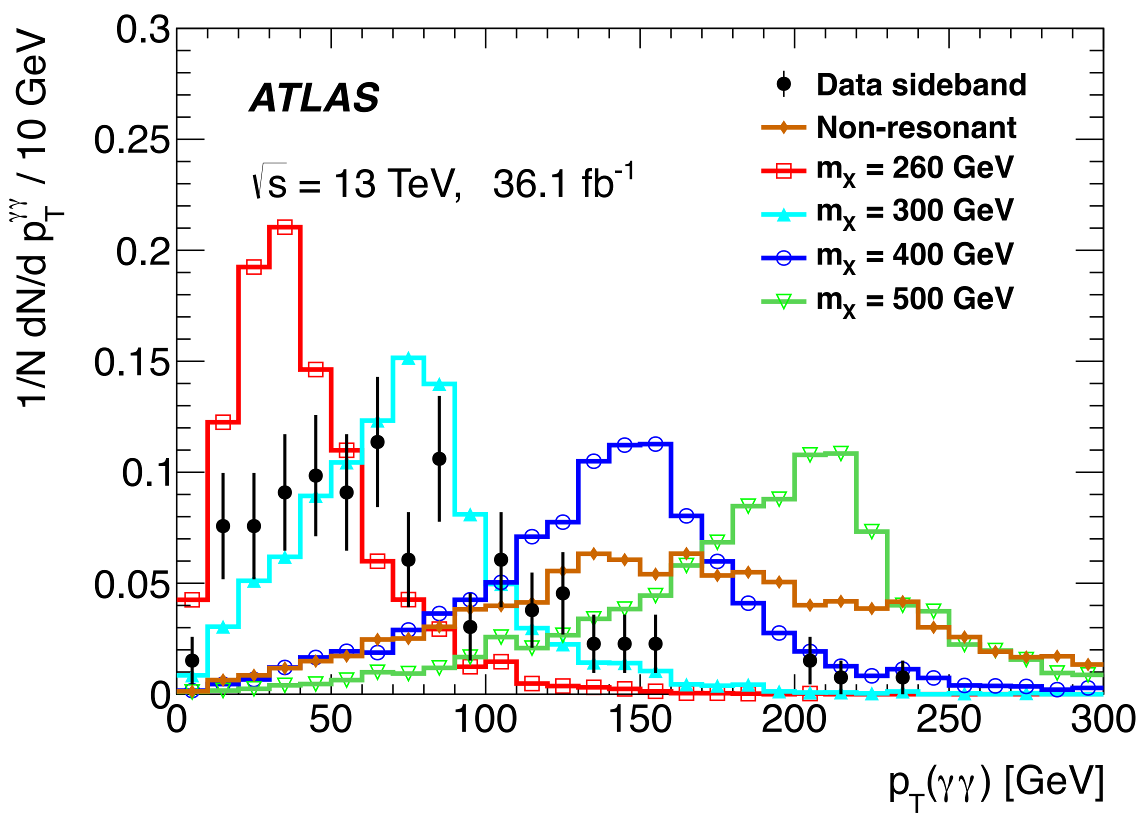
- ATLAS performed search for two scalar bosons decaying to WW*WW*
  - Uses 36.1 fb^{-1} of data at 13 TeV
- Three final states examined: 2 same-sign leptons, 3 leptons, 4 leptons
- Combination of channels sets limit on non-resonant Higgs pair production cross-section
  - Observed (expected) limit is 160 (120) times SM prediction

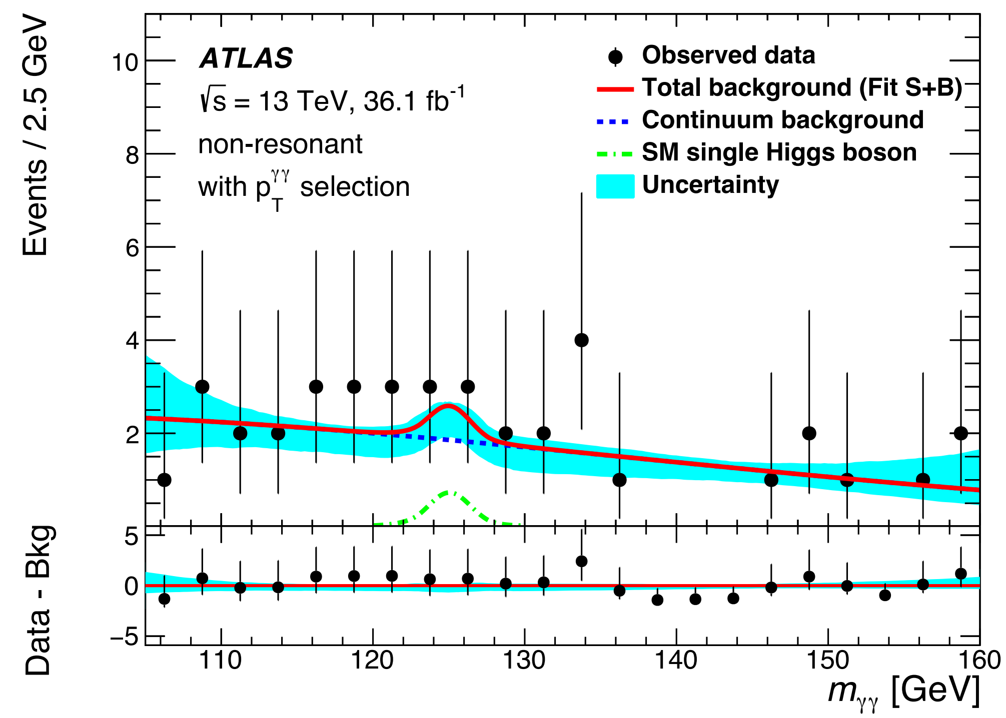


- Expected and observed yields in each channel after all selection criteria for the non-resonant HH production searches. The label NSFOS indicates the number of same-flavour, opposite-sign lepton pairs in the channel. Low and high $m_{4\ell}$ indicates $m_{4\ell} < 180$ GeV and $m_{4\ell} > 180$ GeV, respectively. The shaded band in the ratio plot shows the systematic uncertainty in the background estimate. The signal is scaled by a factor of 20.

EPJC 78 (2018) 1007

- ATLAS performed search Higgs boson pair production, decaying to WWγγ
  - Final state composed of $\gamma\gamma\ell\nu jj$
  - Uses 36.1 fb^{-1} of data at 13 TeV
- Limit set on non-resonant Higgs pair production cross-section
  - Observed (expected) limit is 7.7 (5.4) pb at 95% CL

