Combination of searches for Higgs boson pair production in the ATLAS experiment

Partikeldagarna 2024, Uppsala

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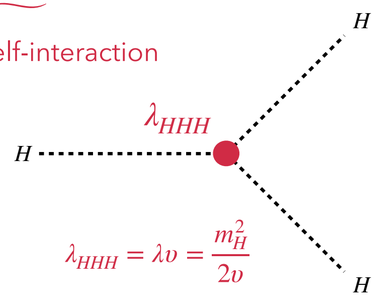
Why look for Higgs boson pairs?

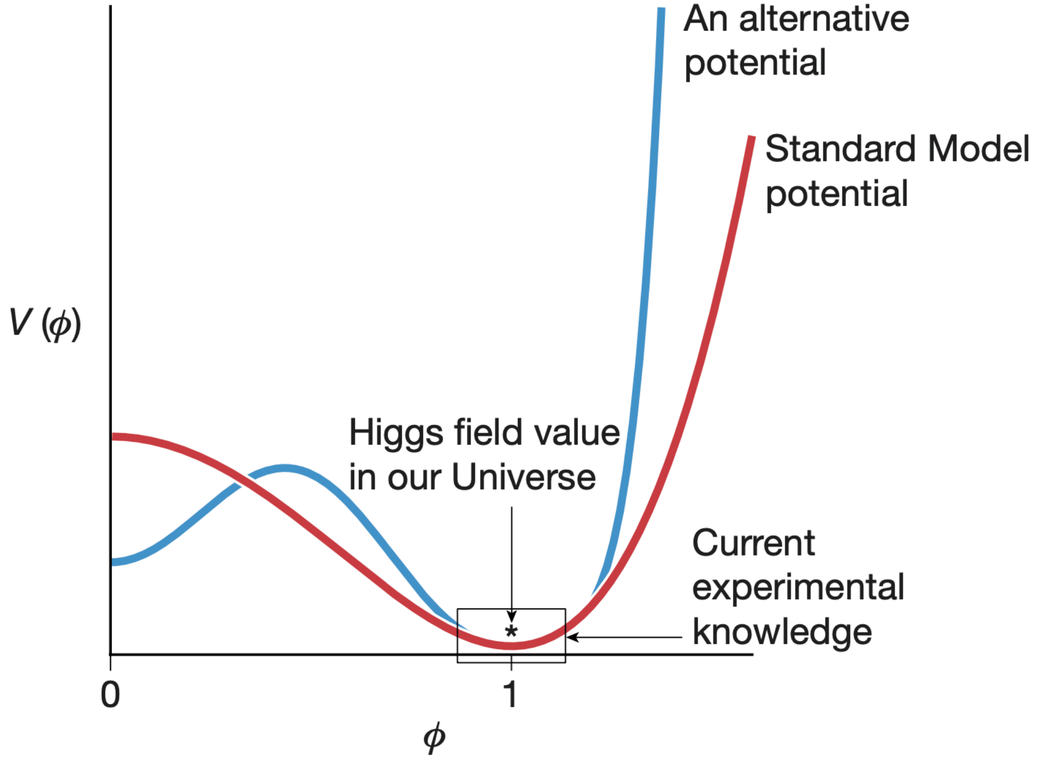
Experimental probe of the Higgs boson self-interaction

- Little knowledge about the Higgs potential shape
- Substantial differences away from minimum possible based on current data
- Crucial to measure the **Higgs boson self-coupling**

In SM: $V(\phi) = -\mu^2\phi^2 + \lambda\phi^4 \supset \lambda v^2 H^2 + \lambda v^3 + \ldots$

trilinear self-interaction



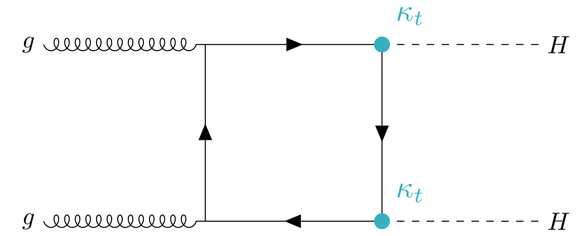


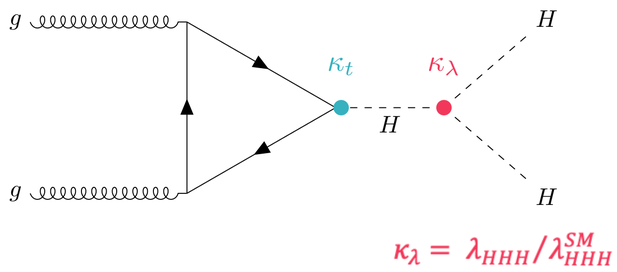
Nature 607, 41-47 (2022)

HH production at the LHC

Dominant ggF production mode

- Elusive process according to SM
  - Destructive interference between the two diagrams
- New physics parameterised with coupling modifiers



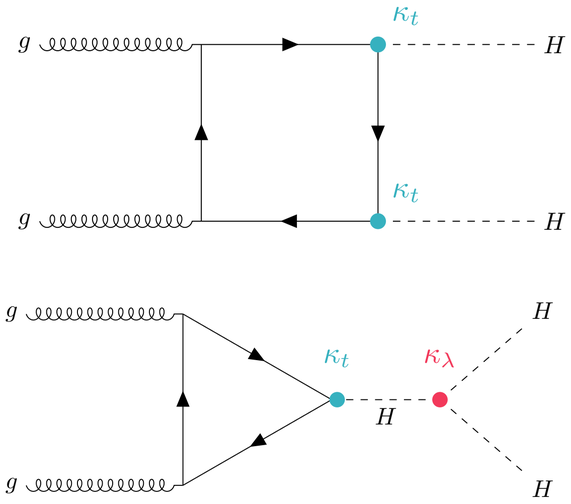


$\kappa_\lambda = \lambda_{HHH}/\lambda_{HHH}^{SM}$

HH production at the LHC

Dominant ggF production mode

- Elusive process according to SM
  - Destructive interference between the two diagrams
- New physics parameterised with coupling modifiers
- HH cross-section and kinematics vary with κ_λ



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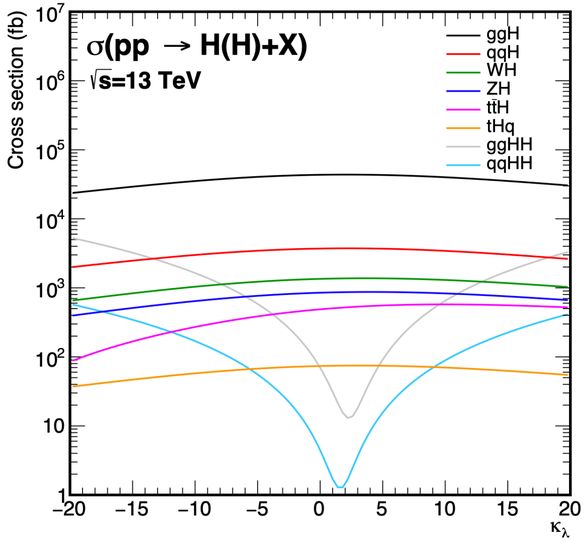
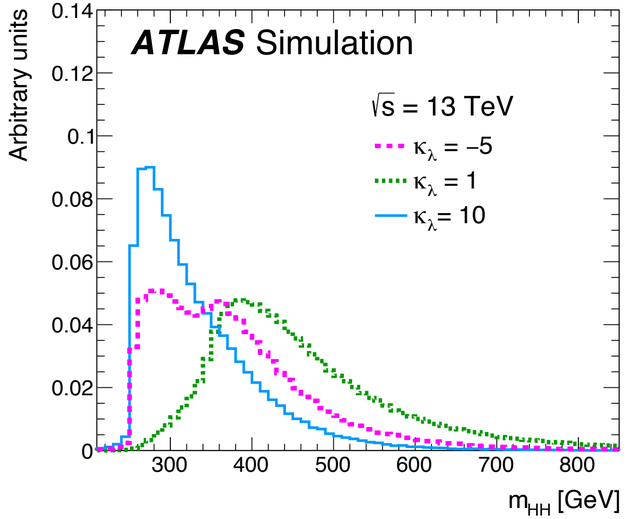


