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

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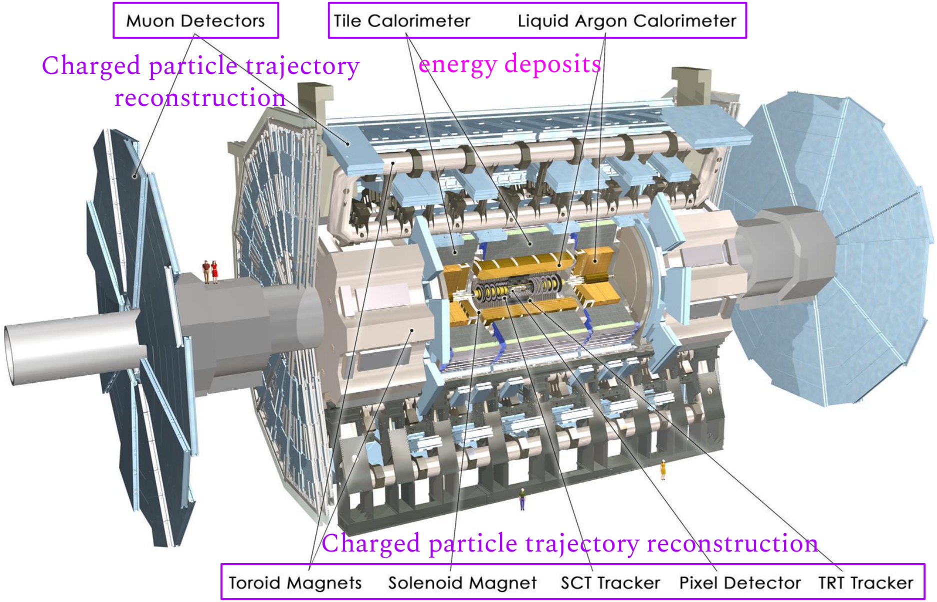
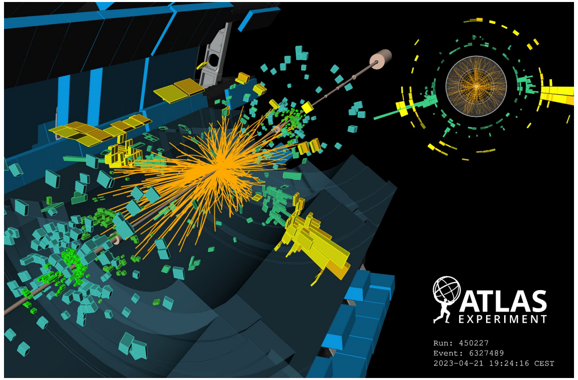
Instituto de Física Corpuscular (IFIC, CSIC-UV)

30th Anniversary of the Rencontres du Vietnam - Windows on the Universe
Vietnam, 6-12 August 2023

The ATLAS Experiment



Bunch crossing: 40 MHz
Detector readout (first level trigger): 100 kHz
Write to disk (second level trigger): 1 kHz

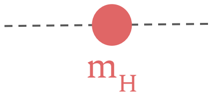


Higgs Boson Self-Coupling *(why Higgs pairs?)*

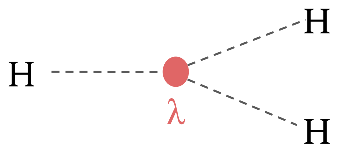
$$V(\phi) = \mu^2(\phi^\dagger\phi) + \lambda(\phi^\dagger\phi)^2 \xrightarrow{\text{Expanding around minimum}} V_H = \boxed{\tfrac{1}{2} m_H H^2} + \boxed{\lambda v H^3} + \ldots$$

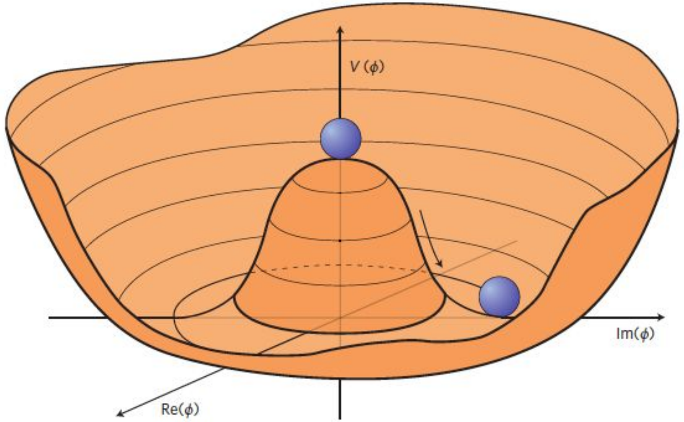
Spontaneous symmetry breaking when $v \neq 0$
when $\lambda > 0$, $\mu^2 < 0$: Minimum $(v) = \sqrt{(\mu^2/2\lambda)}$
$v_{SM}(\text{computed}) = (\sqrt{2}G_F)^{-1/2} = 246$ GeV
$\Rightarrow \lambda_{SM}(\text{computed}) \simeq 0.129$

