Search for HH in the γγbb final state with the ATLAS detector

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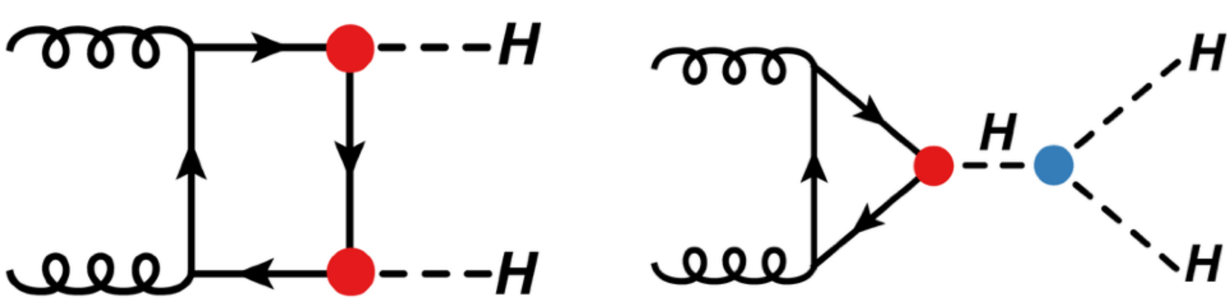
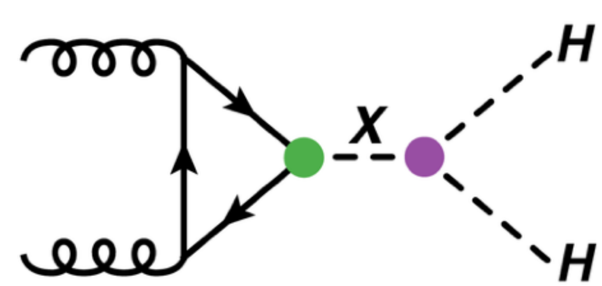
Introduction

- Higgs boson pair production is predicted in the SM and allows the possibility of measuring the Higgs boson self-coupling
- Destructive interference between diagrams results in a small cross section: σ = 33.41 fb at $\sqrt{s}$ = 13 TeV: 1000 times smaller than the Higgs cross section
  - Not yet sensitive with the current LHC dataset
- However, enhancements to non-resonant HH production can occur through an enhanced self-coupling ($\kappa_\lambda = \lambda_{HHH} / \lambda_{SM}$) or potentially BSM couplings (eg ttHH vertex)
- Various models predict a new particle that can decay to pairs of Higgs bosons, referred to as resonant HH production
- In the $bb\gamma\gamma$ final state, a search is performed for both resonant and non-resonant HH production

Standard Model



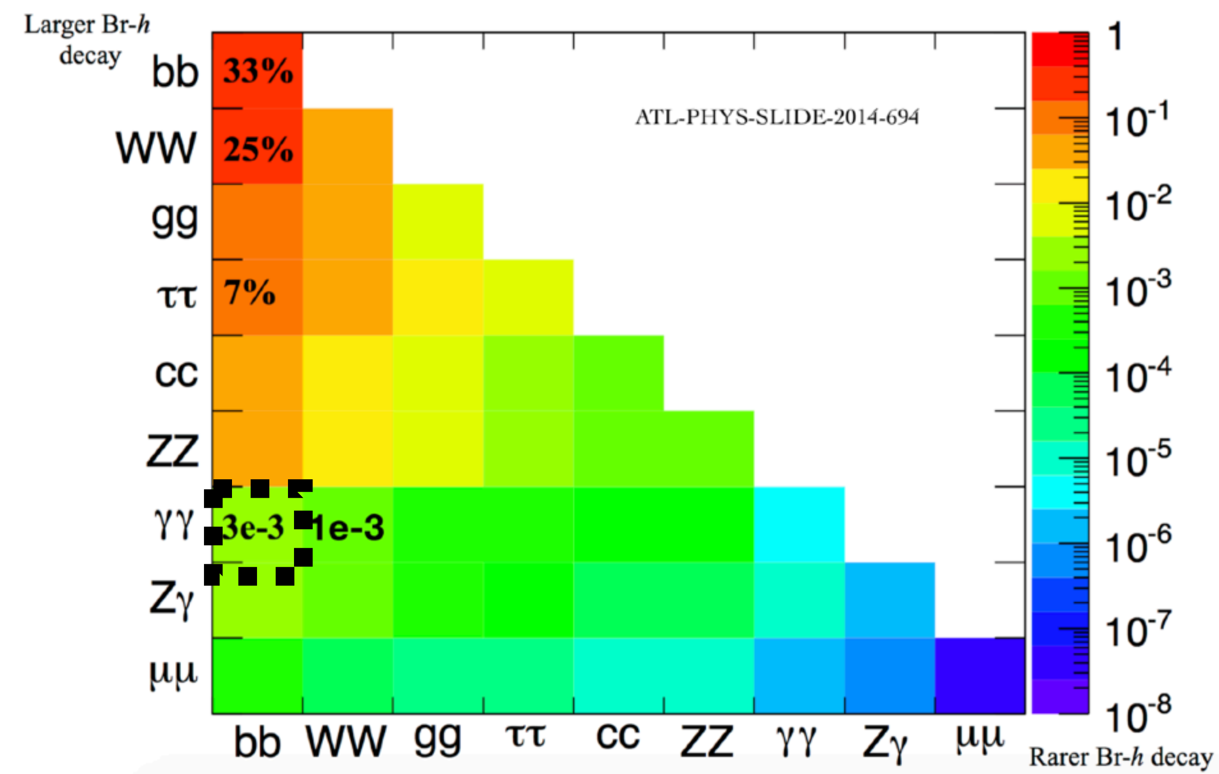
Beyond Standard Model

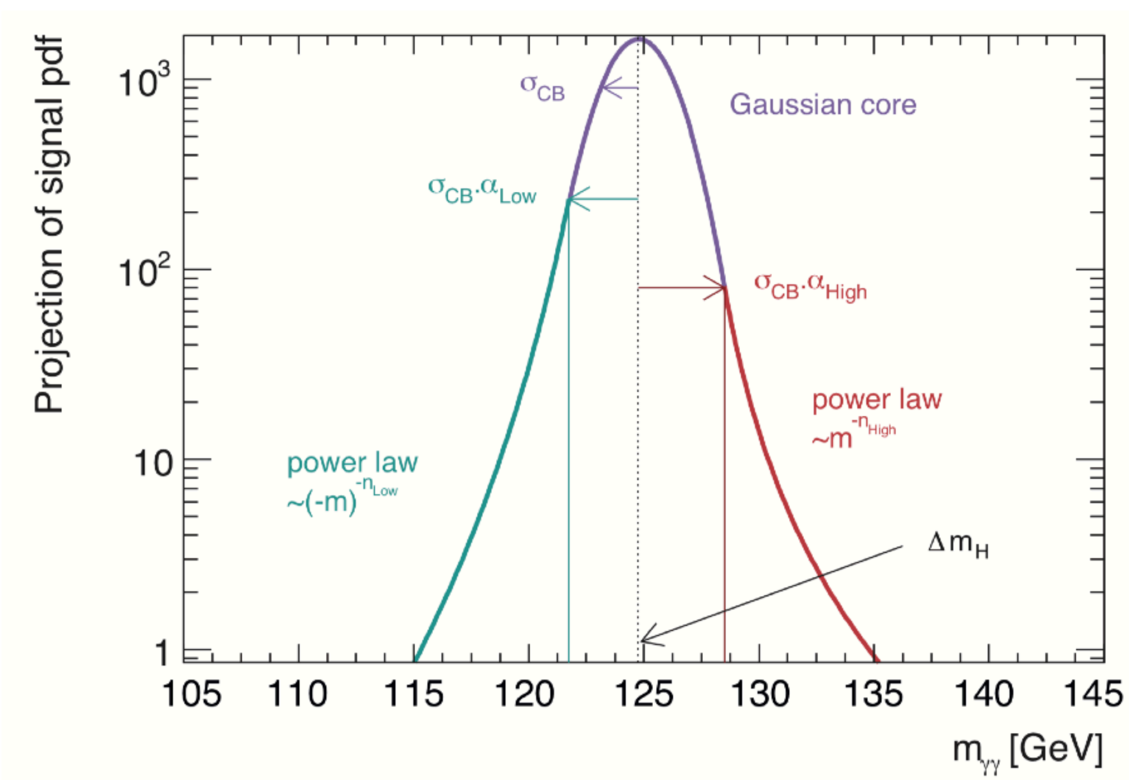


$$\mathcal{L}_H = \frac{1}{2}\left(\partial^\mu H \partial_\mu H\right) - \lambda v^2 H^2 - \lambda v H^3 - \frac{1}{2}\lambda H^4$$

Motivations for bbγγ

- HH → bbγγ is one of the most attractive ways to study HH production
  - High H→bb branching ratio (~57%)
  - Photon ID can effectively reject multi-jet backgrounds
  - Efficient di-photon trigger gives high signal efficiency
  - Excellent photon energy resolution gives a narrow H → γγ mass peak (σCB typically 1.6 GeV in ATLAS)





Data and MC samples

- The HH → bbγγ analysis uses 36.1 fb^{-1} of data collected by ATLAS in 2015 + 2016
- Signal MC samples:
  - Approximate NLO SM (κλ = 1) HH using MadGraph + Herwig
  - LO varied κλ HH using MadGraph + Pythia8 used to re-weight NLO sample for κλ interpretation
  - NLO BSM resonant HH using Madgraph + Herwig
- Background MC samples:
  - Single Higgs background: most important are ggF, ttH and ZH but all are considered
  - γγ + jets: used in the background decomposition and to guide the choice of functional form

Process	Generator	Showering	PDF set	σ [fb]	Order of calculation of σ
Non-resonant SM HH	MadGraph5_aMC@NLO	Herwig++	CT10 NLO	33.41	NNLO+NNLL
Non-resonant BSM HH	MadGraph5_aMC@NLO	Pythia 8	NNPDF 2.3 LO	-	LO
Resonant BSM HH	MadGraph5_aMC@NLO	Herwig++	CT10 NLO	-	NLO
$\gamma\gamma$ plus jets	Sherpa	Sherpa	CT10 NLO	-	LO
ggH	Powheg-Box NNLOPS (r3080) [60]	Pythia 8	PDF4LHC15	48520	N^{3}LO(QCD)+NLO(EW)
VBF	Powheg-Box (r3052) [61]	Pythia	PDF4LHC15	3780	NNLO(QCD)+NLO(EW)
WH	Powheg-Box (r3133) [62]	Pythia	PDF4LHC15	1370	NNLO(QCD)+NLO(EW)
$q\bar{q} \to ZH$	Powheg-Box (r3133) [62]	Pythia 8	PDF4LHC15	760	NNLO(QCD)+NLO(EW
$t\bar{t}H$	MadGraph5_aMC@NLO	Pythia 8	NNPDF3.0	510	NLO(QCD)+NLO(EW)
$gg \to ZH$	Powheg-Box (r3133)	Pythia 8	PDF4LHC15	120	NLO+NLL(QCD)
$b\bar{b}H$	MadGraph5_aMC@NLO	Pythia	CT10 NLO	490	NNLO(5FS)+NLO(4FS)
t-channel tH	MadGraph5_aMC@NLO	Pythia 8	CT10 NLO	70	LO(4FS)
W-associated tH	MadGraph5_aMC@NLO	Herwig++	CT10 NLO	20	NLO(5FS)