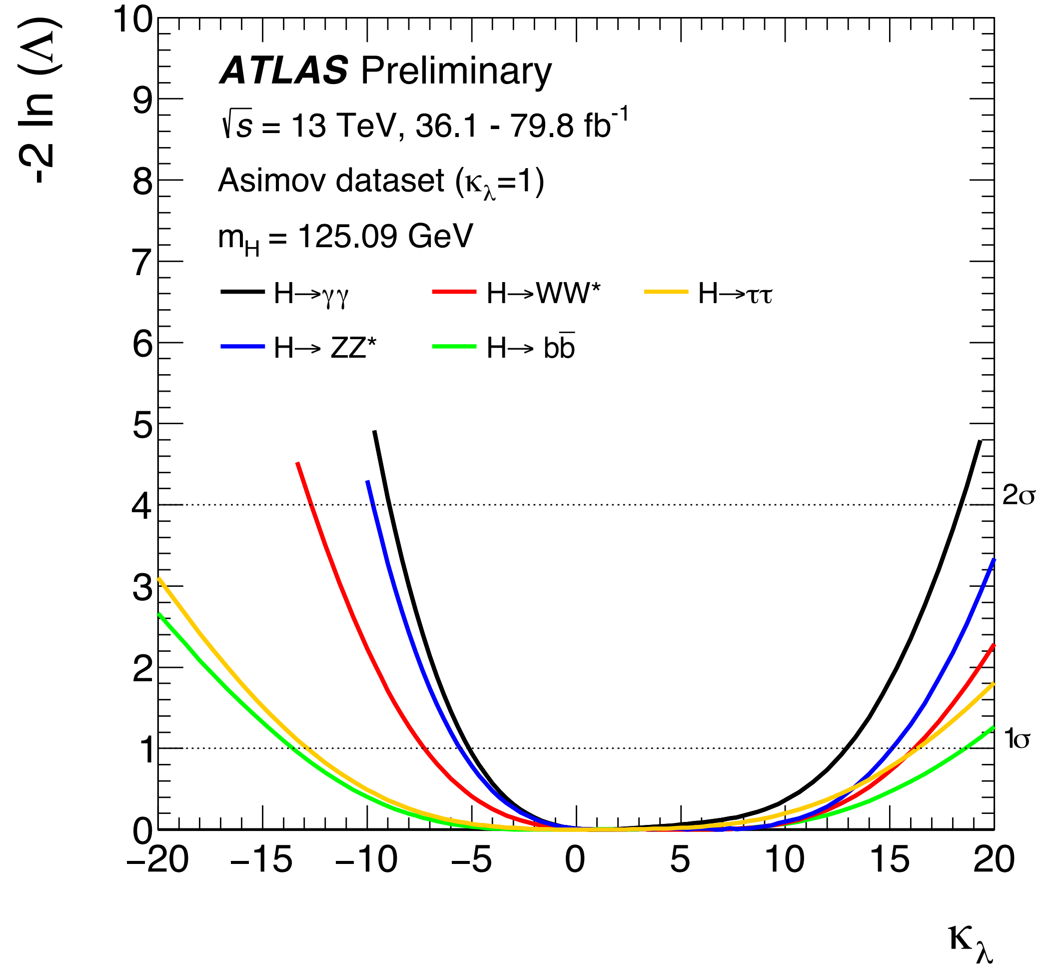


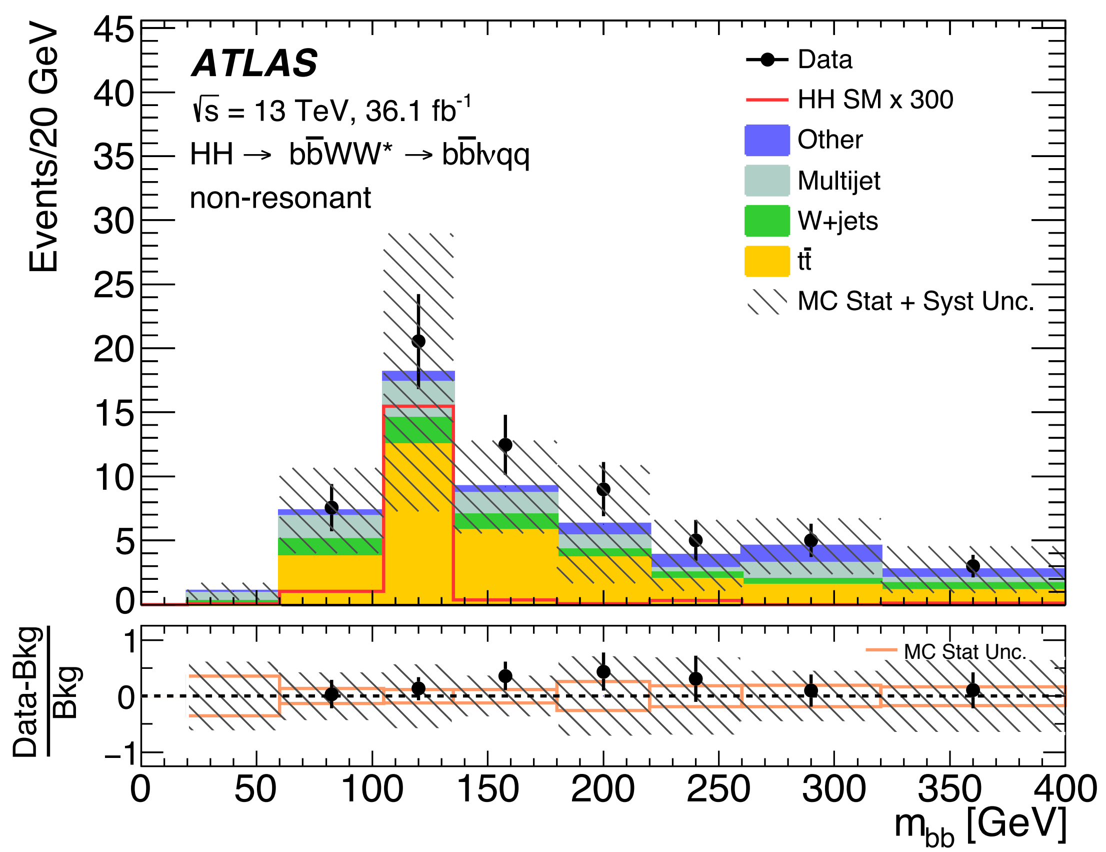


- Distributions of the reconstructed transverse momenta of the diphoton system with all event selections, except the $p_T^{\gamma\gamma}$ selection, applied for various signal models, as well as sideband data, normalised to unit area.
- Diphoton invariant mass spectrum in searche for non-resonant HH production, with the corresponding backgrounds for the case with a $p_T^{\gamma\gamma} > 100$ GeV selection. Fits to $m_{\gamma\gamma}$ performed using the full signal-plus-background model.

Run 2: Other Noteworthy Results

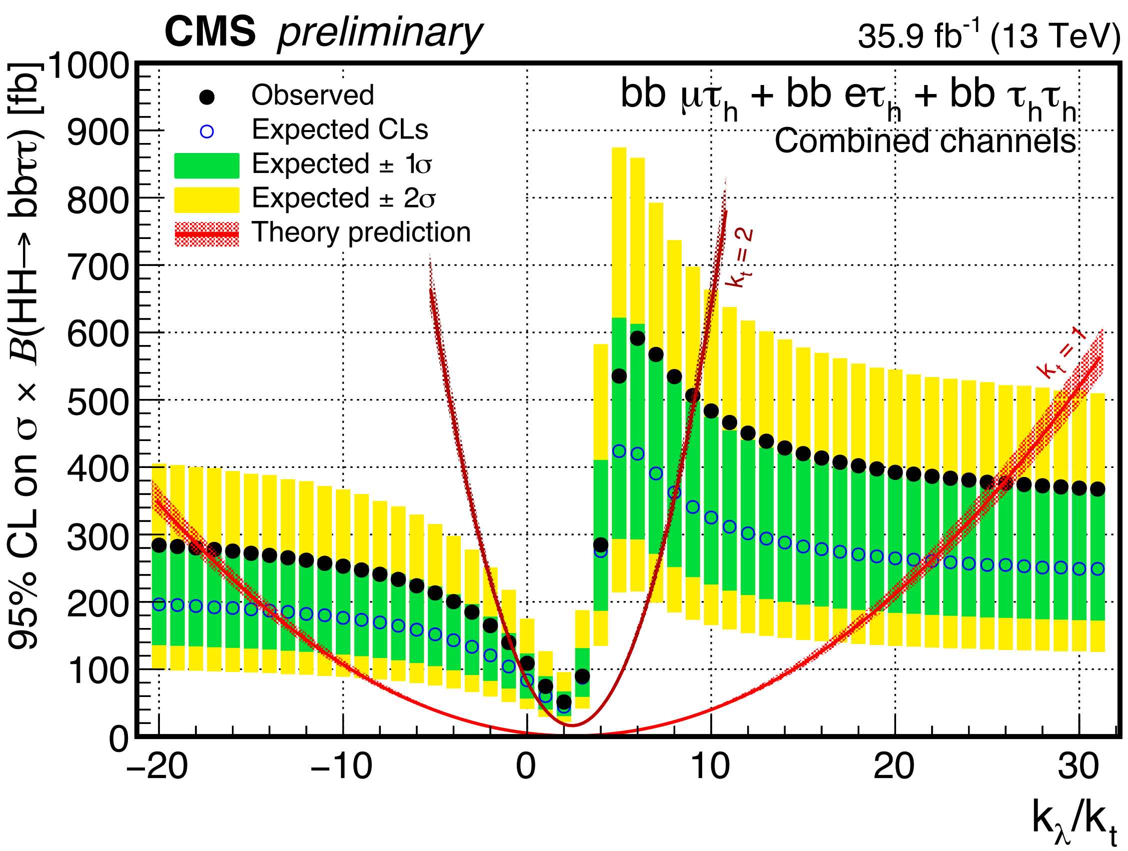
- Single Higgs boson production also constrains self-coupling
  - NLO electroweak corrections from self-coupling
  - Corrections affect Higgs cross-section, branching fractions, and kinematics
- ATL-PHYS-PUB-2019-009 uses 80 fb^{-1} of data at 13 TeV
  - Examines single Higgs boson decaying to:
    - $\gamma\gamma$, ZZ^*, WW^*, $\tau\tau$, $b\bar{b}$
  - Assumption that new physics only affects κ_λ
  - Measures $\kappa_\lambda = 4.0_{-4.1}^{+4.3}$
  - $\kappa_\lambda < -3.2$ and $\kappa_\lambda > 11.9$ excluded at 95% CL

