Higgs self coupling

Zhijun Liang
(On behalf of the the ATLAS collaboration)
Institute of High energy physics, CAS

Higgs Hunting 2024
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Di-Higgs production

❖**Challenge: HH cross-section is ~ O(1000) times smaller than single Higgs**

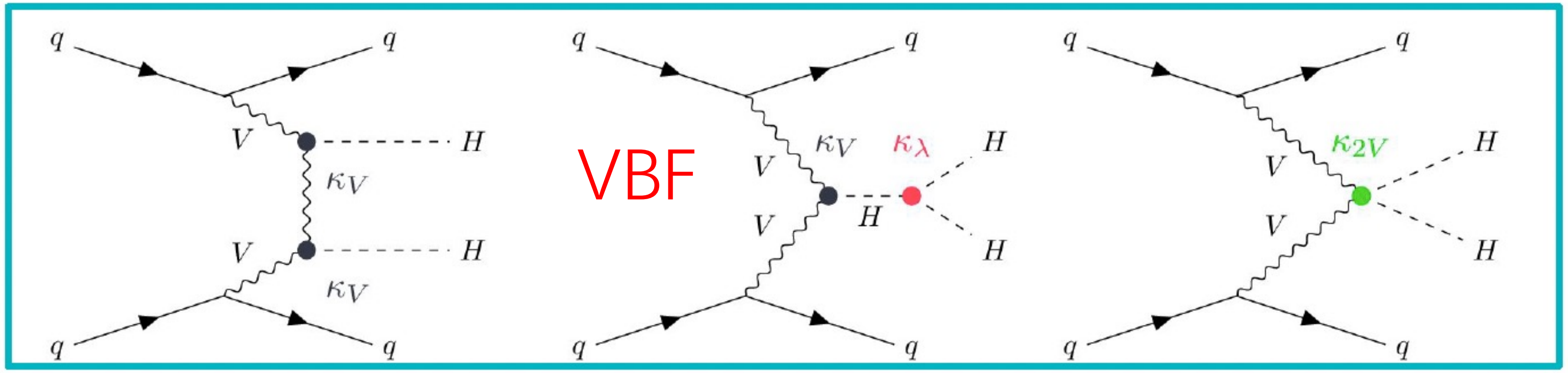
❖**ATLAS di-Higgs searches set constraints on κ_λ and κ_{2V}**

$\kappa_\lambda = \lambda_{hhh}/\lambda_{hhh(SM)}$

$\kappa_{2V} = \lambda_{hhVV}/\lambda_{hhVV(SM)}$

$$V(H) = \frac{1}{2}m_H^2 H^2 + \lambda v H^3 + \frac{\lambda}{4}H^4 - \frac{\lambda}{4}v^4$$

$$\lambda_{HHH} = \lambda_{HHHH} = \frac{m_H^2}{2v} \approx 0.13$$



Production mode	Branching Ratio
ggF	90.2%
VBF	5%
VHH	2.5%
Ohters	2.3%

Higgs self-coupling measurment in ATLAS

❖ ATLAS explores different channels to increase sensitivity using run2 data (140 fb^{-1})

- HH→ bbbb. (Largest B.R) , new boosted VBF channel update arXiv:2404.17193
- HH→ bbττ (analysis re-optimisation targeting κ_λ, κ_{2V} and XS / EFT limits)
  Phys. Rev. D 110 (2024) 032012
- HH→ bbγγ , JHEP 01 (2024) 066 (re-optimisation to improve sensitivity)
- HH→ Multilepton(new channel in combination!)
  JHEP 08 (2024) 164
- VHH production
- Combination, Phys. Rev. Lett. 133 (2024) 101801
  (New Higgs self-coupling combination)

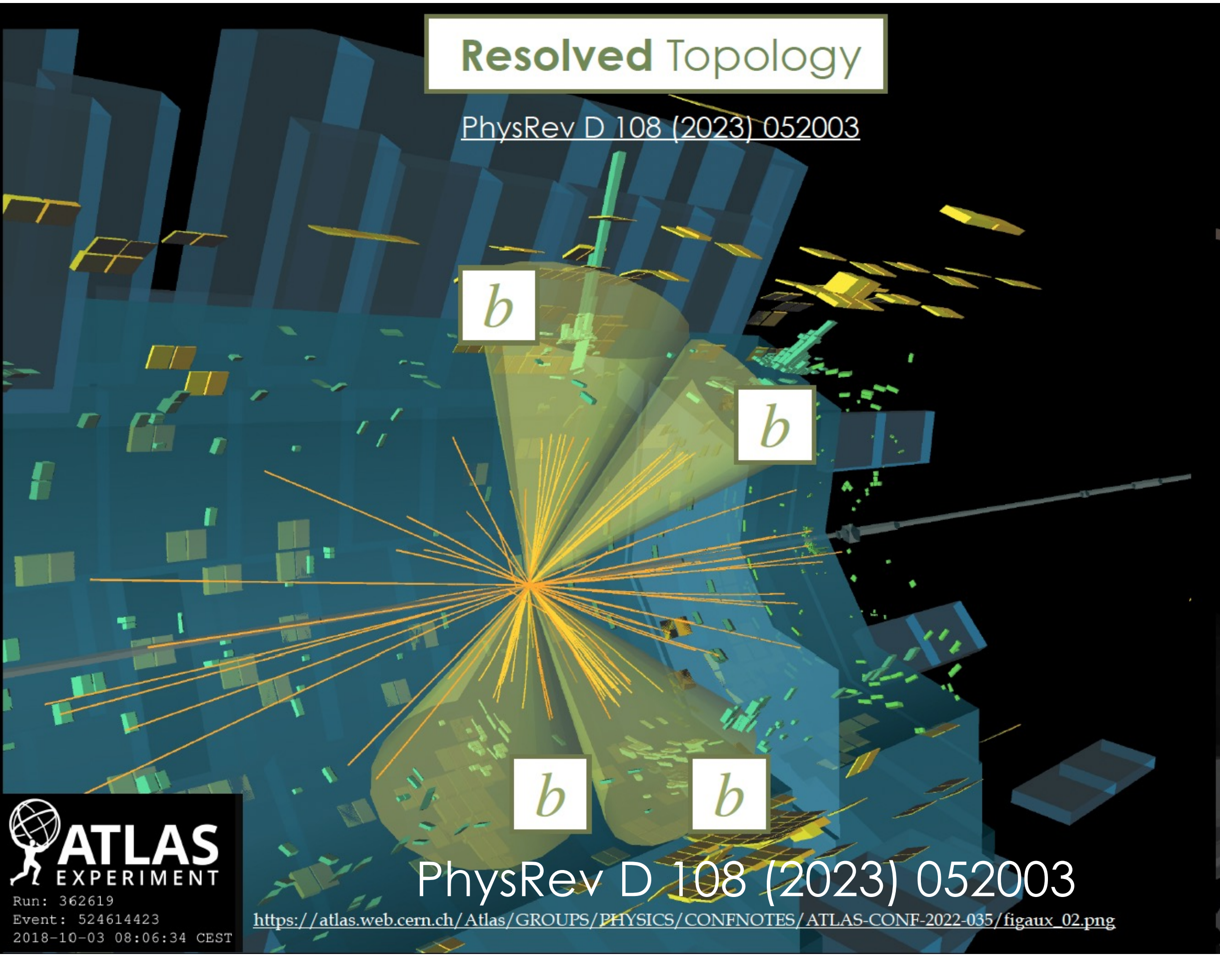
	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

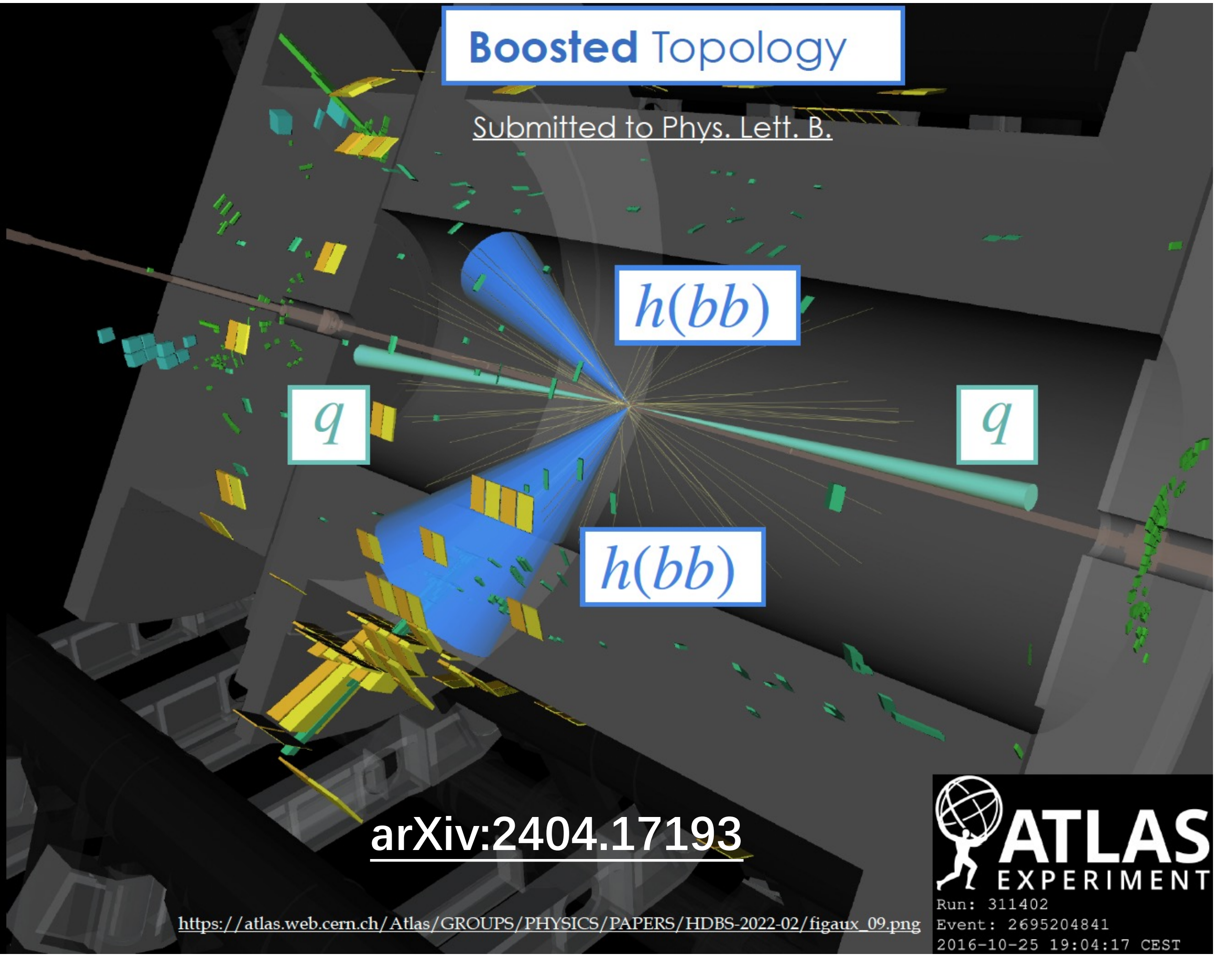
HH → bbbb @ run 2

❖ **Largest signal BR (34%), but large multi-jet background**

❖ **Resolved topology and boosted topology**

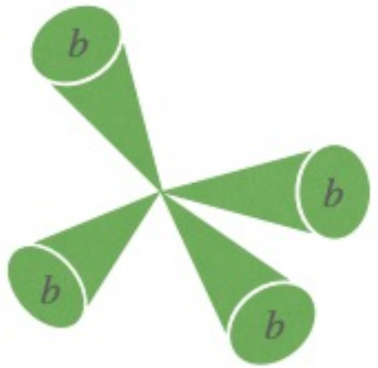
	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%





