Angela Burger
LPC
On behalf of the ATLAS collaboration
34th Rencontres de Blois 2023
17/05/2023

Probing the nature of electroweak symmetry breaking with Higgs boson pairs in ATLAS

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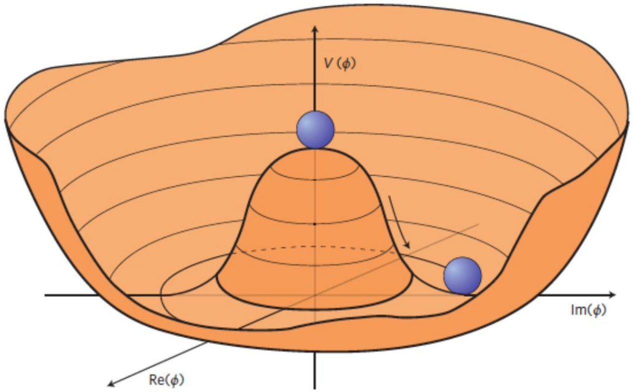
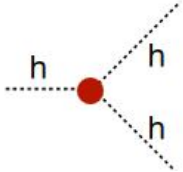
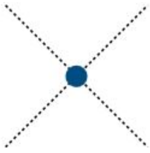
Motivation - The Higgs boson

- After discovery of the Higgs boson, measure properties of the Higgs boson, like (self-)coupling(s)
- Higgs boson self-coupling measurement probes Higgs potential shape



$$V(h) = \frac{1}{2}m_h^2 h^2 + \lambda_3 \nu h^3 + \frac{1}{4}\lambda_4 h^4$$





- Measurement of HH production sensitive to Higgs self-coupling λ_3 (coupling modifier κ_λ)

$$\kappa_\lambda = \frac{\lambda_3}{\lambda_3^{SM}}$$

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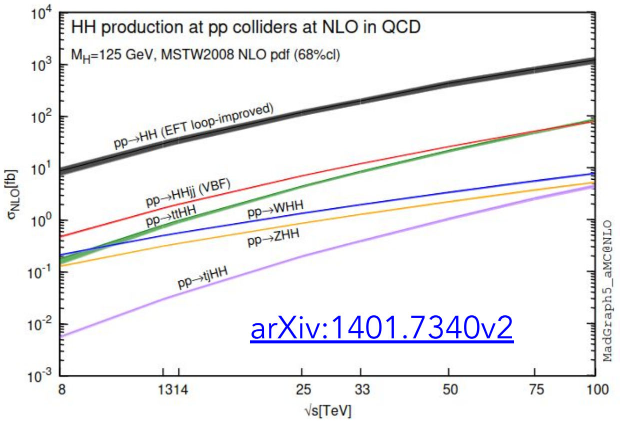
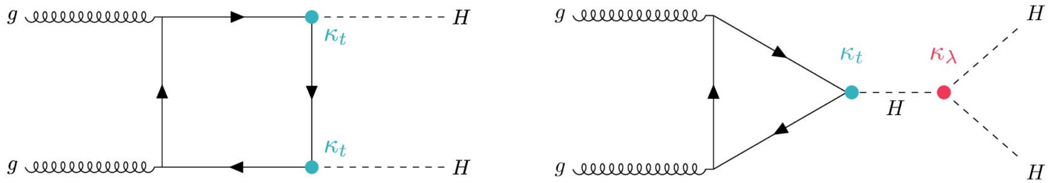
Motivation - HH Production & Couplings

- Current HH searches consider two production modes:
  - gluon-gluon fusion (ggF) & vector-boson fusion (VBF)
  - Different couplings involved (κ_λ: HHH, κ_t: Htt, κ_V: HVV, κ_{2V}: VVHH)



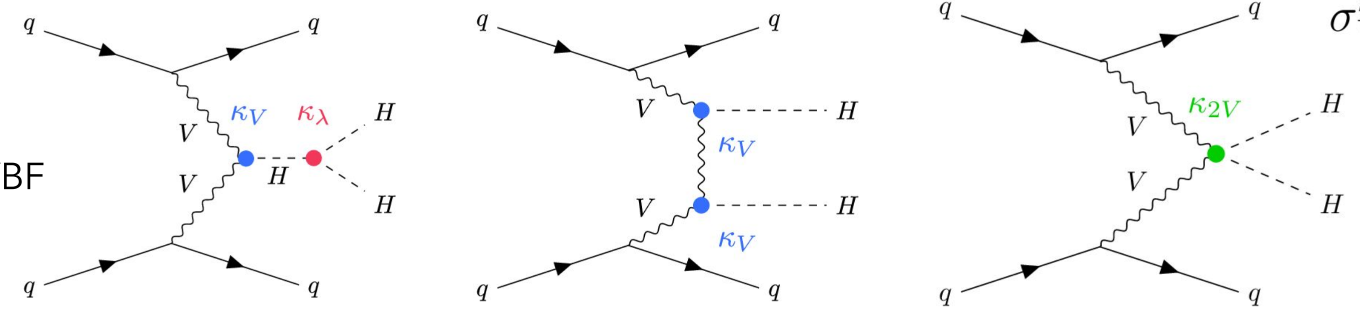
ggF



$$\sigma^{SM}_{ggF} = 31.05 \text{ fb } (NNLO)$$

destructive interference between two diagrams ⇒ cross-section ~1000x lower than single H production (out of reach for Run-2 assuming Standard Model (SM))

VBF



$$\sigma^{SM}_{VBF} = 1.72 \text{ fb } (N3LO)$$

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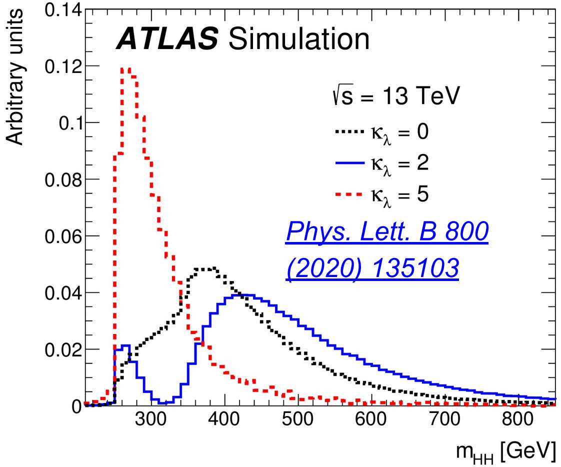
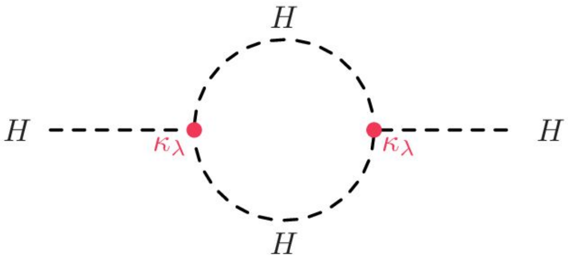
Motivation - HH Production & Couplings

- Production cross-sections and kinematic distributions, like m_{HH}, sensitive to self-coupling





- Additional constraints on the Higgs self-coupling from single-Higgs production through NLO EW corrections

Introduction

- Huge effort in ATLAS to constrain di-Higgs production and self-coupling with many signatures to increase sensitivity in combination
- $HH \rightarrow bb\gamma\gamma$, $HH \rightarrow bb\tau\tau$, $HH \rightarrow bbbb$ most sensitive channels

	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

- Present latest results in these three channels using full Run-2 ATLAS data (2015-2018):
  - HH production cross section limits
  - Constraints on Higgs self-coupling
  - Interpretations in terms of effective field theory parameterisations (SMEFT and HEFT)
  - Extrapolation to HL-LHC
  - $139 fb^{-1}$ of data, for $HH \rightarrow bbbb$: $126 fb^{-1}$