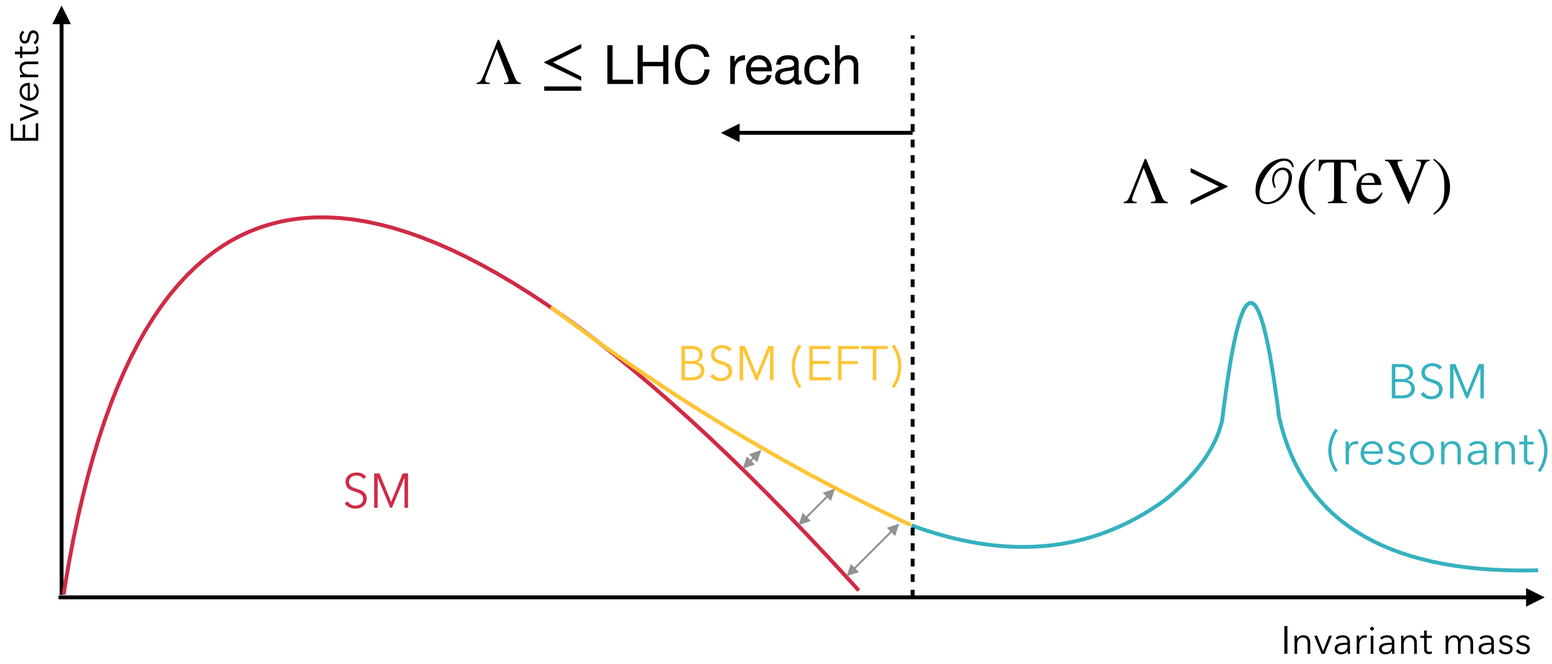


Any deviation of κ_λ from 1 is a sign of new physics ✨

HH production beyond the SM

… through Effective Field Theories (EFTs)

- EFTs may reveal high-energy phenomena through precise measurements at low energy
- They introduce higher-order operators or point-like anomalous couplings to model the new physics effects



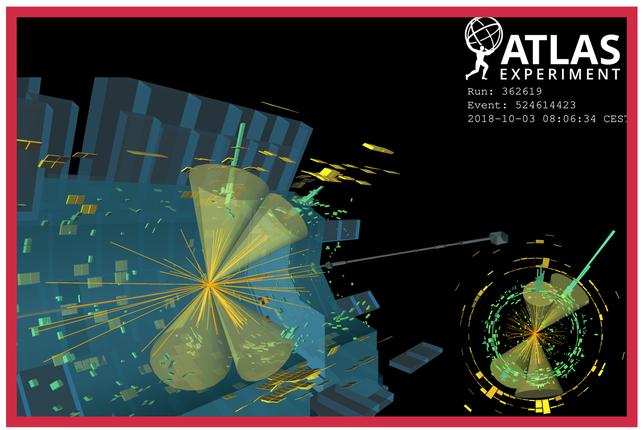
HH decay modes

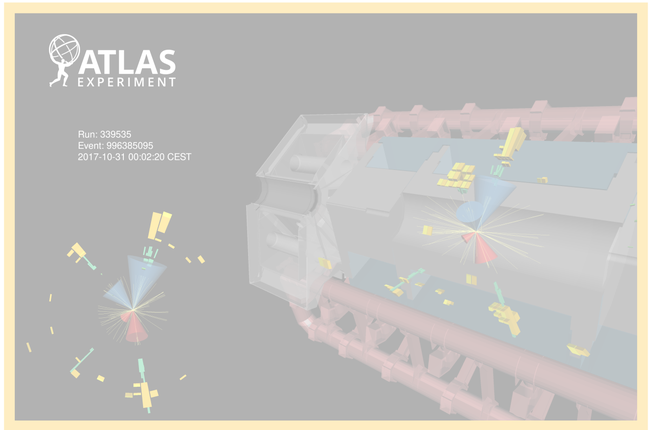
Multiple topologies but 3 most sensitive search channels

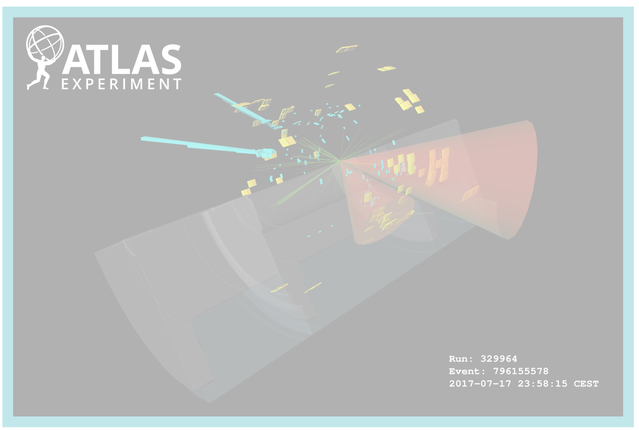
- $HH \to bbbb$ plenty of signal 👍, but challenging multijet background 😢
- $HH \to bb\tau\tau$ moderate signal rate, relatively clean final state ⚖️
- $HH \to bb\gamma\gamma$ very clean signature 👍, but tiny branching ratio 😢

Branching ratios

	$b\bar{b}$	W^+W^-	$\tau^+\tau^-$	ZZ^*	$\gamma\gamma$
$b\bar{b}$	34%				
W^+W^-	25%	4.6%			
$\tau^+\tau^-$	7.3%	2.7%	0.39%		
ZZ^*	3.1%	1.1%	0.33%	0.069%	
$\gamma\gamma$	0.26%	0.097%	0.028%	0.012%	0.00052%







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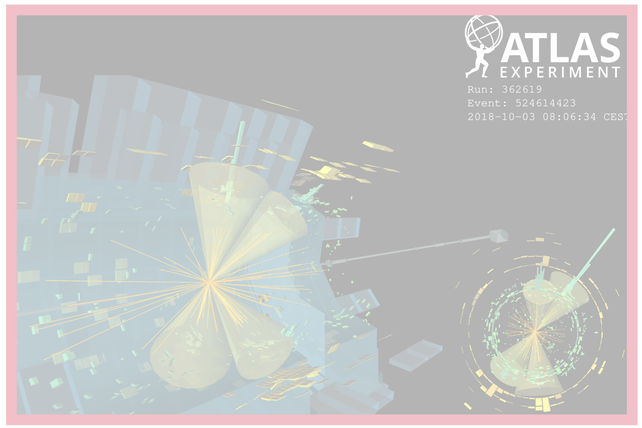