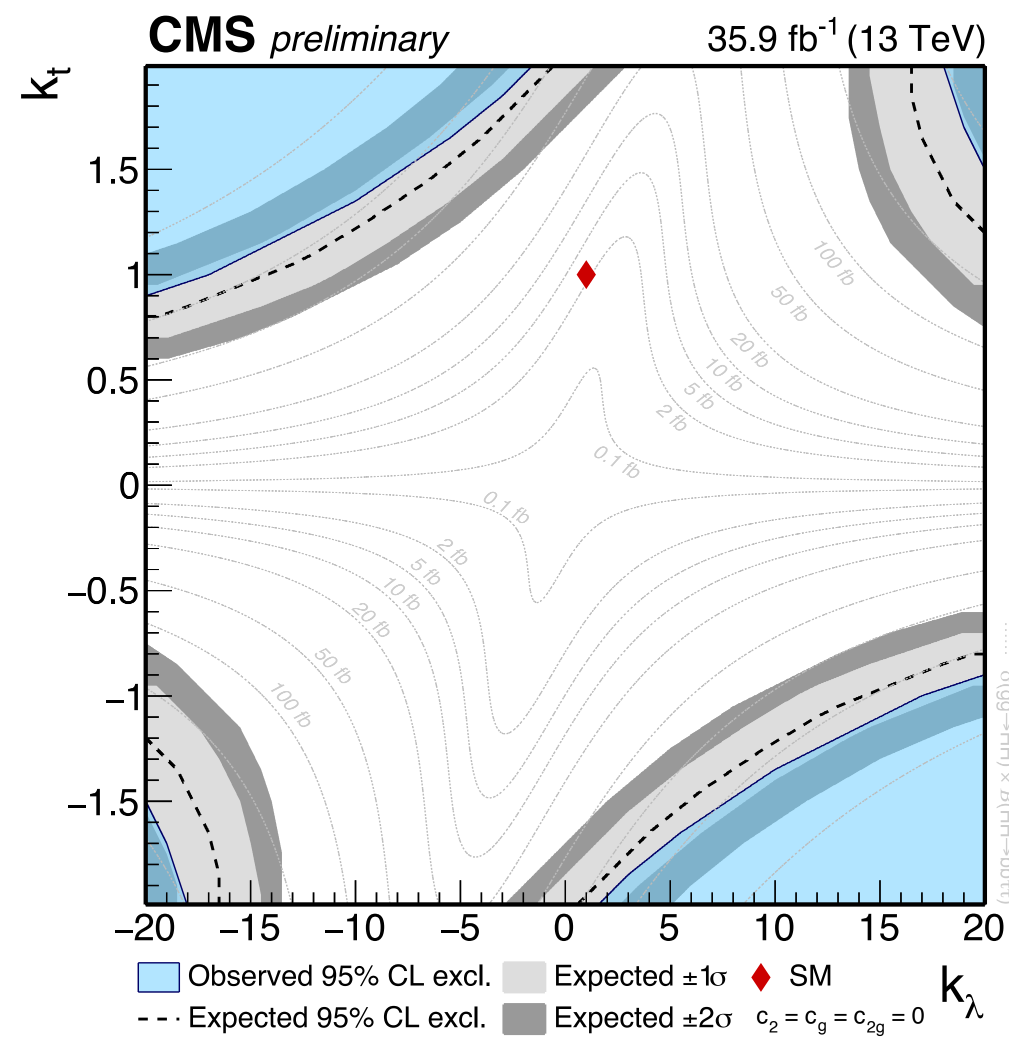




- HH → $b\bar{b}WW^*$ decay mode examined
- JHEP 04 (2019) 092 uses 36.1 fb^{-1} of data at 13 TeV
- Upper limit set on non-resonant pair production cross-section
  - $\sigma(pp \to HH) \cdot \mathfrak{B}(HH \to b\bar{b}WW^*)$ <2.5 pb at 95% CL
  - Corresponds to 300 times SM prediction

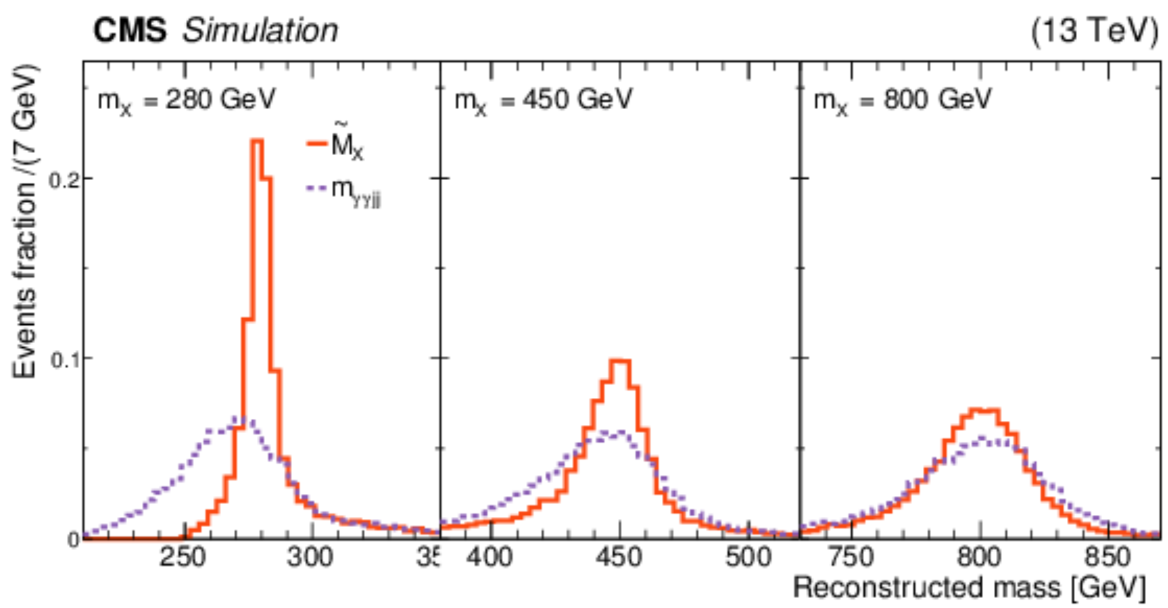
CMS Run 2 HH→$b\bar{b}\tau\tau$





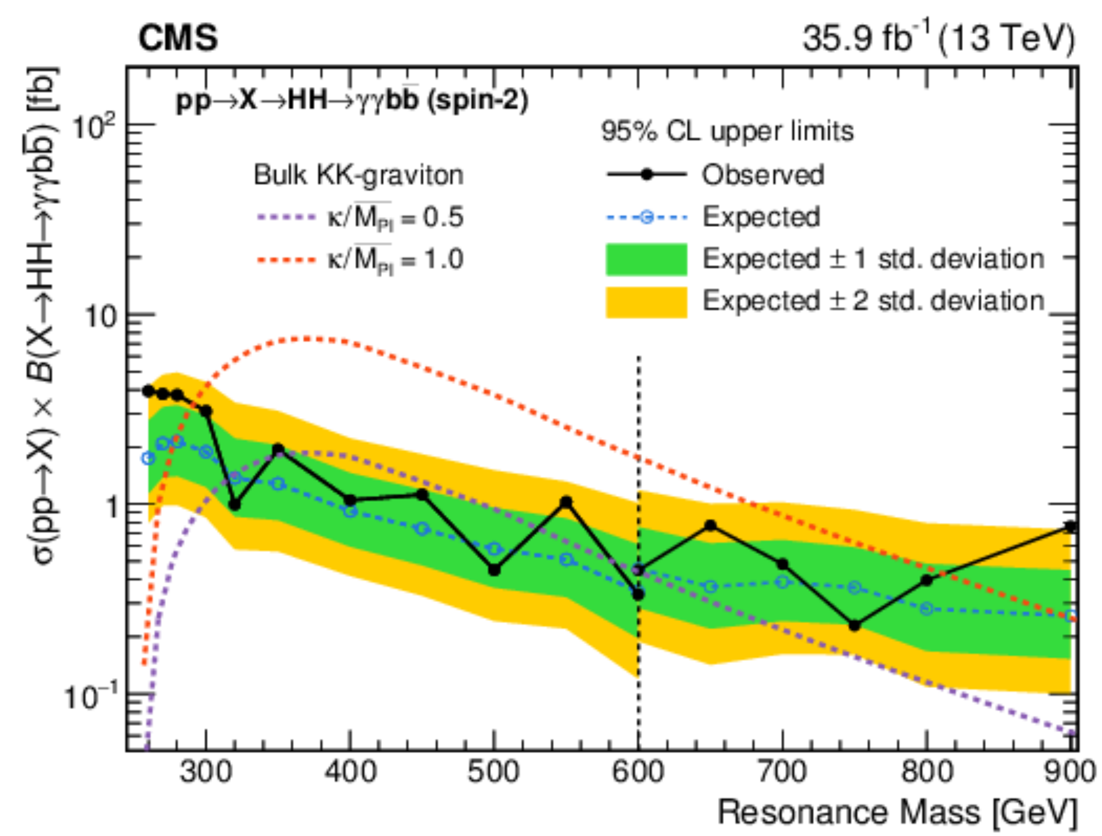
- Left: Observed and expected 95% CL upper limits on cross-section times branching fraction as a function of k_λ/k_t. The two red bands show the theoretical cross section expectations and the corresponding uncertainties for k_t = 1 and k_t = 2.
- Right: Test of k_λ and k_t anomalous couplings. The blue region denotes the parameters excluded by the data at 95% CL, while the dashed black line and the grey regions denote the expected exclusions and the 1σ and 2σ bands. The dotted lines indicate trajectories in the plane with equal values of cross section times branching fraction that are displayed in the associated labels. The diamond-shaped symbol denotes the couplings predicted by the SM. The theory predictions and the expected and observed limits are symmetric through a $(k_\lambda, k_t) \leftrightarrow (-k_\lambda, -k_t)$ transformation.
- In both figures, the couplings that are not explicitly tested are assumed to correspond to the SM prediction.