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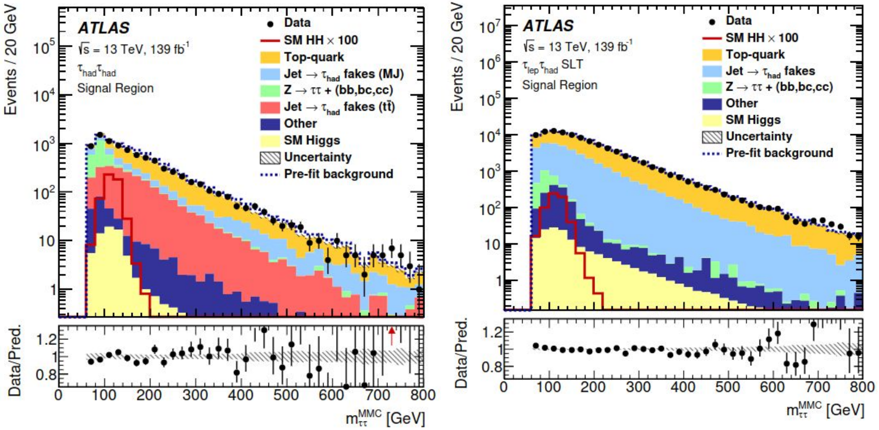
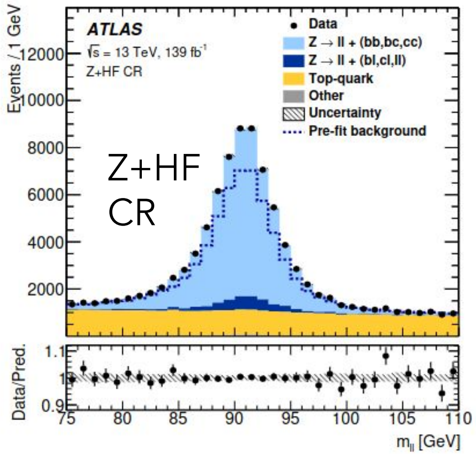
arXiv:2209.10910

HH → bbττ: Analysis strategy

- Events with 2 hadronic taus ($\tau_{had}+\tau_{had}$) and hadronic+ leptonic tau: $\tau_{had}+\tau_{lep}$
- Main features of selection:
  - ==2 b-tagged jets
  - $\tau_{had}+\tau_{had}$
    - ==2 oppositely charged τ_{had}
    - No leptons
  - $\tau_{had}+\tau_{lep}$:
    - ==1 electron (e) OR muon (mu)
    - ==1 τ_{had} opposite charge to e, mu
- Background
  - fake τ_{had} background (ttbar and multijet): semi-data driven methods
  - True τ_{had} background: simulation
  - Normalization of ttbar and Z+jets constrained in combined fit in Z+heavy flavour (HF) control region



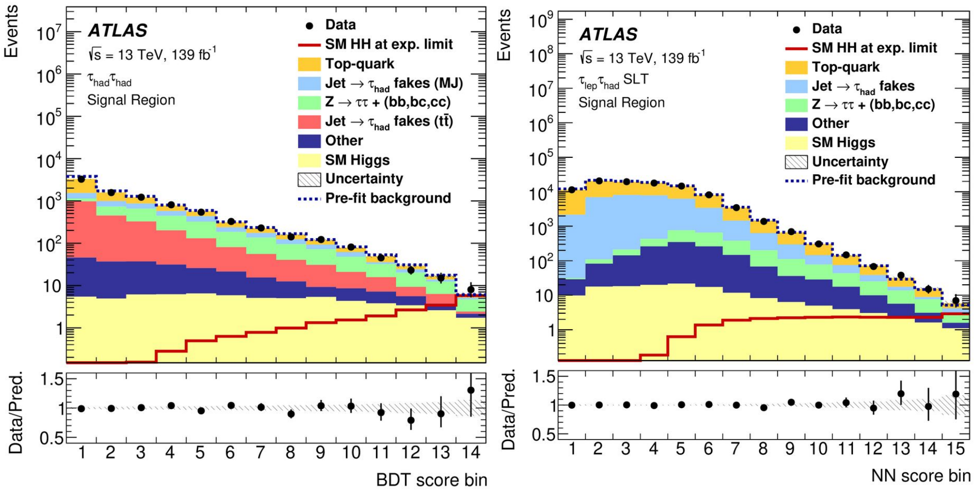
di-τ invariant mass



HH → bbττ: Analysis strategy

arXiv:2209.10910

- Analysis strategy:
  - Multivariate discriminant:
    - $\tau_{had}+\tau_{had}$: BDT
    - $\tau_{had}+\tau_{lep}$: Neural Network
  - Simultaneous binned maximum likelihood fit to all analysis category signal regions and Z+HF CR
- Analysis limited by statistical uncertainty of data in signal region



HH → bbττ: Results

Observed & expected 95% CL upper limits for non-resonant HH production cross-section

arXiv:2209.10910

Channel	$\sigma_{ggF+VBF}/\sigma^{SM}_{ggF+VBF}$ (Observed)	$\sigma_{ggF+VBF}/\sigma^{SM}_{ggF+VBF}$ (Expected)
$\tau_{had}\tau_{had}$	5.0	$4.4^{+1.7}_{-1.2}$
$\tau_{lep}\tau_{had}$	9.7	$7.8^{+3.2}_{-2.2}$
Combined	4.7	$3.9^{+1.5}_{-1.1}$

Previous ATLAS results with $36 fb^{-1}$: Phys. Rev. Lett. 121, 191801

Final state	Obs. 95% CL	Exp. 95% CL	Obs. value$^{+1\sigma}_{-1\sigma}$
$HH \to b\bar{b}\tau^+\tau^-$	$-2.7 < \kappa_\lambda < 9.5$	$-3.1 < \kappa_\lambda < 10.2$	$\kappa_\lambda = 1.5^{+5.9}_{-2.5}$

arXiv:2211.01216

Limits on non-resonant HH cross section improves w.r.t previous ATLAS result by factor of 4: increased data set (factor 2) and improvements in τ and b-jet reconstruction & identification

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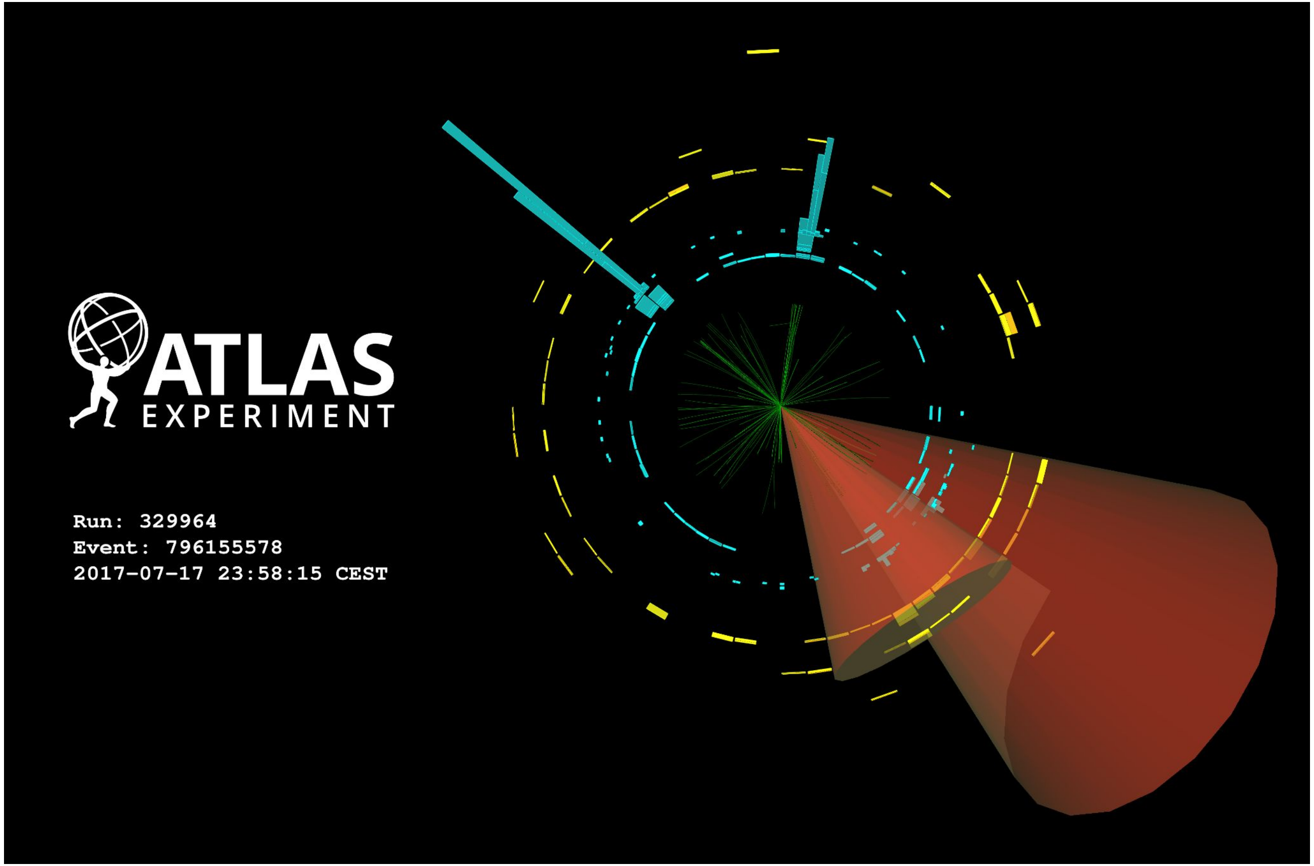
HH → bbγγ: Event display