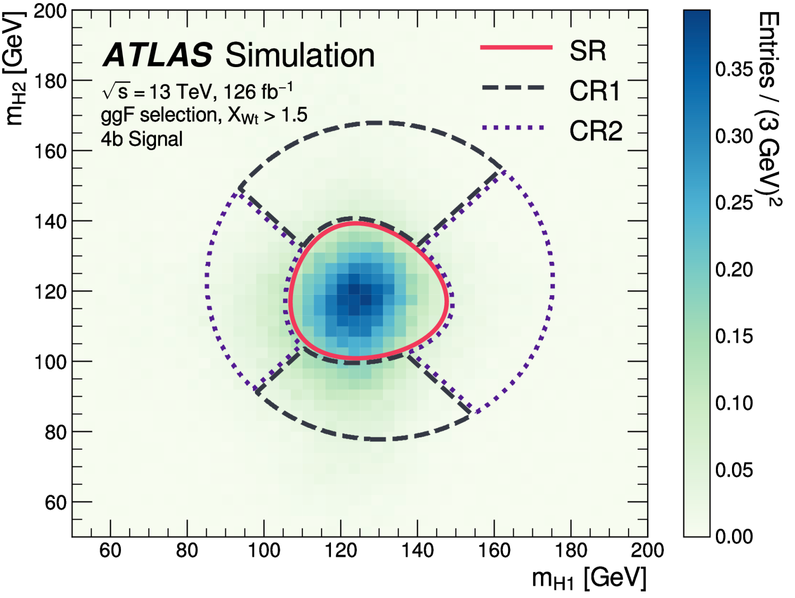
$HH \rightarrow bbbb$ resolved topology

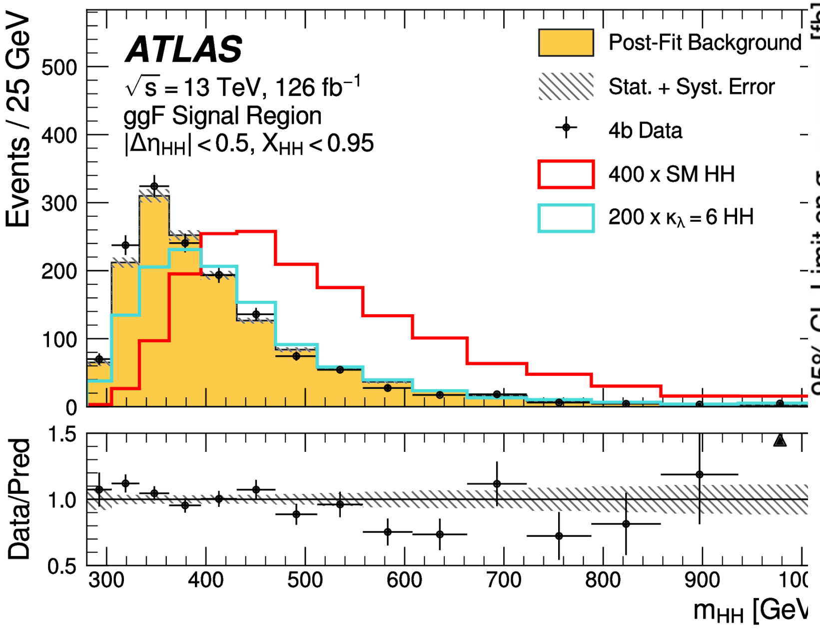
Phys Rev D 108 (2023) 052003

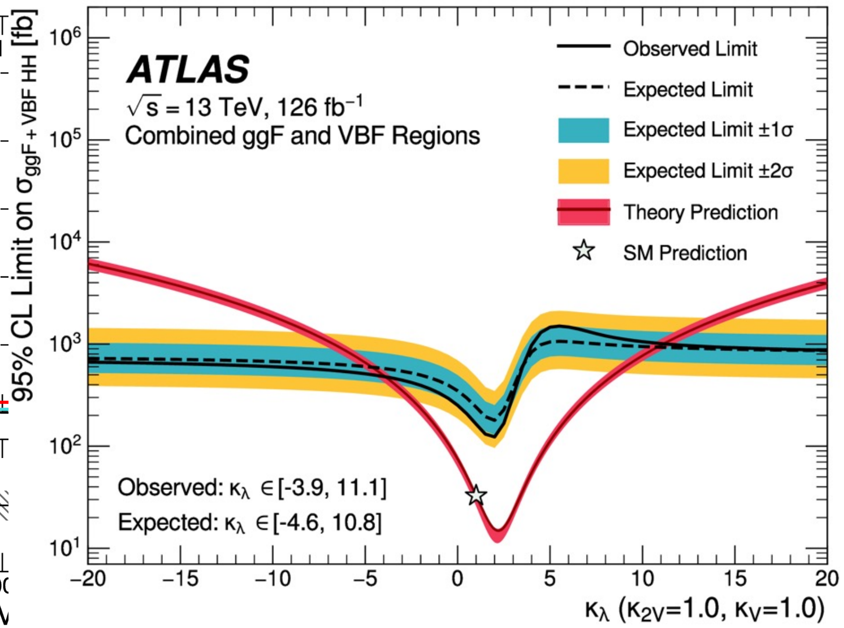


- ❖4 b-tagged jets, Signal in the center of in m_{H1}- m_{H2} plane
- ❖Discriminating variable fitted is m_{HH},
- ❖No excess in data ,Observed (expected) upper limit on μ_{HH} is 5.4 (8.1).

Observed: $\kappa_{\lambda} \in [-3.9, 11.1]$
Expected: $\kappa_{\lambda} \in [-4.6, 10.8]$

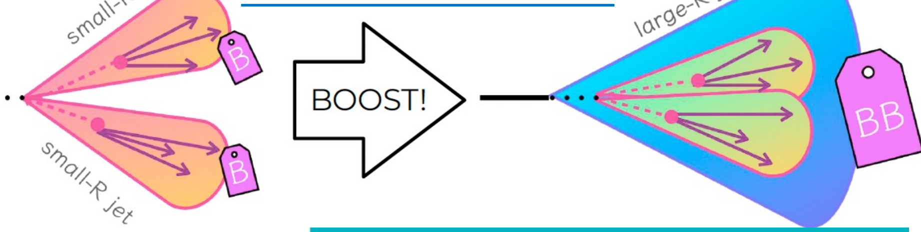






HH → bbbb boosted topology

arXiv:2404.17193

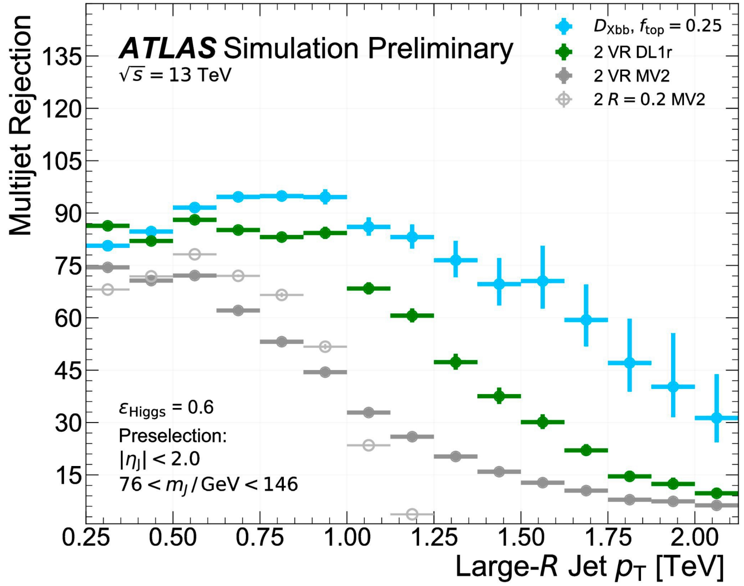


ATL-PHYS-PUB-2020-019
ATL-PHYS-PUB-2021-035

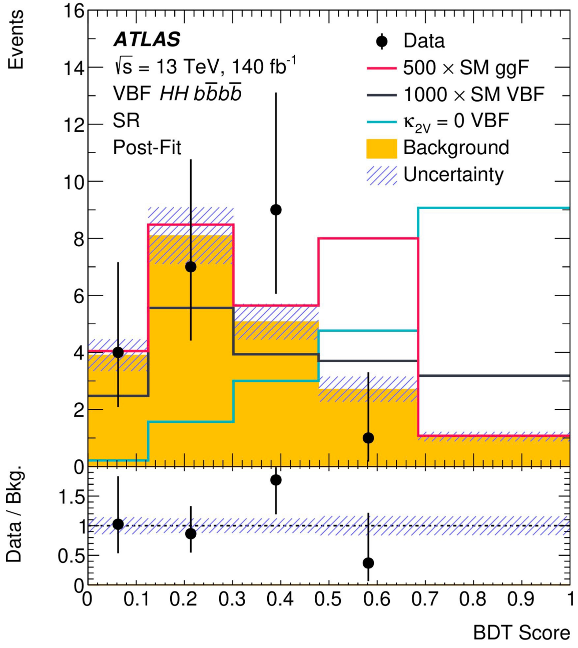
- ❖New ML technique to identify in boosted region
- ❖Select two Xbb- tagged jets and two additional VBF jets
- ❖Boosted VBF HH analysis enhances K_{2V} sensitivity

Observed: $\kappa_{2V} \in [-0.55,1.49]$
Expected: $\kappa_{2V} \in [-0.37,1.67]$

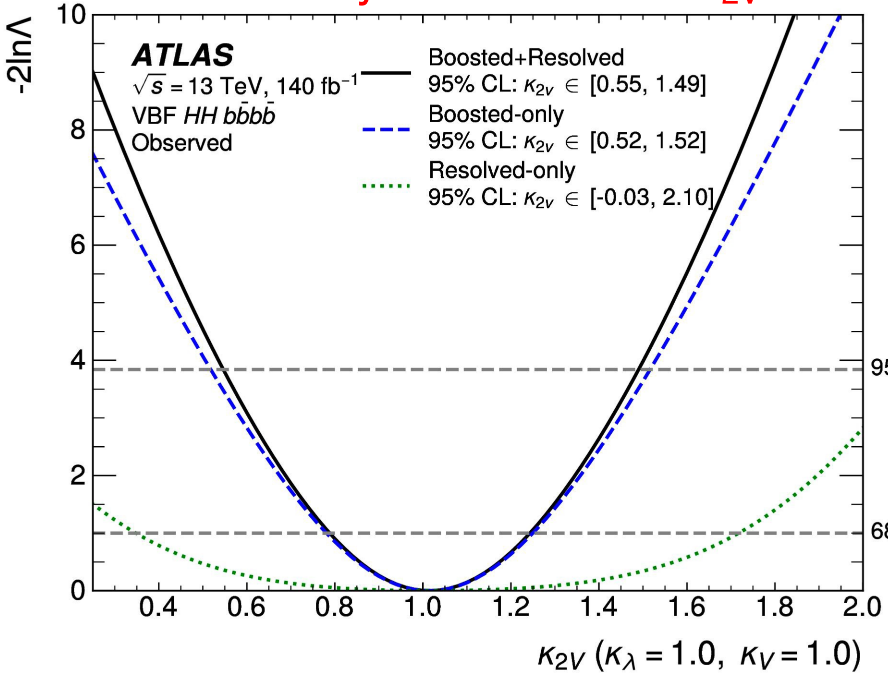
Xbb-tagger performance



Signal extraction for BDT score



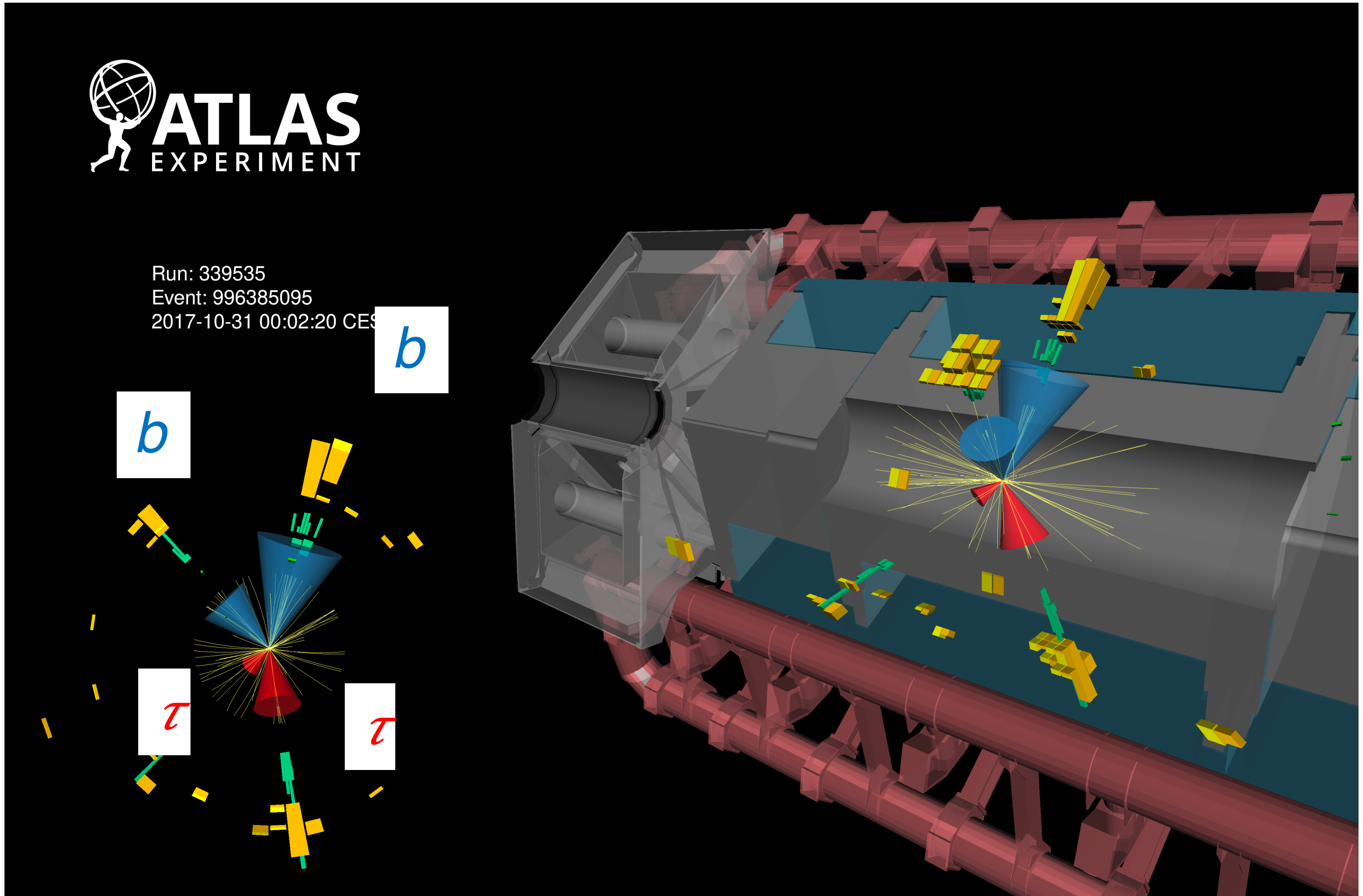
Resolved vs boosted
Boosted analysis dominated K_{2V} sensitivity