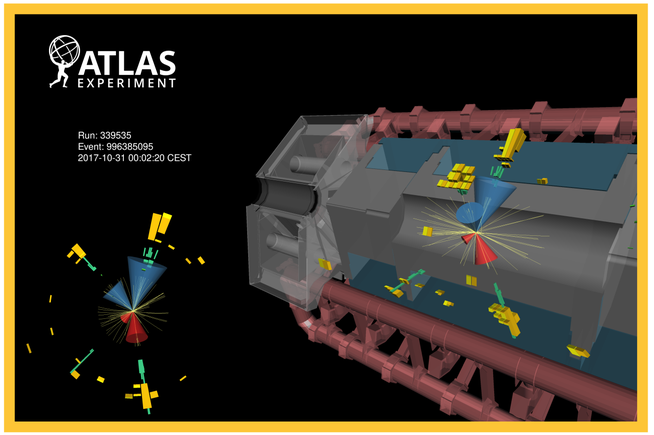

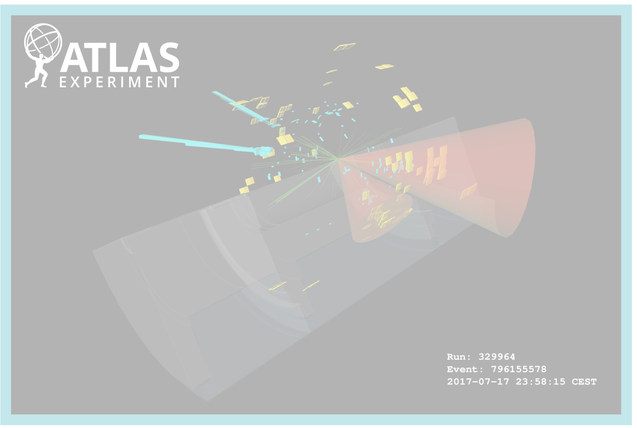

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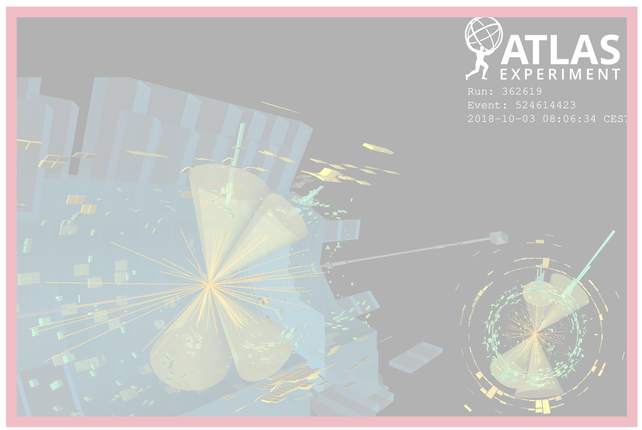
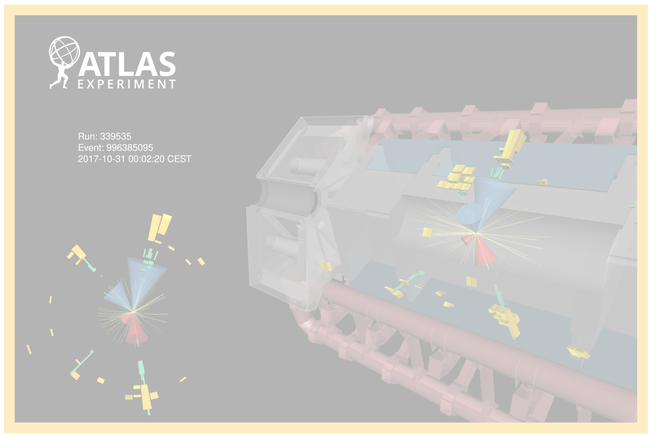
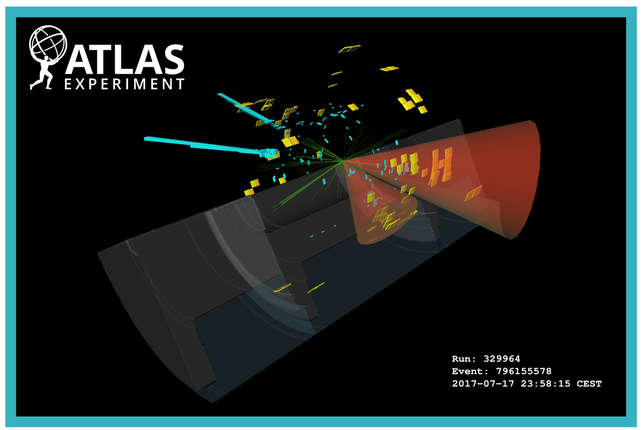


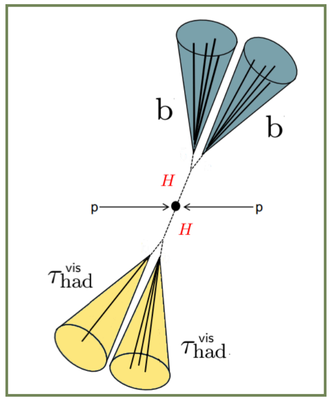


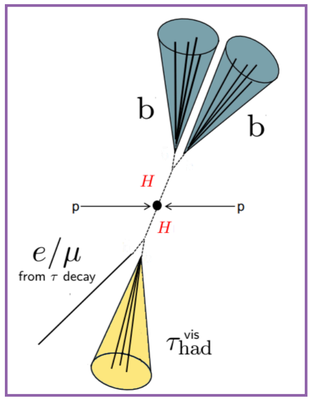


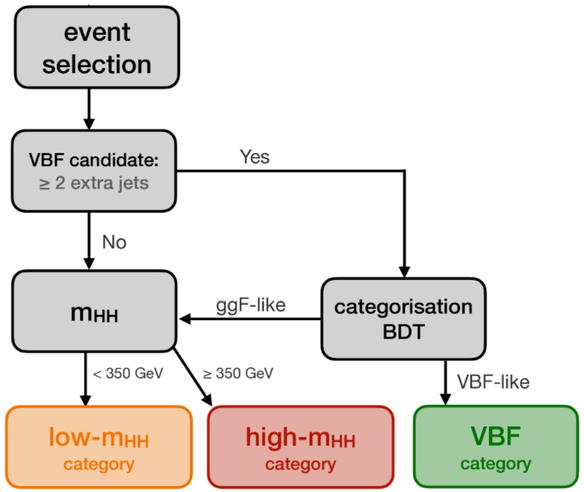
Overview of the HH→bbττ search

Spoiler: strongest limits on HH production, tight constraints on κ_λ

- $bb\tau_{\text{had}}\tau_{\text{had}}$ and $bb\tau_{\text{lep}}\tau_{\text{had}}$ final states
- 3 regions driven by triggers
- + further event categorisation for each region ⇒ 9 SRs







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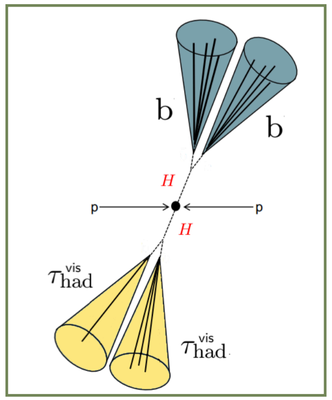
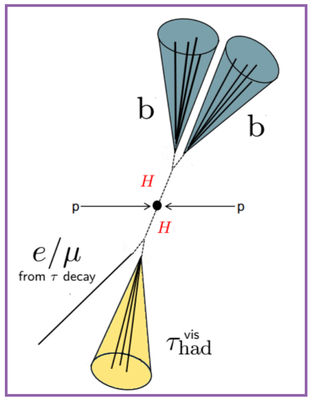
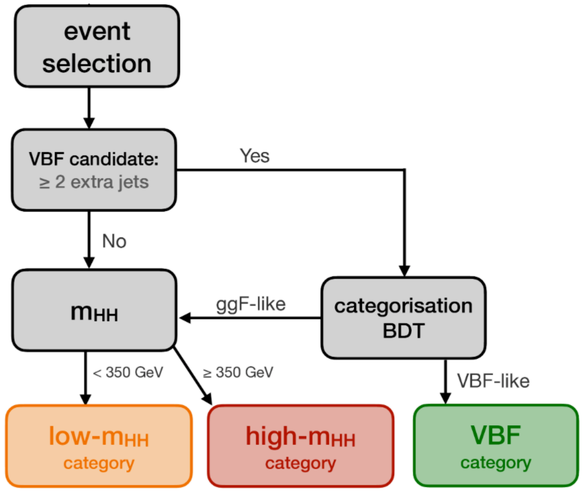
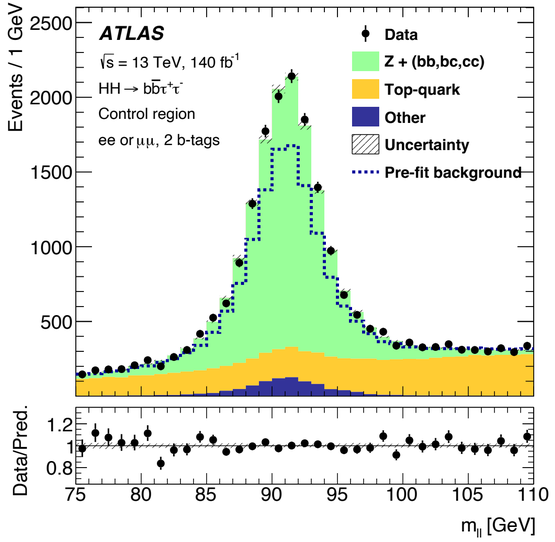
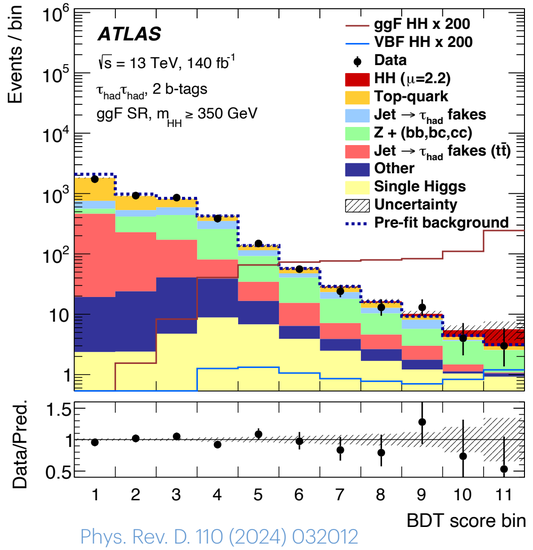
- 3 regions driven by triggers
- + further event categorisation for each region ⇒ 9 SRs
- 1 CR to constrain the Z+bb/cc background
- Signal extraction: BDTs in the 9 SRs, m_{ll} in the CR