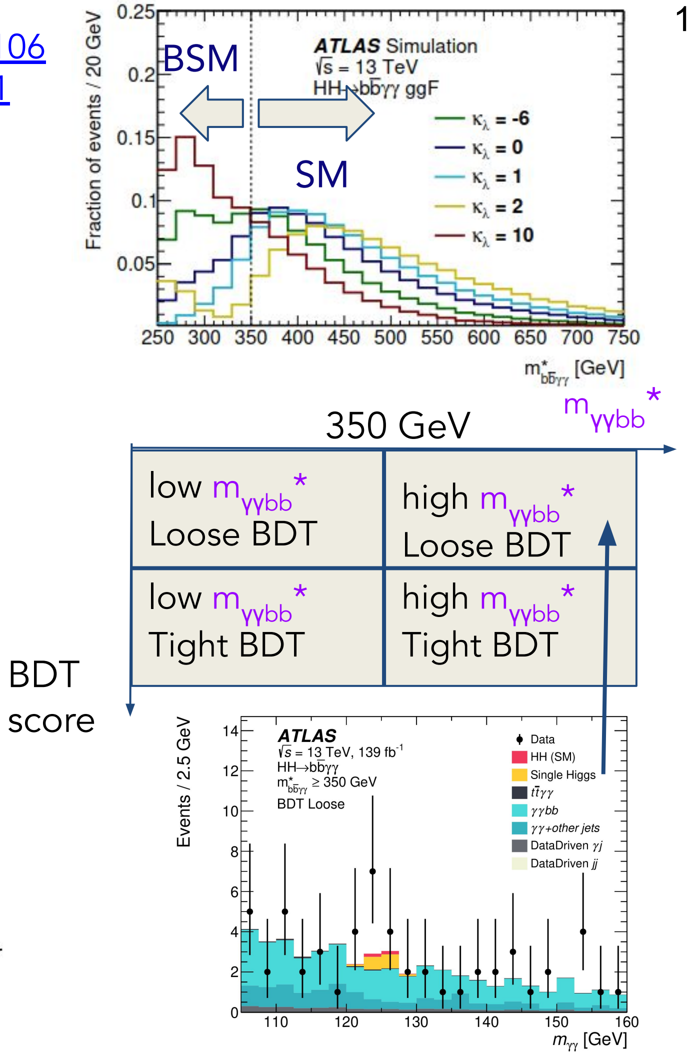


HH → bbγγ: Analysis strategy

[Phys. Rev. D 106 (2022) 052001]

- Low branching ratio but low background and good H → γγ mass resolution
- Main features of selection:
  - No leptons
  - N(jets)<=6 (reject ttH with ttbar to hadrons)
  - N(b-tagged) ==2
  - N(γ) >= 2
  - 105 < m(γγ) < 160 GeV
    - Signal Region: 120 < m(γγ) < 130 GeV
    - data sideband to constrain background
  - BDT to enhance signal over background
  - Two regions in corrected m(γγbb) ($m_{\gamma\gamma bb}^{*}$)

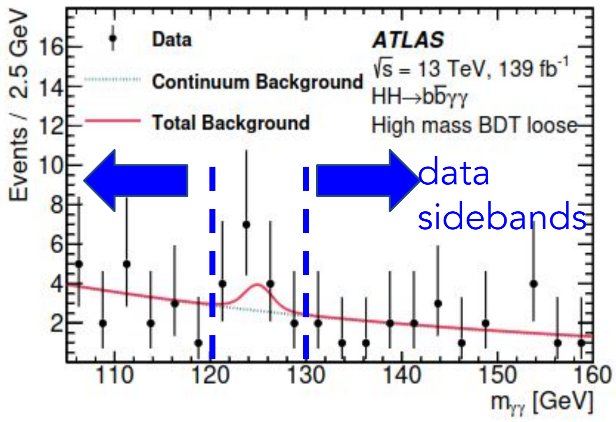
$$m^{*}_{bb\gamma\gamma} = m_{bb\gamma\gamma} - m_{bb} - m_{\gamma\gamma} + 250\ \mathrm{GeV}$$



HH → bbγγ: Analysis strategy

Phys. Rev. D 106 (2022) 052001

- Analysis strategy:
  - Determine functional form in highly populated MC template and normalize in m(γγ) data sideband
  - Model HH and single Higgs background with Crystal Ball function (fixed width, floating normalization)
  - Combined maximum likelihood fit to m(γγ) to all regions
- Analysis sensitivity limited by statistical precision
- Largest systematic uncertainties on choice of functional form for continuum background (spurious signal)



Source	Type	Relative impact of the systematic uncertainties [%] Nonresonant analysis HH	Resonant analysis $m_X = 300$ GeV
Experimental			
Photon energy resolution	Norm. + Shape	0.4	0.6
Jet energy scale and resolution	Normalization	< 0.2	0.3
Flavor tagging	Normalization	< 0.2	0.2
Theoretical			
Factorization and renormalization scale	Normalization	0.3	< 0.2
Parton showering model	Norm. + Shape	0.6	2.6
Heavy-flavor content	Normalization	0.3	< 0.2
$\mathcal{B}(H \to \gamma\gamma, b\bar{b})$	Normalization	0.2	< 0.2
Spurious signal	Normalization	3.0	3.3

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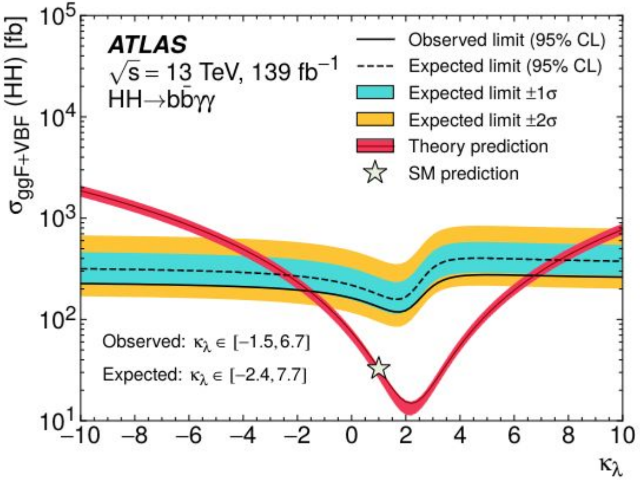
HH → bbγγ: Results

[Phys. Rev. D 106 (2022) 052001]



Previous ATLAS results ($36fb^{-1}$): [JHEP11(2018)040]

- Observed (expected) 95% CL limit on signal strength of 4.2 (5.7) x SM
- Observed limit on coupling modifier $\kappa_\lambda \in [-1.5,6.7]$