Higgs boson mass term



Self-interaction term

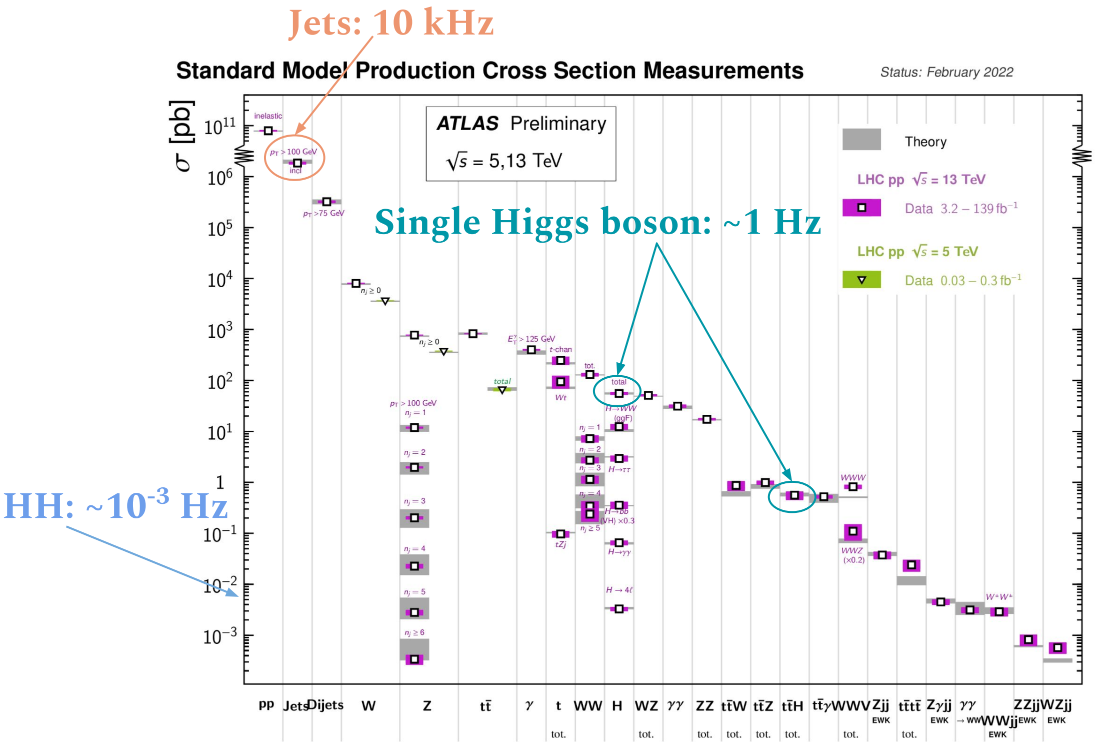




Higgs boson pair-production measurement
↓
direct measurement of Higgs boson self-coupling
↓
direct probe of shape of Higgs potential

$\lambda \neq \lambda_{SM} \Rightarrow$ new physics

HH production cross sections *(needle in a haystack...)*



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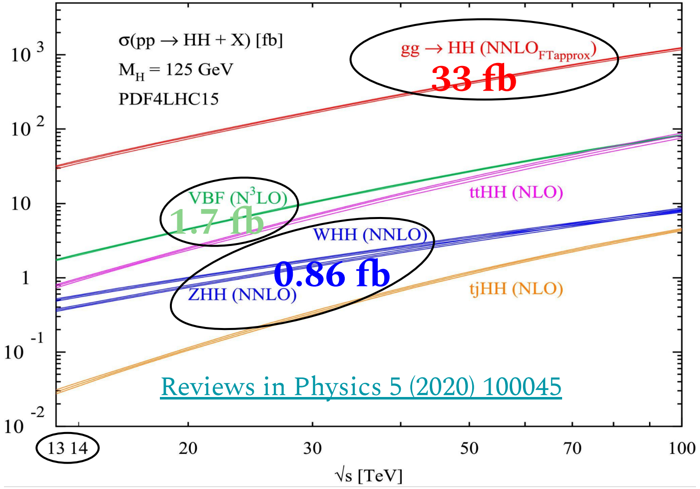
Non-resonant HH production: 1/hr

σ_{HH} → ~10^3 times smaller than σ_H
⇒ difficult search

HH production modes

ATLAS EXPERIMENT



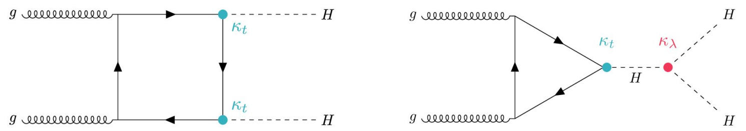
Using the κ framework to parametrize BSM physics

Assumption: New physics only modifies SM couplings, where κ is the coupling strength modifier

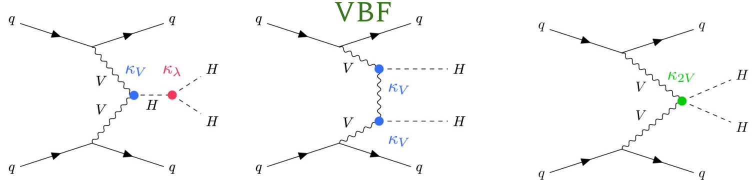
$$\kappa_\lambda = \frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}} \quad \therefore \quad \kappa_i \neq 1 \Rightarrow \text{new physics}$$

Non-resonant production modes probed in ATLAS

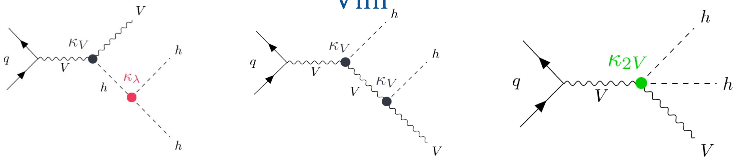
gluon- gluon fusion



VBF



Vhh



$$\kappa_i^2 = \frac{\sigma_i}{\sigma_i^{SM}}$$

κ_λ: Higgs trilinear coupling strength modifier
κ_t: top - Higgs coupling strength modifier
κ_V: VVH coupling strength modifier
κ_{2V}: VVHH coupling strength modifier