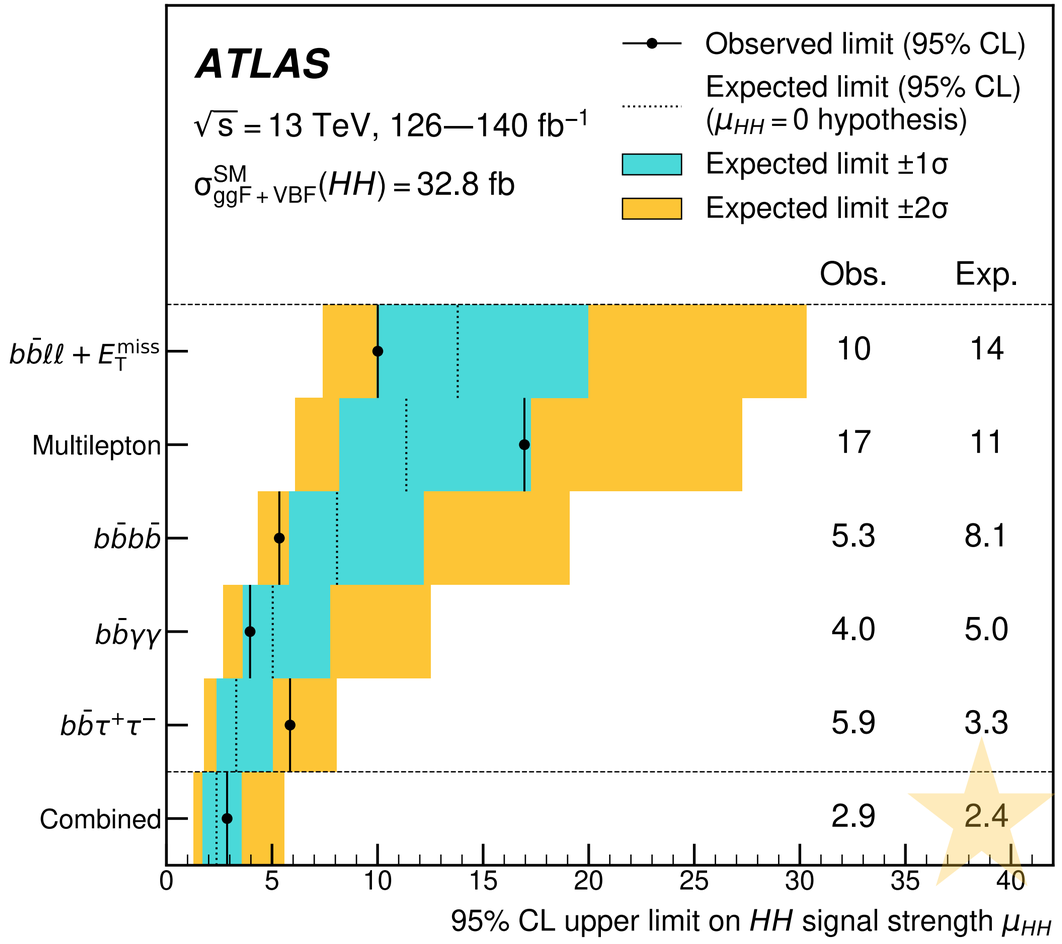


Phys. Rev. D. 110 (2024) 032012

Combination of HH searches

SM HH sensitivity

- Each analysis uses the full Run 2 dataset
- Combining them all maximises sensitivity
- Strongest expected constraints to date on μ_{HH}
  - 17% improvement wrt previous Run 2 combination

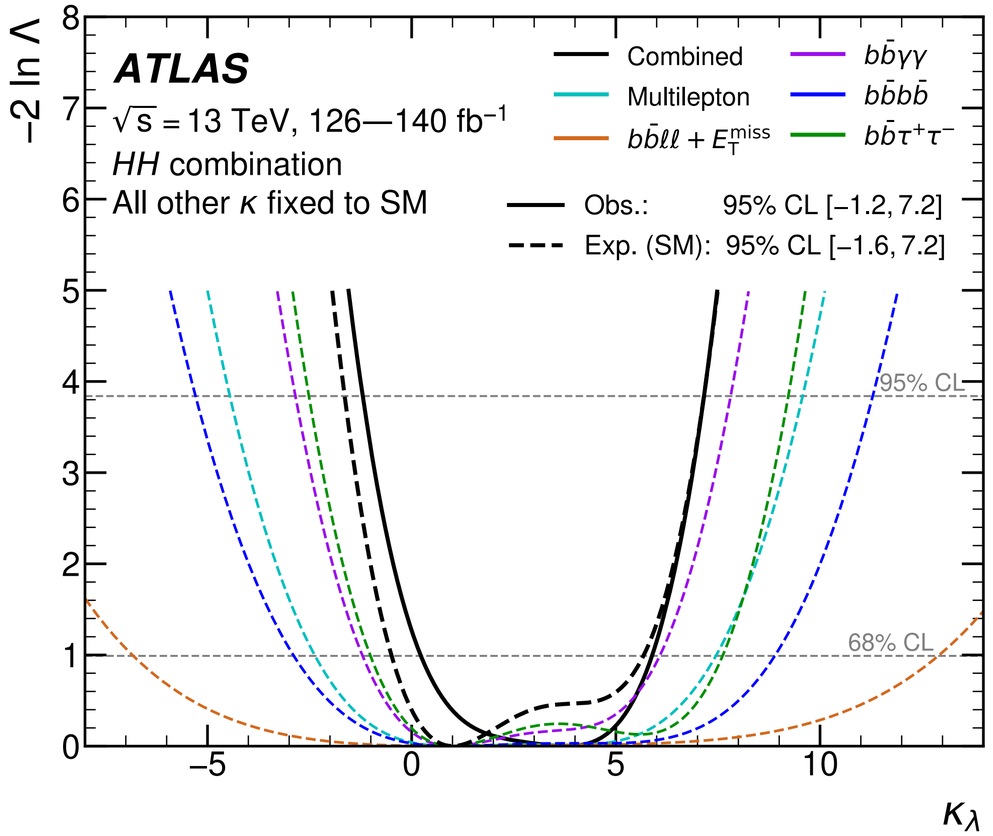


Phys. Rev. Lett. 133 (2024) 101801

Combination of HH searches

Constraints on the Higgs boson self-coupling

- Each analysis uses the full Run 2 dataset
- Combining them all maximises sensitivity
- Complementarity of channels to cover full κ_λ (m_{HH}) spectrum
- Observed: -1.2 < κ_λ < 7.2
- Expected: -1.6 < κ_λ < 7.2