- Categorization in $m_{\gamma\gamma bb}^*$, multivariate event selection, better object reconstruction and calibration ⇒ increase sensitivity beyond expected by increase of dataset
- Non-resonant HH cross-section limits w.r.t partial Run-2 result improved by factor 5

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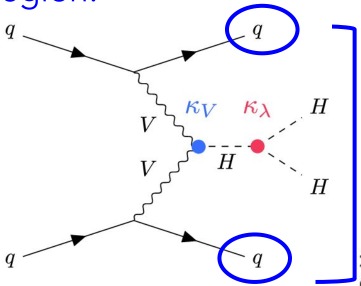
HH → bbbb: Analysis strategy

[arXiv:2301.03212]

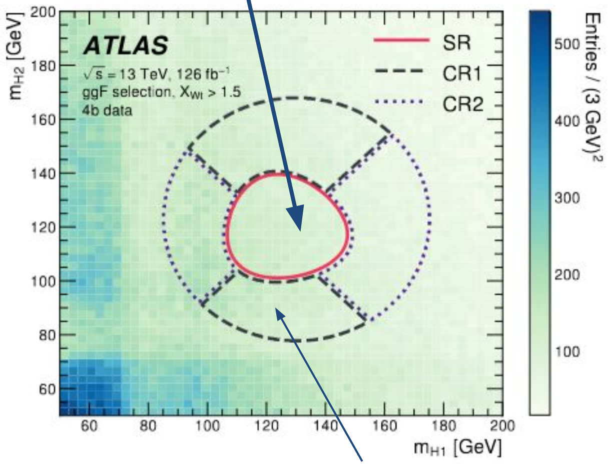
$$X_{HH} = \sqrt{\left(\frac{m_{H1} - 124\ \text{GeV}}{0.1\ m_{H1}}\right)^2 + \left(\frac{m_{H2} - 117\ \text{GeV}}{0.1\ m_{H2}}\right)^2} < 1.6$$

- Br(HH → bbbb) ~ ⅓ , large background from QCD production
- Regions specialized to ggF and VBF
- Main features of selection
  - >= 4 b-tagged jets ⇒ Higgs candidates
  - Additional cuts reject top quarks and enrich in HH signal (e.g. X_{HH})
  - Additional selection for VBF region:

+ >= 2 (non-btagged) jets
(largest invariant mass mjj)

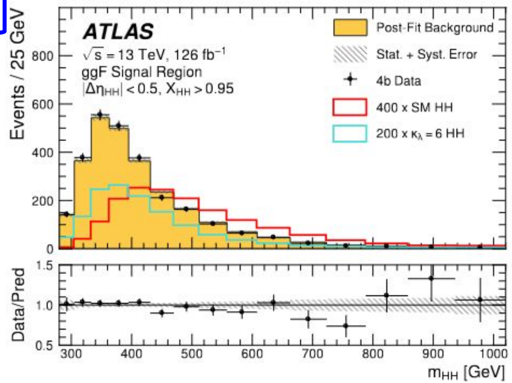


large mjj & pseudo-rapidity separation



sidebands to determine background reweighting

- Background estimation:
  - Reweight distributions in a N(b-tagged)==2 region to 4 b-jet region using Neural Network
  - Nominal and systematics of reweighting determined in Higgs candidates mass plane (m_{H1} vs. m_{H2}) in sidebands
- Combined maximum likelihood fit combined fit to m_{HH}



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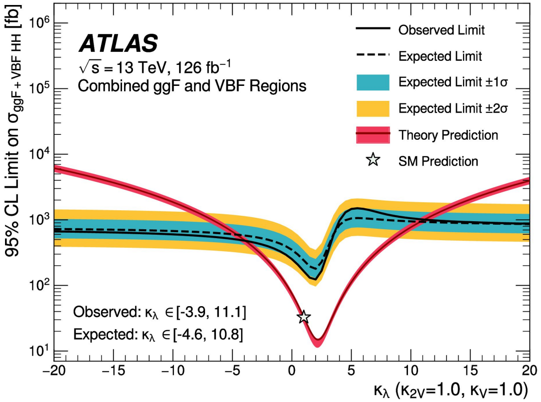
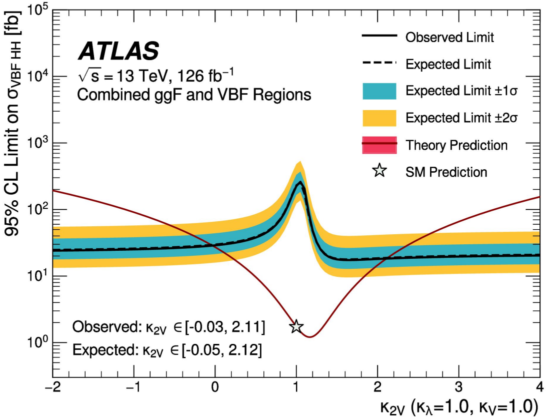
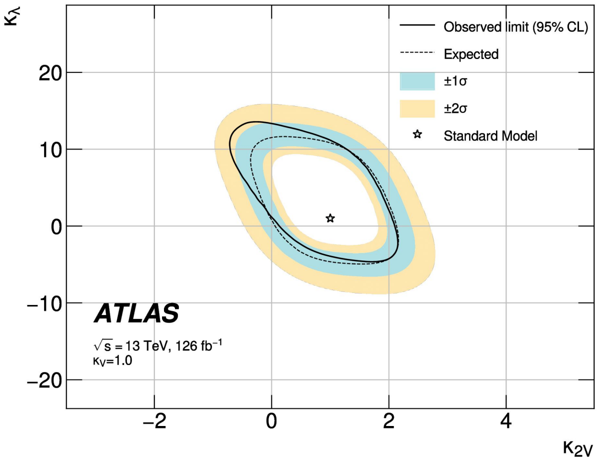
HH → bbbb: Results

arXiv:2301.03212

	Observed Limit	-2σ	-1σ	Expected Limit	$+1\sigma$	$+2\sigma$
μ_{ggF}	5.5	4.4	5.9	8.2	12.4	19.6
μ_{VBF}	130	70	100	130	190	280
$\mu_{ggF+VBF}$	5.4	4.3	5.8	8.1	12.2	19.1







- Upper limits on signal strength (ggF, VBF & combined)
- Limits on coupling modifiers (κ_λ,κ_{2V}): 1D & 2D

Previous results:
ggF (27fb^{-1}): JHEP01(2019)030
VBF (126fb^{-1}): JHEP07(2020)108

- ggF production limits improved by factor 2 ⇒ 20% from advances in analysis techniques (background estimation) and object reconstruction (jets & b-tagging)
- VBF production cross section limit over 75% lower, entirely from analysis strategy and object reconstruction

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HH couplings in SMEFT and HEFT

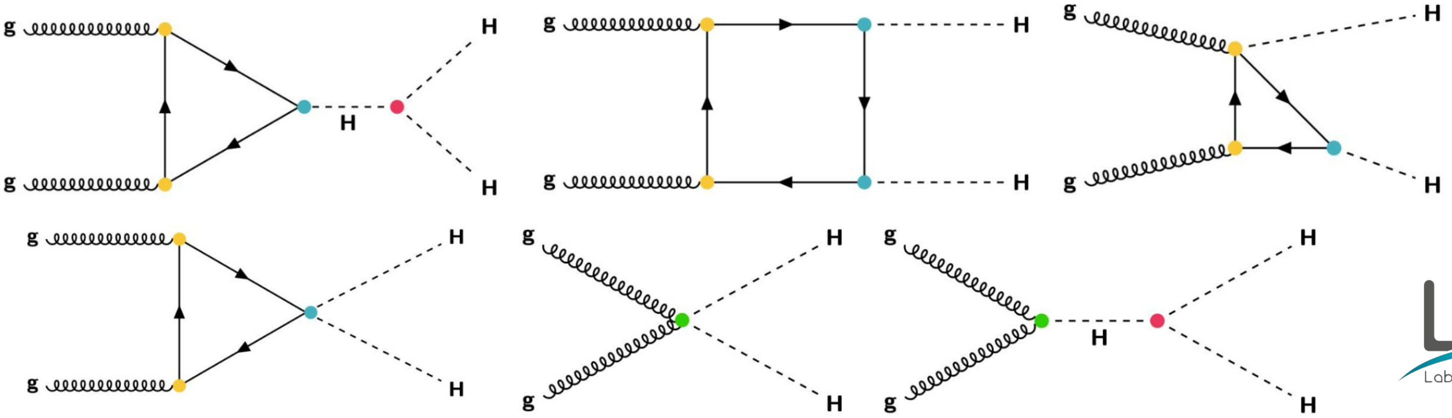
- Constraints derived in terms if Effective Field theory (EFT) parameterization:
- SM EFT (SMEFT):