$HH \rightarrow bb\tau\tau$ @ run 2

❖ **Medium Branching fraction BR (7.3%), good signal selection purity**

➢ **2 b-jets and 2τ (two hadronic $\tau_h\tau_h$, or one leptonic and one hadronic $\tau_\ell\tau_h$)**



	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
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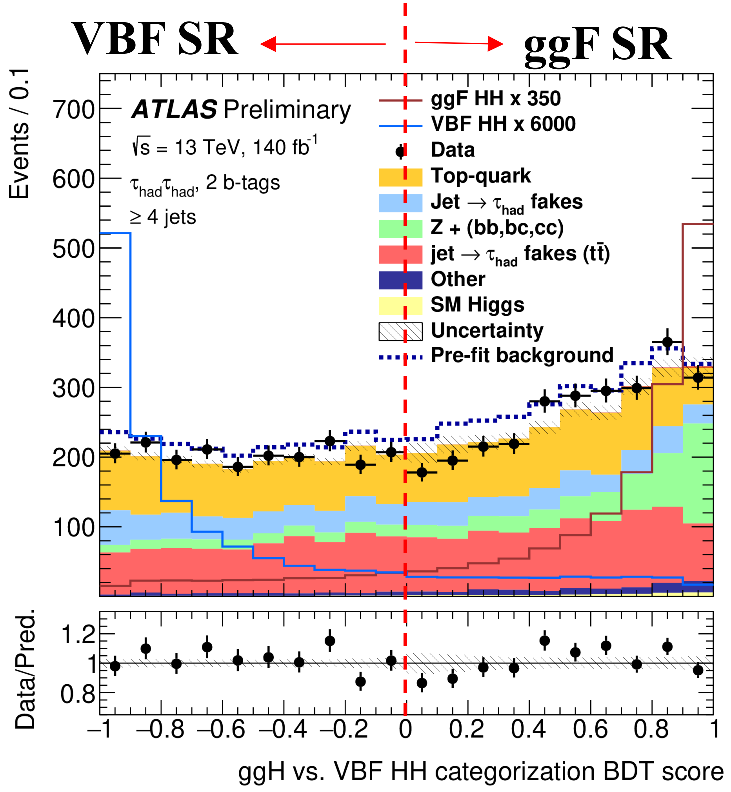
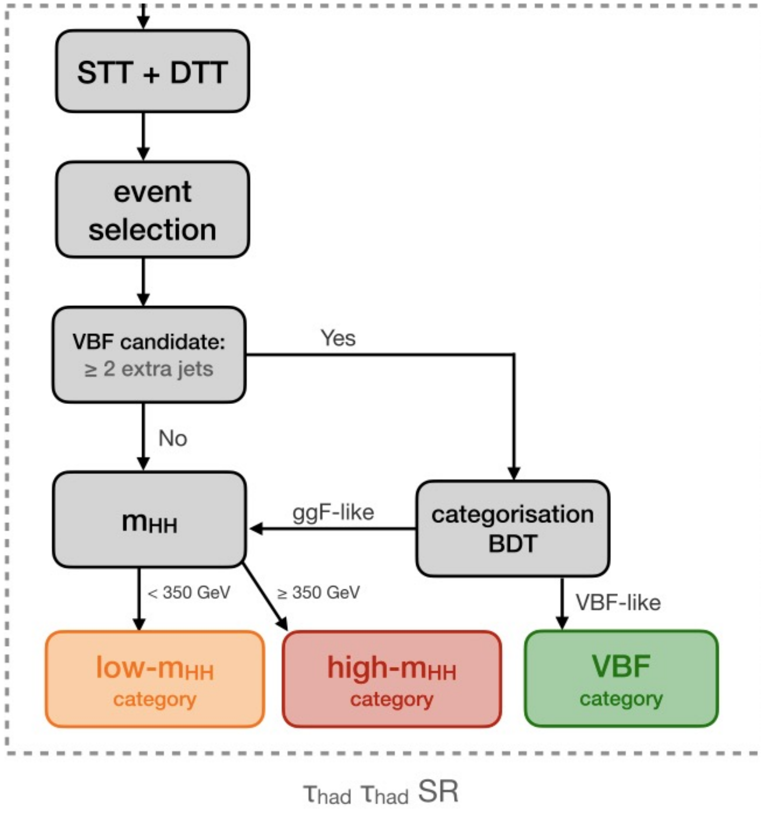
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

$HH \rightarrow bb\tau\tau$

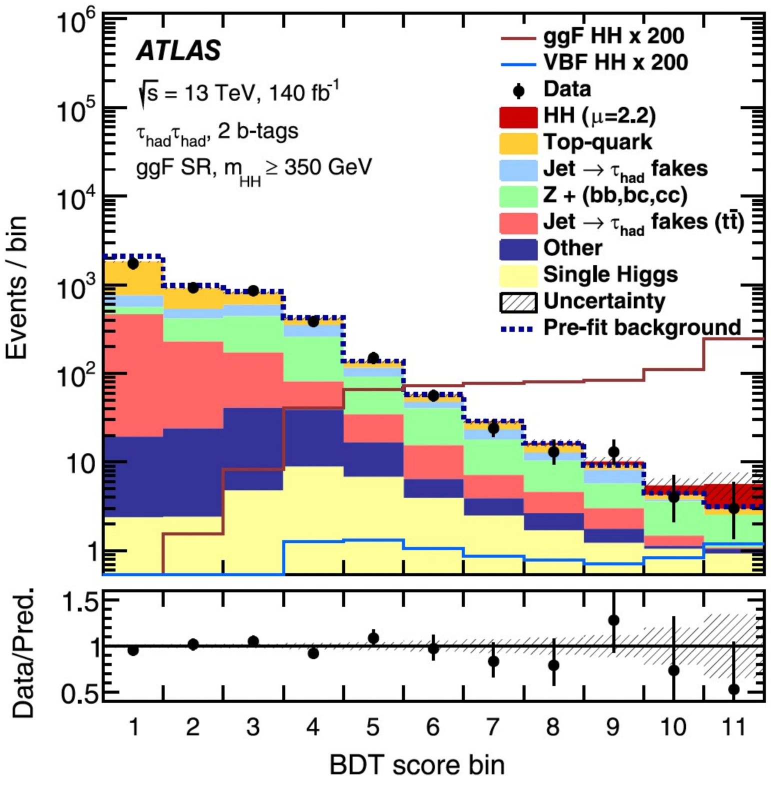
Phys. Rev. D 110 (2024) 032012

- **Event selection:** 2 b-jets and 2τ ($\tau_h\tau_h$ or $\tau_\ell\tau_h$), BDT to category VBF and ggF
- **Strategy :** BDT score is fitted in 3 categories: ggF low-m_{HH}, ggF high-m_{HH} and VBF
- **Background:** real τ from ttbar, Z→τ τ+ jets, fake τ from multijets and ttbar





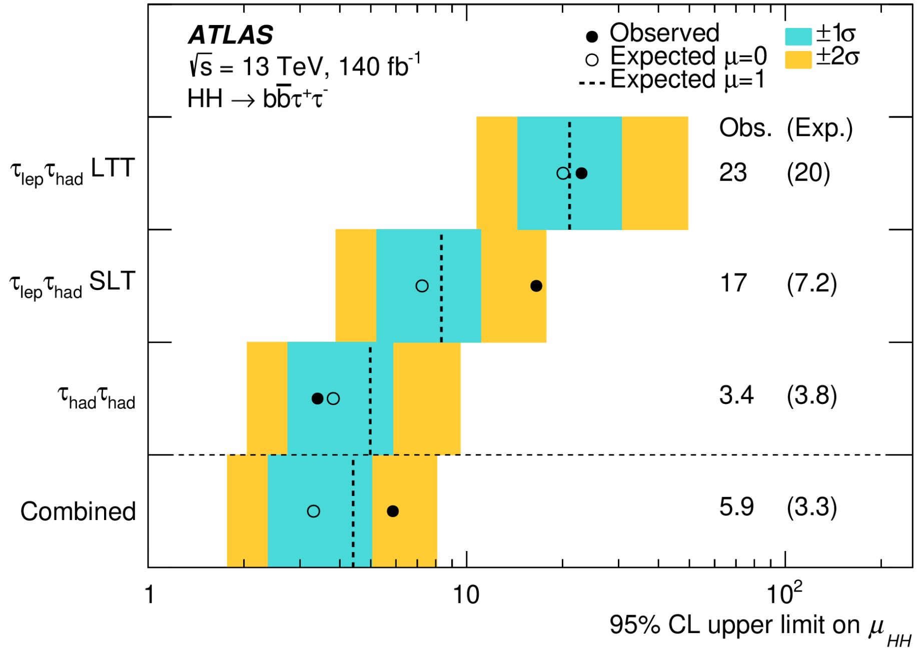
BDT output for signal extraction



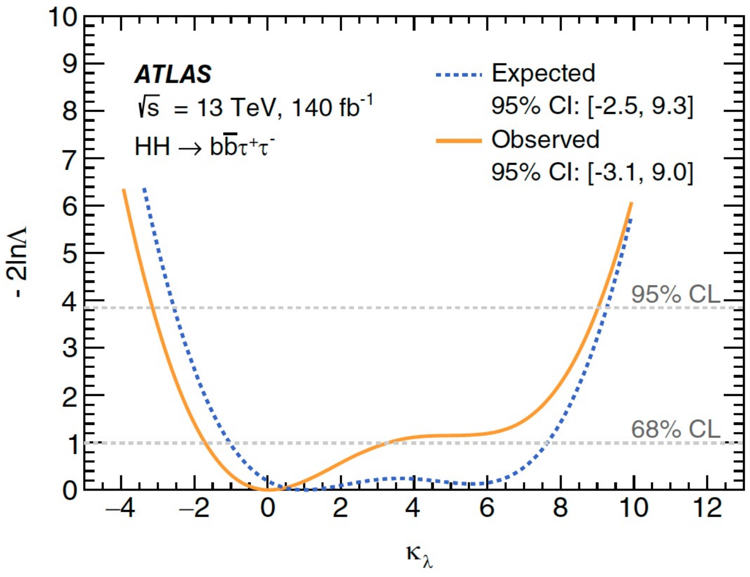
❖**Signal extraction:** by combining the BDT scores across the 3 Signal Regions

❖**Result:** sensitivity driven by fully hadronic channel $\tau_h\tau_h$

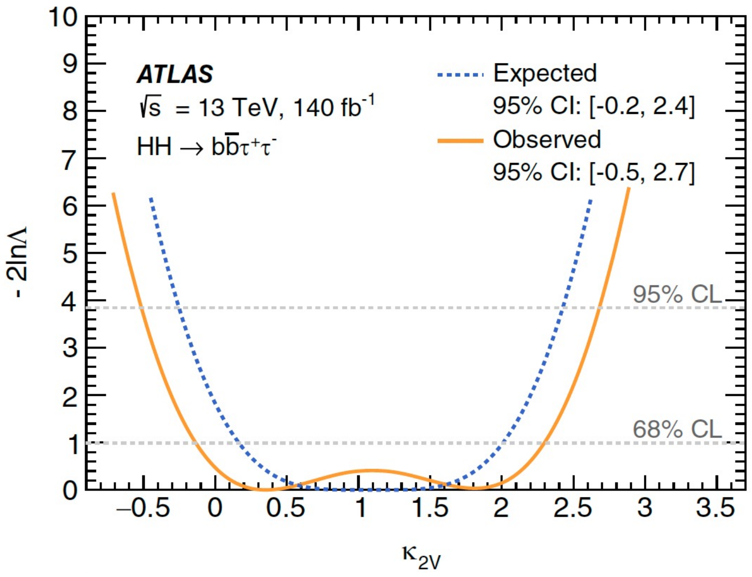
❖**Observed (expected) upper limit on μ_{HH} is 5.9 (3.3)**



Observed: $\kappa_{\lambda} \in [-3.1, 9.0]$
Expected: $\kappa_{\lambda} \in [-2.5, 9.3]$