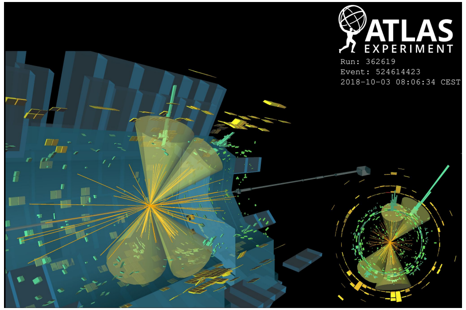
HH decay modes *(no single golden channel...)*

	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%

Channels probed in ATLAS

- Exploit all decays channel with at least one $b\bar{b}$ pair in the final state - comparatively higher BR than without $b\bar{b}$
- Different production modes (non- resonant: ggF, VBF; resonant production) exploited
- 3 main channels & their production modes probed in ATLAS:
  - $b\bar{b}b\bar{b}$ - highest BR, large background (ggF, VBF, VHH)
  - $b\bar{b}\gamma\gamma$ - small background, low signal yields (ggF, VBF)
  - $b\bar{b}\tau\tau$ - balance of both (ggF, VBF)

$HH \rightarrow b\bar{b}b\bar{b}$ *(largest signal)*

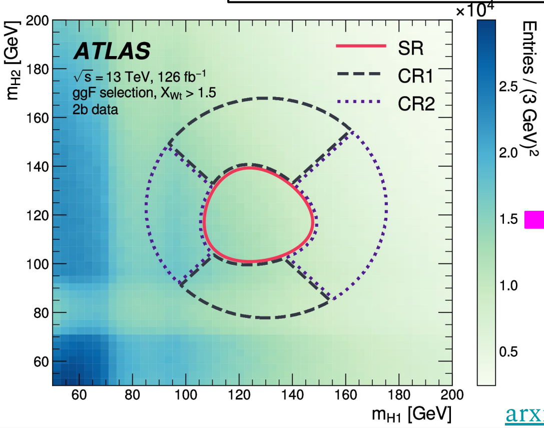


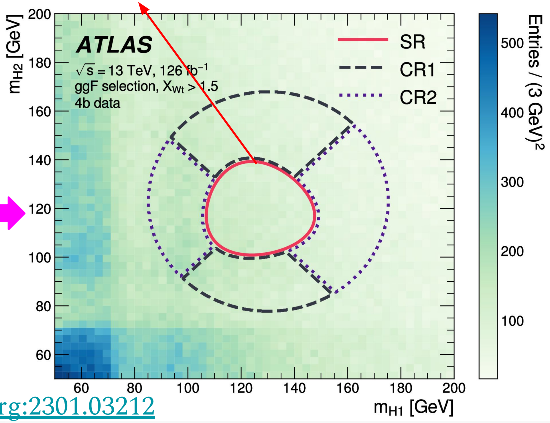
Event selection: 4 b-tagged jets

Analysis strategy:

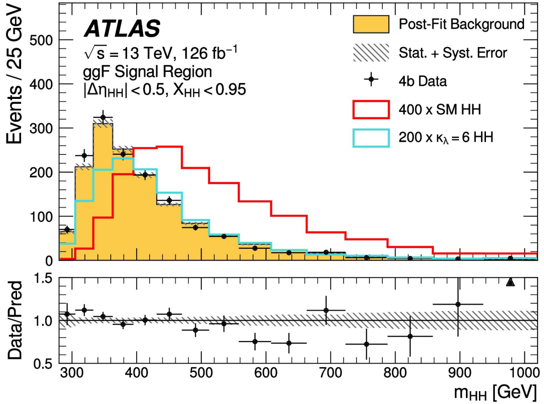
- *Higgs reconstruction*: jets paired to minimize ΔR for p_T leading dijet system
- $|\Delta\eta_{HH}|$ and X_{HH} categories to improve κ_λ and κ_{2V} sensitivity
- *Background estimate*:
  - Data from 2b region reweighted to 4b SR (defined in m_{H1}- m_{H2} plane) using NN
- *Signal extraction:* Limit from fit to m_{HH} distribution

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

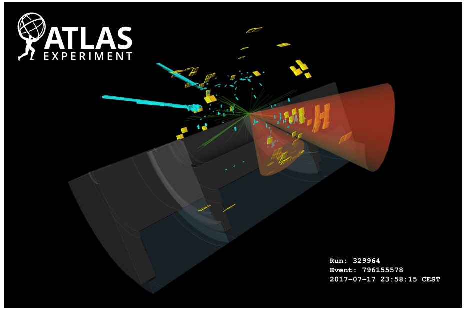


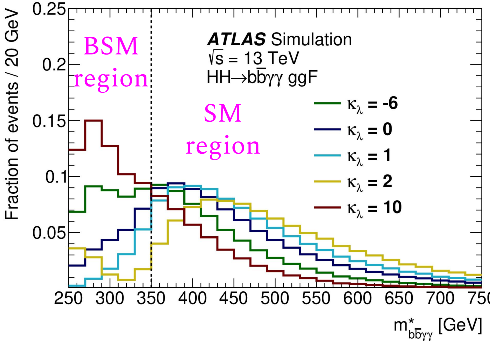


arxiv.org:2301.03212

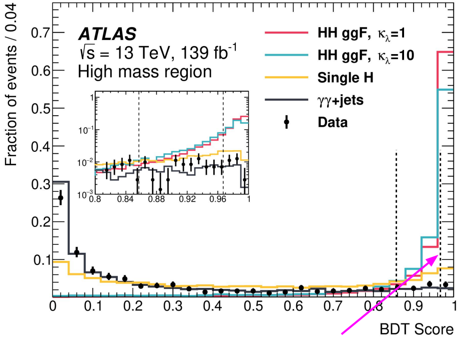


HH→$b\bar{b}\gamma\gamma$ *(clean signature)*





($m^*_{b\bar{b}\gamma\gamma} = m_{b\bar{b}\gamma\gamma} - m_{b\bar{b}} - m_{\gamma\gamma}$ + 250 GeV)