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2} \sum_k c_k^{(6)} O_k^{(6)}$$

Effective Lagrangian — SM — mass scale of NP — Wilson coefficient (=0 in SM) — dimension-six operators

Wilson Coefficient	Operator
c_H	$(H^\dagger H)^3$
$c_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
c_{tH}	$(H^\dagger H)(\bar{Q}\tilde{H}t)$
c_{HG}	$H^\dagger H G^A_{\mu\nu} G^{\mu\nu}_A$
c_{tG}	$(\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{H}G^A_{\mu\nu}$

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + c_H(H^\dagger H)^3 + c_{H\Box}(H^\dagger H)\Box(H^\dagger H) + c_{tH}(H^\dagger H)(\bar{Q}\tilde{H}t) + c_{HG}H^\dagger H G^A_{\mu\nu} G^{\mu\nu}_A + c_{tG}(\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{H}G^A_{\mu\nu}$$



$c_i = 0$ in Standard Model

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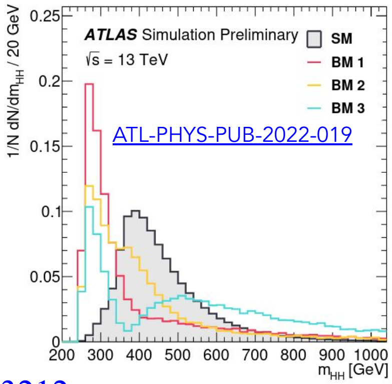
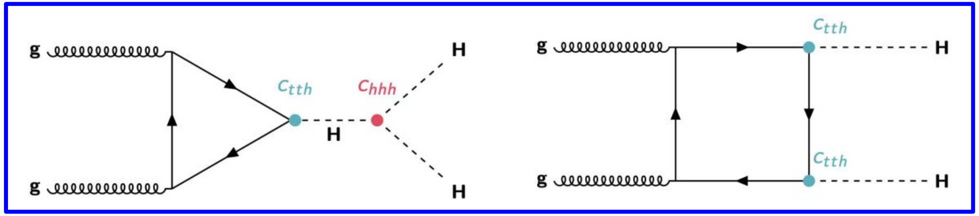
HH couplings in SMEFT and HEFT

- Constraints derived in terms if Effective Field theory (EFT) parameterization:
- Higgs EFT (HEFT):
  - 5 Wilson coefficients describe ggF HH: $c_{hhh} = \kappa_\lambda$ and $c_{tth} = \kappa_t$, others BSM (c_i =0 in SM)
  - Separate treatment of H and HH couplings
  - Change in couplings change diagram contribution and interference ⇒ modify di-Higgs invariant mass spectrum m_{HH}
  - Set limits on benchmark models and c_{tthh} and c_{gghh}

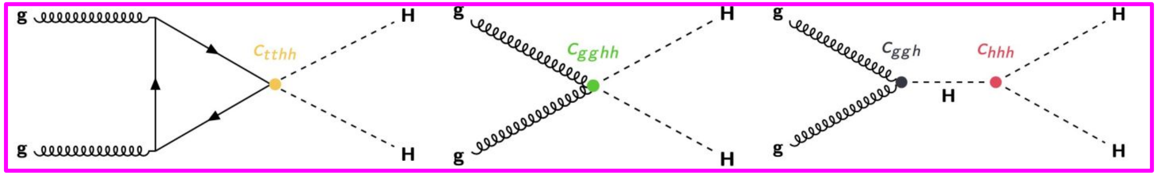




SM (4 dim.)

arXiv:2301.03212

Benchmark Model	c_{HHH}	c_{ttH}	c_{ggH}	c_{ggHH}	c_{ttHH}
SM	1	1	0	0	0
BM1	3.94	0.94	1/2	1/3	−1/3
BM2	6.84	0.61	0.0	−1/3	1/3
BM3	2.21	1.05	1/2	1/2	−1/3
BM4	2.79	0.61	−1/2	1/6	1/3
BM5	3.95	1.17	1/6	−1/2	−1/3
BM6	5.68	0.83	−1/2	1/3	1/3
BM7	−0.10	0.94	1/6	−1/6	1



BSM (6 dim.)

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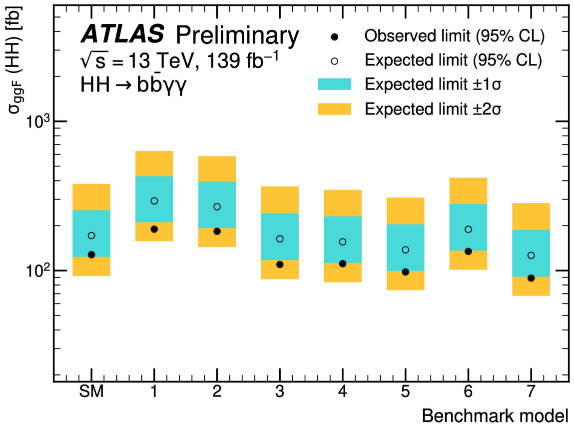
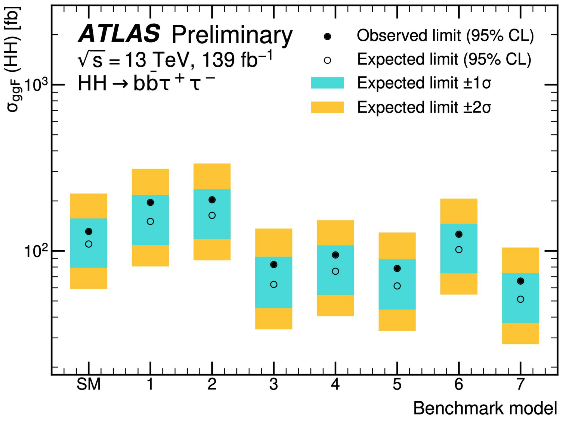
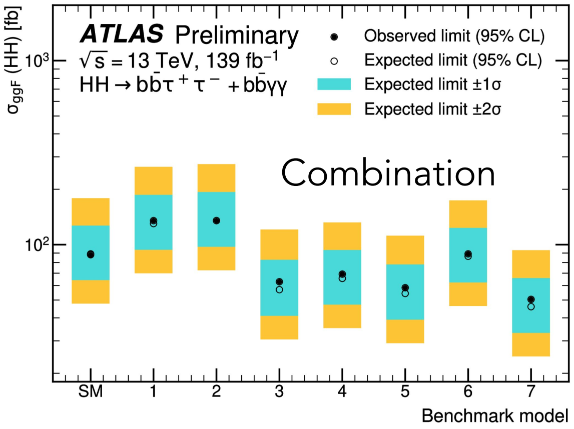
HEFT interpretations of HH → bbγγ and HH → bbττ & combination

HEFT Benchmark Models limits:

ATL-PHYS-PUB-2022-019







Wilson coefficient	$b\bar{b}\gamma\gamma$ Obs.	$b\bar{b}\gamma\gamma$ Exp.	$b\bar{b}\tau^+\tau^-$ Obs.	$b\bar{b}\tau^+\tau^-$ Exp.	Combination Obs.	Combination Exp.
c_{gghh}	$[-0.4, 0.5]$	$[-0.5, 0.7]$	$[-0.4, 0.4]$	$[-0.4, 0.4]$	$[-0.3, 0.4]$	$[-0.3, 0.3]$
c_{tthh}	$[-0.3, 0.8]$	$[-0.4, 0.9]$	$[-0.3, 0.7]$	$[-0.2, 0.6]$	$[-0.2, 0.6]$	$[-0.2, 0.6]$