CMS Run 2 HH→b$\bar{b}$γγ



- Comparison of M_X (red line) with $m_{\gamma\gamma jj}$ (purple dotted line) for different spin-2 resonance masses. All distributions are obtained after the full baseline selection, and are normalized to unit area.

- Observed and expected 95% CL upper limits on the product of cross section and branching fraction σ(pp → X)B(X → HH → γγbb) obtained through a combination of the two analysis categories (HPC and MPC) for spin-0 hypothesis. Also shown are theoretical predictions corresponding to WED mod- els for bulk radions (top) and bulk KK gravitons (bottom). The vertical dashed lines show the boundary between the low- and high-mass regions. The limits for mX = 600 GeV are shown for both methods.

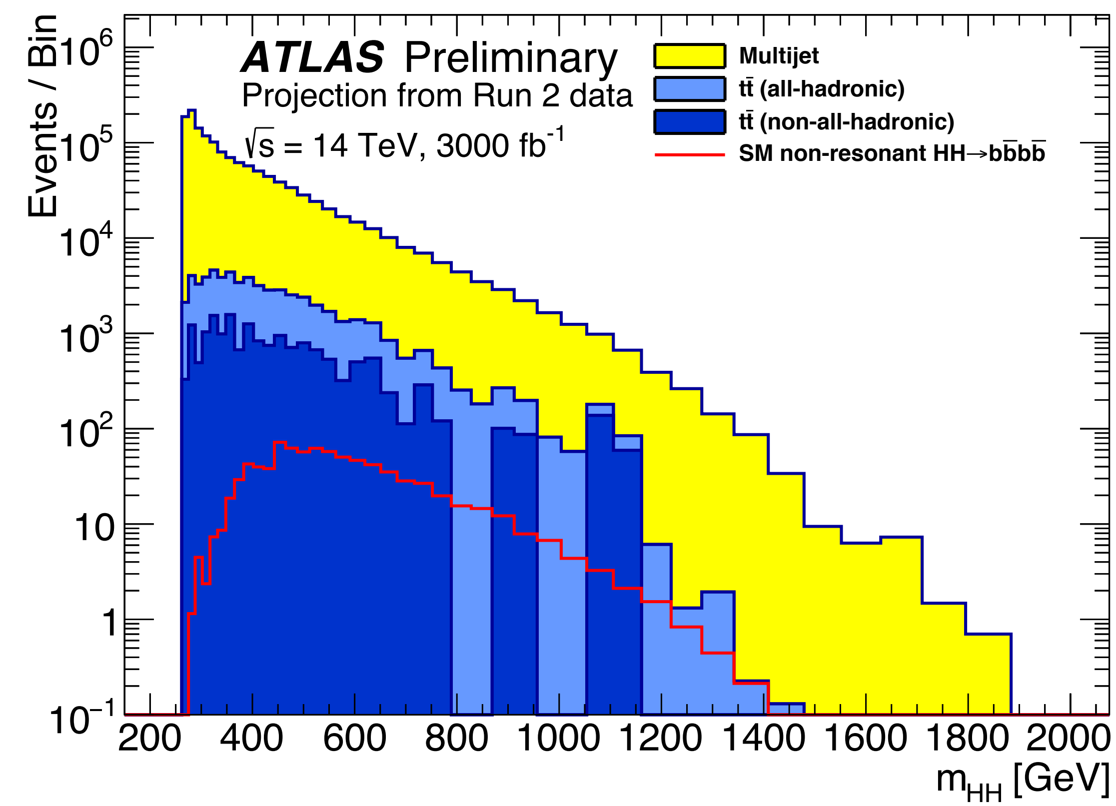


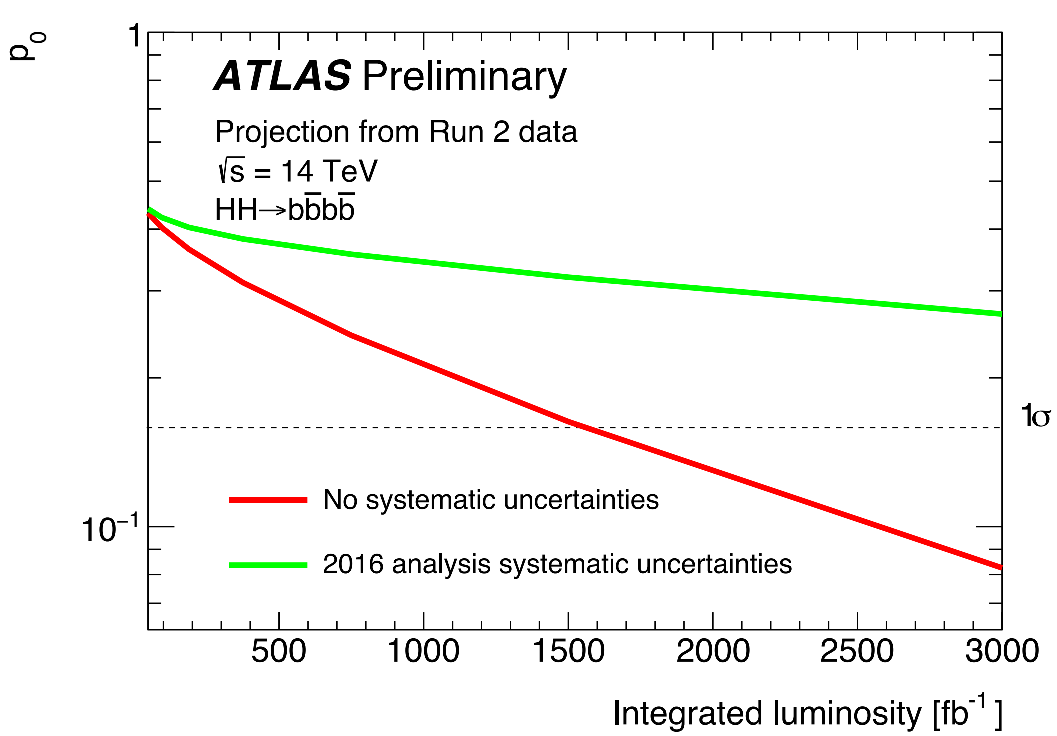
ATLAS HH→$b\bar{b}b\bar{b}$ at HL-LHC

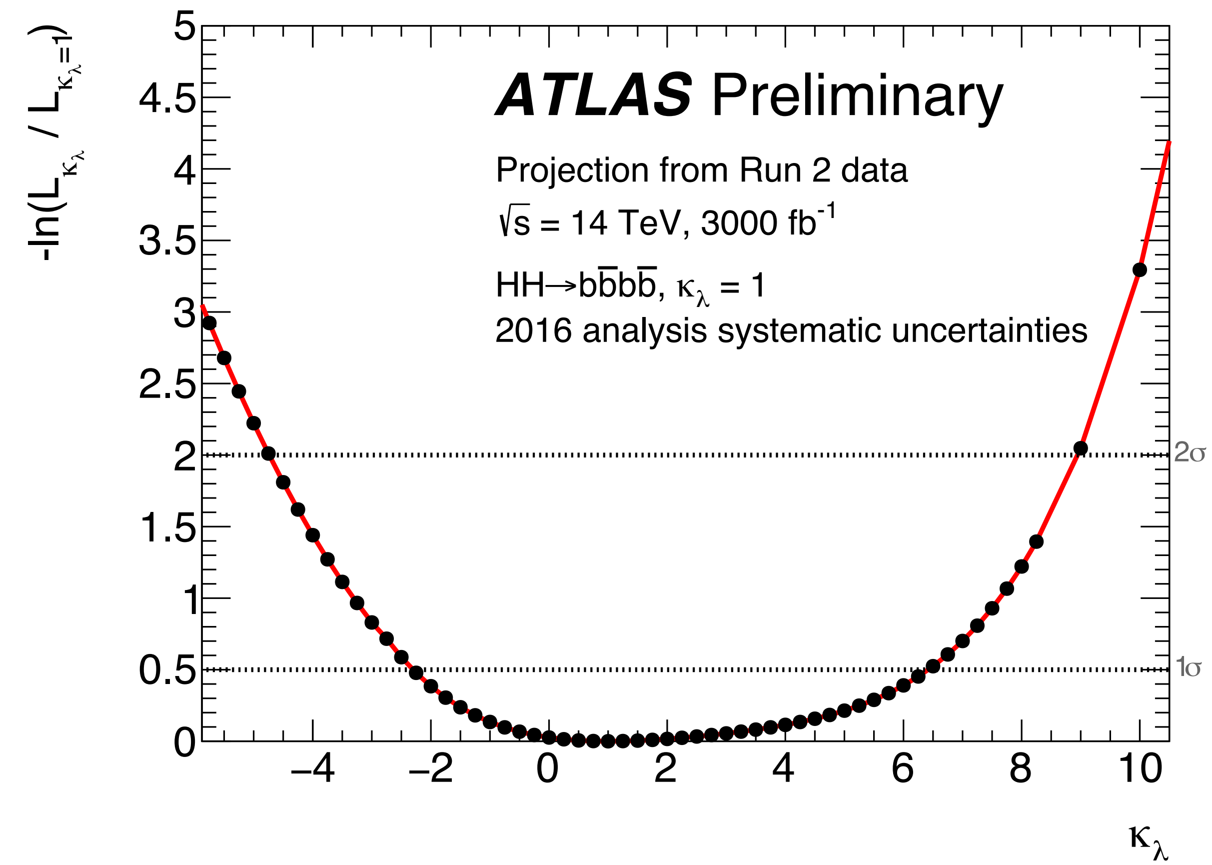
- Extrapolation of 24.3fb^{-1} of 13 TeV 2016 data to HL-LHC
  - Based on Run 2 publication
- Assume same jet reconstruction performance as 2015-16
  - ATLAS detector will be upgraded
  - Expect reconstruction algorithm improvements
  - These should mitigate effect of increased pileup