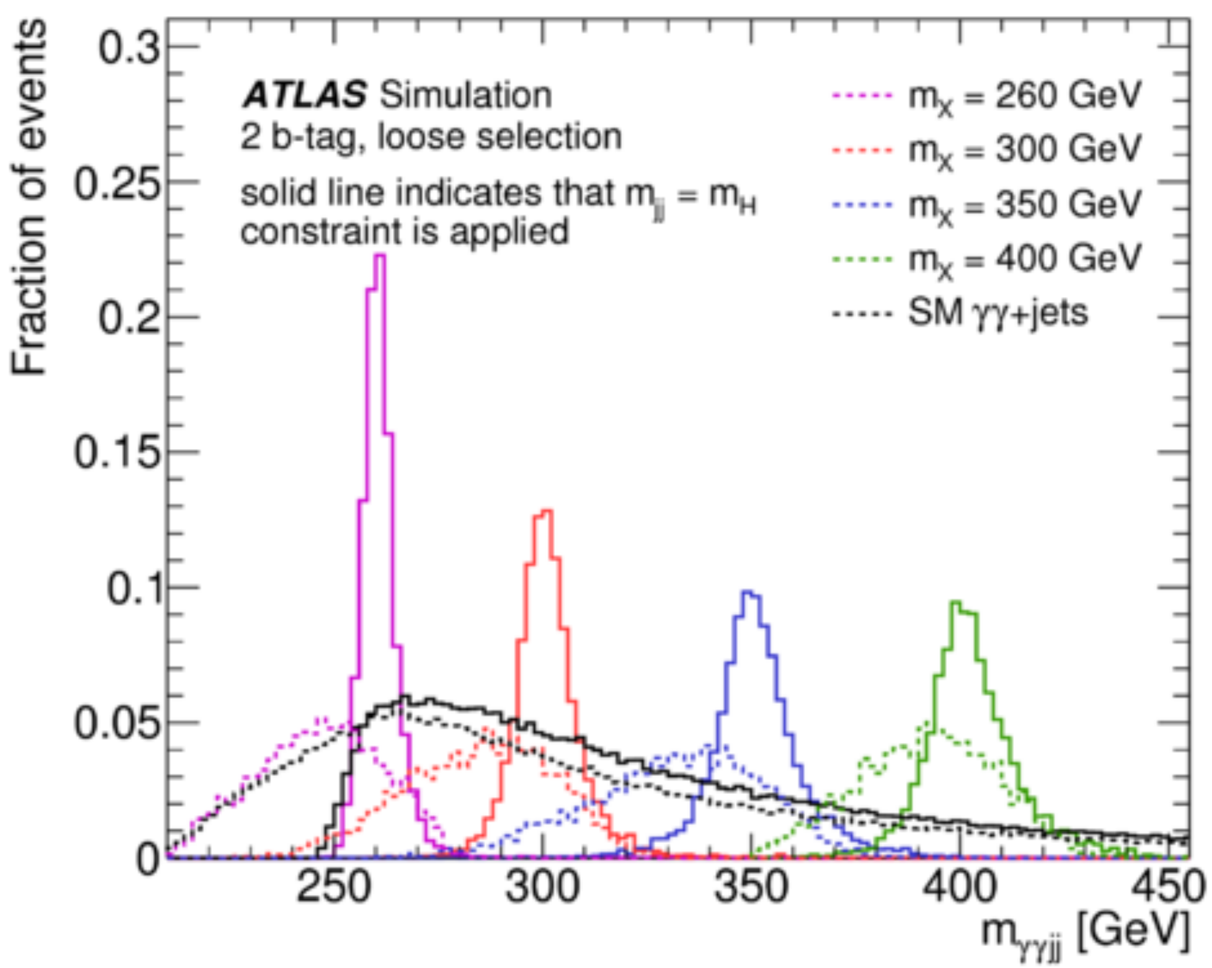
Event Selection

$H\to\gamma\gamma$ event selection:

- Two tight ID and isolated photons with P_T / $m_{\gamma\gamma}$ > 0.35 (0.25) for the leading (subleading) photon
- Events are then sorted into categories with exactly 2 b-tags or 1 b-tag

Jet b-Tagging WPs:

- MV2@60% in 1tag and 70% in 2tag region

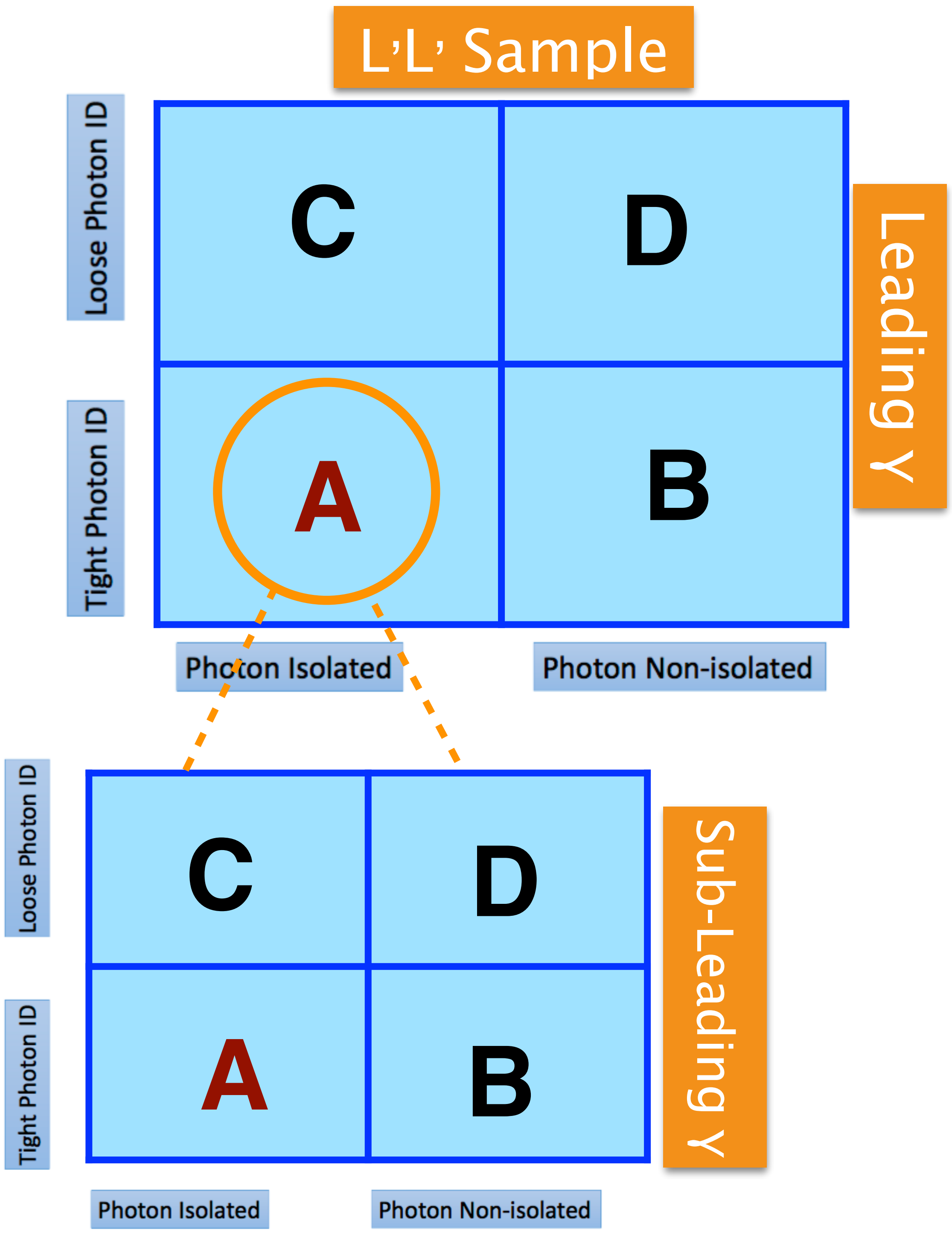


Two different selections are used:

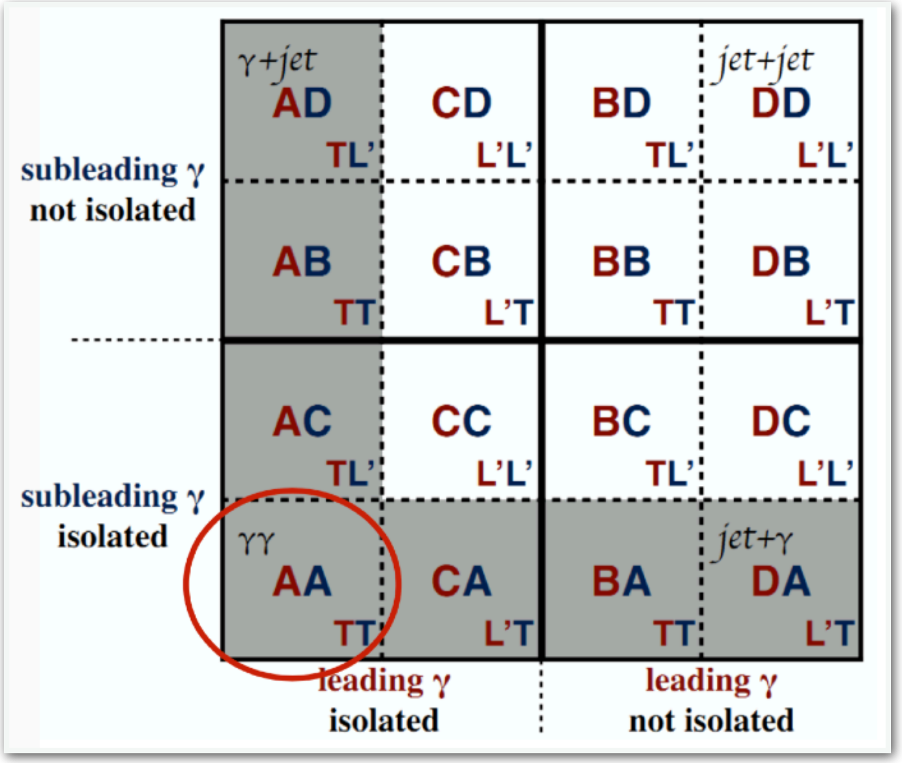
- **Loose selection:**
  - Used for resonant masses between 260 and 500 GeV and the κ_λ interpretation
  - jet P_T > 40 (25) GeV
    m_{bb} in the interval [80,140] GeV
  - <u>Resonant analysis only</u>: $|m_{\gamma\gamma} - m_H| < 4.7$ GeV
- **Tight selection:**
  - used for resonant masses between 500 GeV and 1 TeV and the limit on the SM cross-section
  - jet P_T > 100 (30) GeV
    m_{bb} in the interval [90,140] GeV
  - <u>Resonant analysis only</u>:
    $|m_{\gamma\gamma} - m_H| < 4.3$ GeV
- **Resonant analysis only:**
  - The di-jet Higgs candidate 4-vector is rescaled such that its invariant mass is equal to 125 GeV
  - Improves the $m_{\gamma\gamma bb}$ resolution, particularly at low m_X