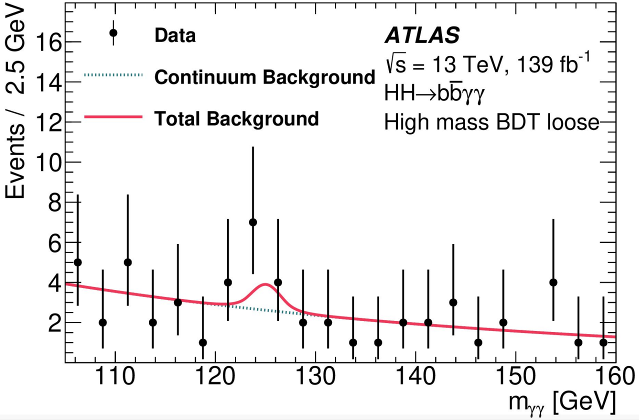


BDT loose: BDT Score ∈ [0.967,1]

Event selection: 2 photons, 2 b-tagged jets, no e/μ

Analysis strategy:

- *Signal region definitions*: regions based on $m^*_{b\bar{b}\gamma\gamma}$ targeting SM and BSM couplings
- *Signal extraction*: 2 BDT categories: tight, loose by maximizing the combined counting significance using signal and background yields in $m_{\gamma\gamma}$ ∈ [120, 130 GeV]



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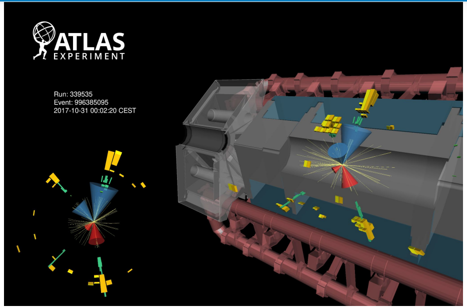
HH→$b\bar{b}\tau\tau$ *(balance of both)*



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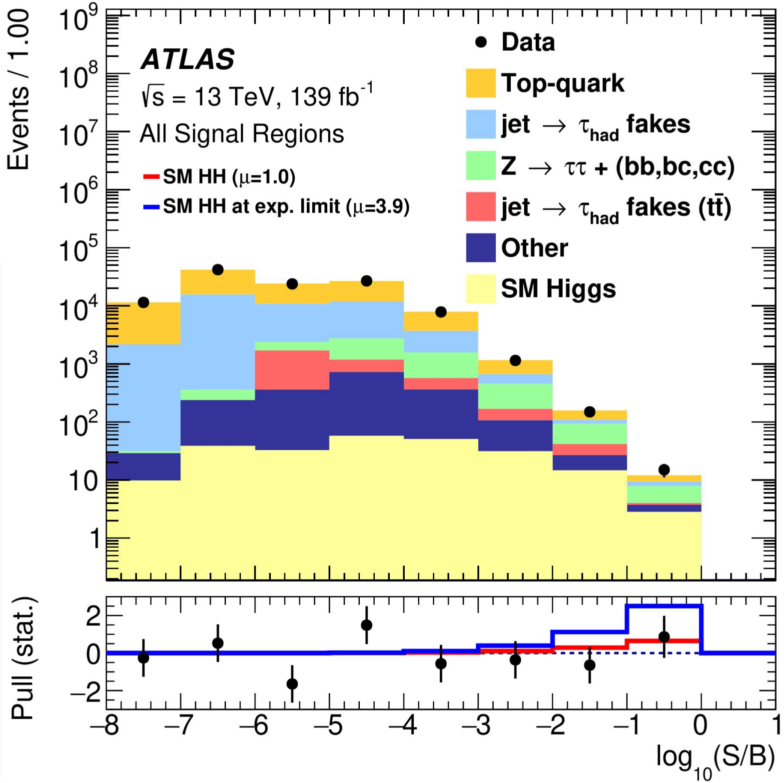
Event selection:

- 2 hadronic τs ($\tau_{had}\tau_{had}$) OR 1 τ + 1e/μ ($\tau_{lep}\tau_{had}$); $m_{\tau\tau}$ > 60 GeV using MMC
- 2 b-tagged jets

Analysis strategy:

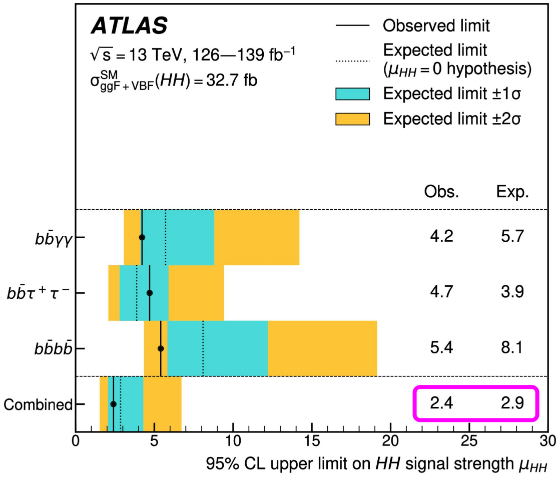
- *Signal region definitions*: 3 regions
  - $\tau_{had}\tau_{had}$
  - $\tau_{lep}\tau_{had}$ *SLT* - single lepton triggers
  - $\tau_{lep}\tau_{had}$ *LTT* - lepton - τ triggers
- *Signal extraction:*
  - $\tau_{had}\tau_{had}$ *channel*: BDT; $\tau_{lep}\tau_{had}$ *channel*: NN
  - *Final discriminant*: MVA score
  - combine 3 channels - bins of $\log_{10}$(S/B)