- Combination of multiple b-jet triggers required
  - Challenging to identify four jets
  - Combination 90% efficient for SM non-resonant signal
- Jets then selected with pt>40GeV

- Signal normalised to 14 TeV cross-section and luminosity
- Background yields scaled by:
  - Luminosity increase (24.3fb^{-1}→3000 fb^{-1})
  - Factor 1.18 (for increase in gluon luminosity)







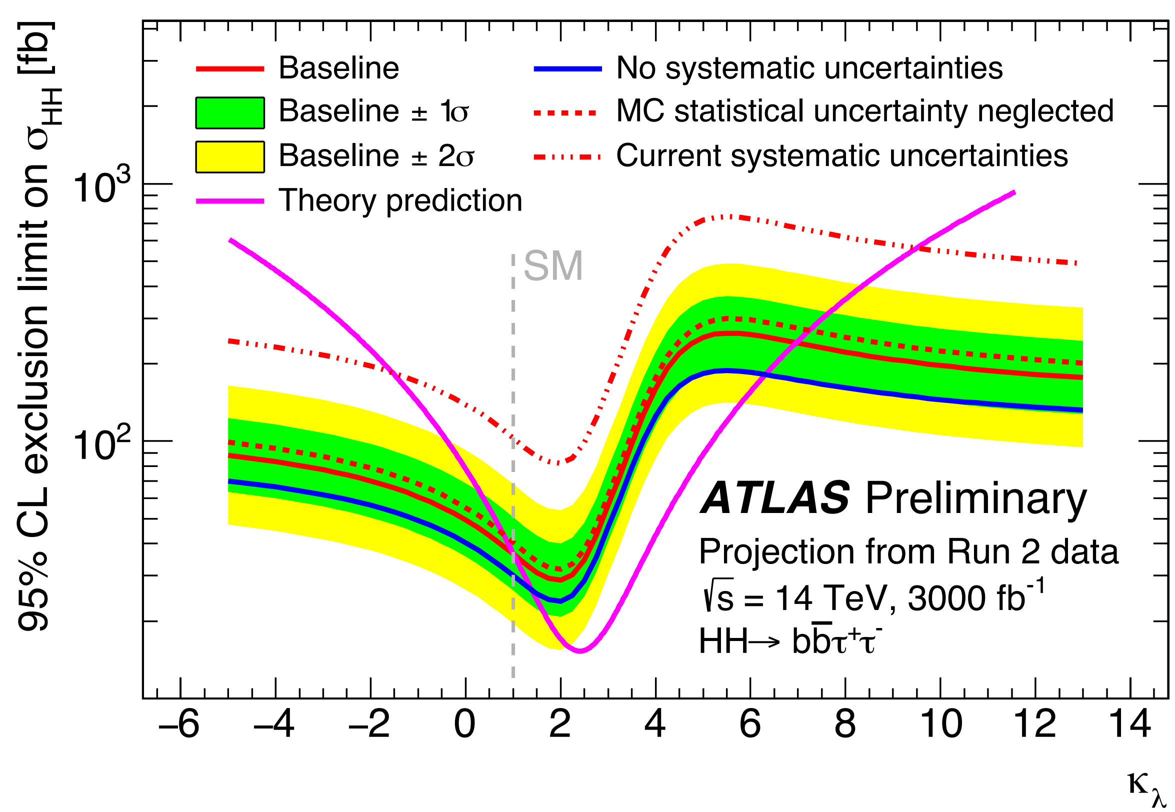
ATLAS HH→$b\bar{b}\tau\tau$ at HL-LHC

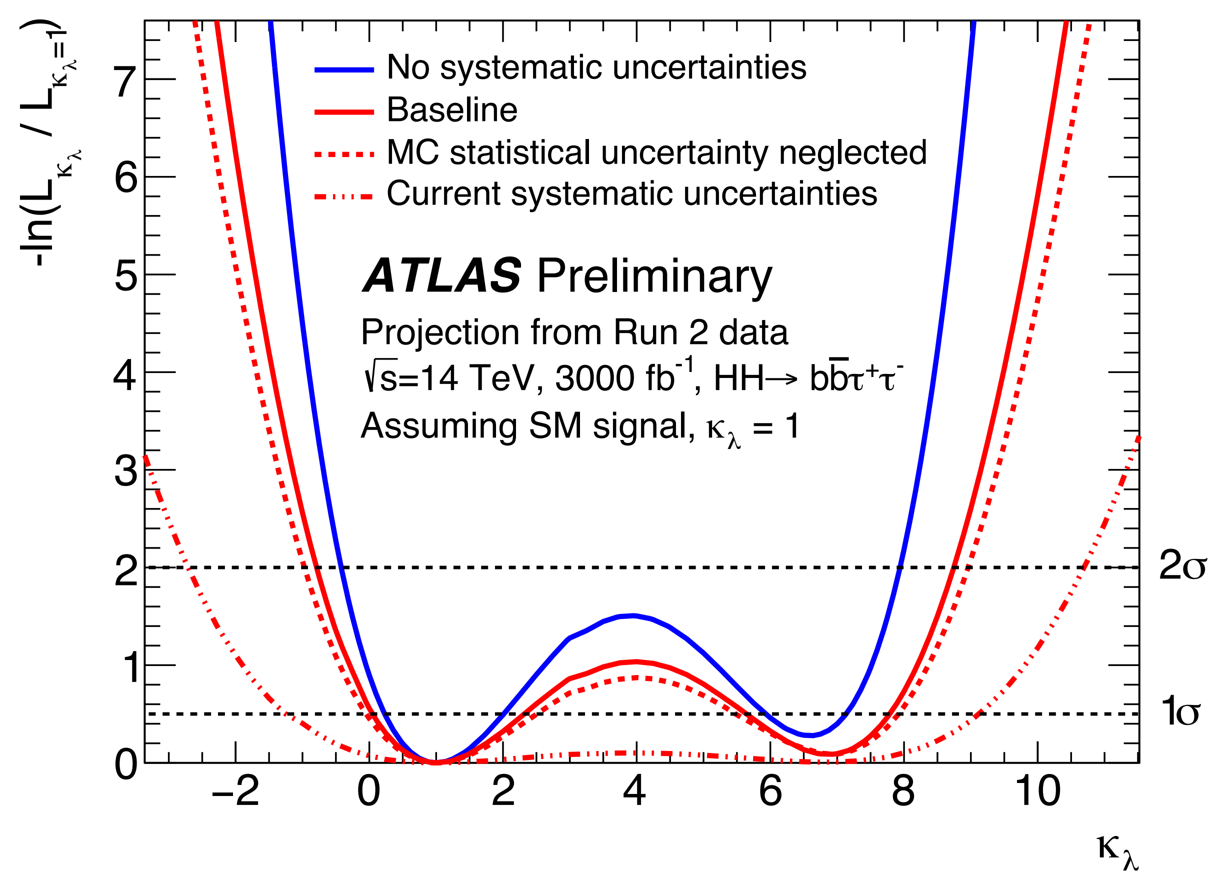
- Analysis is an extrapolation of the Run 2 publication,
- Signal, background rescaled to 3000fb^{-1} and 14 TeV