Background Decomposition

- Studied using a **2x2D sideband method** where photon identification and isolation requirements are loosened
- Dominant SM background processes:
  - γγ (irreducible), γ-jet, and jet-jet (reducible)
- Data-driven background decomposition:
  - 16 regions (15 background control region and 1 signal region)
  - each region categorised based on photon ID and isolation
  - required inputs from simulation: photon efficiencies
  - solve the 16 equations to extrapolate rates of the different background event processes from the background control regions into the signal region



Background Decomposition (2)



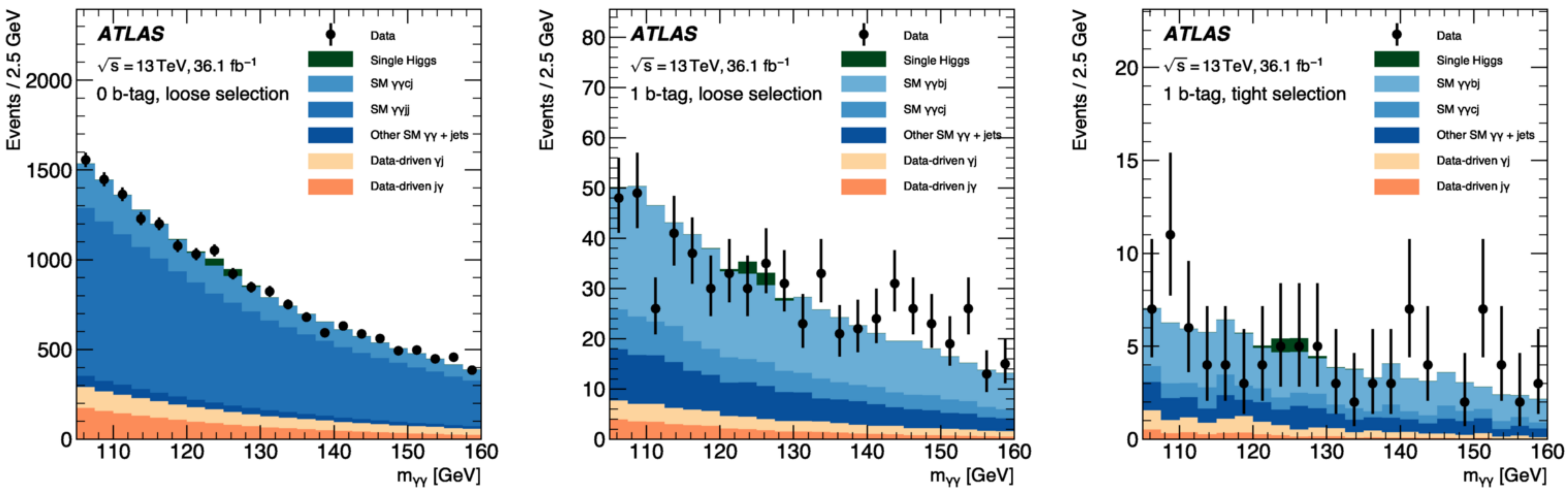
- What we have in the real data?
  - Event yields in the 16 regions
- What we need?
  - Event yields of the 4 components in the signal (AA) region

$$N^{all}_{AA} = N^{\gamma\gamma}_{AA} + N^{\gamma J}_{AA} + N^{J\gamma}_{AA} + N^{JJ}_{AA}$$

	Typical Result	Uncertainty
γγ Purity	84%	5%
γj-jγ Fraction	15%	2%
j-j Fraction	1%	0.1%

Background Decomposition (3)

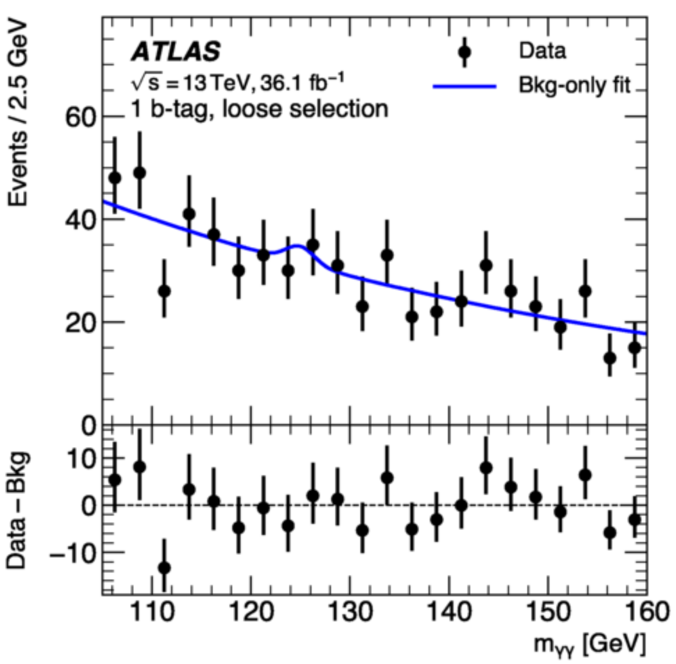
- Flavour information extracted from the truth information in the Monte Carlo sample
- In the 2-tag category which dominates the sensitivity, the background is mostly made up of the irreducible $\gamma\gamma bb$



0 tag category used for cross checks only

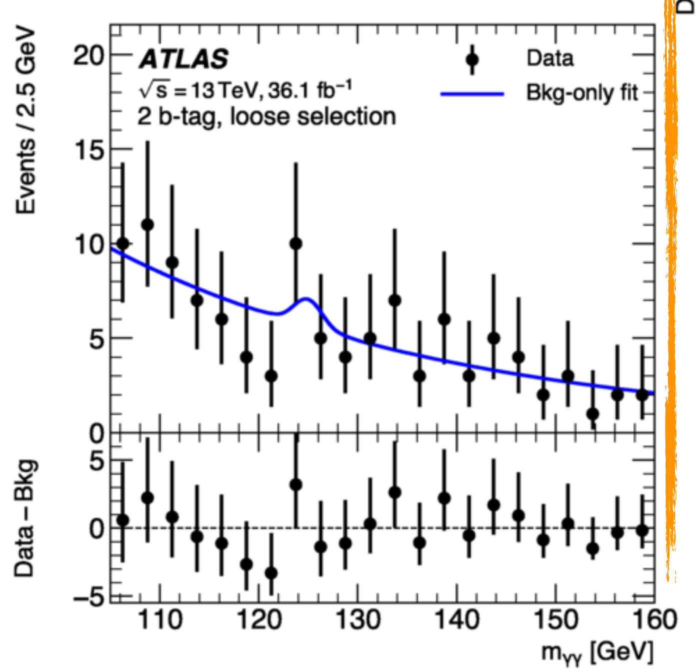
Signal Extraction (non resonant)

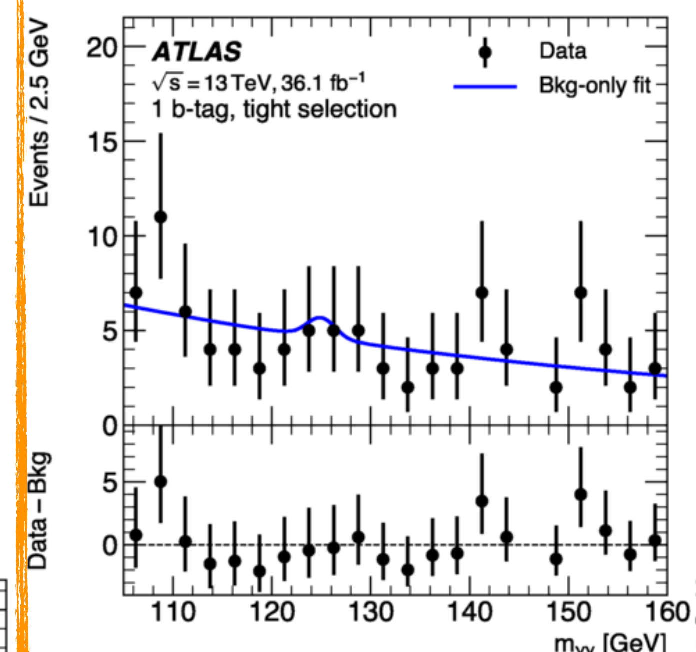
- For the non-resonant analysis, the signal is extracted by performing a fit to the di-photon mass, $m_{\gamma\gamma}$ using a double-sided Crystal ball to model the signal and the single Higgs background and an exponential to model the continuum background



Loose selection

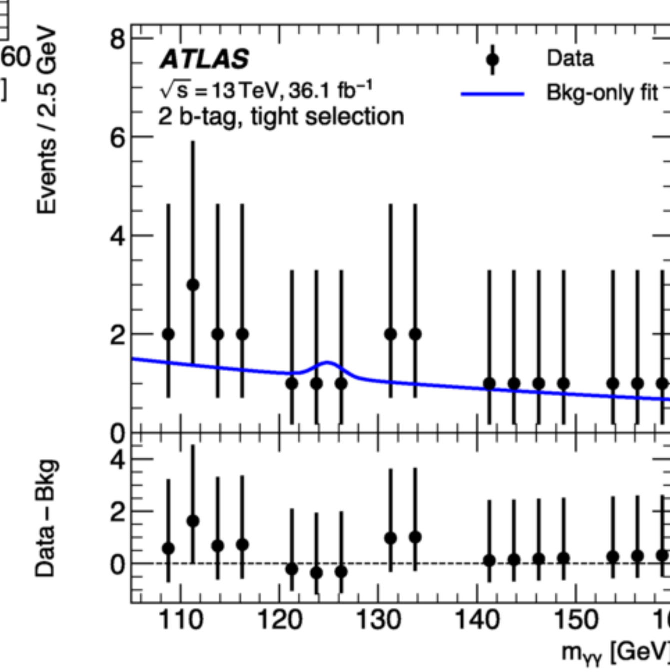
κλ analysis





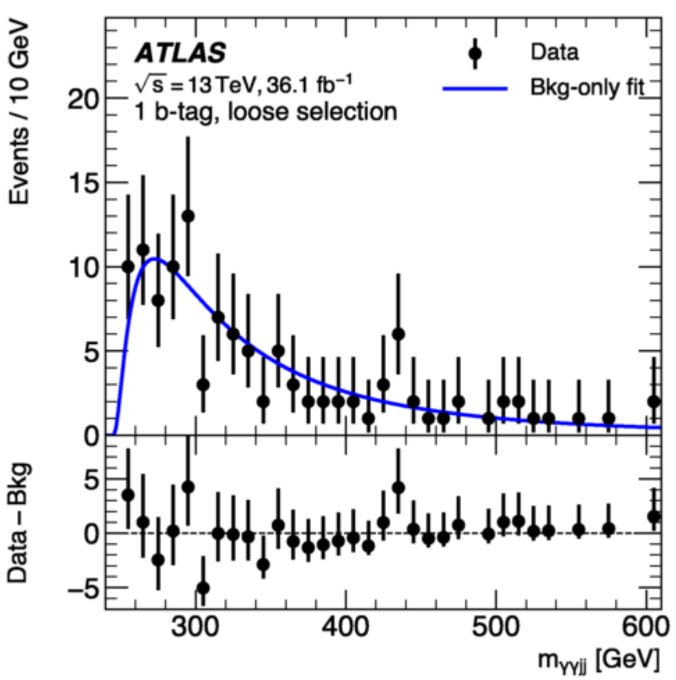
Tight selection

SM limit



Signal Extraction (resonant)