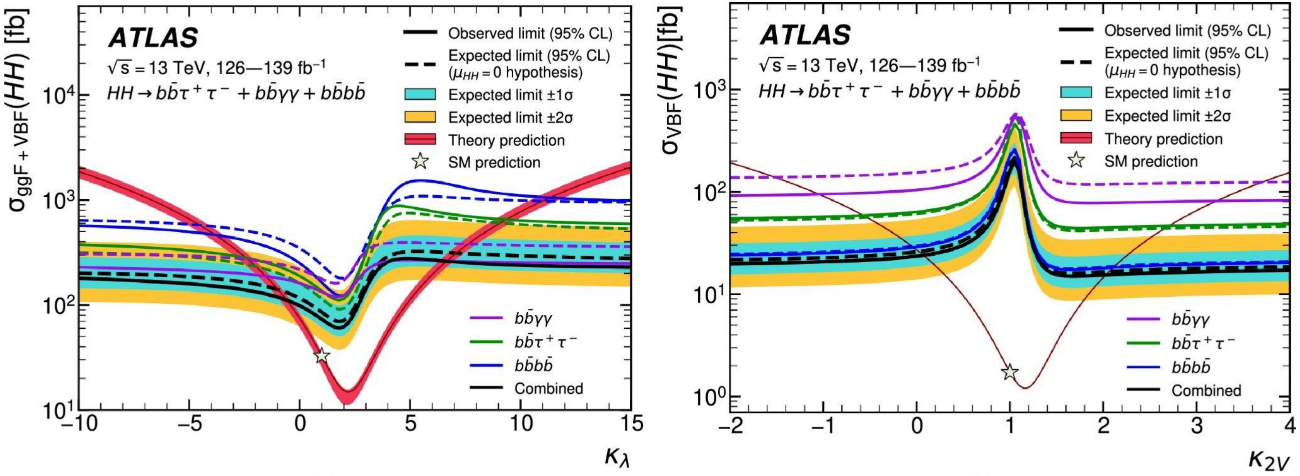


Results (combination)

Limits on μ_{HH}, κ_λ and κ_{2V} at 95% CL

μ_{HH} < 2.4 observed | **κ_λ(observed) ∈ [-0.6,6.6]** | **κ_{2V}(observed) ∈ [0.1,2.0]**





(a) (b)

Combining 3 most sensitive channels increases sensitivity

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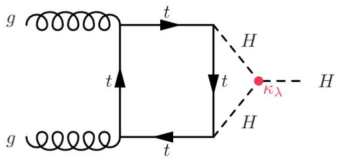
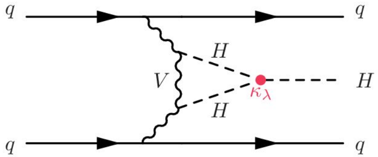
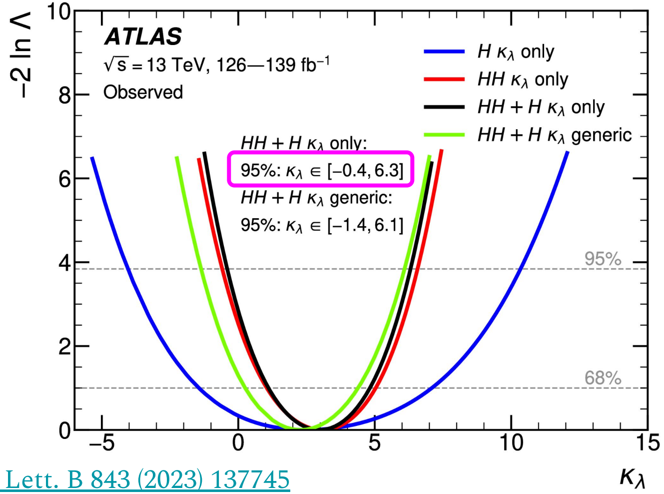
H+HH combination

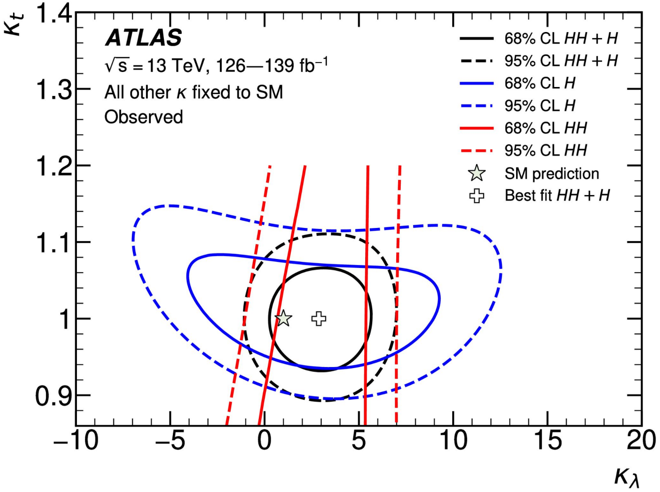
Single Higgs boson production is also sensitive to λ through loop corrections. Examples (ggF and VBF):





Better sensitivity: HH combination: $\kappa_\lambda \in [-0.6,6.6]$ vs HH+H combination: $\kappa_\lambda \in [-0.4,6.3]$





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VHH production

Sensitive to ZZHH and WWHH separately as opposed to VBF
Probed in the $b\bar{b}b\bar{b}$ final state

Event selection:

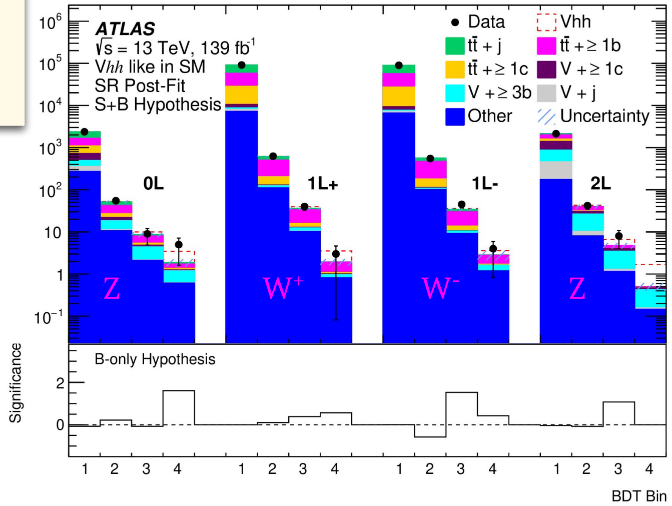
- 4 b-tagged jets (from HH)
- $Z \to \nu\nu$ (0L), $W \to l\nu$ (1L), $Z \to ll$ (2L)

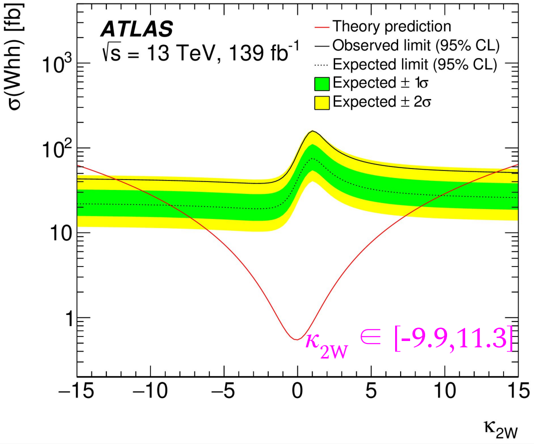
Analysis Strategy:

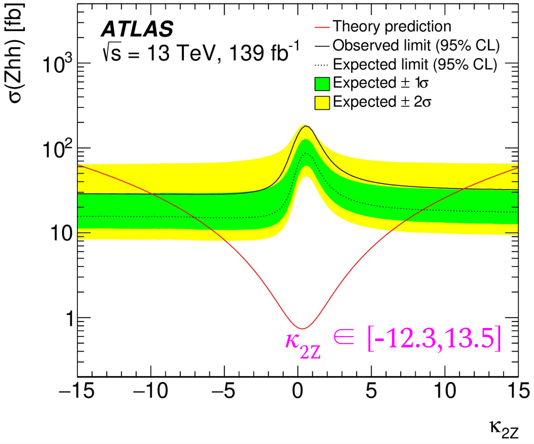
- 3 signal regions (0L, 1L, 2L)
- S-B separation: simultaneous fit to BDT distributions

Observed limits at 95% CL:

- $-34.4 < \kappa_\lambda < 33.3$
- $-8.6 < \kappa_{2V} < 10.0$







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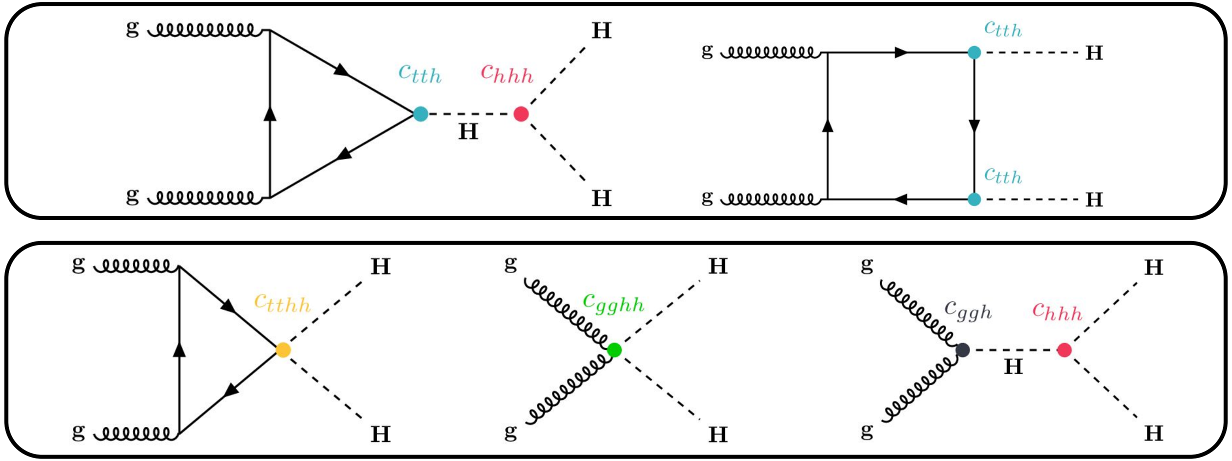
Effective Field Theories (EFT)

Parametrise new physics without strong model dependance
Two common frameworks in HH: SMEFT and Higgs EFT (HEFT); HEFT ⊂ SMEFT
Effective operators can modify gg→HH production in various ways