- Background dominated by tt, QCD multi-jet, Z+heavy jets
- Irreducible background from SM ZH(Z→bb)
- Processes involving jets faking taus use data-driven methods

- Event Selection in three categories
  - Two b-tagged jets with:
  - $\tau_{had}\tau_{had}$ (Single Tau Trigger and Di-Tau Trigger)
  - $\tau_{lep}\tau_{had}$ (Single Lepton Trigger)
  - $\tau_{lep}\tau_{had}$ (Lepton Tau Trigger)
- BDT distinguishes signal from background
- BDT score used as final discriminant
  - Significant boost to sensitivity

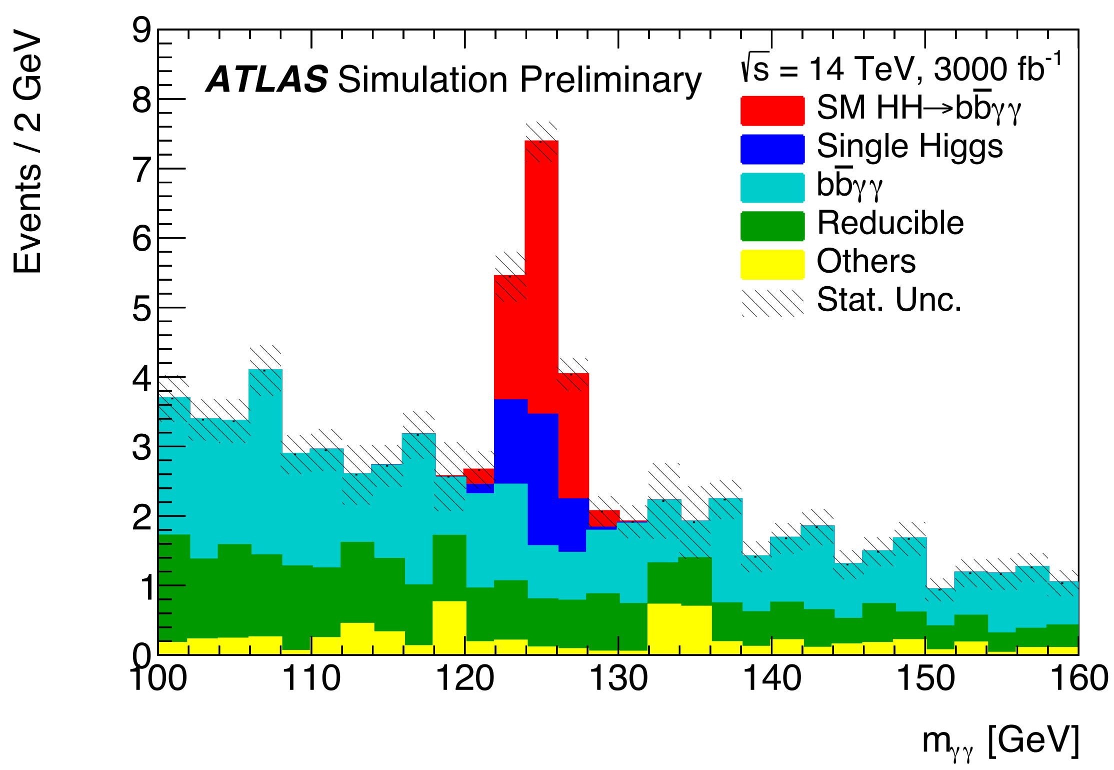
Scenario	-1σ	Expected limit	$+1\sigma$	Significance [σ]
No systematic uncert.	0.58	0.80	1.12	2.5
Baseline	0.71	0.99	1.37	2.1
MC statistical uncert. neglected	0.8	1.2	1.6	1.7
Current systematic uncert.	1.9	2.7	3.7	0.65

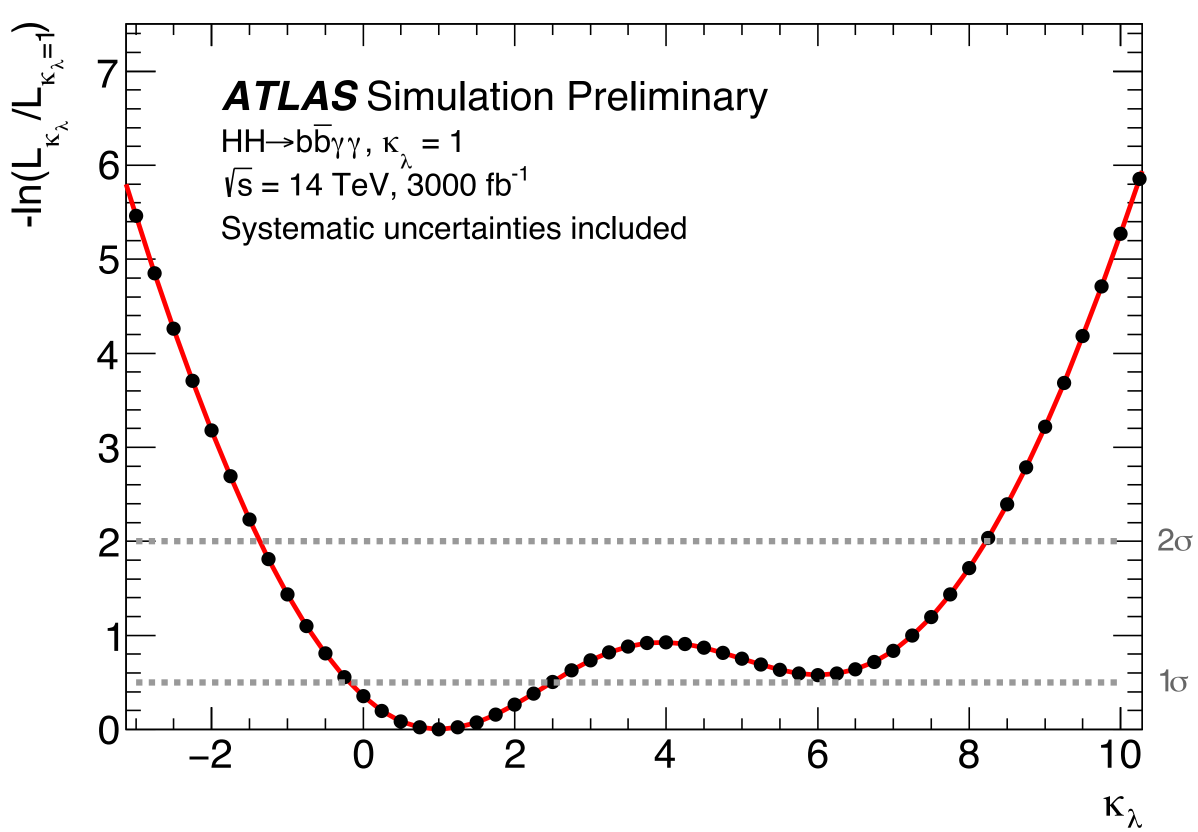




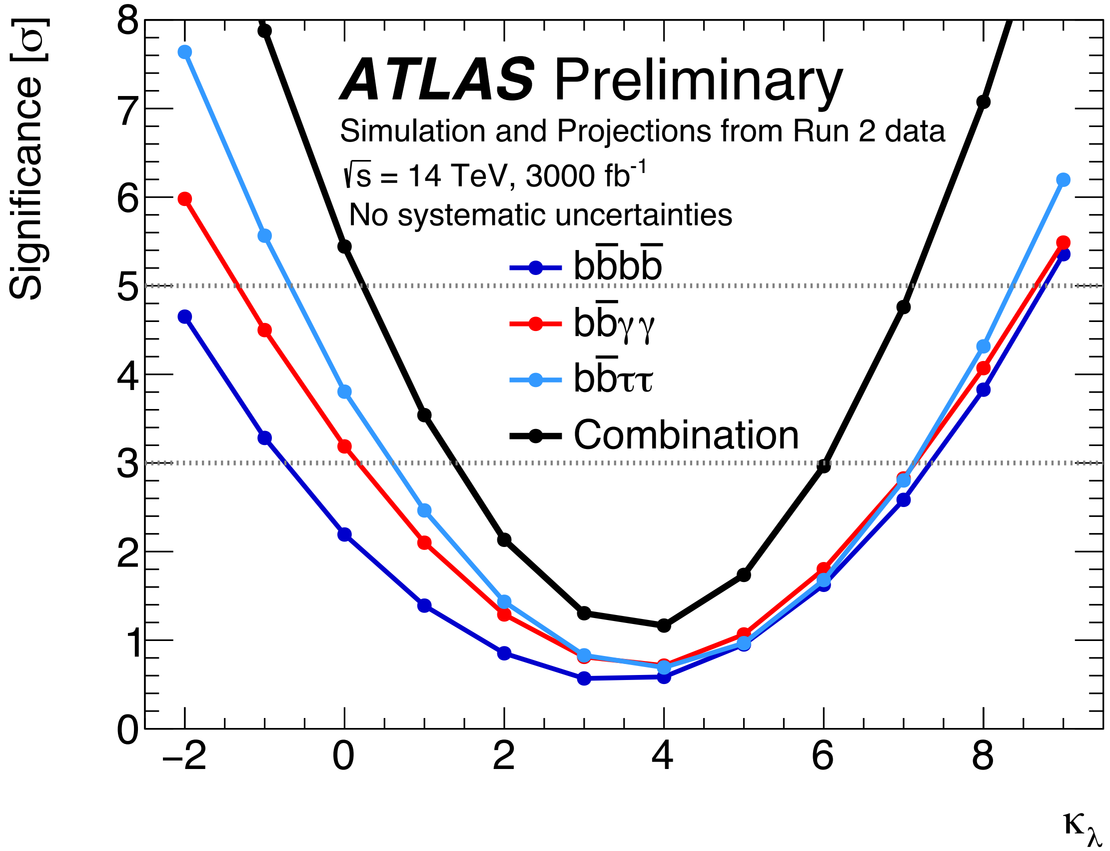
- Analysis proceeds from dedicated truth-level MC samples
- Every way of reconstructing each truth particle considered
  - Enhances statistical power of samples
- Functions based on fully simulated single particles/events applied to emulate expected detector response
- Model expected improvements in ATLAS inner tracker