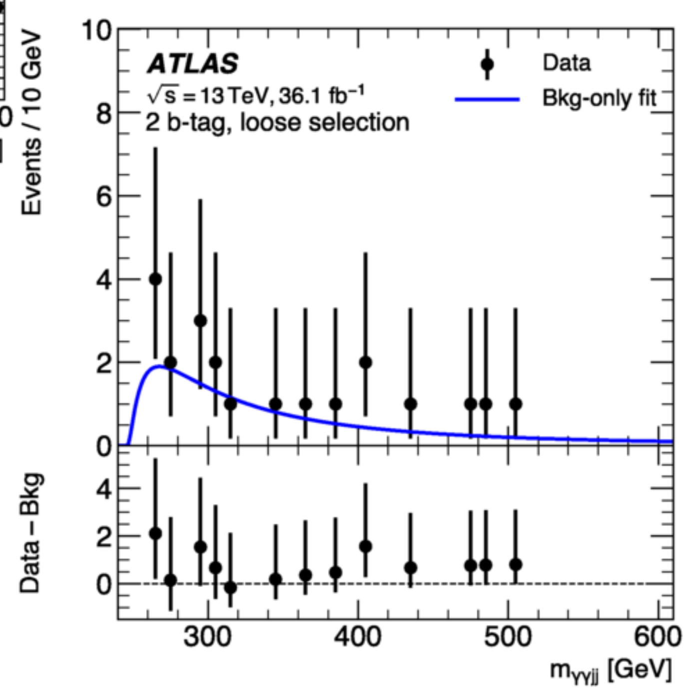
- For the resonant analysis, the signal is extracted by performing a fit to the four-body mass, $m_{\gamma\gamma jj}$ using a Gaussian with exponential tails as signal model and a Novosibirsk (exponential) for the loose (tight) selection

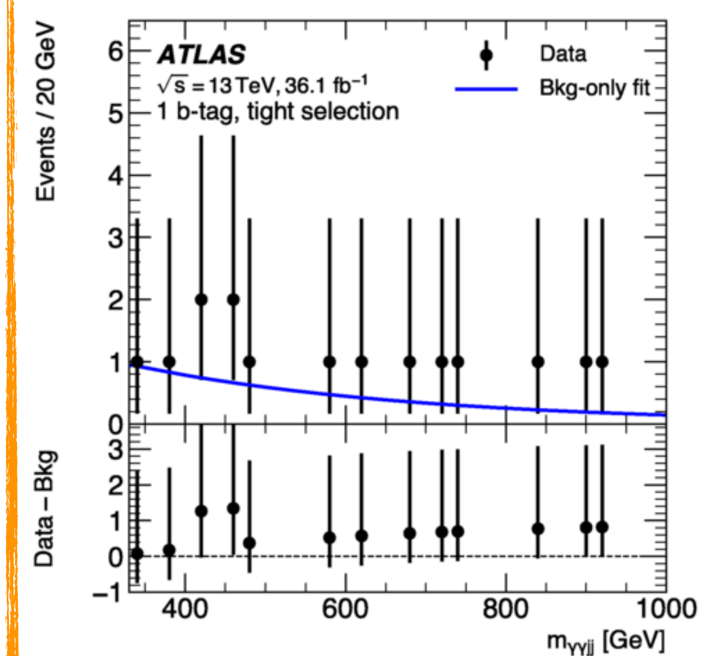


Loose selection

M_X < 500 GeV

($X \rightarrow HH \rightarrow bb\gamma\gamma$)

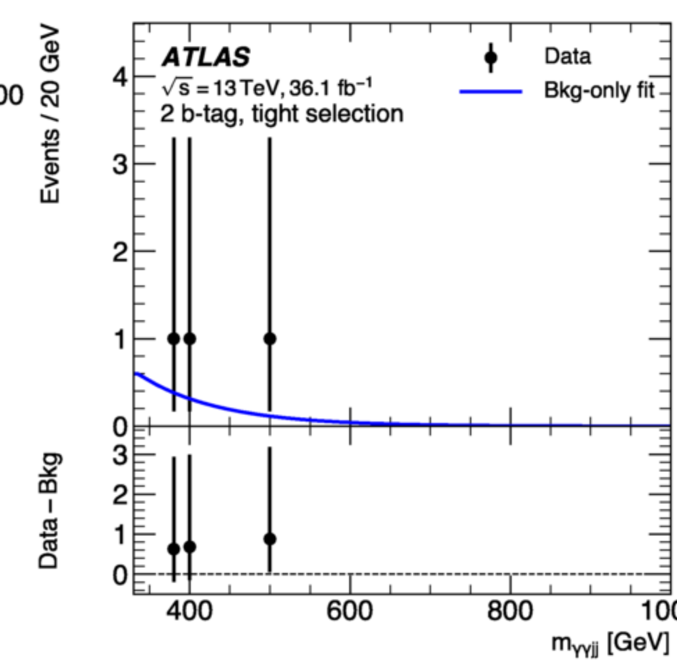




Tight selection

M_X > 500 GeV

($X \rightarrow HH \rightarrow bb\gamma\gamma$)



Systematic Uncertainties

- Analysis is almost entirely statistically limited
- The largest systematic uncertainties are:
  - conservative 100% theory uncertainty on ggF + Heavy Flavour production
  - Photon ID, JES/JER and flavour tagging

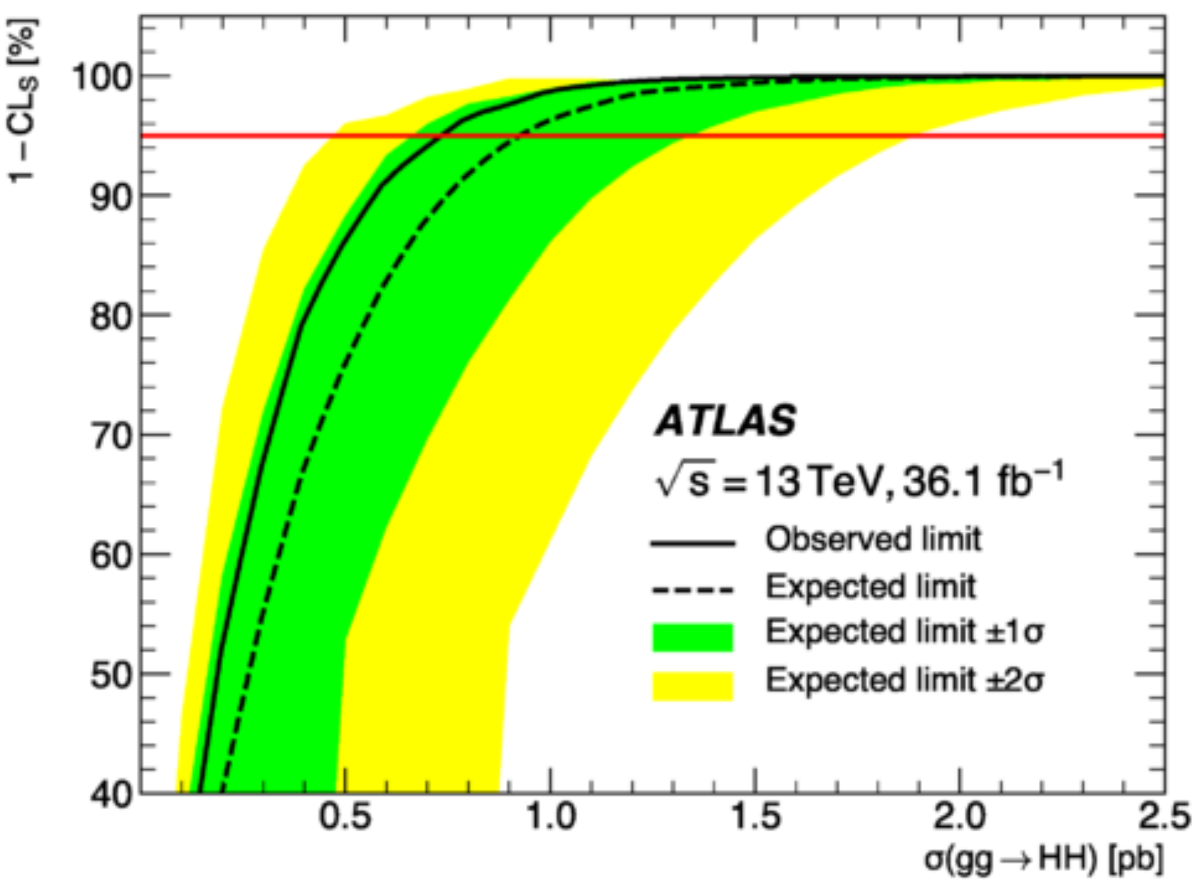
Source of systematic uncertainty		% effect relative to nominal in the 2-tag (1-tag) category: Non-resonant analysis		Resonant analysis: BSM HH	
		SM HH signal	Single-H bkg	Loose selection	Tight selection
Luminosity		±2.1 (±2.1)	±2.1 (± 2.1)	±2.1 (±2.1)	±2.1 (±2.1)
Trigger		±0.4 (±0.4)	±0.4 (± 0.4)	±0.4 (±0.4)	±0.4 (±0.4)
Pile-up modelling		±3.2 (±1.3)	±2.0 (± 0.8)	±4.0 (±4.2)	±4.0 (±3.8)
Photon	identification	±2.5 (±2.4)	±1.7 (± 1.8)	±2.6 (±2.6)	±2.5 (±2.5)
	isolation	±0.8 (±0.8)	±0.8 (± 0.8)	±0.8 (±0.8)	±0.9 (±0.9)
	energy resolution	-	-	±1.0 (±1.3)	±1.8 (±1.2)
	energy scale	-	-	±0.9 (±3.0)	±0.9 (±2.4)
Jet	energy resolution	±1.5 (±2.2)	±2.9 (± 6.4)	±7.5 (±8.5)	±6.4 (±6.4)
	energy scale	±2.9 (±2.7)	±7.8 (± 5.6)	±3.0 (±3.3)	±2.3 (±3.4)
Flavour tagging	b-jets	±2.4 (±2.5)	±2.3 (± 1.4)	±3.4 (±2.6)	±2.5 (±2.6)
	c-jets	±0.1 (±1.0)	±1.8 (±11.6)	-	-
	light-jets	<0.1 (±5.0)	±1.6 (± 2.2)	-	-
Theory	PDF+α_S	±2.3 (±2.3)	±3.1 (± 3.3)	n/a	n/a
	Scale	+4.3 (+4.3)	+4.9 (+ 5.3)	n/a	n/a
		−6.0 (−6.0)	+7.0 (+ 8.0)	n/a	n/a
	EFT	±5.0 (±5.0)	n/a	n/a	n/a