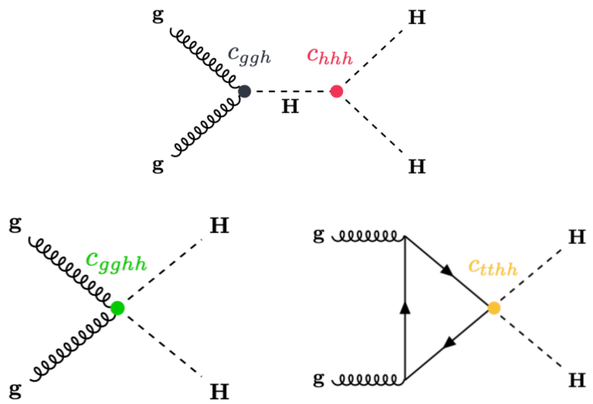


Phys. Rev. Lett. 133 (2024) 101801

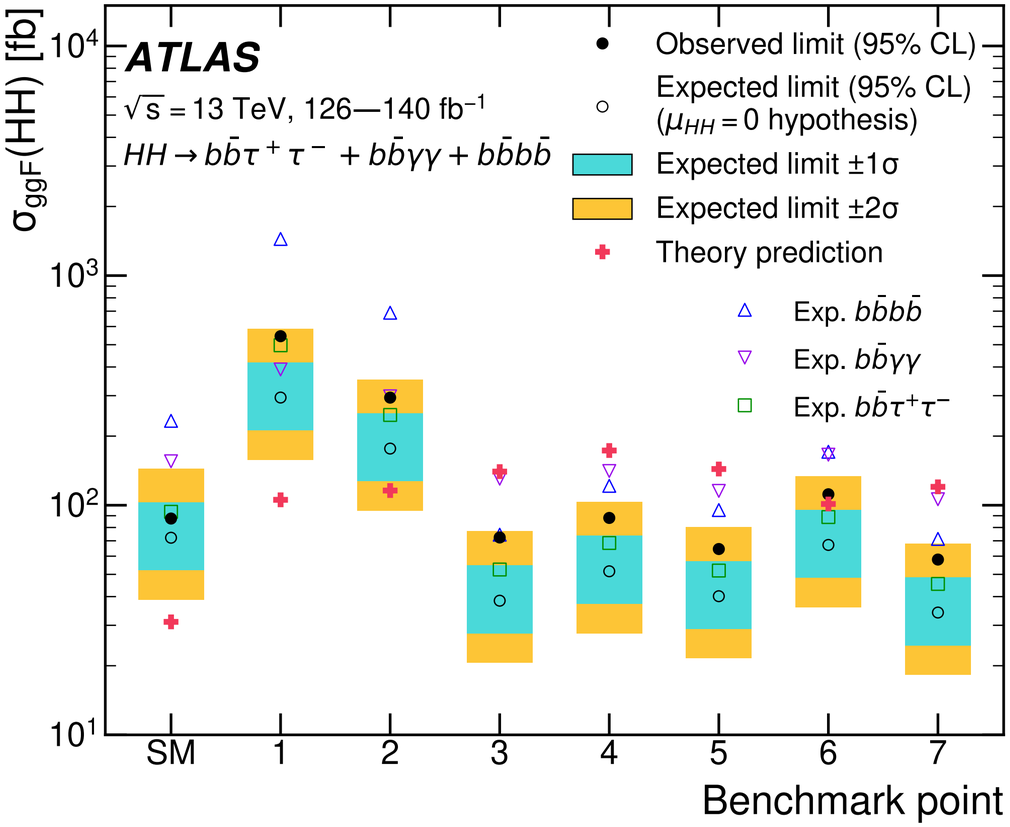
Beyond the Higgs boson self-interaction

Higgs EFT (HEFT) interpretations of HH searches

- Vary anomalous couplings in the HEFT formalism
- Seven HEFT benchmarks are used, with representative m_{HH} shape features [SciPost Phys. Comm. Rep. 2 (2024)]
- More stringent upper limits on the HH cross-section for benchmarks with higher m_{HH} values on average



Benchmark	c_{hhh}	c_{tth}	c_{tthh}	c_{ggh}	c_{gghh}
SM	1	1	0	0	0
1	5.11	1.10	0	0	0
2	6.84	1.03	$\frac{1}{6}$	$-\frac{1}{3}$	0
3	2.21	1.05	$-\frac{1}{3}$	$\frac{1}{2}$	$\frac{1}{2}$
4	2.79	0.90	$-\frac{1}{6}$	$-\frac{1}{3}$	$-\frac{1}{2}$
5	3.95	1.17	$-\frac{1}{3}$	$\frac{1}{6}$	$-\frac{1}{2}$
6	−0.68	0.90	$-\frac{1}{6}$	$\frac{1}{2}$	$\frac{1}{4}$
7	−0.10	0.94	1	$\frac{1}{6}$	$-\frac{1}{6}$



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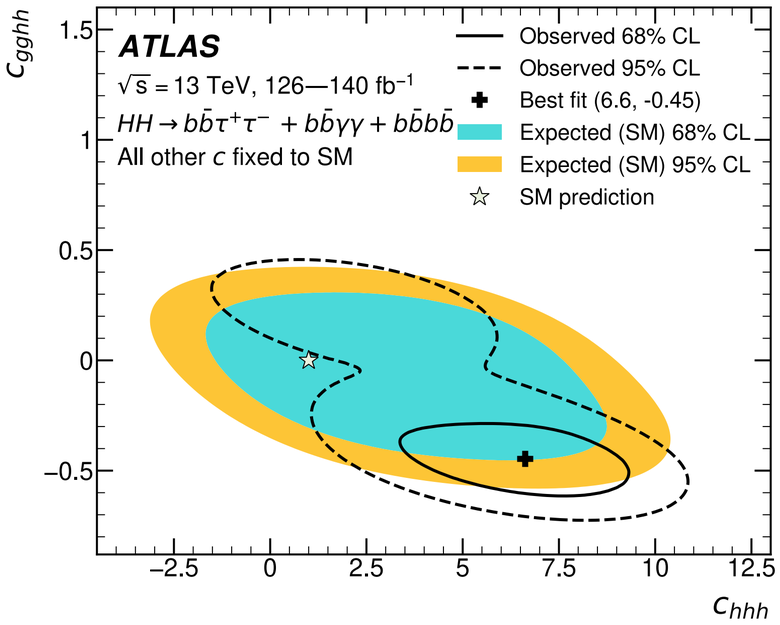
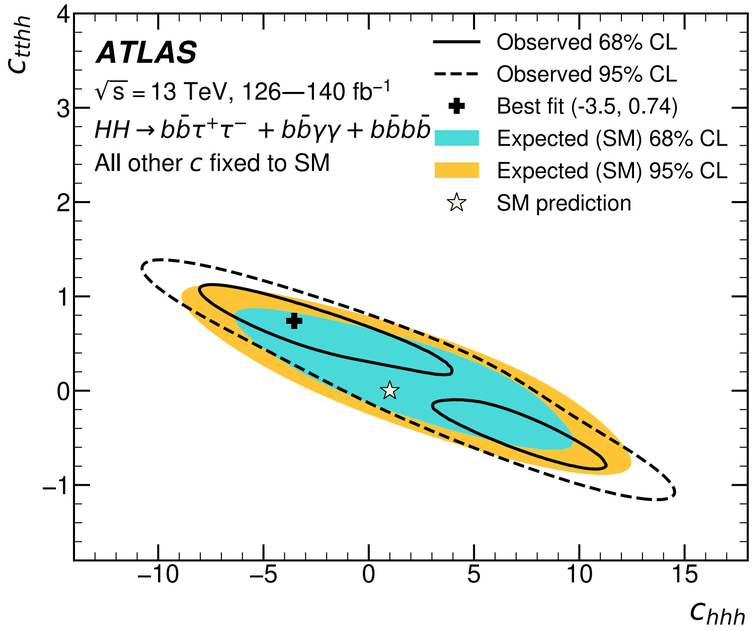
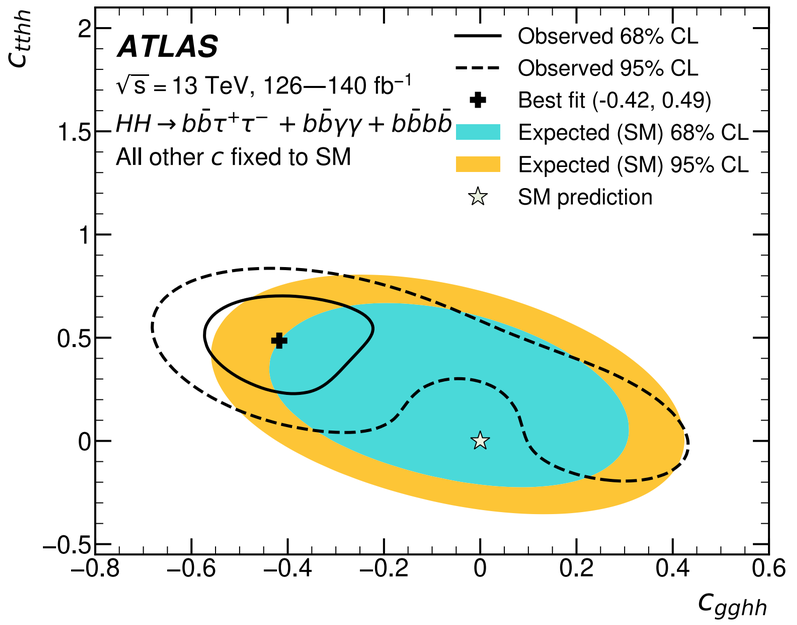
Beyond the Higgs boson self-interaction

HEFT interpretations of HH searches

- Set the most stringent 1-dimensional constraints on c_{gghh} and c_{tthh} up to date
- Also, probe the 2-dimensional HEFT phase space
  - Low compatibility with the SM due to low mass excess in the $HH \rightarrow bbbb$ analysis