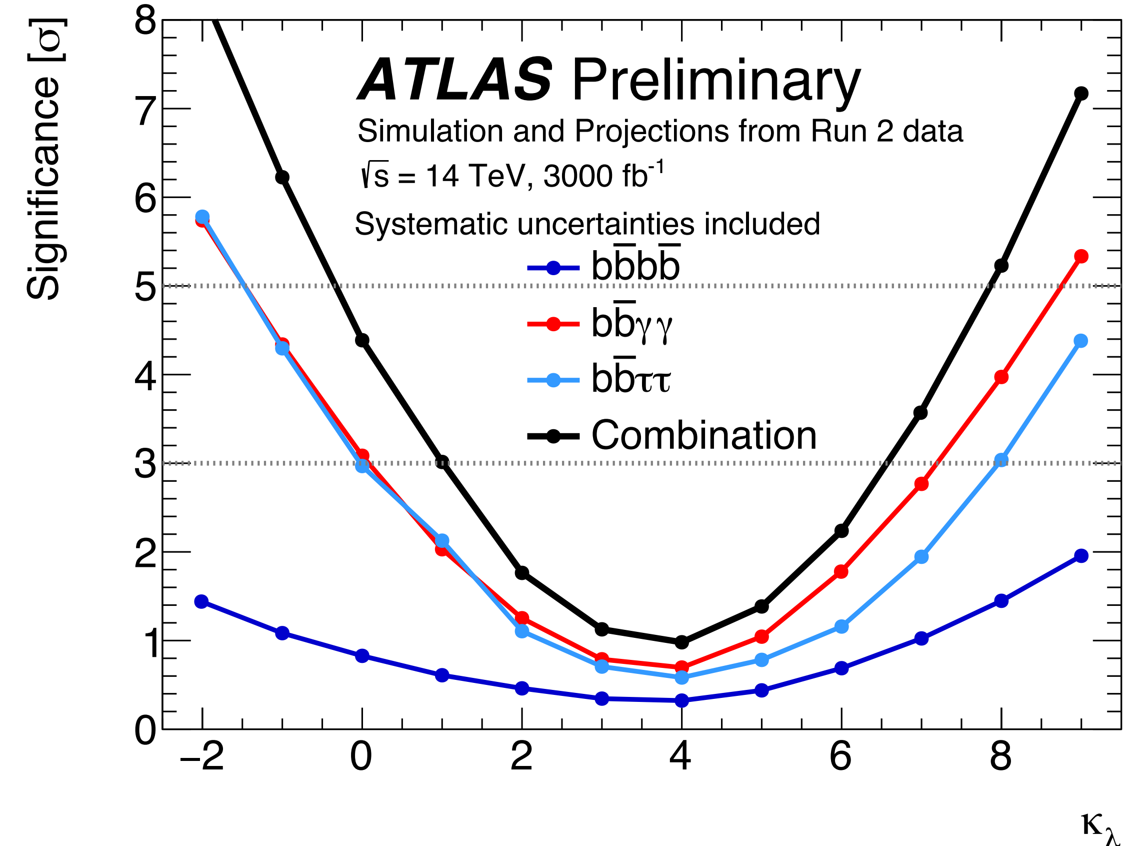
- BDT used for event selection
- Events must pass $123 < m_{\gamma\gamma} < 127$GeV cut
- Systematic uncertainties considered
  - Dominated by photon energy resolution (14%) and ggF QCD scale (50%)





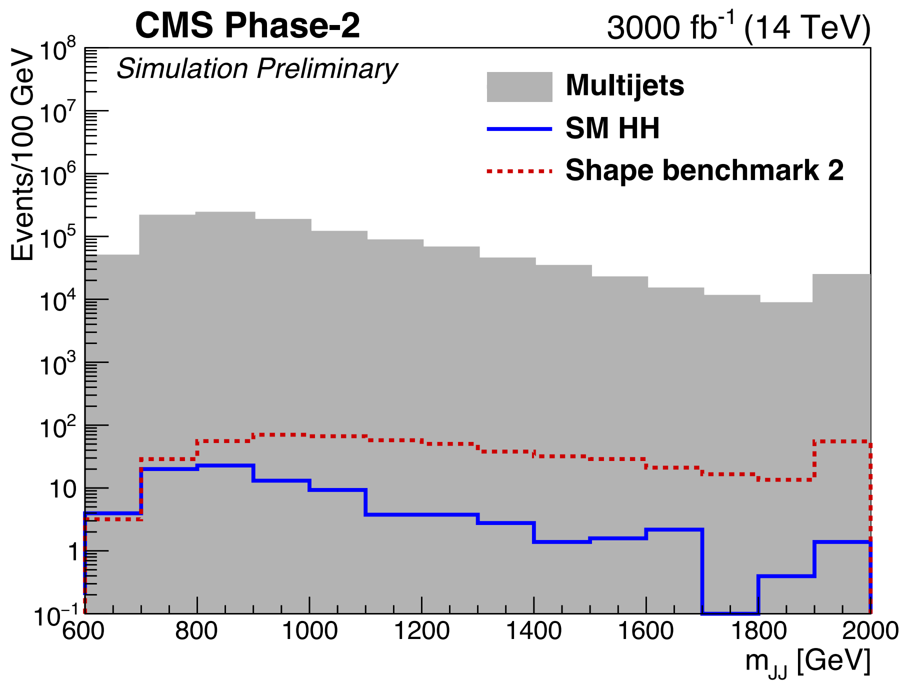
- Full statistical combination performed
- Looking at ATLAS bbbb, bbττ, bbγγ channels only

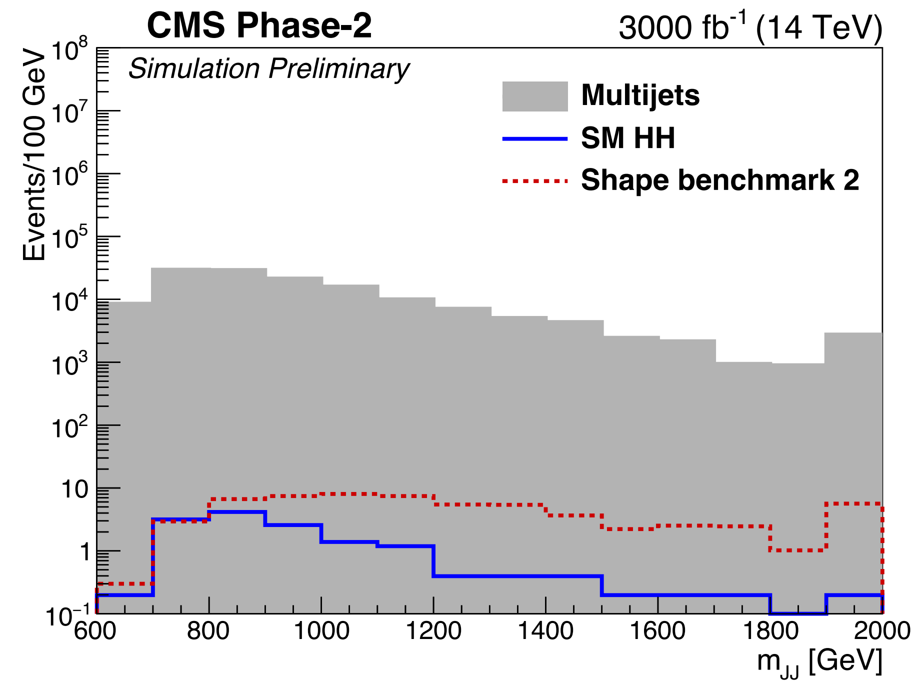




Channel	Statistical-Only	Statistical + Systematics
HH→bbbb	1.4σ	0.61σ
HH→bbττ	2.5σ	2.1σ
HH→bbγγ	2.1σ	2.0σ
Combined	3.5σ	3.0σ