Observed: $\kappa_{2V} \in [-0.5, 2.7]$
Expected: $\kappa_{2V} \in [-0.2, 2.4]$



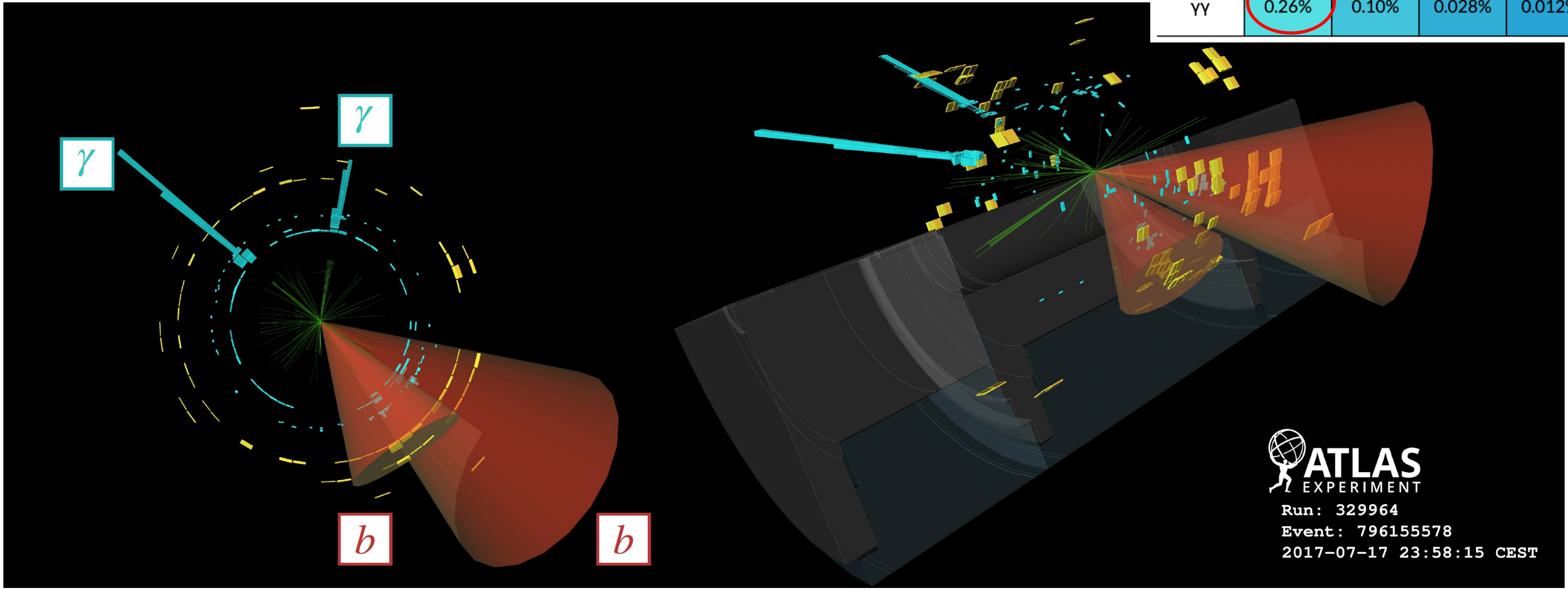
HH → bbγγ @ run 2

JHEP 01 (2024) 066

❖ **Clean channel, but low BR (0.26%)**

❖ **2 *b*-jets and 2 photons**

	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%

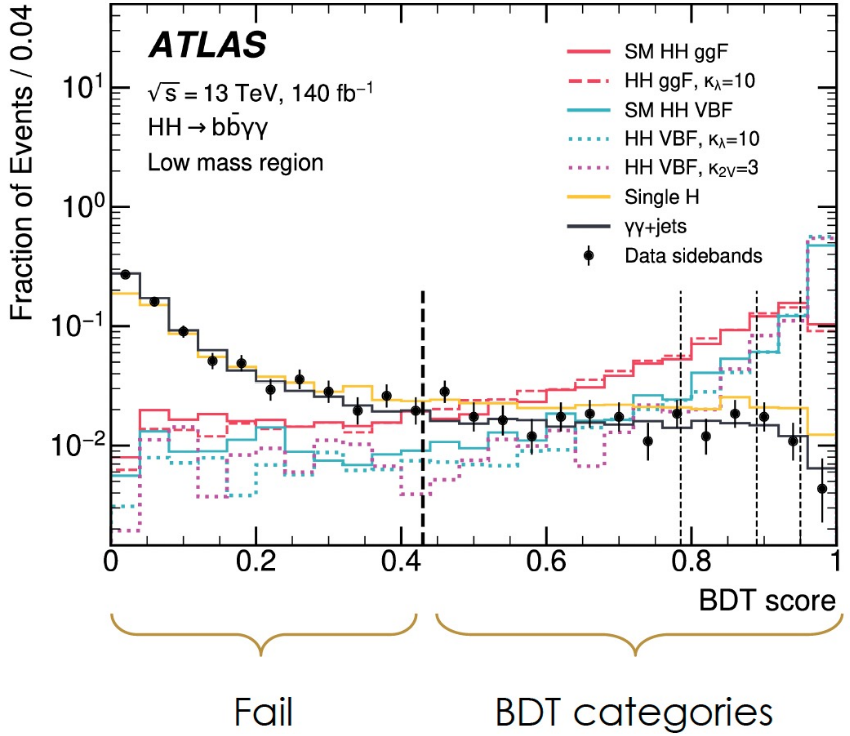


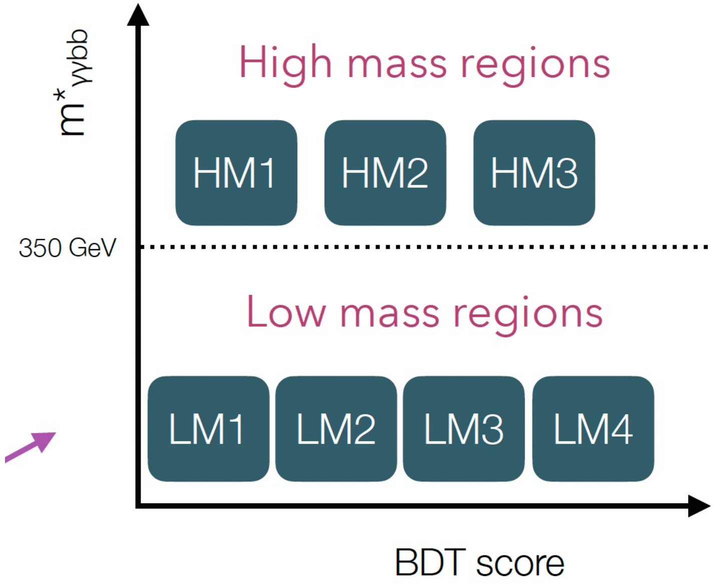
JHEP 01 (2024) 066

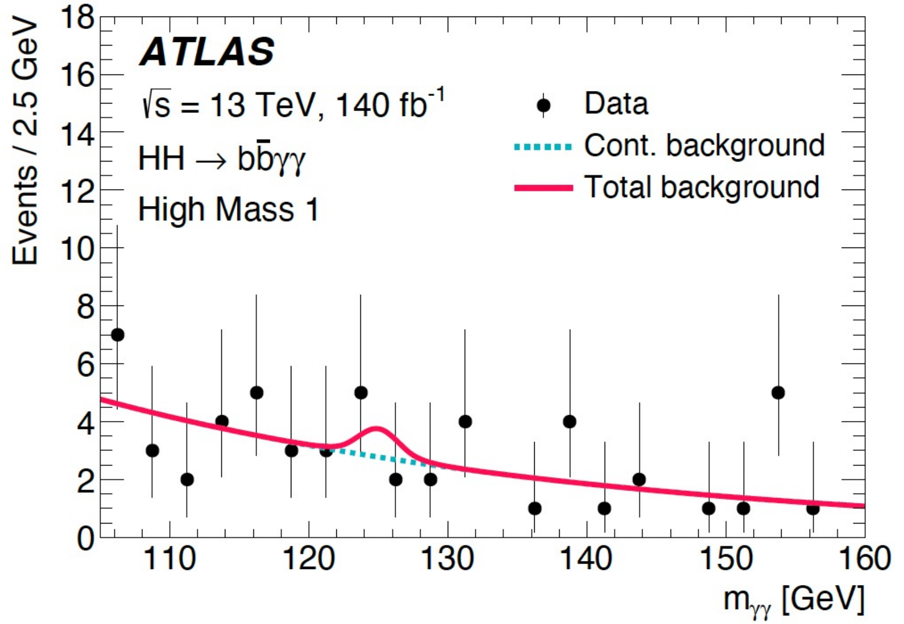
❖ BDT trained to to categorize events according to signal purity

- Events are first split in low/high-mHH regions
- then in each category BDT are trained to categorize events according to signal purity

❖ Extract signal from $m_{\gamma\gamma}$ fit, sidebands from low BDT bins



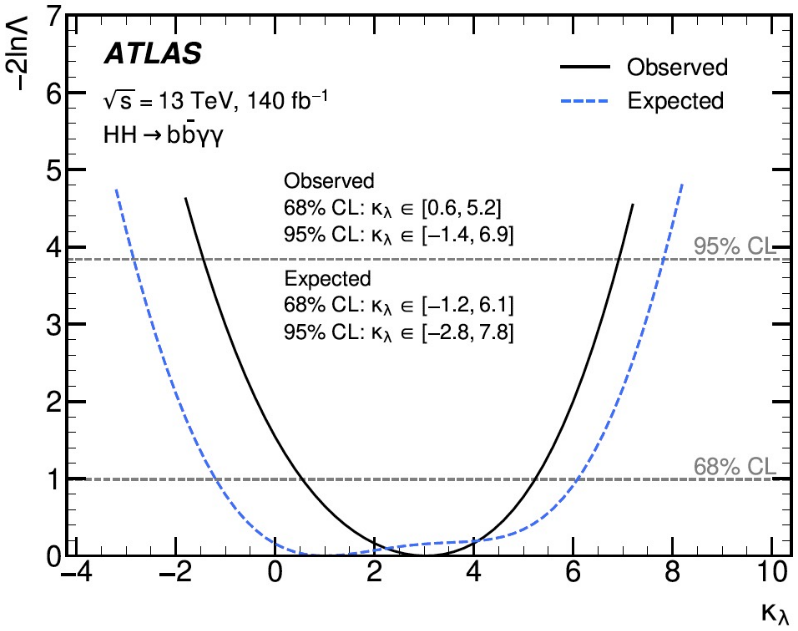


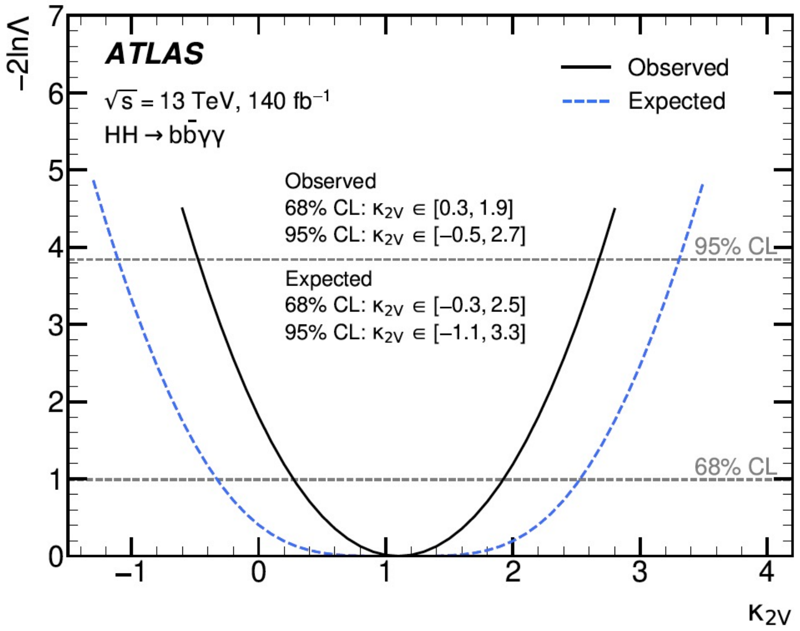


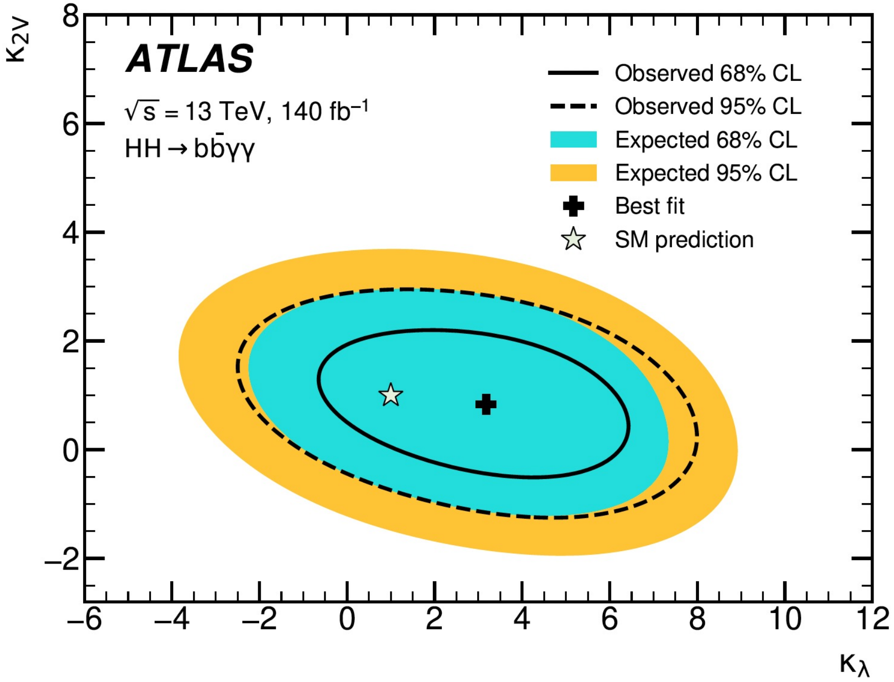
❖Observed (expected) upper limit on μ_{HH} is 4.0 (5.0).