HEFT coupling parameters



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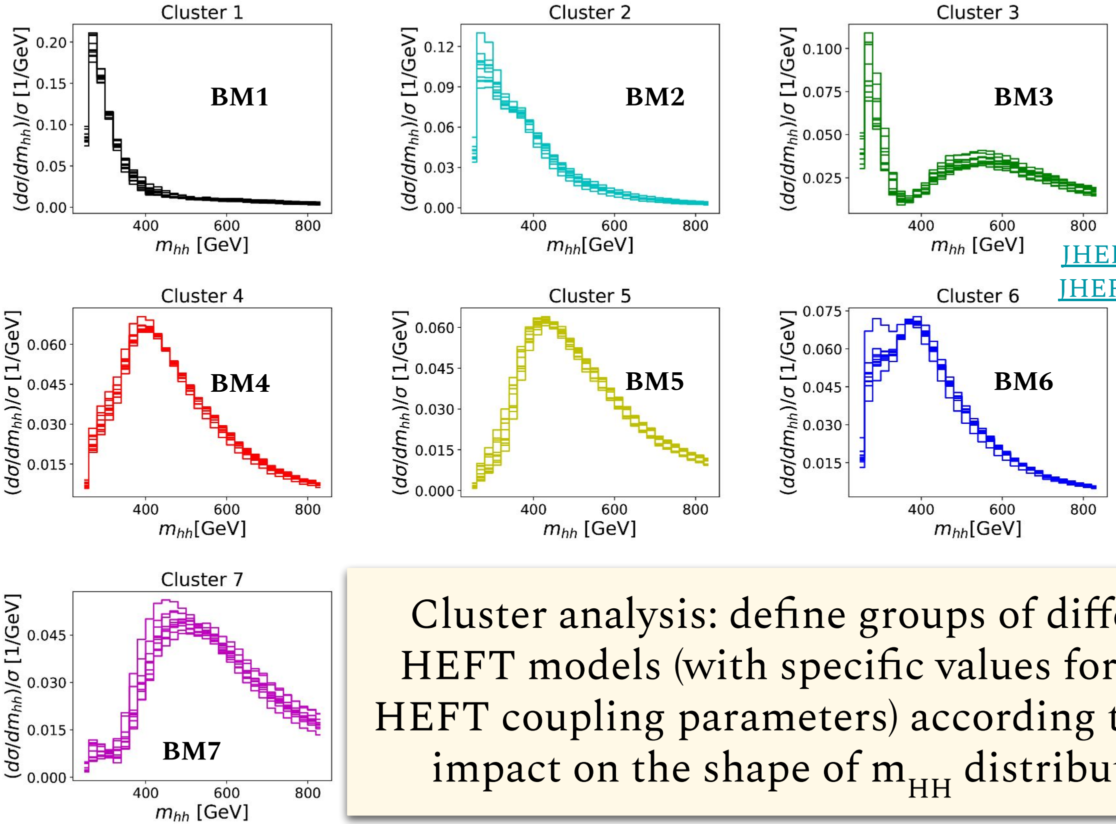
Effective Field Theory (EFT) interpretations for HH

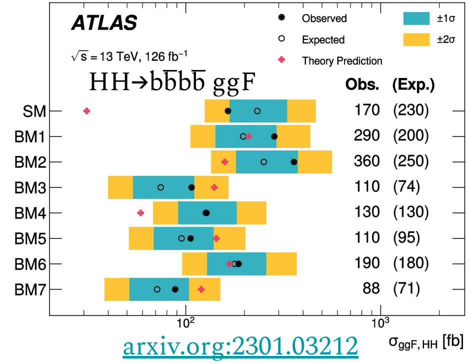


JHEP03(2020)091

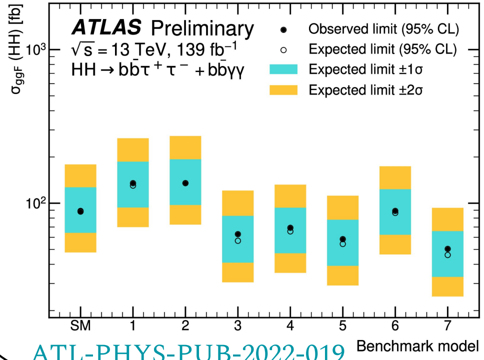
JHEP04(2016)126

Cluster analysis: define groups of different HEFT models (with specific values for the 5 HEFT coupling parameters) according to their impact on the shape of m_{HH} distribution

Upper limits on benchmark models at 95% CL



arxiv.org:2301.03212



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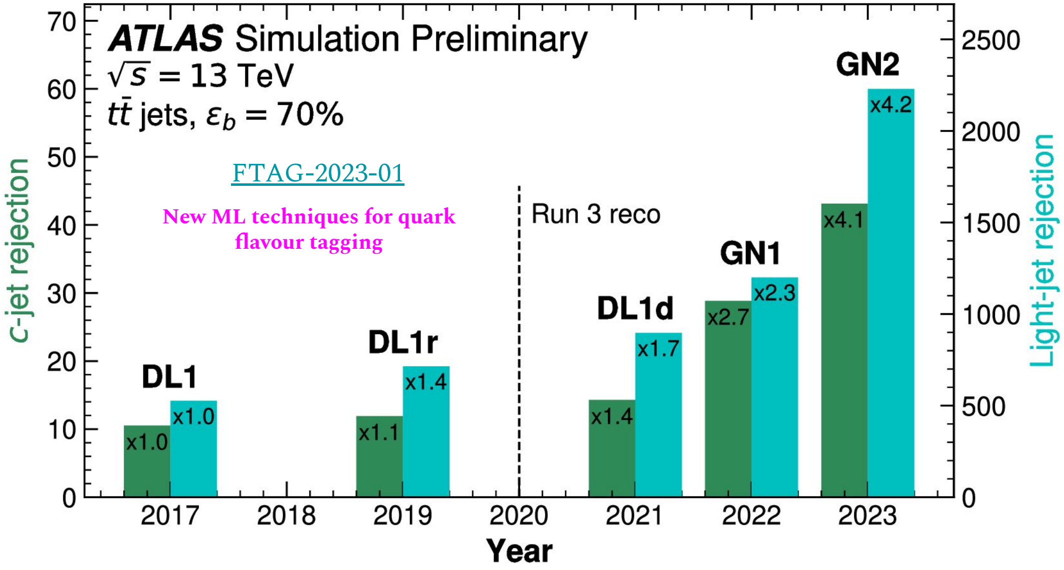
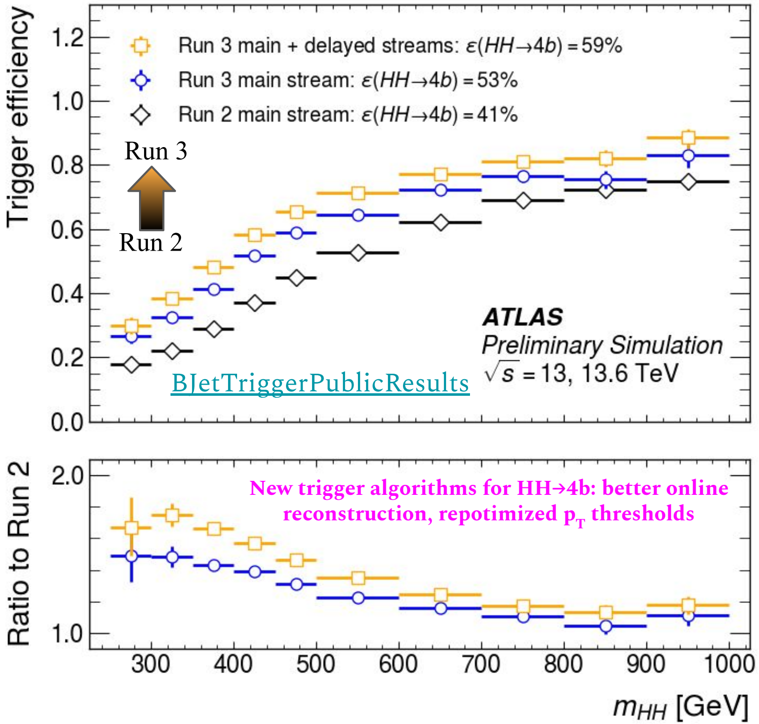
Run 3 improvements *(some examples)*