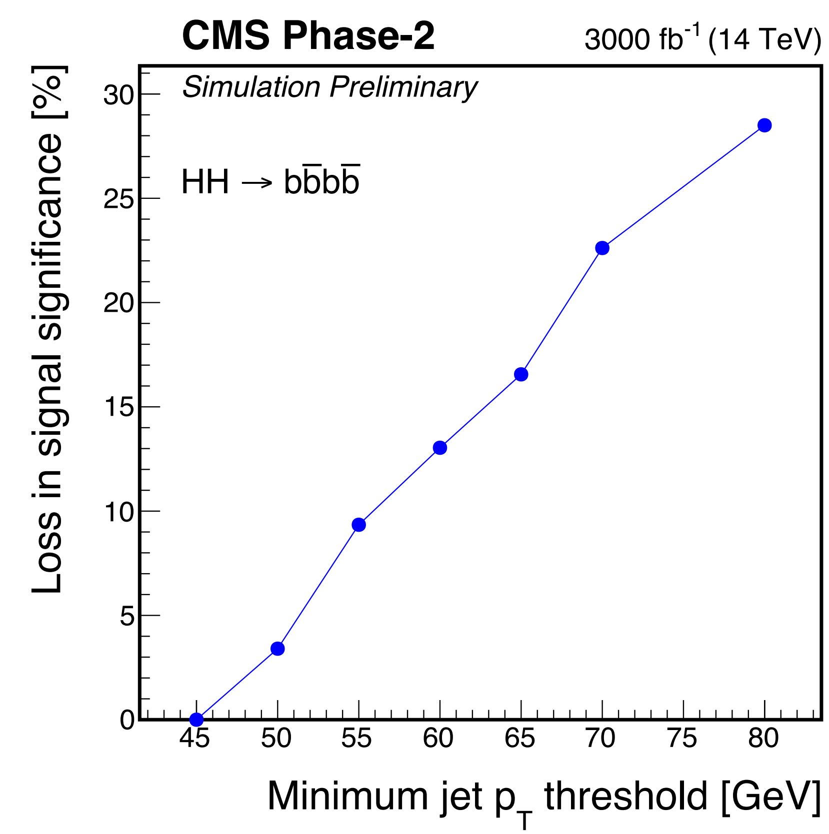
We reach 3σ significance!





- m_{jj} distributions for the estimated multijet background and the SM (blue) and shape benchmark 2 (red) signals. The distributions on the left are for the 3b and those on the right are for the 4b subjet b-tagged categories. Both signals are normalised to the SM HH production cross section for visualisation.

- Loss of sensitivity of the HH → bbbb resolved search as a function of the minimal jet pT threshold (left)



CMS HH→bbVV at HL-LHC

- Two channels considered by CMS
- bbWW → bblνlν
  - Background dominated by two irreducible processes:
    - $t\bar{t}$ production (fully leptonic decay)
    - Drell-Yan production of leptons with associated jets
  - Events selected with neural network
- bbZZ
  - Clean decay channel
  - Four isolated leptons combined to Z boson pairs, with 2 or 3 b-tagged jets

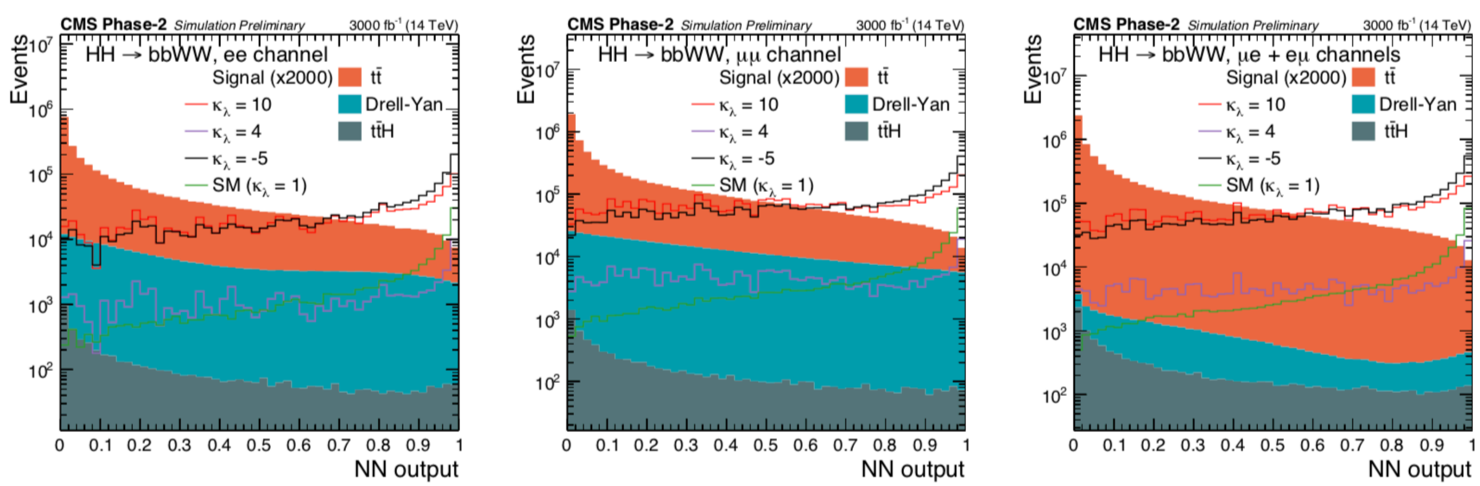
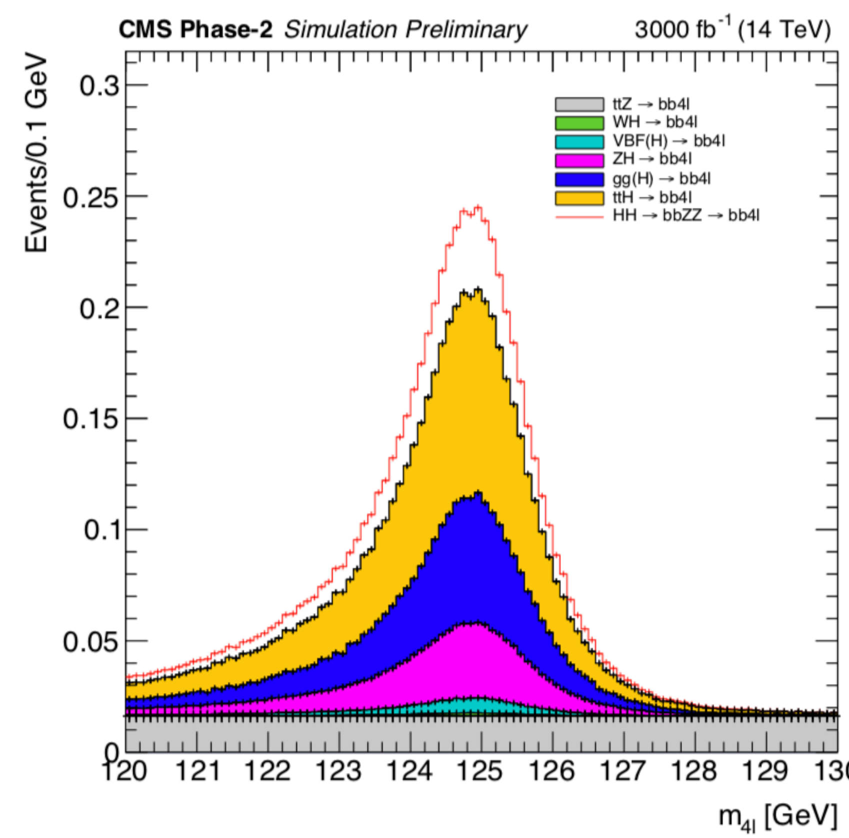


Fig. 62: The output of the bbWW NN after the selections, evaluated in the e^+e^- (left) , $\mu^+\mu^-$ (middle), $e^\pm\mu^\mp$ (right) channels.



ATLAS HH Prospects at HE-LHC

- ATLAS has also examined prospects for the HE-LHC
  - Proposed enhancements to LHC would give $3000 fb^{-1}$ at 27 TeV
  - Detector designs completely unknown, so systematic uncertainties neglected
- In this scenario:
  - $bb\gamma\gamma$ channel: 7.1σ (stats-only)
  - $bb\tau\tau$ channel: 11σ (stats-only)
  - κ_λ measured to 20% precision