Observed: $\kappa_{\lambda} \in$ [-1.4,6.9]
Expected: $\kappa_{\lambda} \in$ [-2.8, 7.8]

Observed: $\kappa_{2V} \in$ [-0.5,2.7]
Expected: $\kappa_{2V} \in$ [-1.1,3.3]





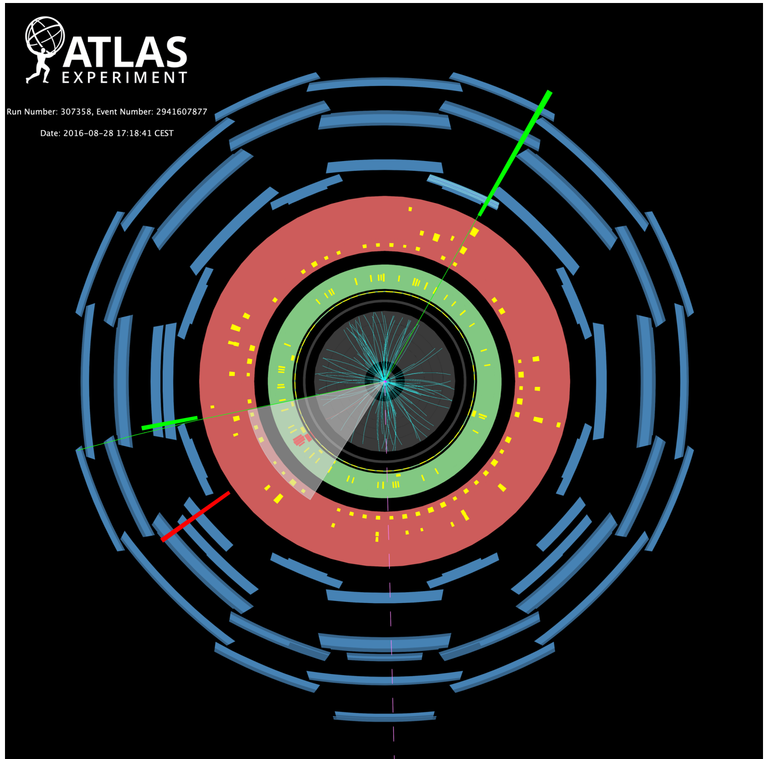


HH → multileptons *@ run 2*

❖**Includes many decay modes:**

- γγ+ multileptons
- Multileptons

❖**Multiple selections based on number of leptons (e, μ, τ) and photons**



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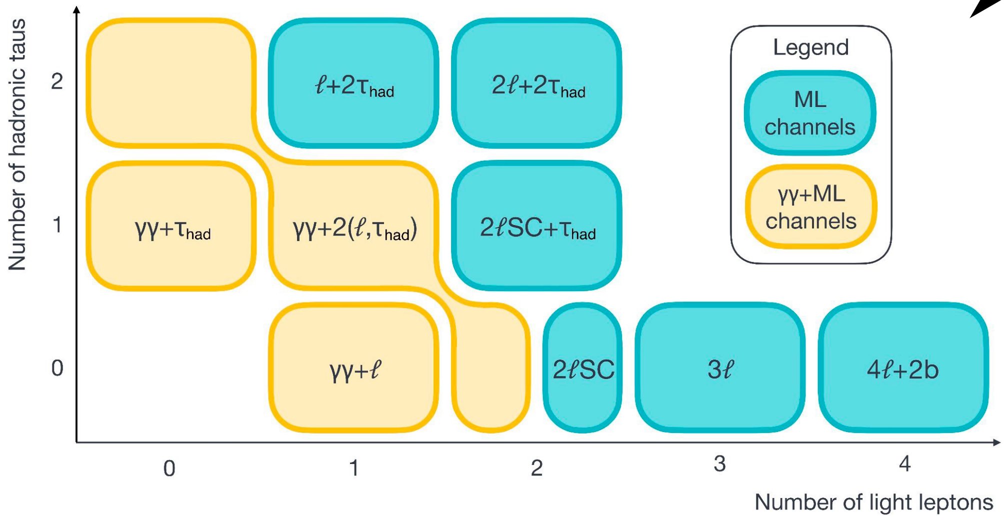
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

HH → multileptons

JHEP 08 (2024) 164

❖ **Selections based on number of leptons (e, μ, τ) and γ**

❖ **9 signal regions, 19 control regions**

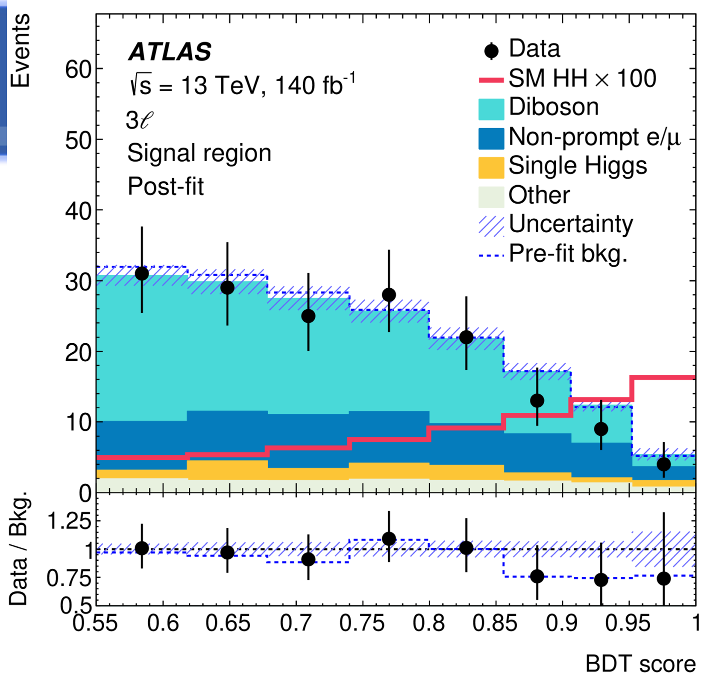


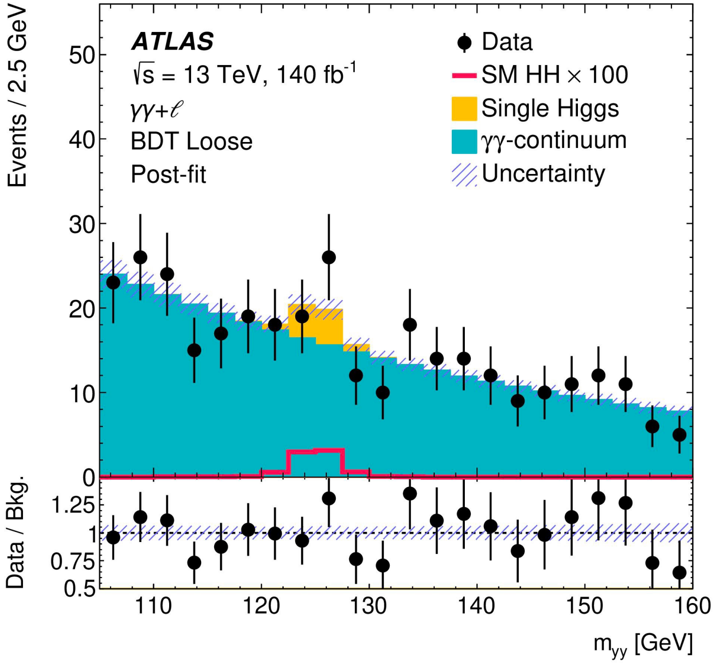
ML channels

- Cut-based categorization
- Signal extraction from BDT score

γγ+ML channels

- BDT categorization
- Signal extraction from $m_{\gamma\gamma}$



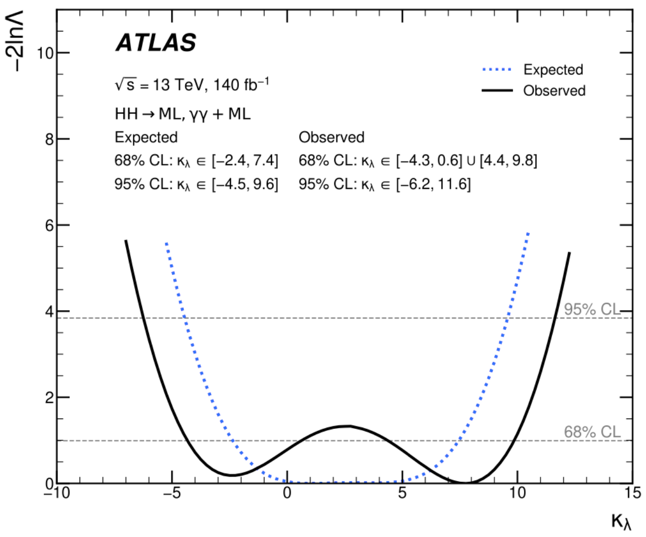


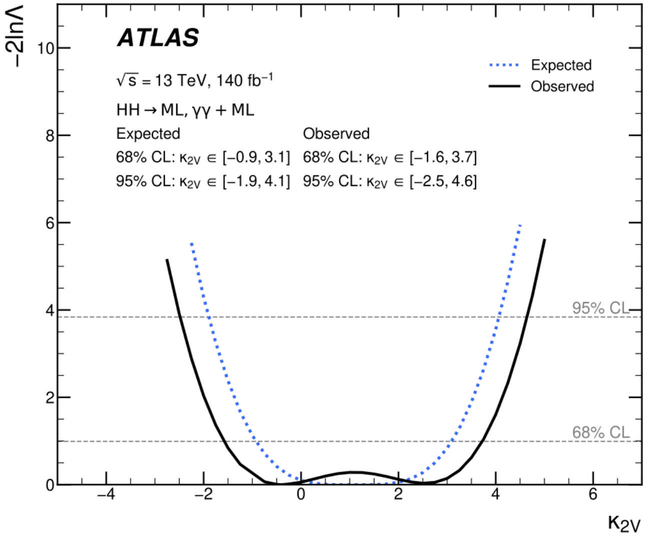
$HH \rightarrow$ multileptons

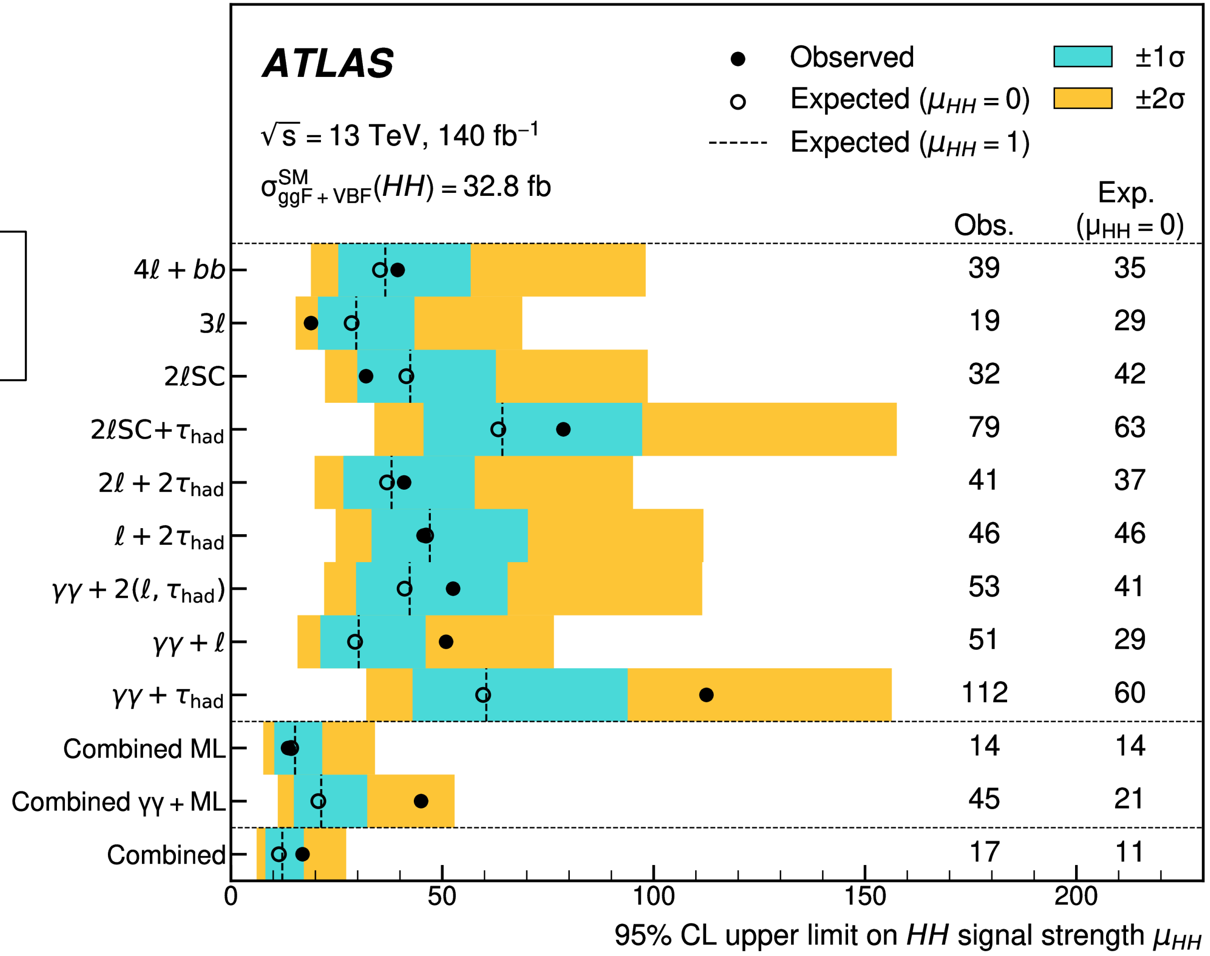
- ❖Observed (expected) upper limit on μ_{HH} is 17 (11).
- ❖No single channel is dominating