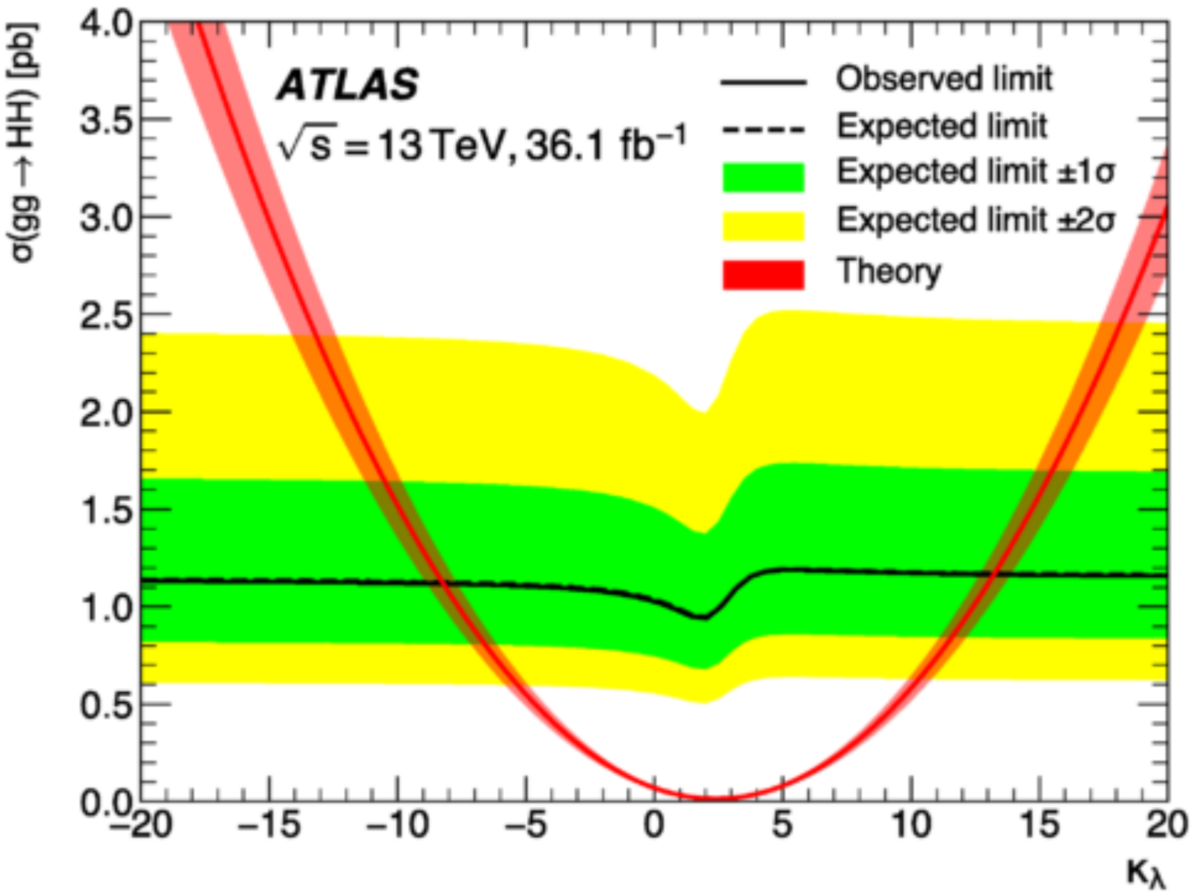
Results (non resonant)

- Single Higgs backgrounds are fixed to their SM expectation in the fit
- Limits on the SM HH cross-section at 95% CL:

	Observed	Expected	-1σ	$+1\sigma$
$\sigma_{gg\to HH}$ [pb]	0.73	0.93	0.66	1.4
As a multiple of σ_{SM}	22	28	20	40

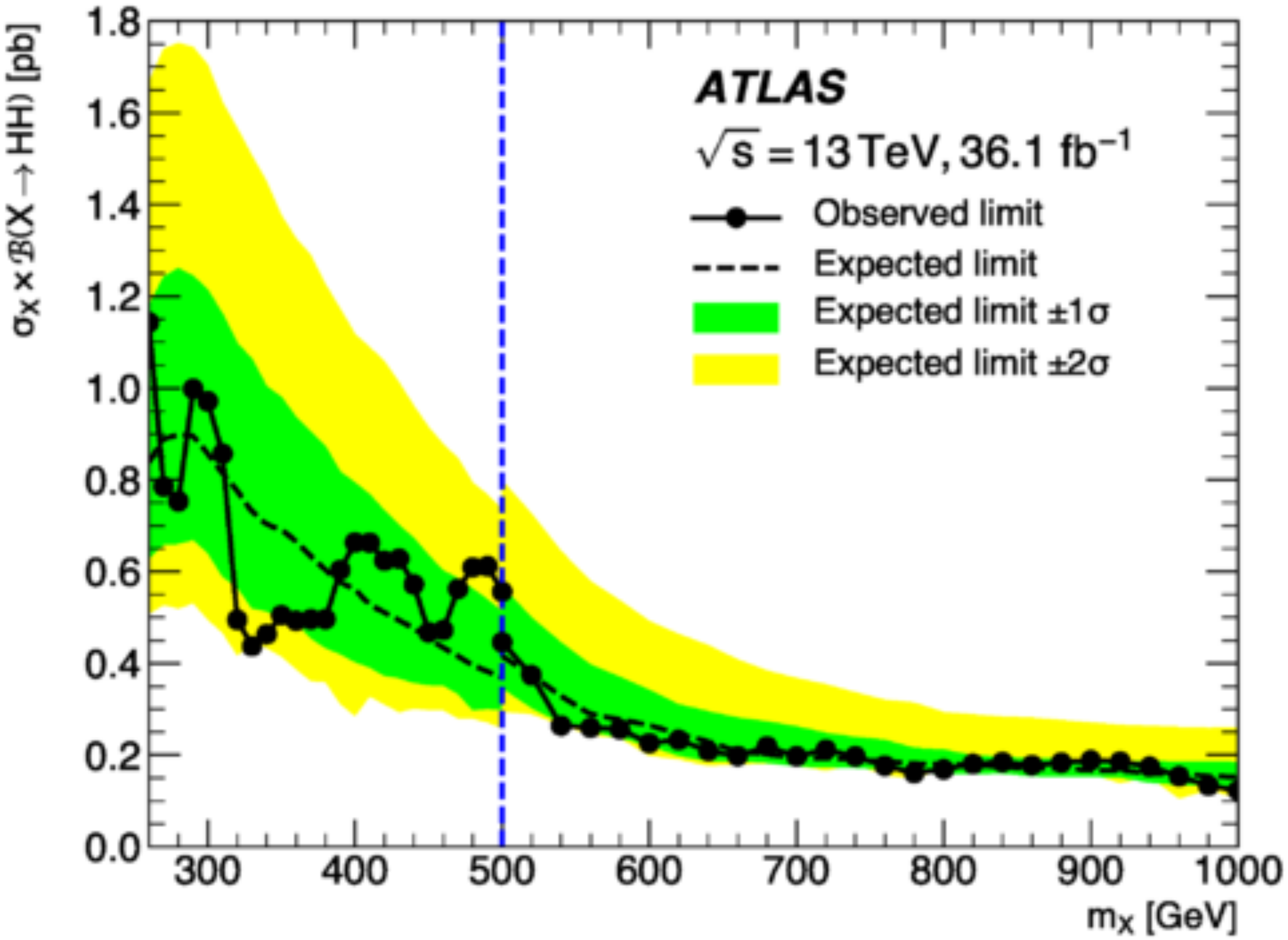
- Selection efficiency parameterised as a function of κ_λ for the interpretation
- κ_λ is observed (expected) to be constrained at 95% CL to $-8.2 < \kappa_\lambda < 13.2$ ($-8.3 < \kappa_\lambda < 13.2$)





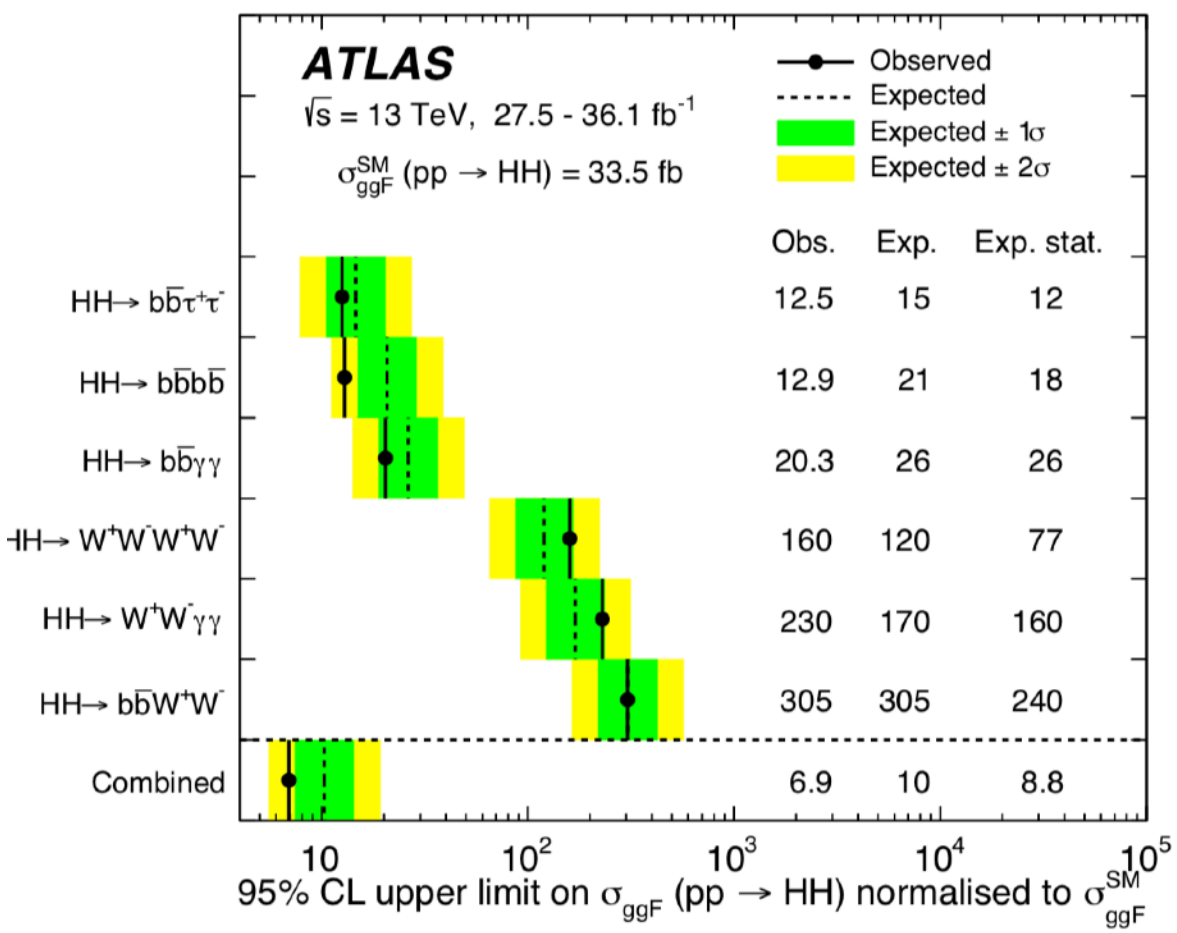
Results (resonant)