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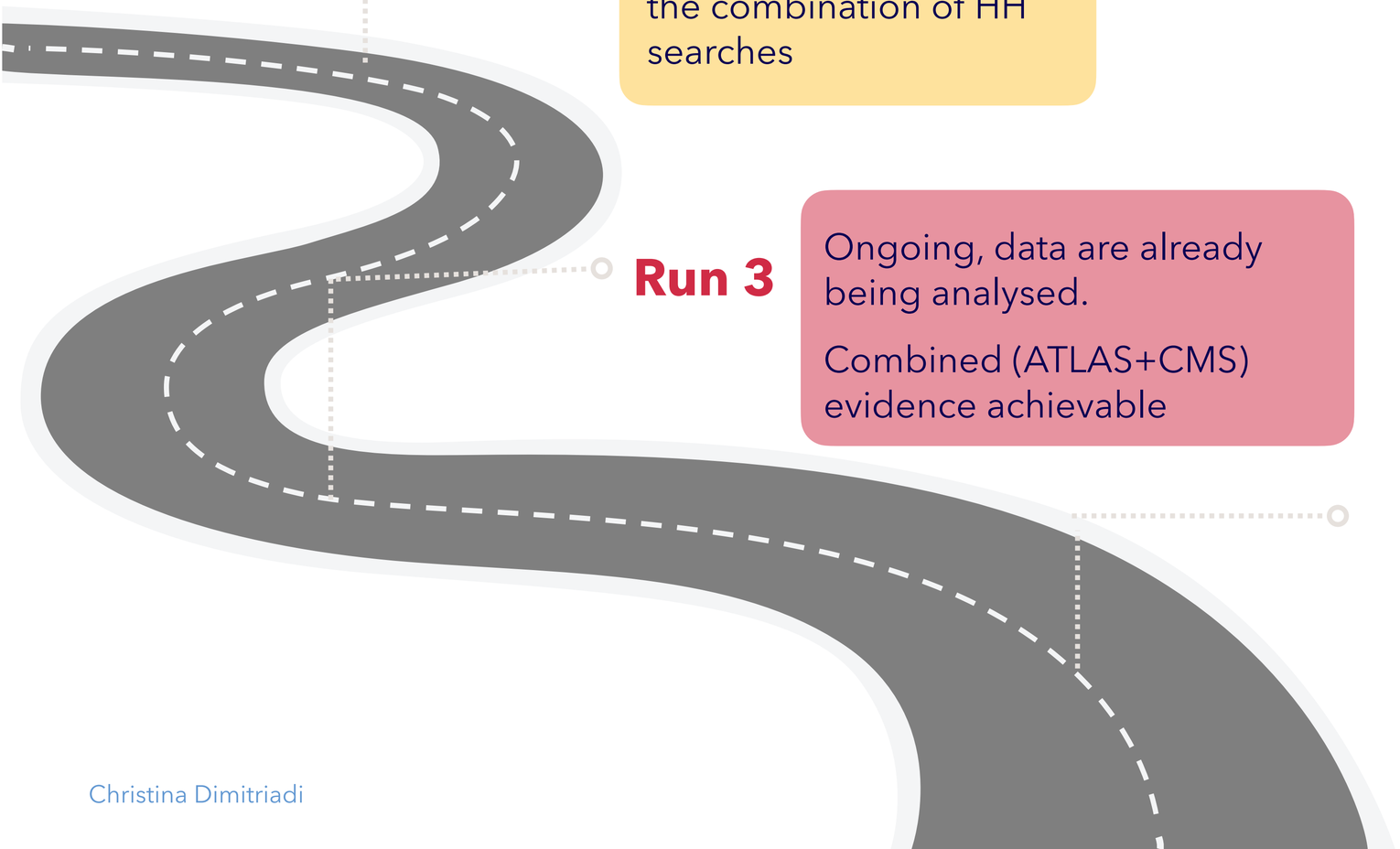
Conclusions

Searches for Higgs boson pairs are at the core of the LHC physics program



Run 2

Impressive results from the combination of HH searches

Run 3

Ongoing, data are already being analysed.