- Limits on HEFT benchmark models and c_{gghh} and c_{tthh} Wilson coefficients (c_{gghh} = c_{tthh} =0 in SM)
- Separately for HH → bbγγ and HH → bbττ and combination

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arXiv:2301.03212

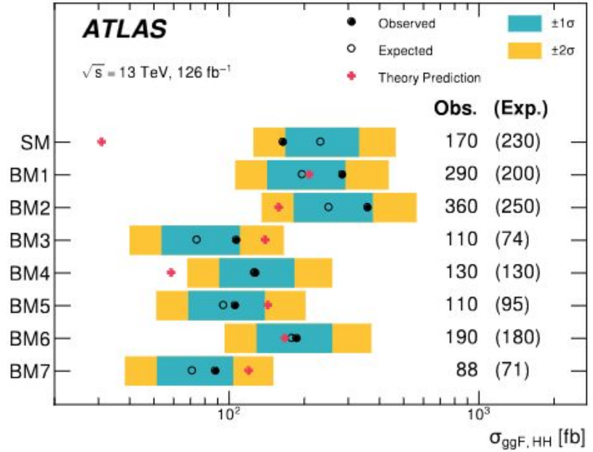
HH → bbbb: SMEFT & HEFT interpretation

SMEFT:

Parameter	Expected Constraint		Observed Constraint	
	Lower	Upper	Lower	Upper
c_H	−20	11	−22	11
c_{HG}	−0.056	0.049	−0.067	0.060
$c_{H\Box}$	−9.3	13.9	−8.9	14.5
c_{tH}	−10.0	6.4	−10.7	6.2
c_{tG}	−0.97	0.94	−1.12	1.15

- 95% CL exclusion limits on SMEFT parameters
    - one parameter varied at a time, 2D limits also derived (not shown)
- Limits on HEFT:
    - Benchmark scenarios: BM3, BM5, BM7 observed to be excluded with more than 95% confidence
    - Limits on c_{gghh} and c_{tthh}

HEFT benchmark models



Wilson coefficient	Observed	Expected
c_{gghh}	[-0.36,0.78]	[-0.42,0.75]
c_{tthh}	[-0.55,0.51]	[-0.46,0.40]

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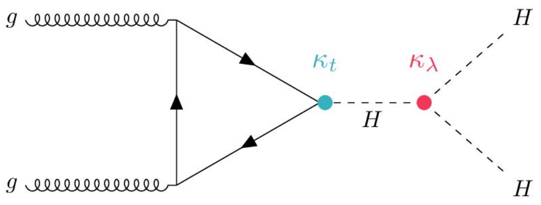
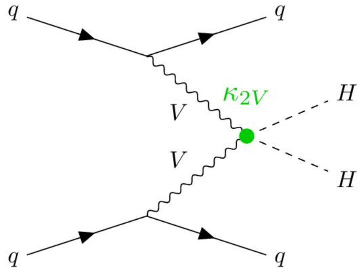
Constraints on Higgs boson self-coupling from HH and H production - Methodology

arXiv:2211.01216

- Combine H and HH analyses to obtain upper limit on κ_λ , relaxing assumptions on Higgs boson couplings (κ_m) ⇒ more generic model
  - up-type quark (κ_t), down-type quark (κ_b), τ lepton (κ_τ) and W or Z (κ_V)
- Use STXS framework: corrections to differential distribution expressed with coupling modifiers

Channel	Integrated luminosity [fb^{-1}]
$HH \to b\bar{b}\gamma\gamma$	139
$HH \to b\bar{b}\tau^+\tau^-$	139
$HH \to b\bar{b}b\bar{b}$	126
$H \to \gamma\gamma$	139
$H \to ZZ^* \to 4\ell$	139
$H \to \tau^+\tau^-$	139
$H \to WW^* \to e\nu\mu\nu$ (ggF,VBF)	139
$H \to b\bar{b}$ (VH)	139
$H \to b\bar{b}$ (VBF)	126
$H \to b\bar{b}$ ($t\bar{t}H$)	139





- Combine limits of HH (bbbb, bbττ, bbγγ) on κ_λ, κ_{2V} and cross section (κ_m fixed to SM)
- HH + H analyses: gradually release assumptions on κ_m and fit κ_λ, κ_t

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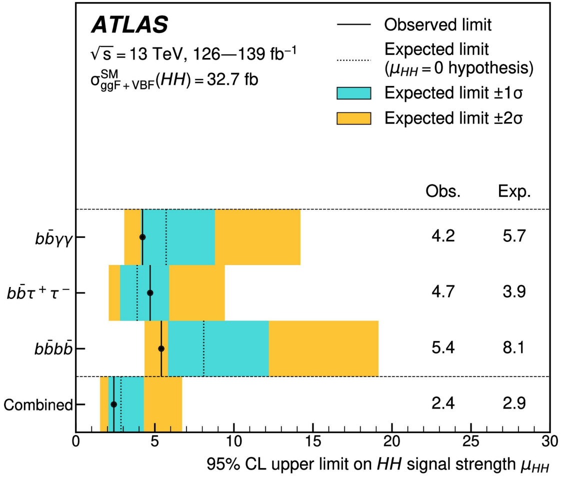
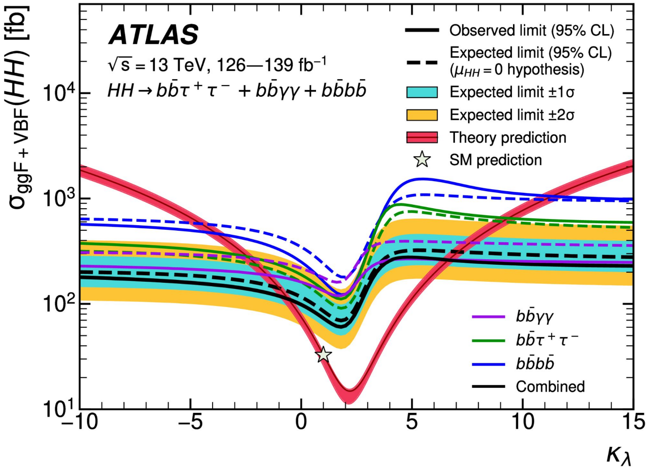
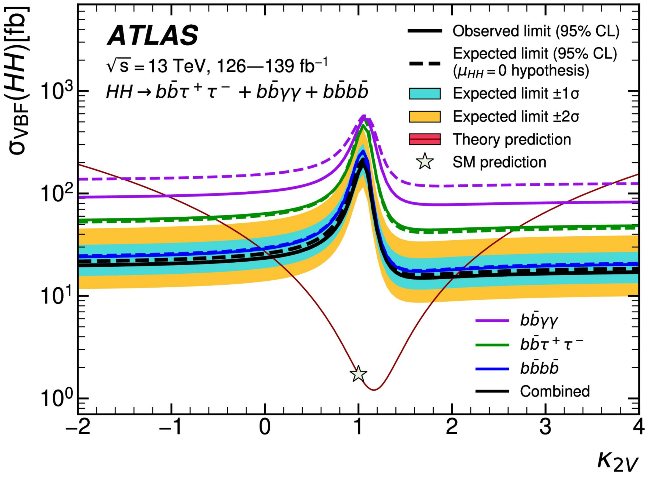
Constraints on Higgs boson self-coupling - HH Combination







arXiv:2211.01216

- Use only HH channels in combination
- Observed (expected) cross section limit: 2.4xSM (2.9xSM)
- Observed (expected) 95% CL limit on κ_λ: $-0.6 < \kappa_\lambda < 6.6$ ($-2.1 < \kappa_\lambda < 7.8$)
- VBF HH process constraints κ_{2V} in combination to $0.1 < \kappa_{2V} < 2.0$ at 95% CL

Only HH → bbbb search contains dedicated analysis regions optimized for VBF ⇒ limits on κ_{2V} driven by HH → bbbb