Observed: $\kappa_{\lambda} \in [-6.2, 11.6]$
Expected: $\kappa_{\lambda} \in [-4.5, 9.6]$

Observed: $\kappa_{2V} \in [-2.5, 4.6]$
Expected: $\kappa_{2V} \in [-1.9, 4.1]$







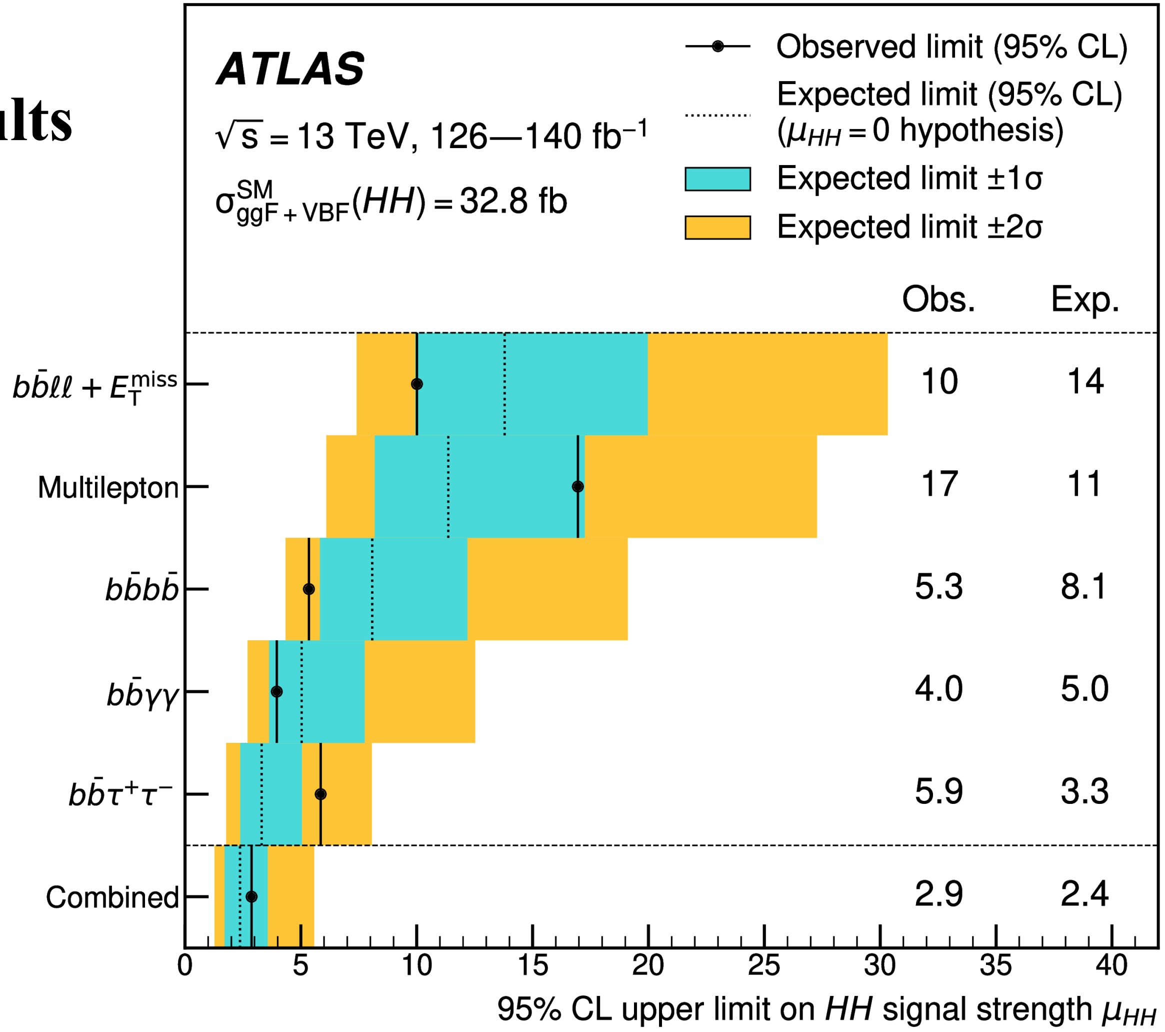
Combination

❖ Recent update in ATLAS HH combination

- ➢ **bbττ, bbγγ improved results**
- ➢ **New boosted VBF 4b added to resolved 4b results**
- ➢ **New multi-leptons and bbℓℓ+MET**

μ_{HH} < 2.9 (2.4 exp.)

σ_{HH} < 85.8 (71.1 exp) fb



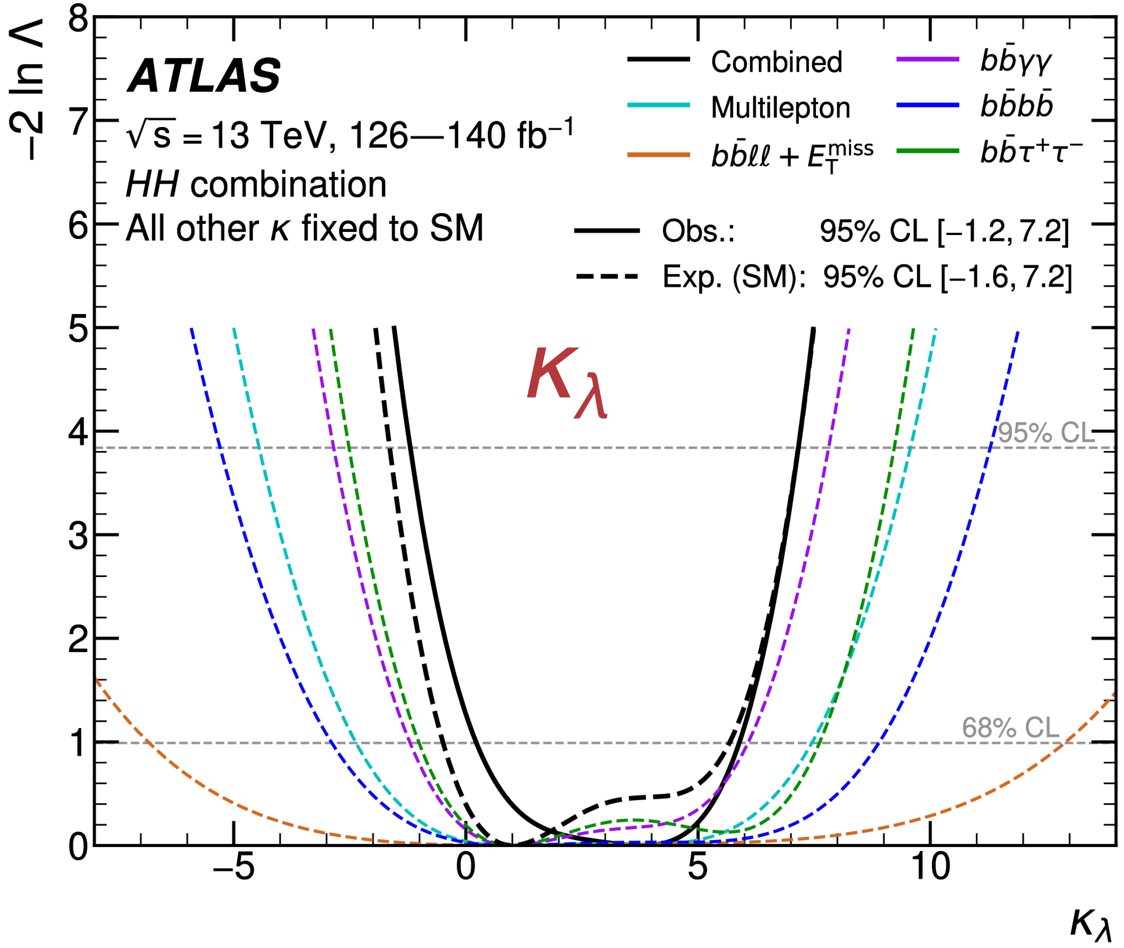
Run 2 HH Combination

Phys. Rev. Lett. 133 (2024) 101801

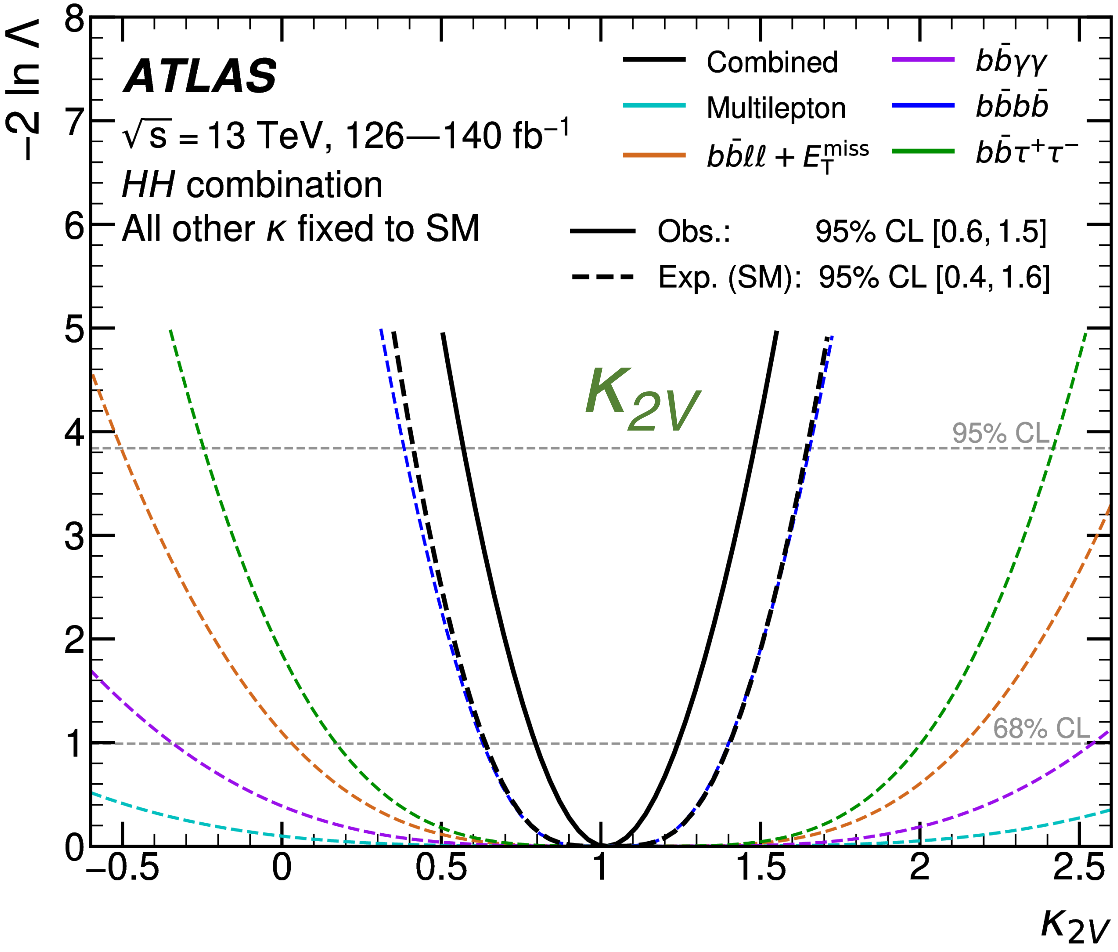
Observed: $\kappa_\lambda \in [-1.2, 7.2]$
Expected: $\kappa_\lambda \in [-1.6, 7.2]$