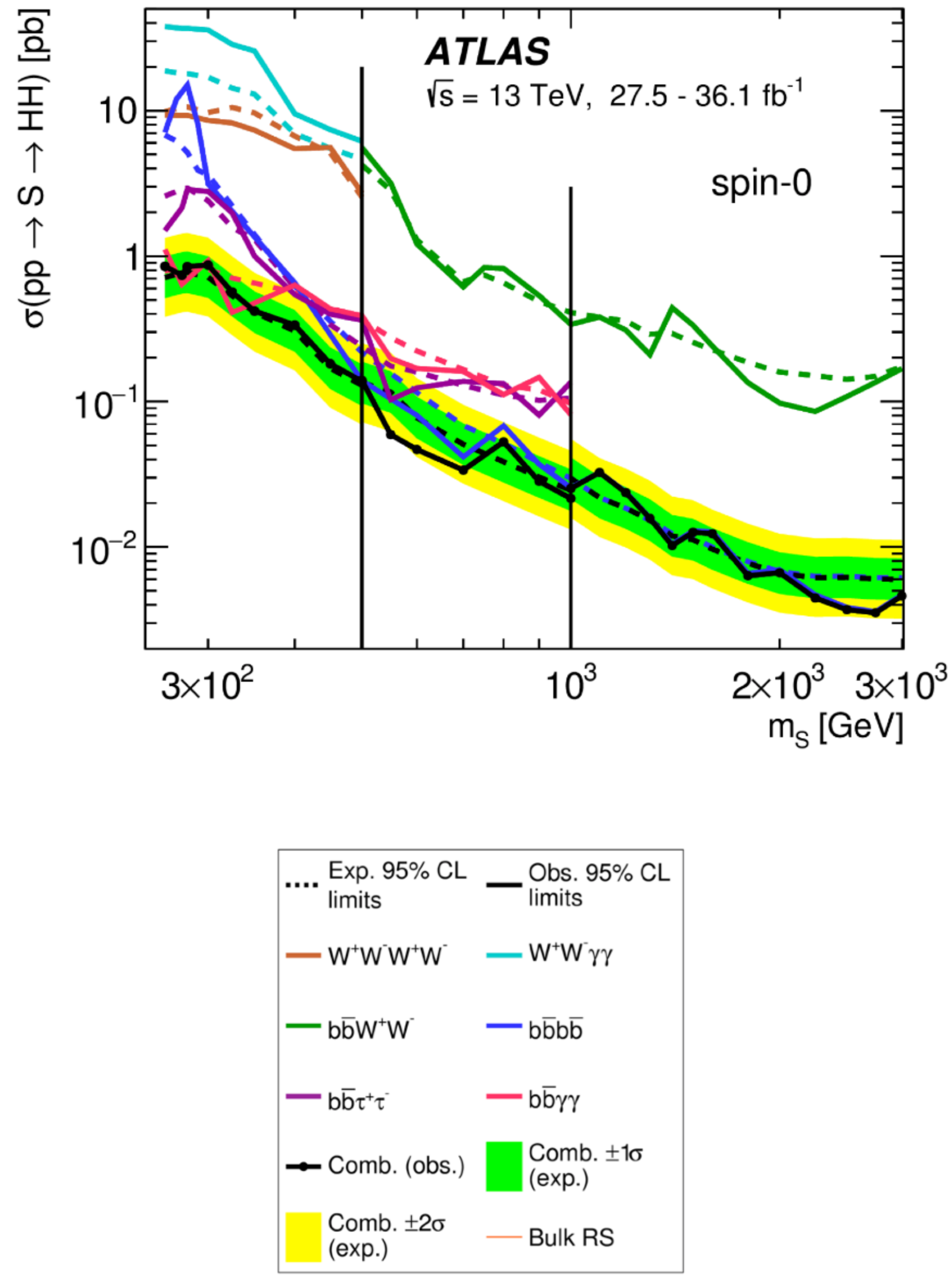
- Largest deviation from the background only hypothesis is 480 GeV (local significance of 1.2 σ)
  - No significant excesses observed
- Observed limits vary from 1.1 pb at M_X = 260 GeV to 0.12 pb at M_X = 1 TeV



HH Combination: arXiv:1906.02025

- ATLAS HH Combination sets an upper limit on the SM HH cross section of 6.9 * SM (10.0 * SM expected) and constrains the Higgs boson self-coupling to $-5.0 < \kappa\lambda < 12.0$
- HH → bbγγ is the 3rd most sensitive channel to SM HH production and the most sensitive channel for large BSM κλ modifications
- HH → bbγγ: best sensitivity to resonant masses less than 350 GeV





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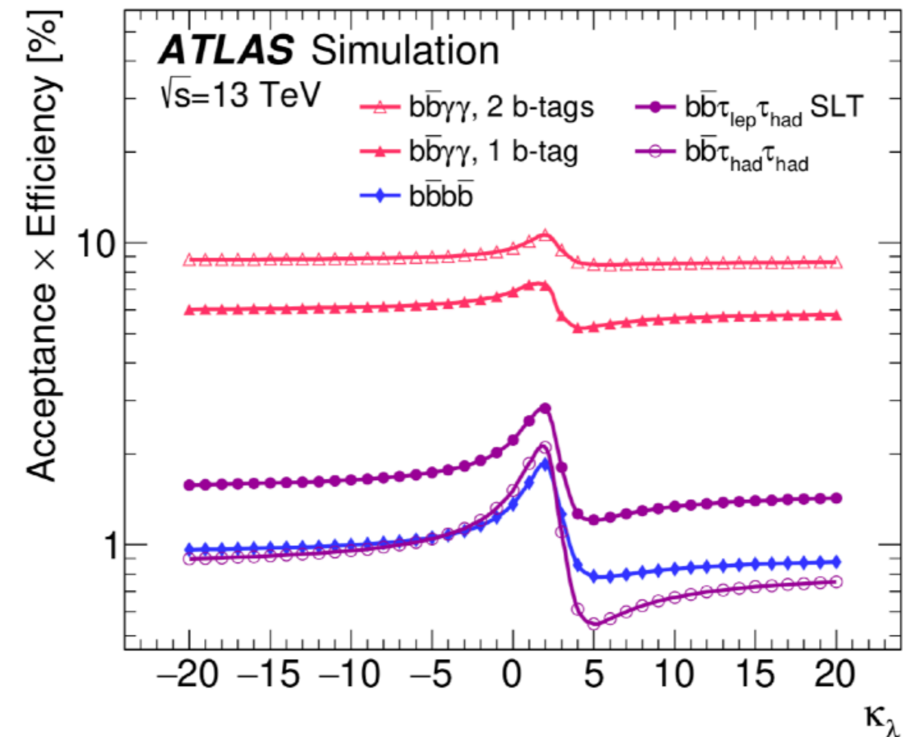
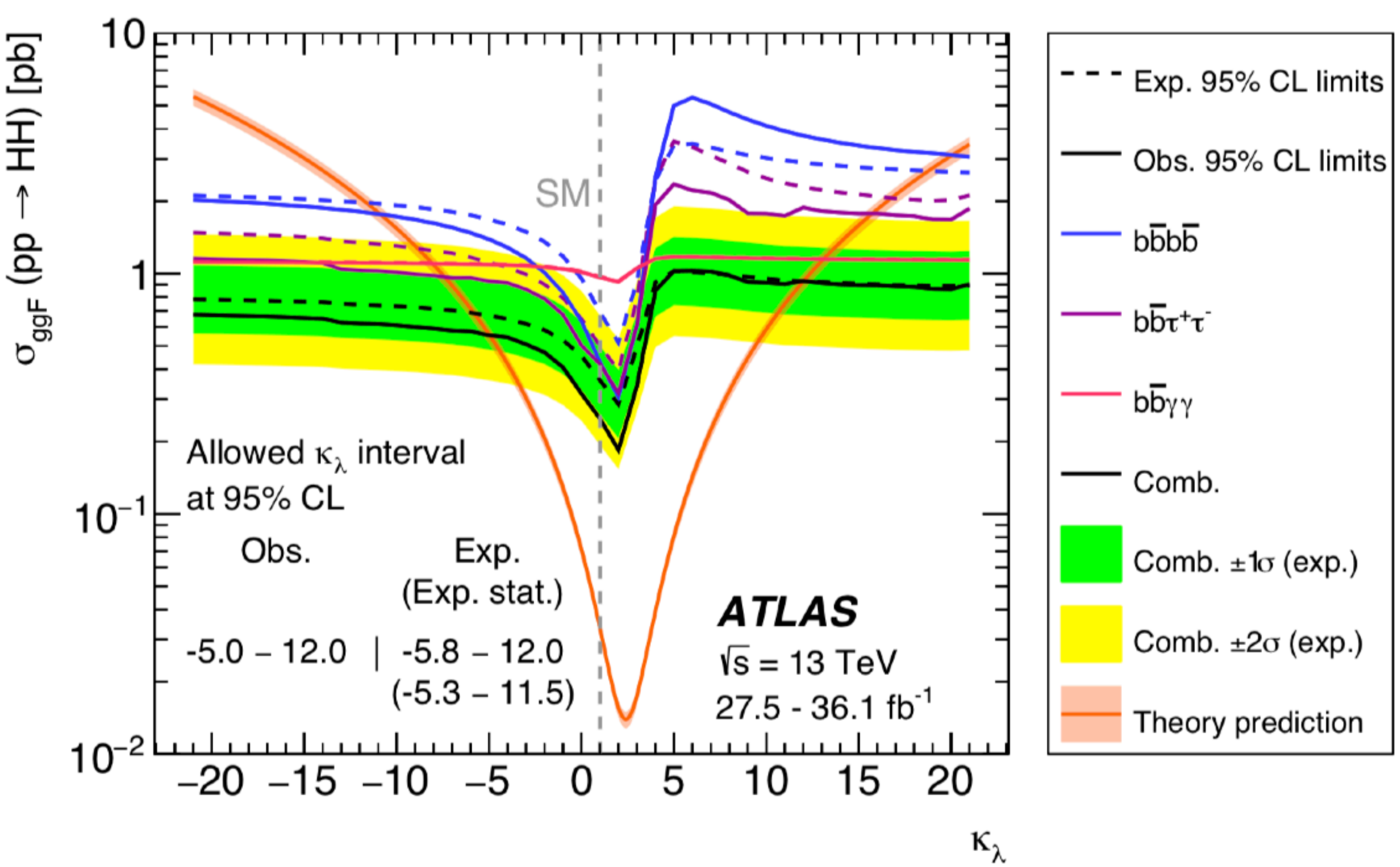