Combined (ATLAS+CMS) evidence achievable

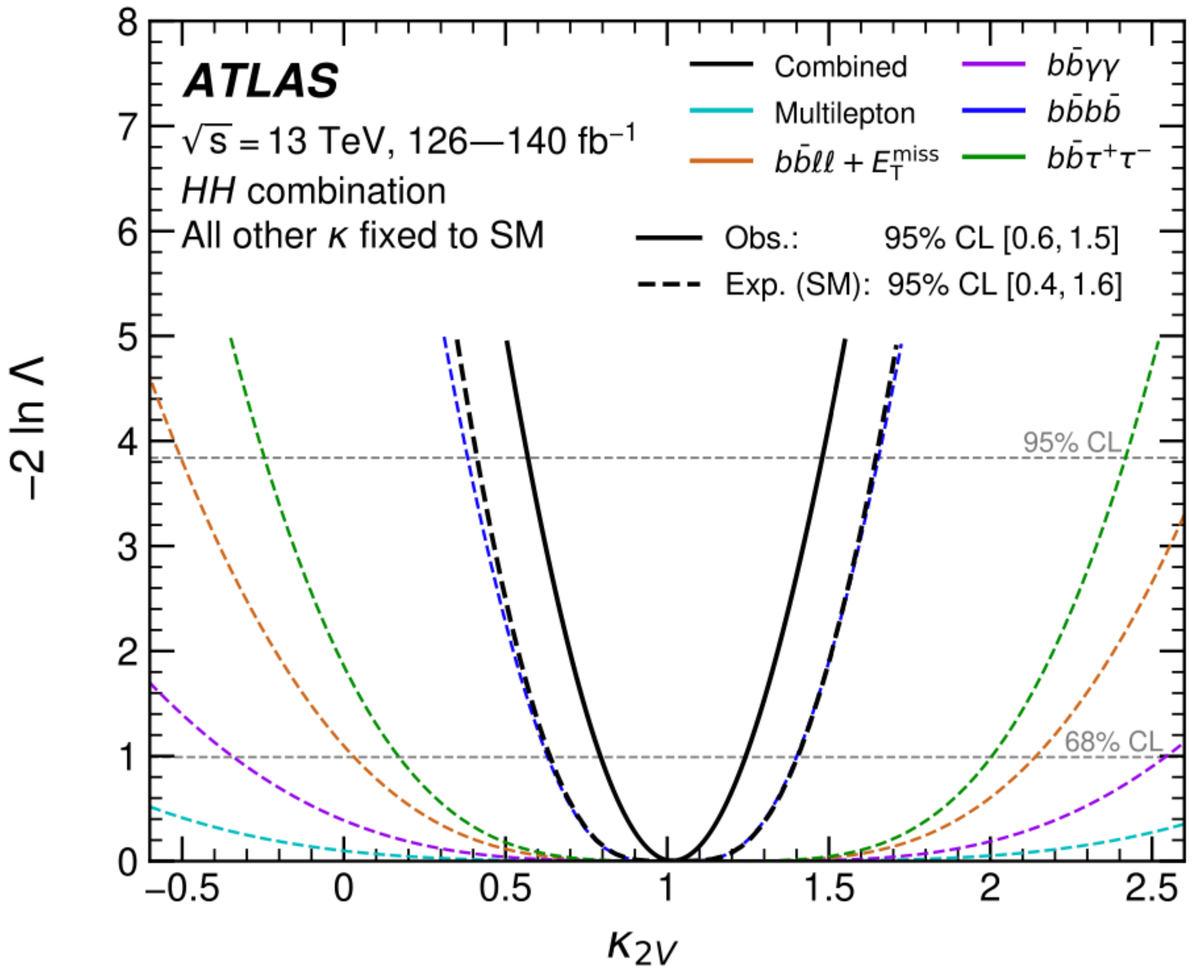
HL-LHC

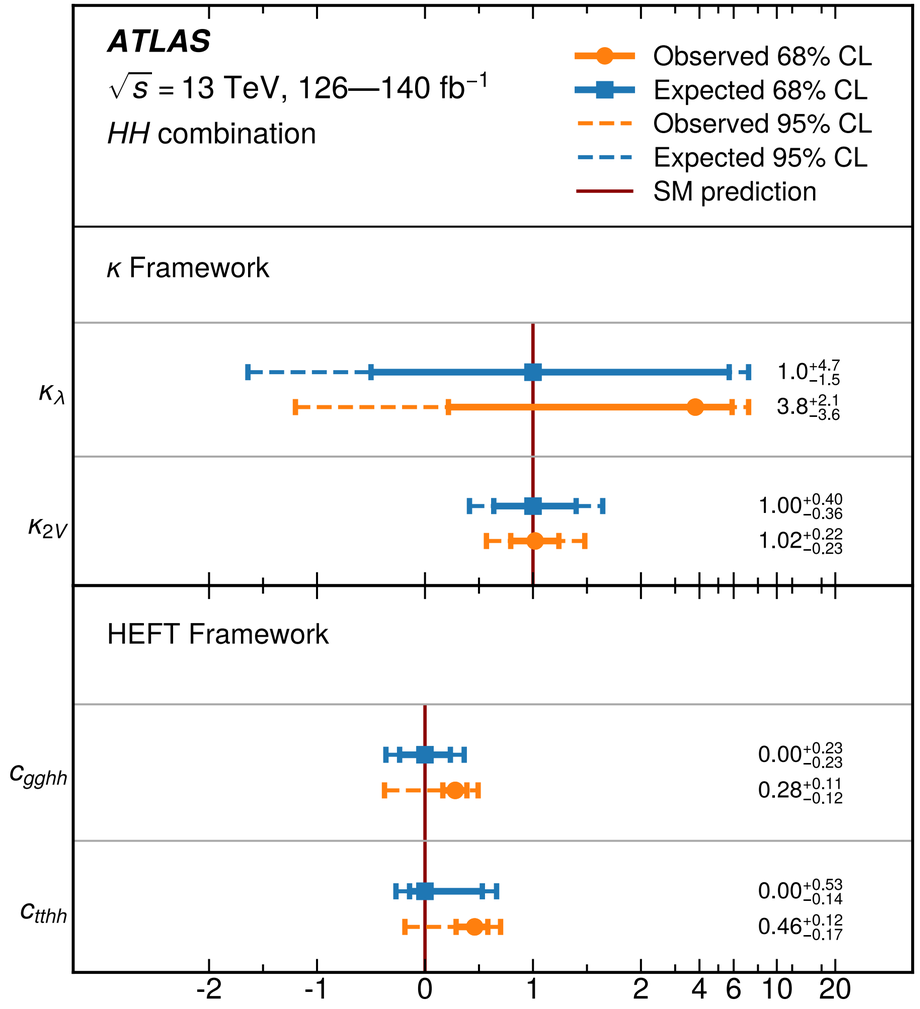
Projections of the HH→bbττ sensitivity to HL-LHC show evidence is possible from just an individual channel

Discovery is at reach!

BACK-UP

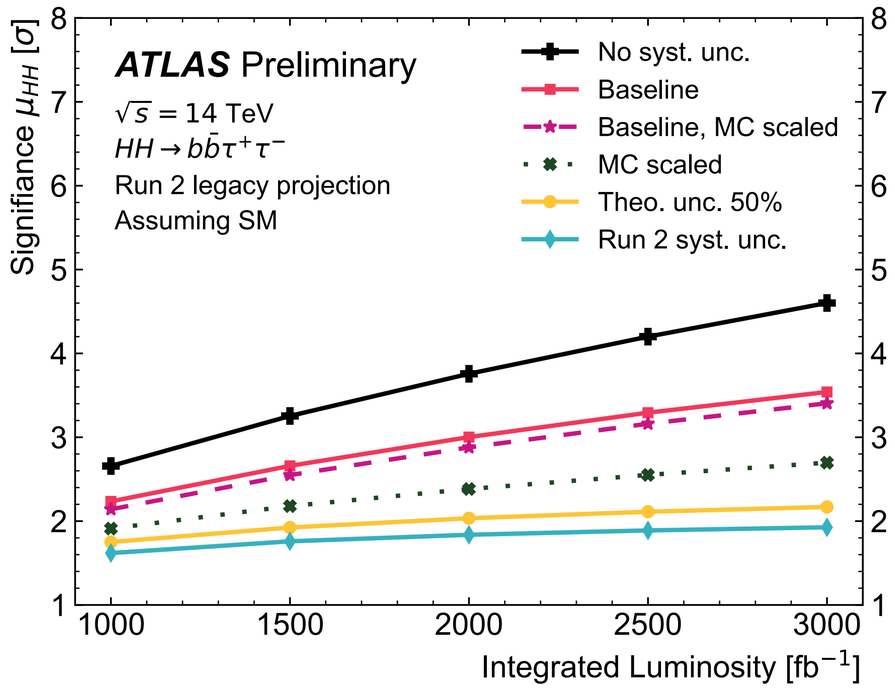
Other results

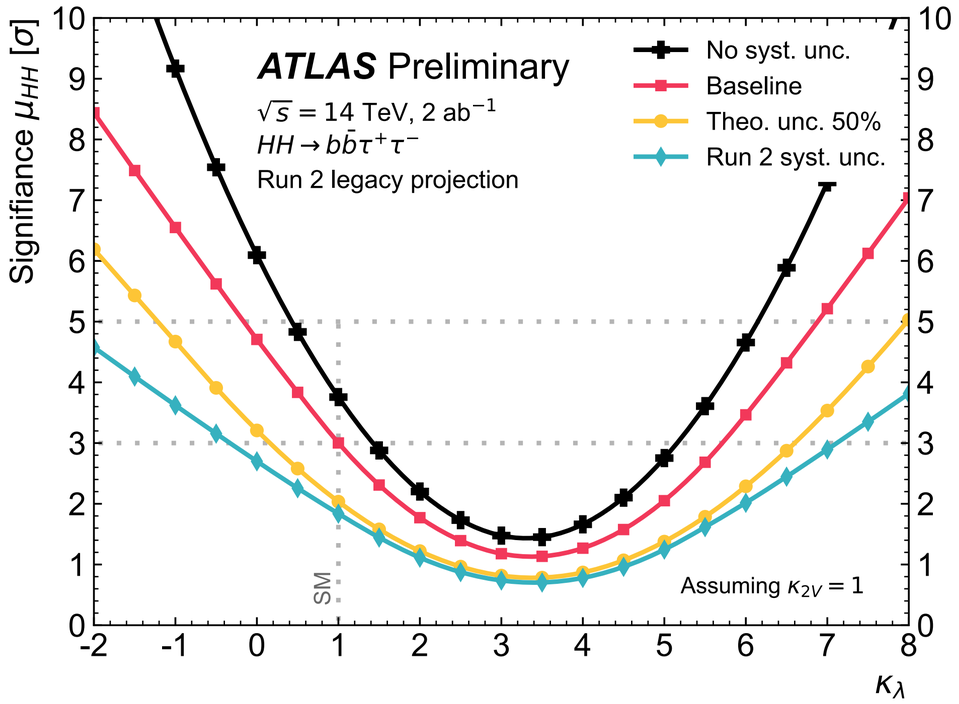




HL-LHC projections [new]