- √s = 13 TeV → 13.6 TeV
- Detector hardware upgrades
- Faster reconstruction algorithms
- Improved triggers



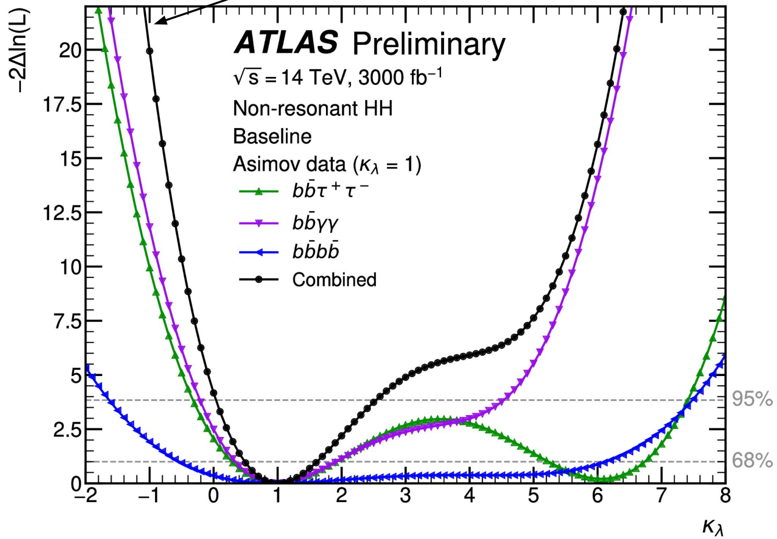


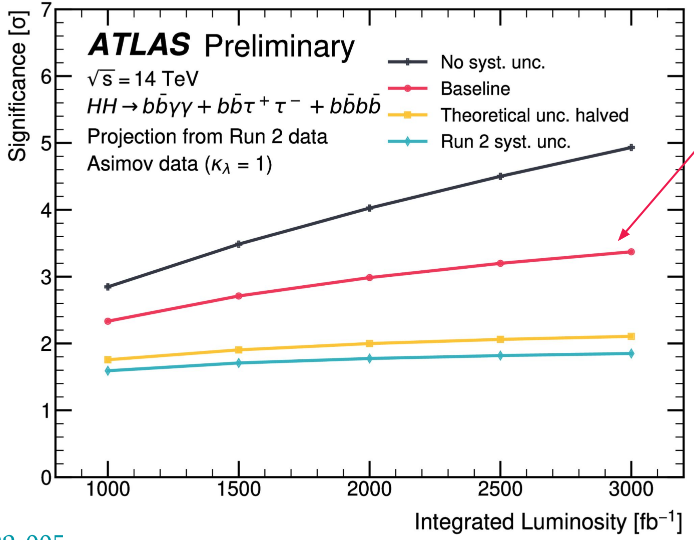
High Lumi - LHC prospects for HH *(ultimate sensitivity?)*

HL-LHC conditions:
$\sqrt{s}$ = 14 TeV; L_{int} = 3 ab^{-1}
High pile up

Prospects studied for $b\bar{b}b\bar{b}$, $b\bar{b}\gamma\gamma$ and $b\bar{b}\tau\tau$ channels

- Predicted constraints for combination at 95% CL:
  - **$0.22 < \kappa_\lambda < 2.2$**
- Expected SM HH production significance combining 3 channels: **3.4σ**





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Conclusions

- No new physics so far, HH search - useful next step if BSM physics exists
- No single golden channel ⇒ parallel searches and combination are necessary
- Can easily be extrapolated to BSM heavy resonance searches
- *HH in ATLAS during Run 2*: enhanced results with combining 3 most sensitive channels, adding single Higgs contributions provides additional constraints
- *Run 3*: Higher centre-of-mass energy, improved detector hardware, software (triggers, reconstruction algorithms etc.)
- *HL-LHC*: 20 × current luminosity, run 2 extrapolation very promising (**3.4σ significance expected**)