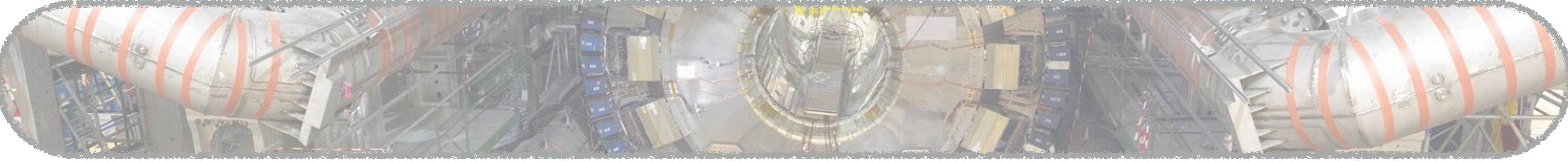


	Allowed κ_λ interval at 95% CL		
Final state	Obs.	Exp.	Exp. stat.
$b\bar{b}b\bar{b}$	−10.9 — 20.1	−11.6 — 18.8	−9.8 — 16.3
$b\bar{b}\tau^+\tau^-$	−7.4 — 15.7	−8.9 — 16.8	−7.8 — 15.5
$b\bar{b}\gamma\gamma$	−8.1 — 13.1	−8.1 — 13.1	−7.9 — 12.9
Combination	−5.0 — 12.0	−5.8 — 12.0	−5.3 — 11.5

Conclusions

- ATLAS has performed a search for HH in the bbγγ final state
- No significant excesses observed in either the non-resonant or resonant search
- Limits set in the non-resonant search:
  - $\sigma_{HH} = 22*\sigma_{SM}$
  - Higgs boson self-coupling constrained to be in the interval $-8.2 < \kappa_\lambda < 13.2$
- Limits in the resonant search range between 1.1 pb to 0.12 pb for $260 < M_X < 1000$ GeV
- Looking forward, ATLAS has now collected ~ 140 fb^{-1} of data
  - HH → bbγγ is statistically limited so can expect large sensitivity increase with the full Run 2 data set

Thank you!



Back-up Slides

Event Selection (2) and Yields

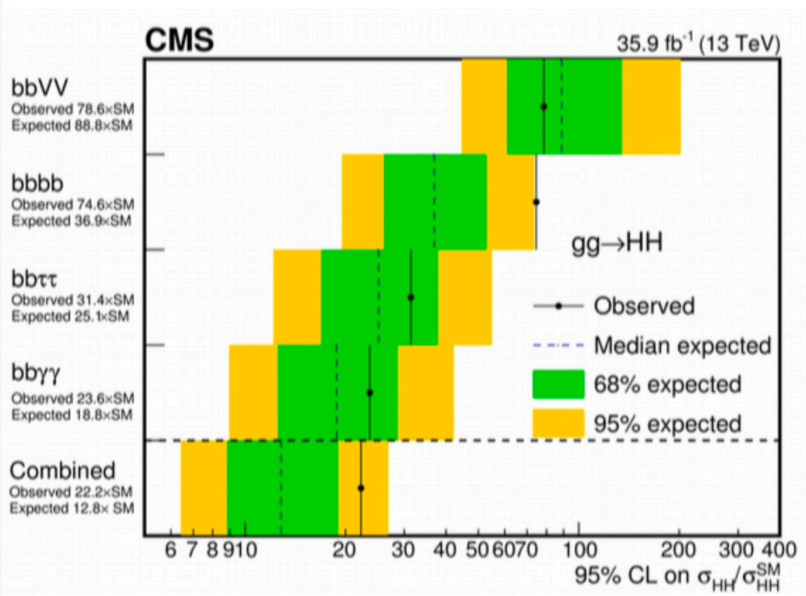
	Non-resonant				Resonant			
	1-tag		2-tag		1-tag		2-tag	
	Loose	Tight	Loose	Tight	Loose	Tight	Loose	Tight
$m_{\gamma\gamma}$ range [GeV]	105–160	105–160	105–160	105–160	120.39–129.79	120.79–129.39	120.39–129.79	120.79–129.39
Jet b-tagging WPs used	60% + BDT	60% + BDT	70%	70%	60% + BDT	60% + BDT	70%	70%
Leading jet p_T [GeV]	>40	>100	>40	>100	>40	>100	>40	>100
Subleading jet p_T [GeV]	>25	>105	>25	>30	>25	>30	>25	>30
m_{jj} range [GeV]	80–140	90–140	80–140	90–140	80–140	90–140	80–140	90–140

	1-tag		2-tag	
	Loose selection	Tight selection	Loose selection	Tight selection
Continuum background	117.5 ±4.7	15.7 ± 1.6	21.0 ± 2.0	3.74 ± 0.78
SM single-Higgs-boson background	5.51 ±0.10	2.20 ± 0.05	1.63 ± 0.04	0.56 ± 0.02
Total background	123.0 ±4.7	17.9 ± 1.6	22.6 ± 2.0	4.30 ± 0.79
SM Higgs boson pair signal	0.219±0.006	0.120± 0.004	0.305± 0.007	0.175± 0.005
Data	125	19	21	3

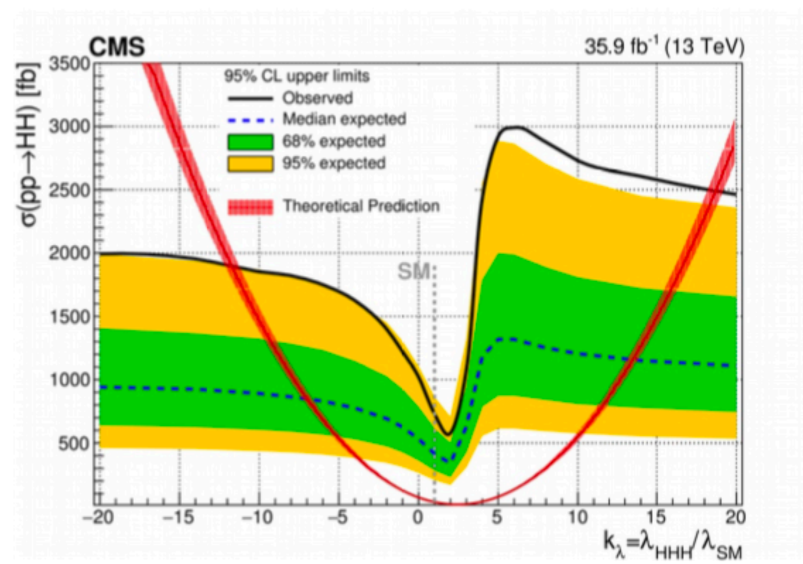
HH searches in CMS

Link to the paper

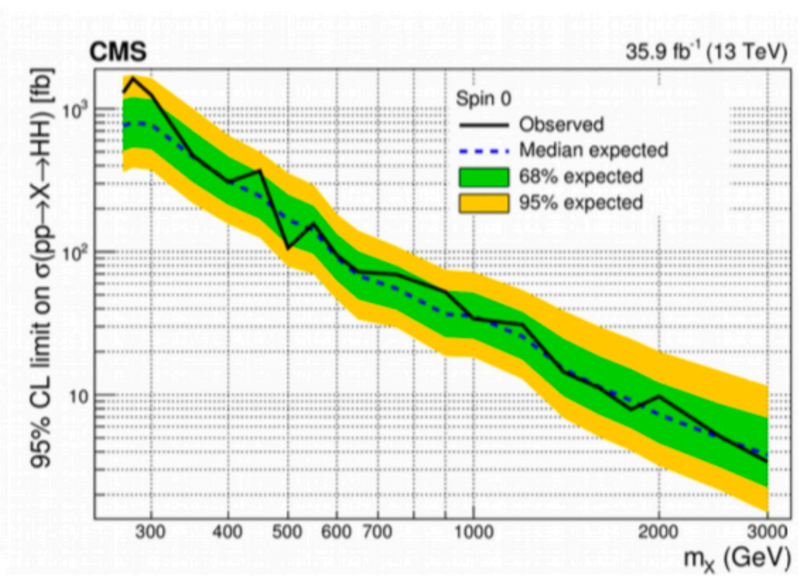
- CMS result on HH search includes the bbγγ, bbττ, bbbb, and bbVV channels, where V represents a W or Z boson
- For the non-resonant production mechanism, the observed (expected) 95% C.L. corresponds to 22.2 (12.8) times the theoretical prediction for the standard model cross section
  - Expected limits similar between ATLAS and CMS: 10 vs 12.8 times SM prediction respectively
- Values of k_λ in the range $-11.8 < k_\lambda < 18.8$ are still allowed (95% C.L.) by the observed data
- For the resonant production mechanism, upper exclusion limits at 95% C.L. are obtained for the production of a narrow resonance with mass ranging from 250 to 3000 GeV (for either spin-0 and spin-2 resonances)