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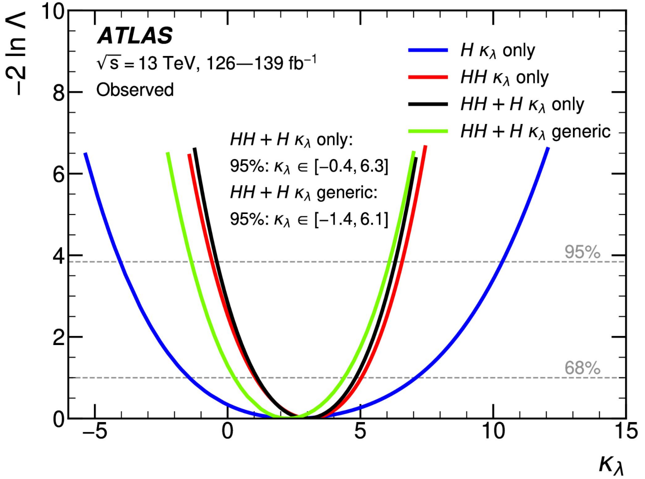
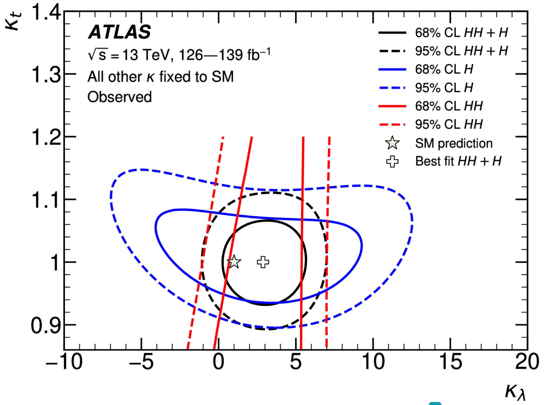
Constraints on Higgs boson self-coupling from HH and H production - H+HH Results and κ_λ

arXiv:2211.01216



Combination assumption	Obs. 95% CL	Exp. 95% CL
HH combination	$-0.6 < \kappa_\lambda < 6.6$	$-2.1 < \kappa_\lambda < 7.8$
Single-H combination	$-4.0 < \kappa_\lambda < 10.3$	$-5.2 < \kappa_\lambda < 11.5$
HH+H combination	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.6$
HH+H combination, κ_t floating	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.6$
HH+H combination, $\kappa_t, \kappa_V, \kappa_b, \kappa_\tau$ floating	$-1.4 < \kappa_\lambda < 6.1$	$-2.2 < \kappa_\lambda < 7.7$



- HH channels: κ_λ considered in H decay and H background through NLO EW correction (negligible impact)
- Limits on κ_λ: only HH, H+HH gradually release parameters

Most stringent constraints on Higgs boson self-interaction to date

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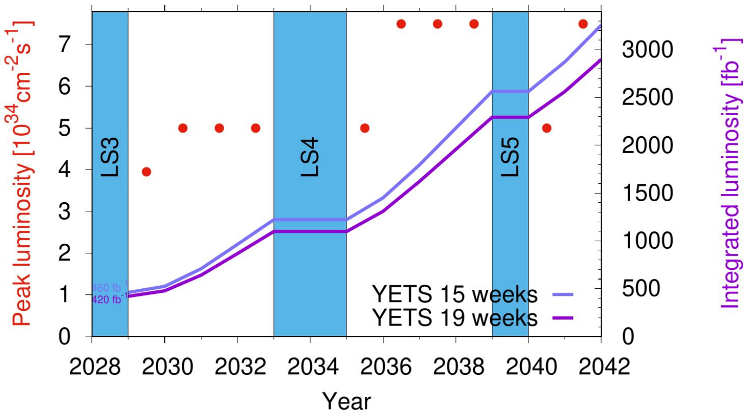
HL-LHC prospects: Methodology

ATL-PHYS-PUB-2022-053



- High-luminosity phase of LHC (HL-LHC) with increased instantaneous luminosity starts in 2029
- Collect 3000fb^{-1} of data at center of mass energy of 14 TeV
- Extrapolate Run-2 results of HH → bbbb search to HL-LHC luminosity and collision energy
- Combination of extrapolation with extrapolated HH → bbγγ and HH → bbττ

Systematic uncertainties	Scale factors for HL-LHC baseline scenario
Theoretical uncertainty	0.5
b-jet tagging efficiency	0.5
c-jet tagging efficiency	0.5
Light-jet tagging efficiency	1.0
Jet energy scale and resolution	1.0
Luminosity	0.6
Background bootstrap uncertainty	0.5
Background shape uncertainty	1.0

- Assume equal detector performance
- Four systematic uncertainty scenarios:
  - No systematics (statistical unc. only)
  - Baseline: scale down relevant systematics according to expected improvements
  - Theory uncertainties halved
  - Run-2 systematics

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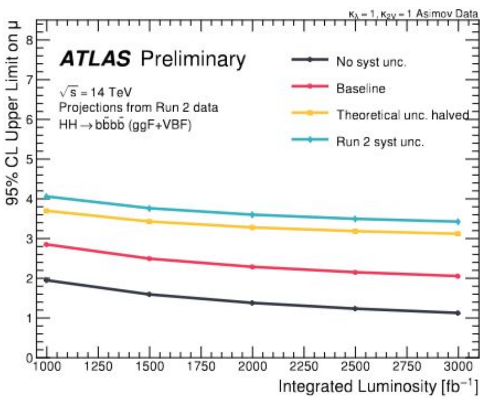
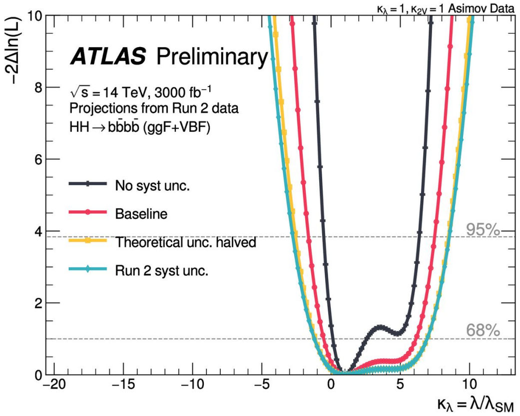
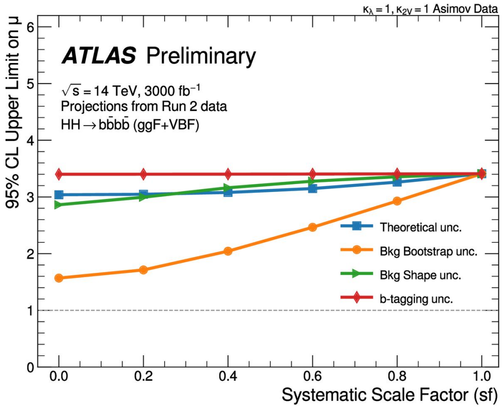
HL-LHC prospects: Results of HH → bbbb extrapolation







Uncertainty scenario	Signal strength 95% CL upper limit	Discovery significance [σ]
No syst. unc.	1.1	1.8
Baseline	2.0	1.0
Theoretical unc. halved	3.1	0.6
Run 2 syst. unc.	3.4	0.6

Uncertainty scenario	κ_λ 68% CI	κ_λ 95% CI
No syst. unc.	[0.1, 2.6]	[-0.5, 6.4]
Baseline	[-0.5, 6.1]	[-1.6, 7.5]
Theoretical unc. halved	[-1.2, 6.9]	[-2.6, 8.5]
Run 2 syst. unc.	[-1.2, 6.9]	[-2.8, 8.5]

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Improved results can be obtained when reducing the background estimation uncertainty and increasing the b-tagging performance (higher b-jet efficiency at same light and charm rejection)

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HL-LHC prospects: Prospects of HH → bbbb, bbγγ, bbττ combination