Observed: $\kappa_{2V} \in [-0.6, 1.5]$
Expected: $\kappa_{2V} \in [-0.4, 1.6]$

Dominated by bbττ, bbγγ



Dominated by boosted VBF 4b



Summary

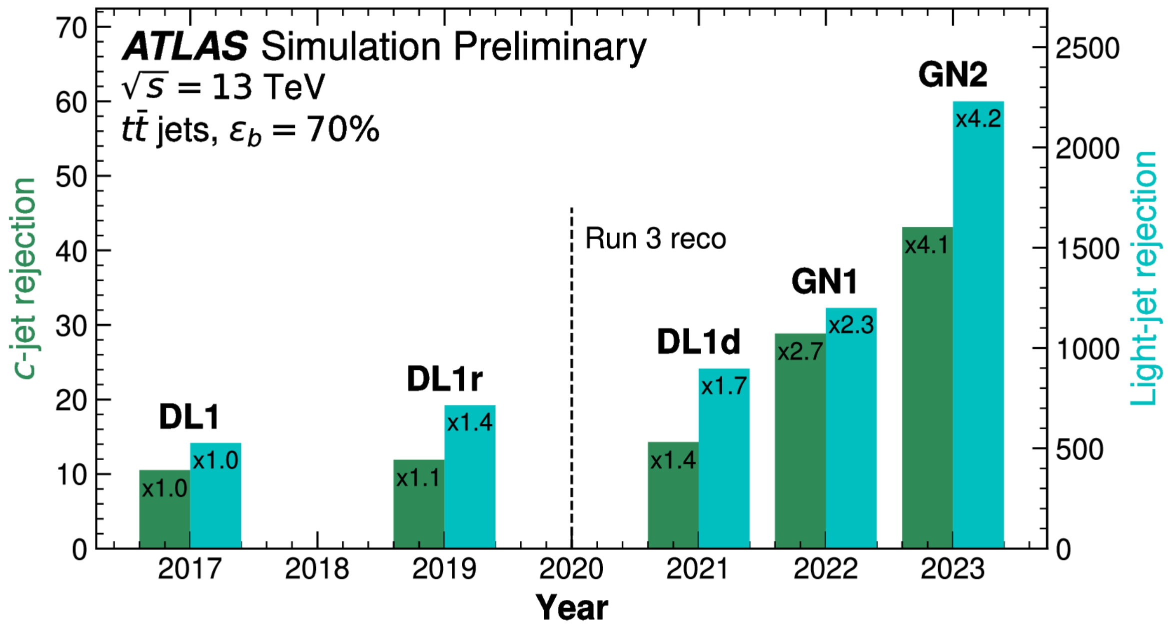
❖ Run 2 combination: Observed (expected) limit on μ_{HH} is 2.9 (2.4).

❖ Run2 Combination results constraints Higgs self-coupling

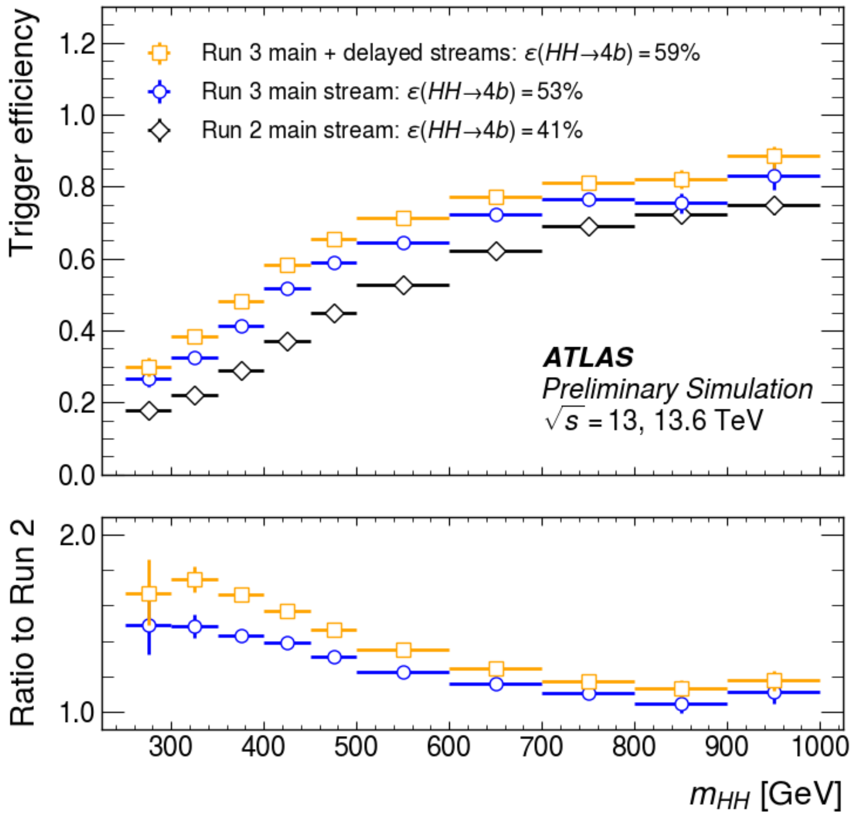
- $\kappa_\lambda \in [-1.2, 7.2]$, $\kappa_{2V} \in [-0.6, 1.5]$ observed limits at 95% CL.

❖ Expect large improvements using Run3 data

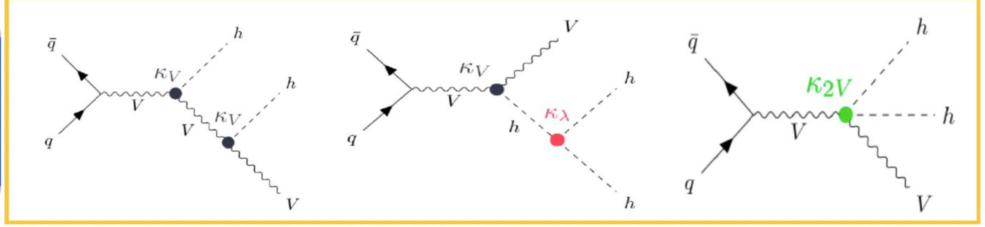
Better flavor jet tagging in run 3



Smarter triggering run 3



VHH @ run 2 Eur. Phys. J. C 83 (2023) 519



❖ **Sensitive to ZZHH and WWHH separately**

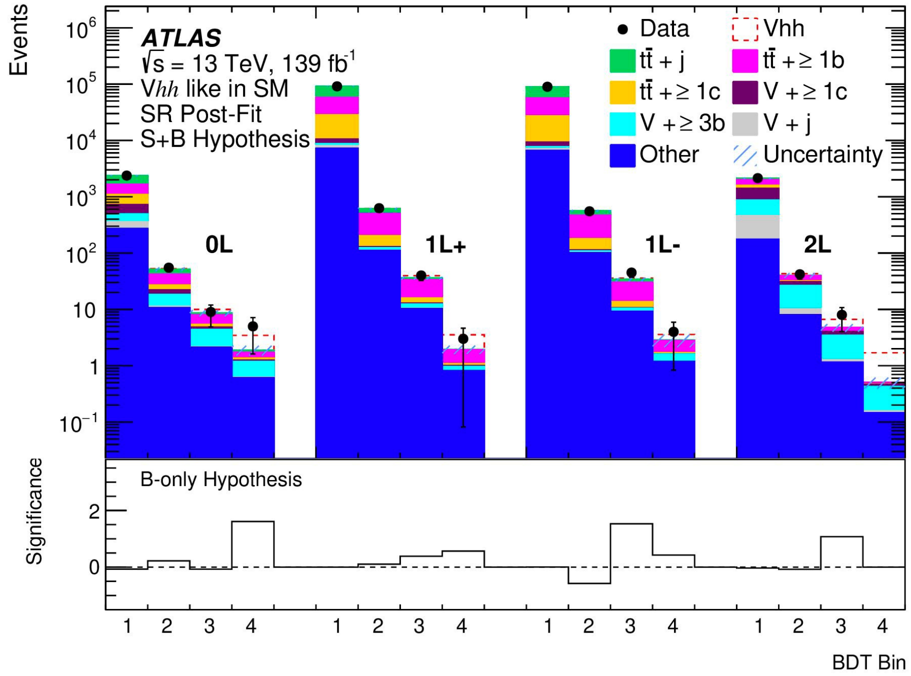
❖ **Different channels explored: Z→$\nu\nu$ (0L), W→lν (1L), Z→ll (2L)**

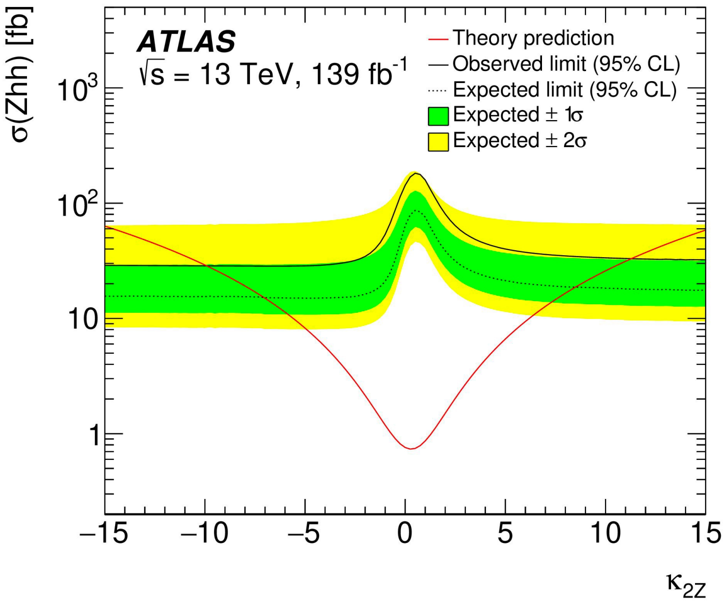
Observed: $\kappa_{2V} \in [-8.6, 10]$
Expected: $\kappa_{2V} \in [-5.7, 7.1]$

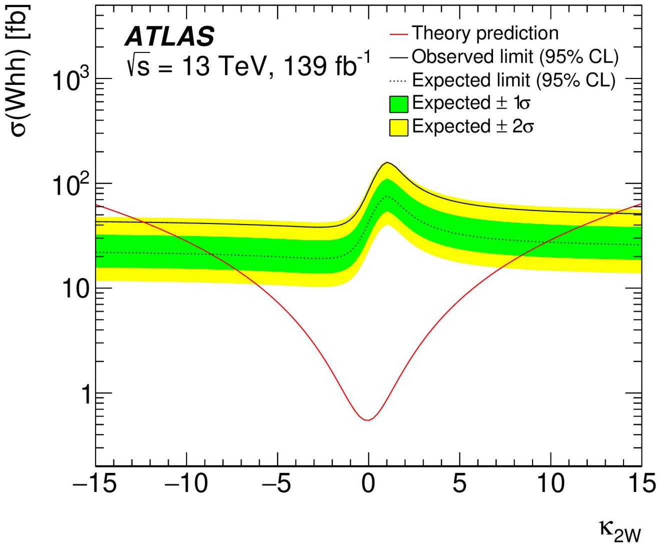
Observed: $\kappa_{\lambda} \in [-34.4, 33.3]$
Expected: $\kappa_{\lambda} \in [-24.1, 22.9]$

Observed: $\kappa_{2Z} \in [-9.9, 11.3]$
Expected: $\kappa_{2Z} \in [-7.1, 8.5]$

Observed: $\kappa_{2W} \in [-12.3, 13.5]$
Expected: $\kappa_{2W} \in [-8.6, 9.8]$