Non-resonant analysis
Observed limit 22.2



Non-resonant analysis
$-11.8 < k_\lambda < 18.8$



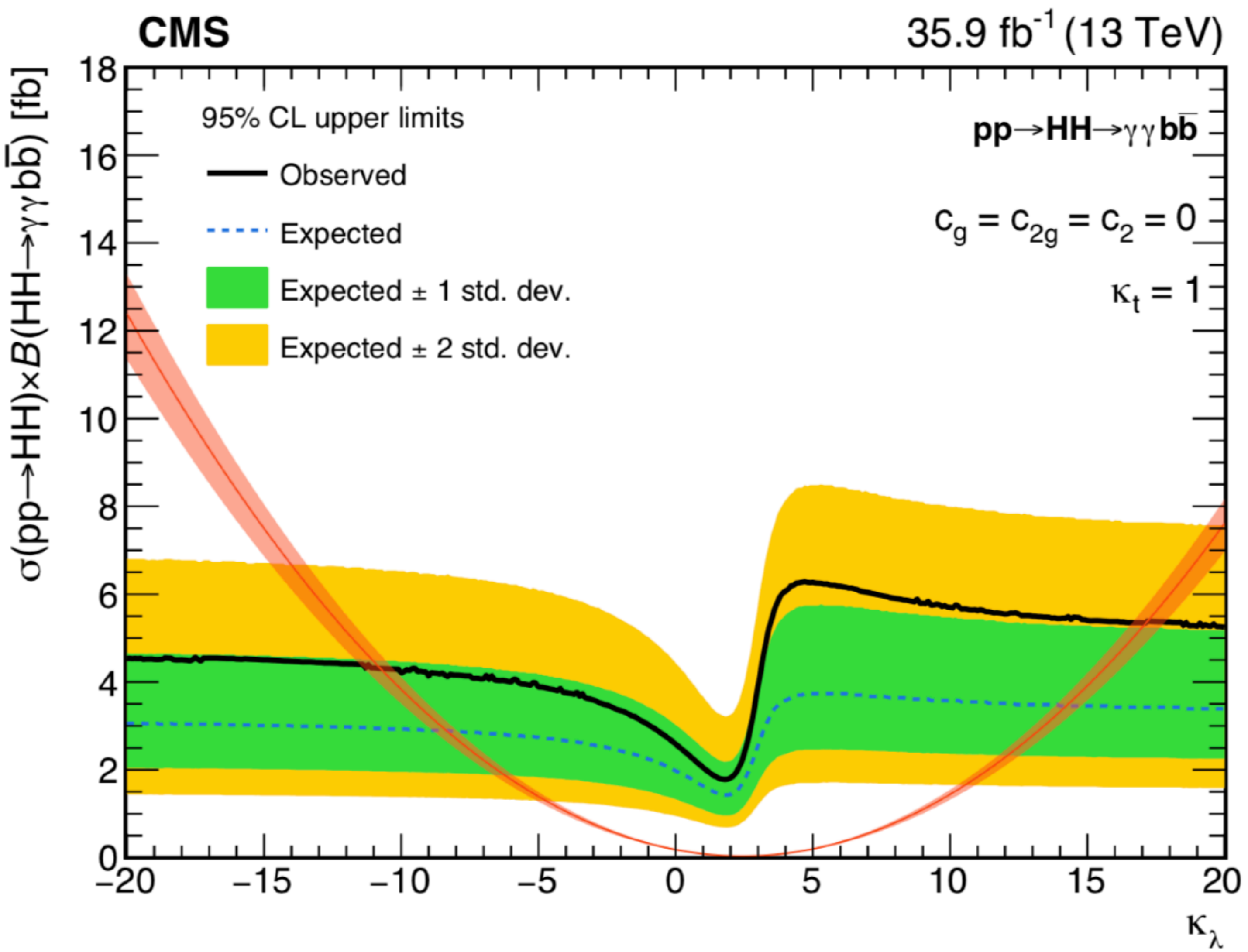
Resonant analysis
Spin 0 hypothesis

HHγγbb searches in CMS

Non Resonant Searches

The observed (expected) 95% CL upper limits on the SM-like pp $\to$ HH $\to$ $\gamma\gamma b\bar{b}$ process are 2.0 (1.6 fb); 0.79 (0.63 pb) for the total ggHH production cross section assuming SM Higgs boson branching fractions. The results can also be interpreted in terms of observed (expected) upper limits on μ_{HH} of 24 (19). This is the most stringent constraint to date from the LHC. In particular, the constraint on μ_{HH} improves over the previous search by a factor of three [23].

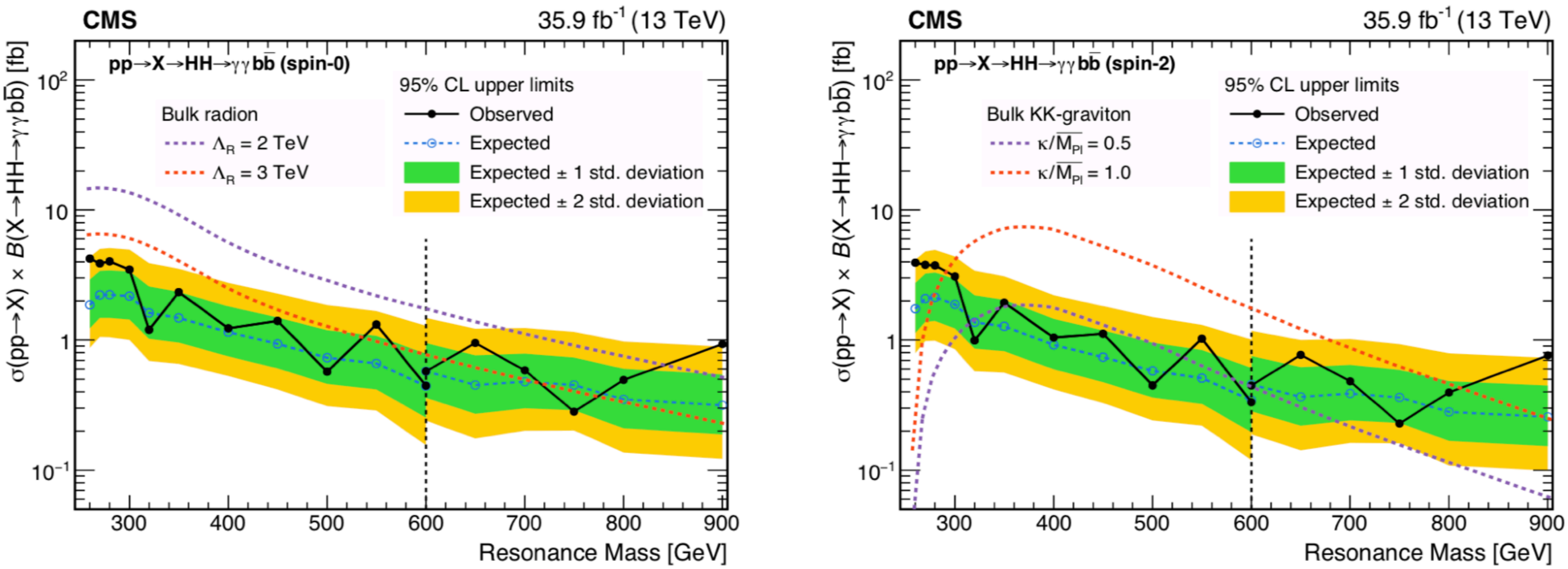
Link to the paper



HHγγbb searches in CMS

Resonant Searches

The observed and median expected upper limits at 95% confidence level (CL) are shown in Fig. 9, for the pp $\rightarrow$ X $\rightarrow$ HH $\rightarrow$ $\gamma\gamma b\bar{b}$ process assuming spin-0 and a spin-2 resonances. The data exclude a cross section of 0.23 to 4.2 fb depending on m_X and the spin hypothesis.



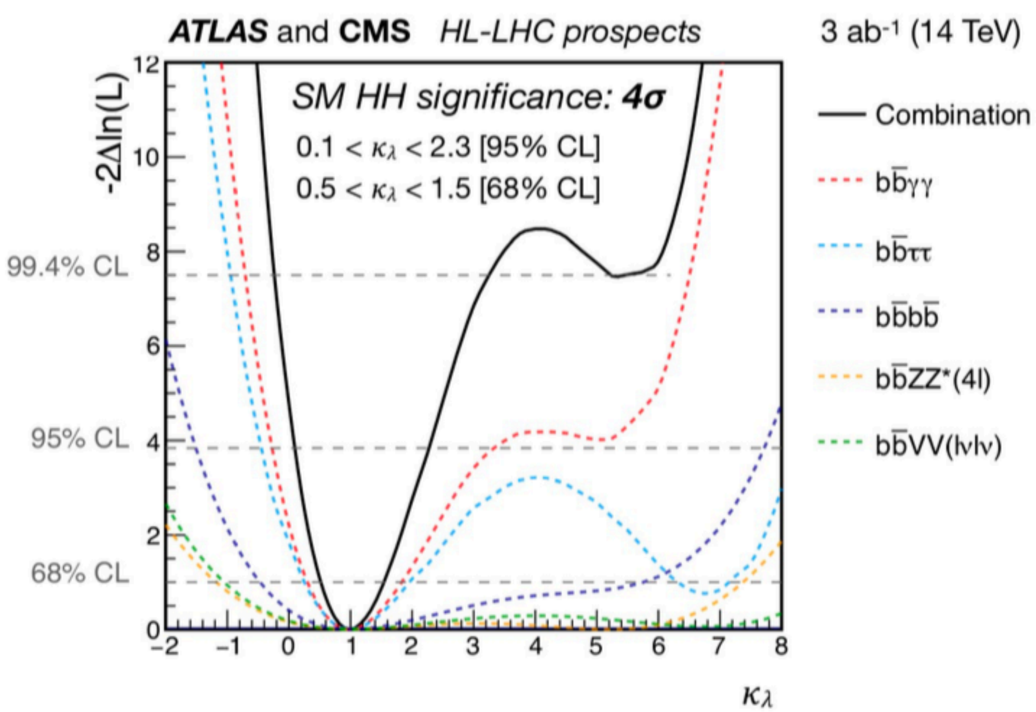
Link to the paper

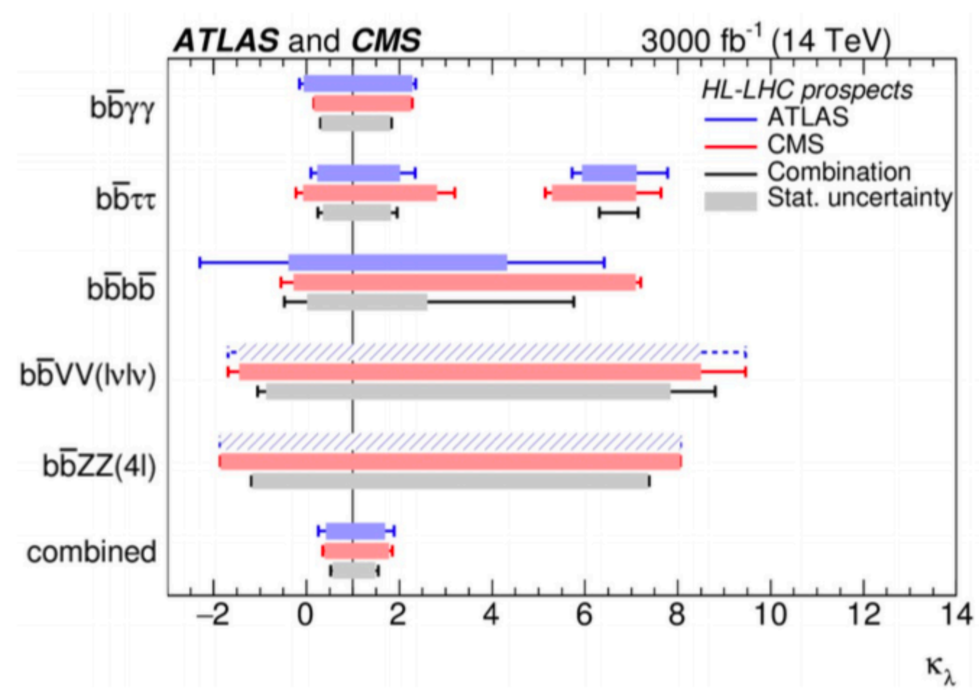
HH Prospects at HL-LHC

	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \to b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6
	Combined 4.5		Combined 4.0	

Link to the paper

- Expected significance of the di-Higgs search for each individual channels as well as their combination with 3000 fb^{-1}





- 95% CL expected limit on λ/λ_{SM}:
  [-0.18,3.6] for CMS
  [-0.40,7.3] for ATLAS
  [0.1,2.3] for the combination
- Second minimum of the likelihood is excluded at 99.4% CL
- Expected a measurement of κ_λ at 50%, if HH is observed with a significance of 4σ

Auxiliary Material, mHH