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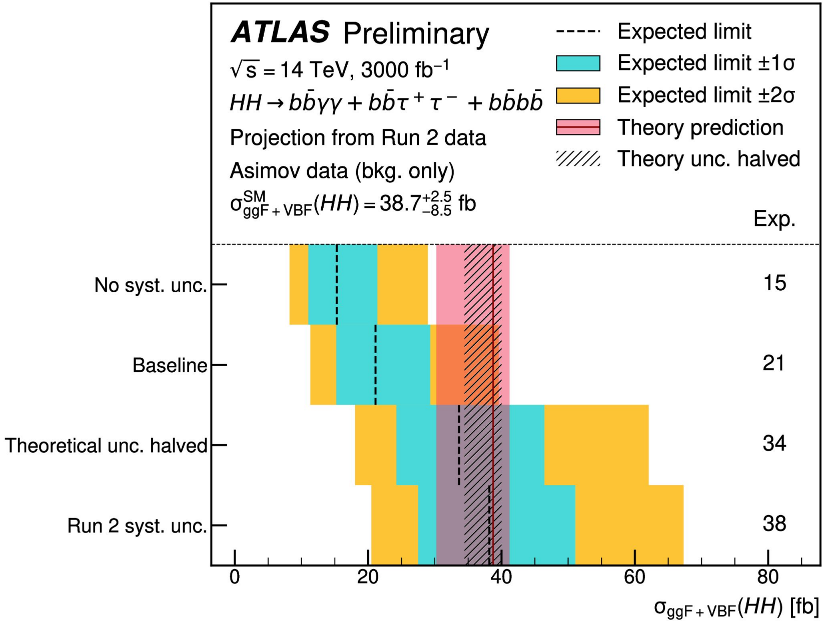
	Significance [σ]				Combined signal
Uncertainty scenario	$b\bar{b}\gamma\gamma$	$b\bar{b}\tau^+\tau^-$	$b\bar{b}b\bar{b}$	Combination	strength precision [%]
No syst. unc.	2.3	4.0	1.8	4.9	−21/+22
Baseline	2.2	2.8	0.99	3.4	−30/+33
Theoretical unc. halved	1.1	1.7	0.65	2.1	−47/+48
Run 2 syst. unc.	1.1	1.5	0.65	1.9	−53/+65

Uncertainty scenario	κ_λ 68% CI	κ_λ 95% CI
No syst. unc.	[0.7, 1.4]	[0.3, 1.9]
Baseline	[0.5, 1.6]	[0.0, 2.5]
Theoretical unc. halved	[0.3, 2.2]	[−0.3, 5.5]
Run 2 syst. unc.	[0.1, 2.4]	[−0.6, 5.6]



- Significance of 3.4σ assuming baseline scenario
- Signal strength measured with +33/-30% uncertainty
- κ_λ constrained to [0.5,1.6] in 1σ confidence interval

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Conclusion

- Competitive limits on HH production cross section and Higgs self-couplings derived in HH → bbbb, $bb\tau\tau$, $bb\gamma\gamma$ decay channels using full Run-2 ATLAS data
- Combination with single Higgs analyses and interpretations in HEFT and SMEFT frameworks
- Combination H+HH provides the most stringent limits on Higgs boson self-coupling to date: $-0.4 < \kappa_\lambda < 6.3$
- Expect evidence for HH production with $3000 fb^{-1}$ of HL-LHC data
- Further improvements in object reconstruction and analysis techniques will help to constrain HH production further towards discovery of non-resonant HH production at the HL-LHC

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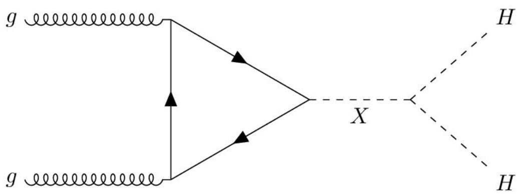
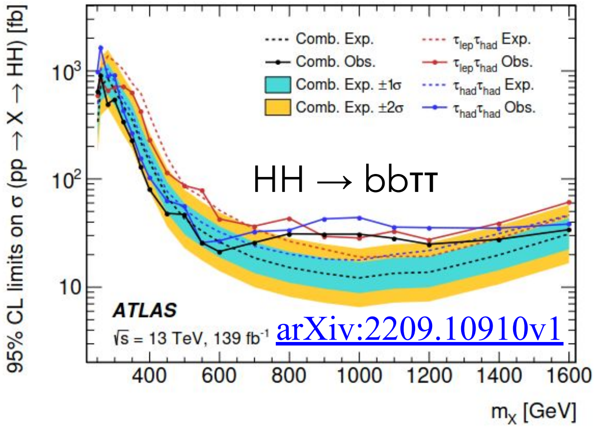
Backup

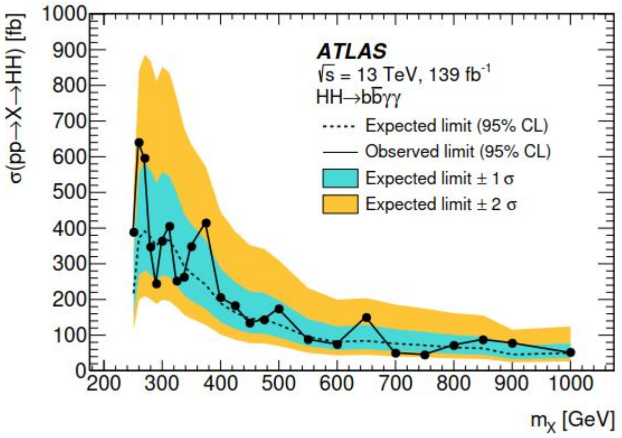
Resonance searches



- Various scenarios beyond the Standard Model predict resonances decaying to a pair of Higgs bosons (like extended Higgs sectors, composite Higgs models)



arXiv:2209.10910v1



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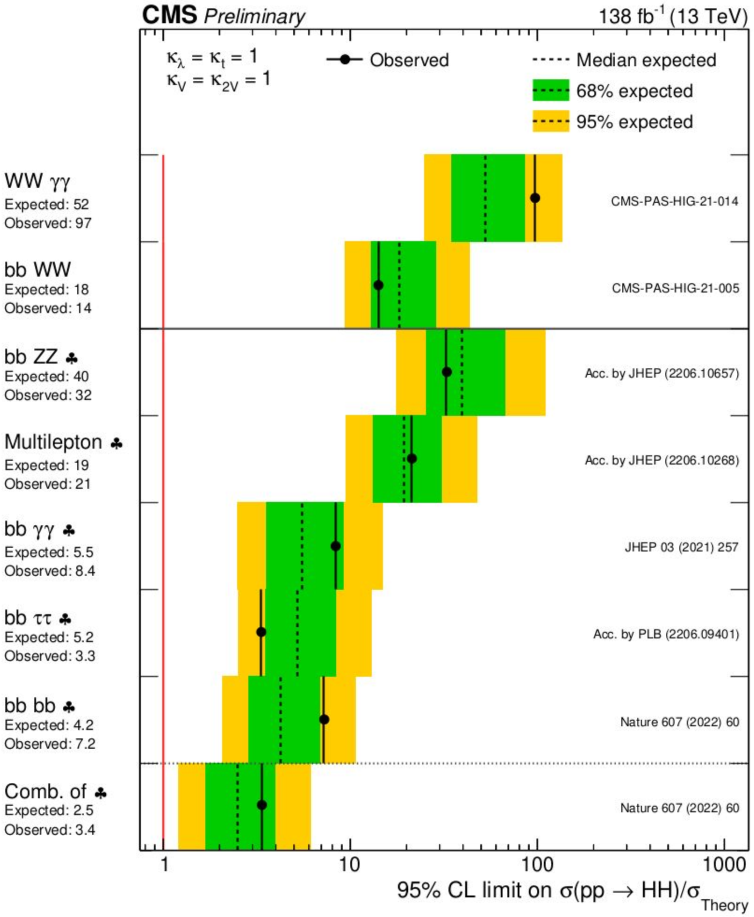
- Resonant searches in HH → bbγγ and HH → bbττ final states
- Exclusion limit on narrow width HH resonance

Summary of HH results from CMS (Status: March 23)



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