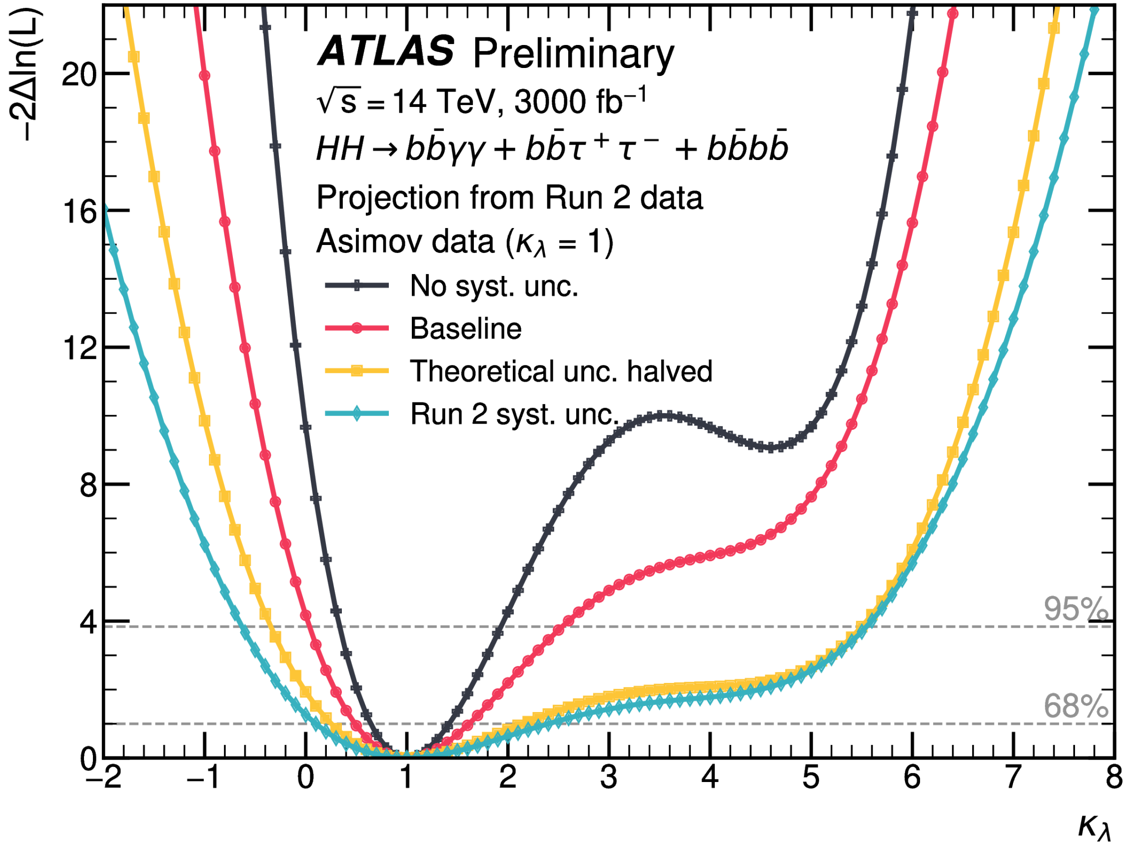


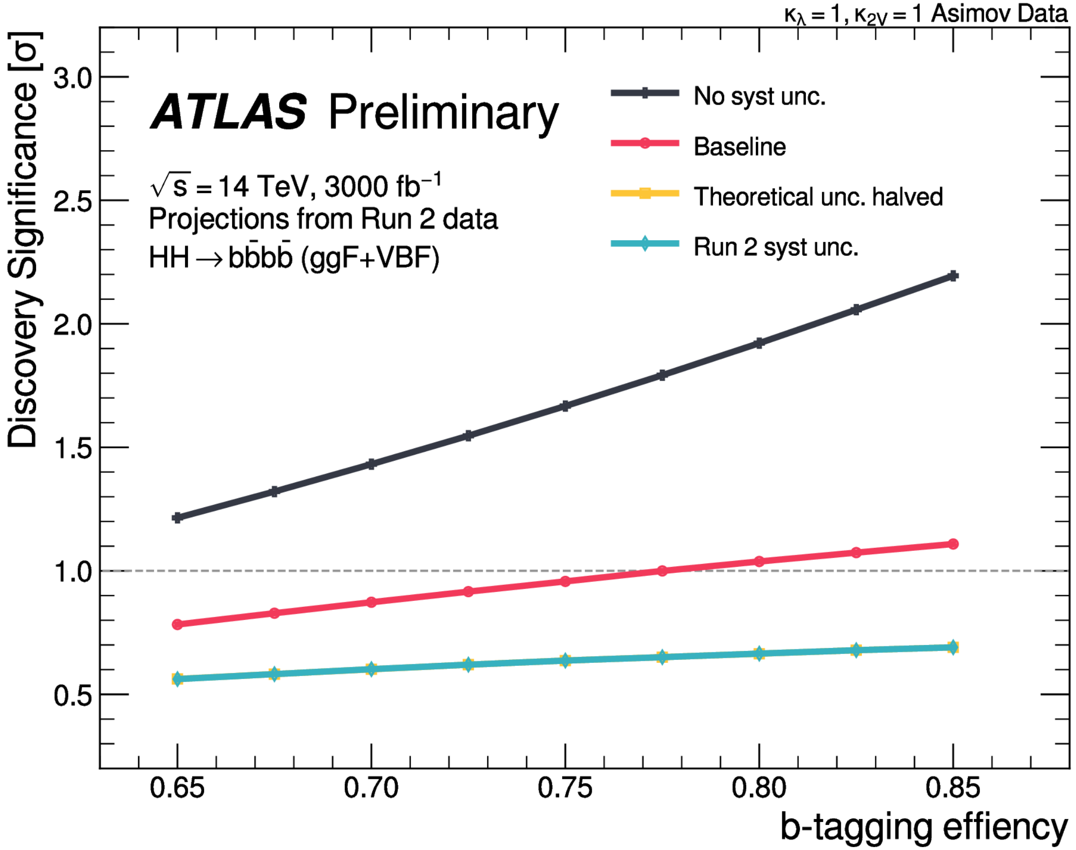


Backup: HL-LHC Projection for $HH \rightarrow bb\gamma\gamma$, $bb\tau\tau$, $bbbb$

- ❖HL-LHC constraints on Higgs self-coupling $\kappa\lambda \in [0.0, 2.5]$
- ❖HL-LHC, systematic uncertainty become limiting factor

ATL-PHYS-PUB-2022-053





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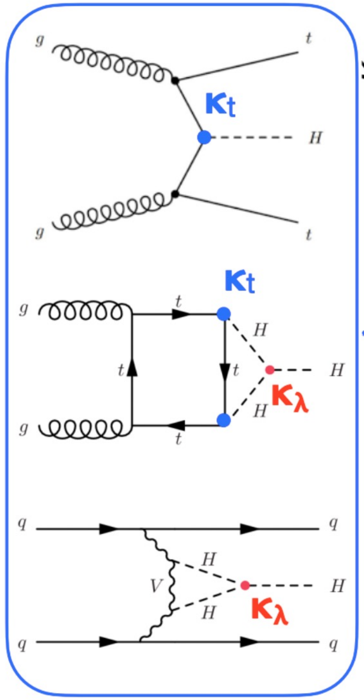
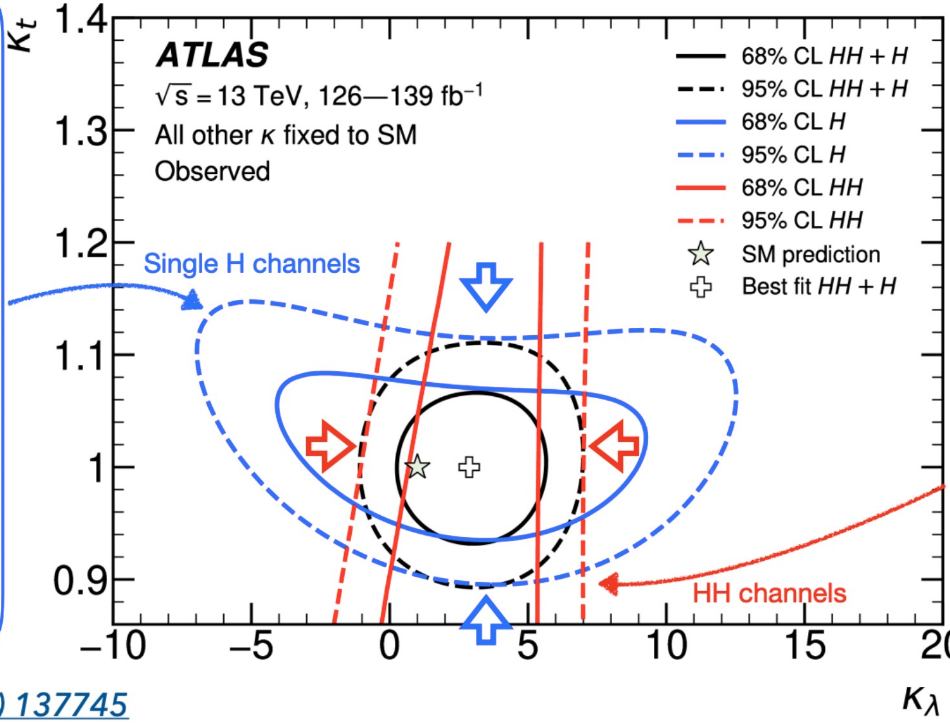
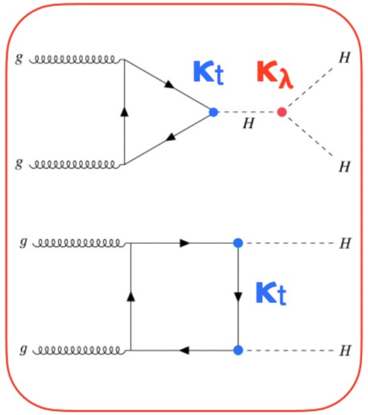
Backup: H+ HH combination

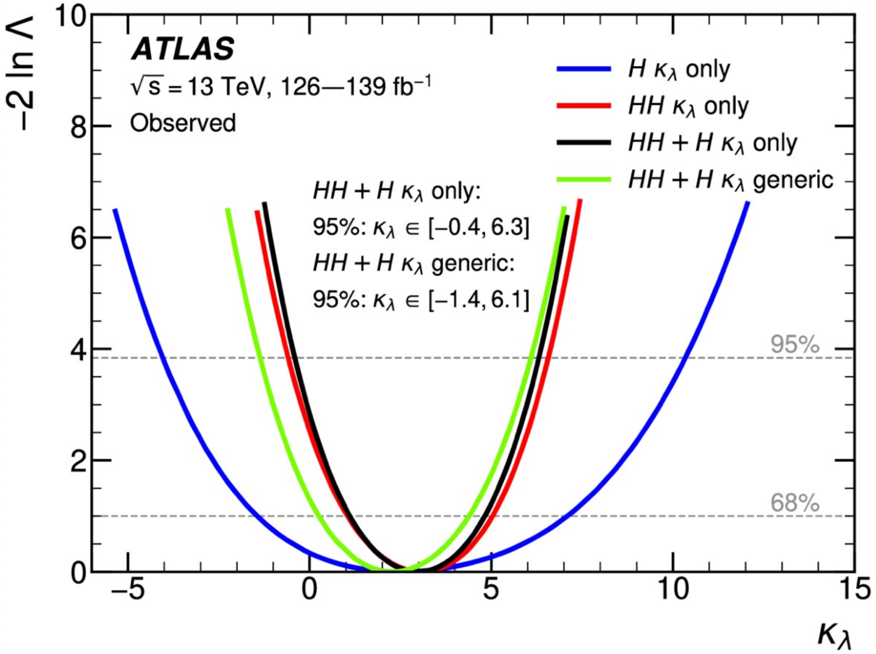
- ❖ κ_λ contributes to single-H at NLO EW corrections (indirect constraint)
- ❖ Combination with partials HH channels

Observed: HH+H only, $\kappa_\lambda \in [-0.4,6.3]$
Expected: HH+H only, $\kappa_\lambda \in [-1.9, 7.6]$









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Introduction

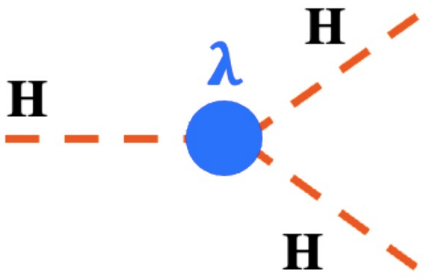
❖ **Study HH production allows for direct probing of the Higgs self-coupling**

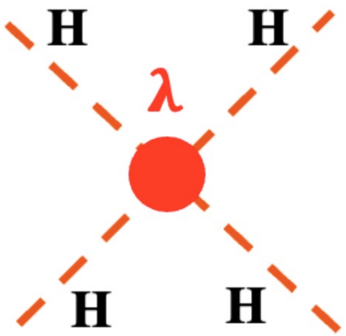
$$V \approx \lambda v^2 h^2 + \lambda v h^3 + \lambda h^4 + \dots$$

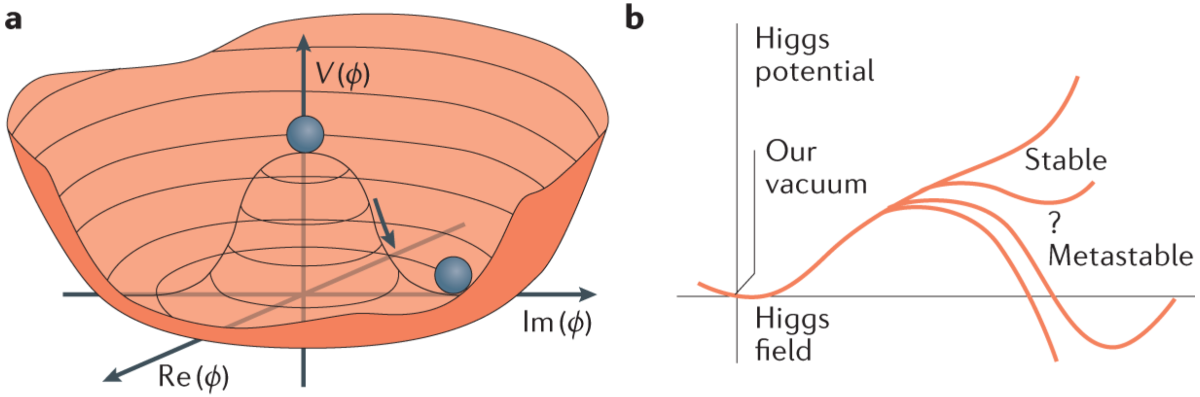
- $\lambda v^2 h^2$ → Mass term: $\frac{1}{2} m_h^2$
- $\lambda v h^3$ → Trilinear coupling: $\lambda_{hhh}^{SM} = \frac{m_h^2}{2v^2} \approx 0.13$

$$\kappa_\lambda = \lambda_{hhh} / \lambda_{hhh(SM)}$$

$$\kappa_{2V} = \lambda_{hhVV} / \lambda_{hhVV(SM)}$$







$HH \rightarrow bb\tau\tau$: category