bbtautau

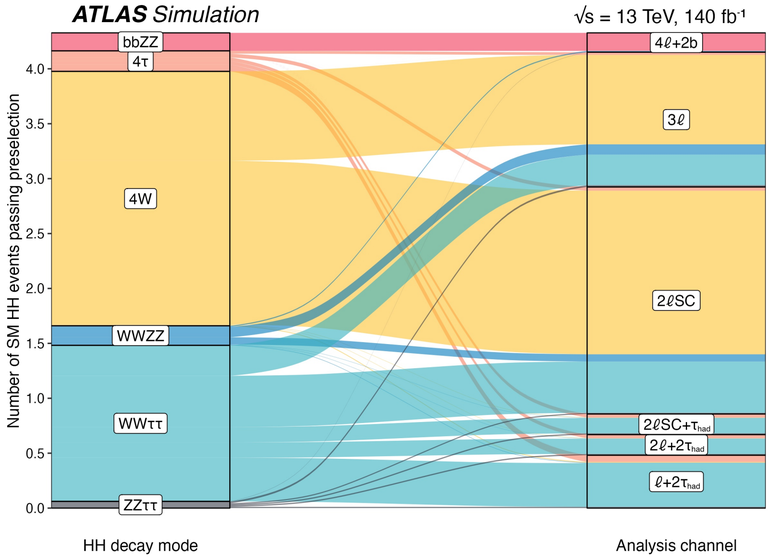


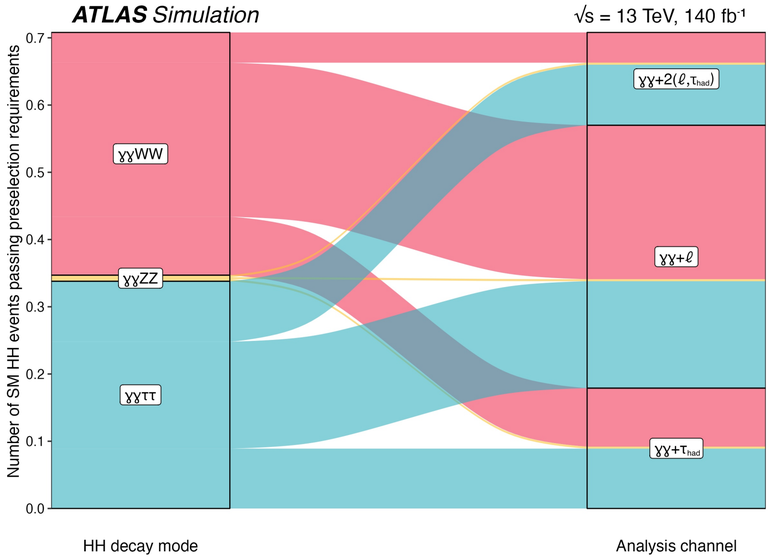


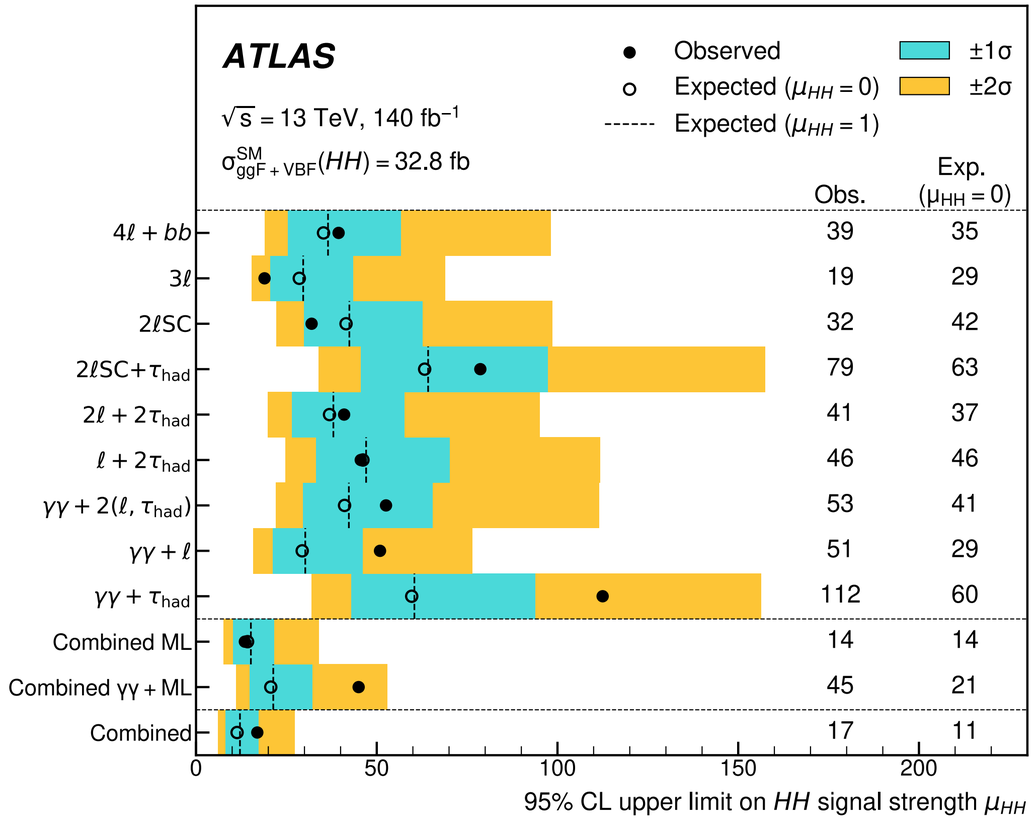
Other HH search channels

Multilepton

- bbZZ
- VVVV (V=W or Z)
- VVττ
- ττττ
- γγττ
- γγVV



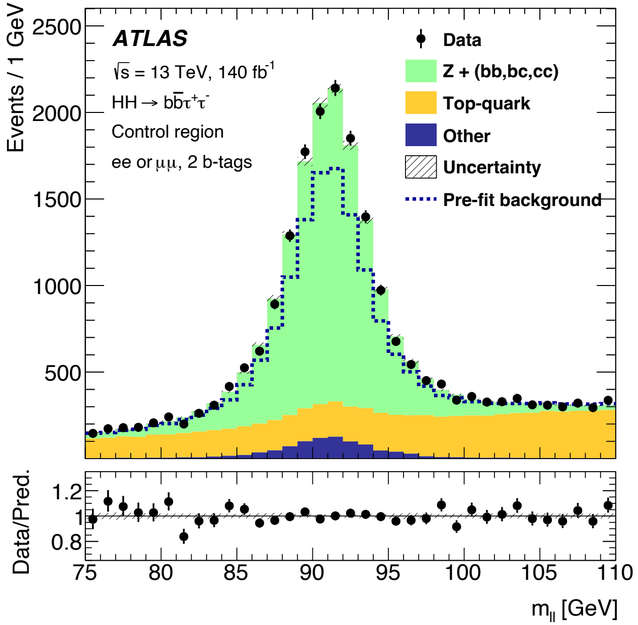




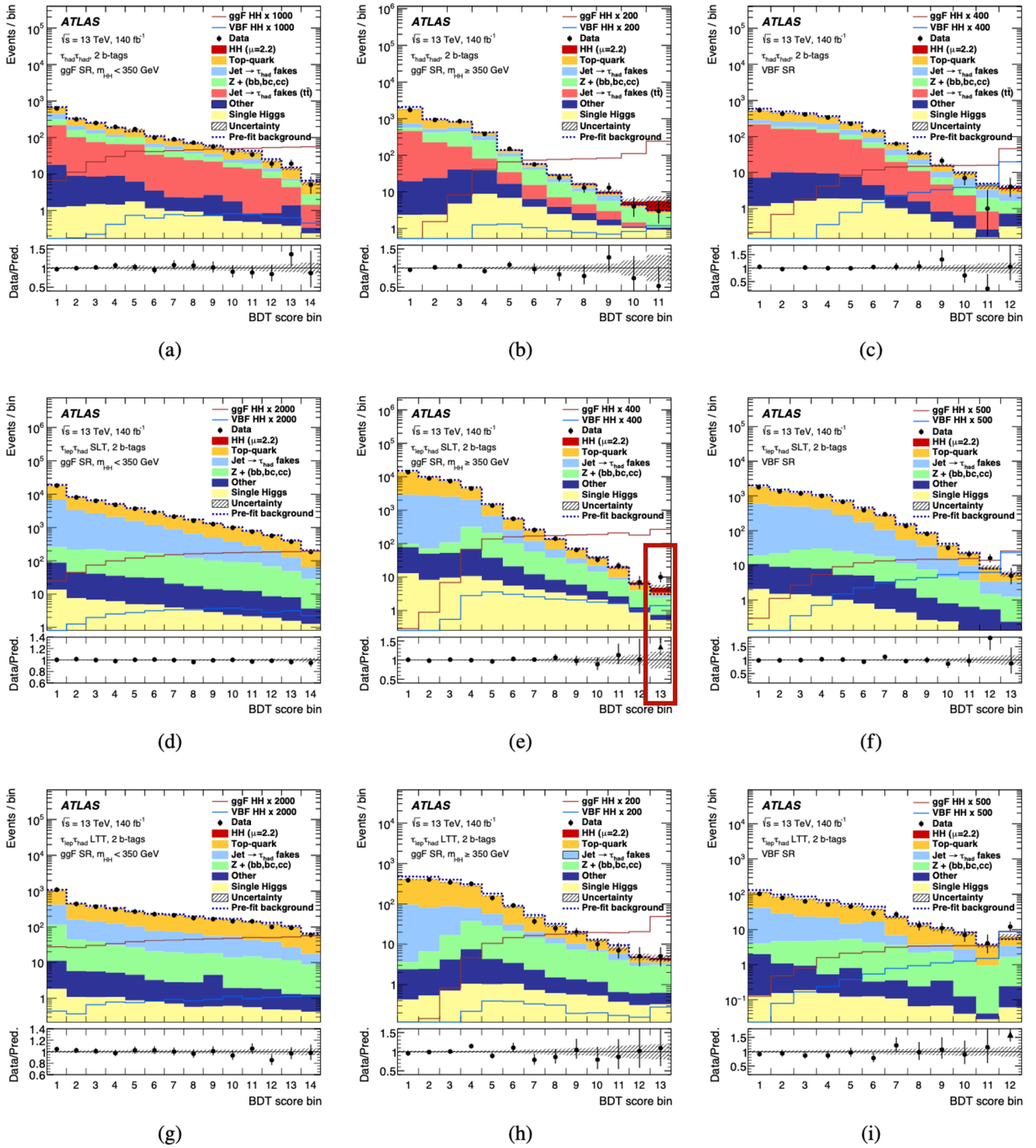
Results

Post-fit plots

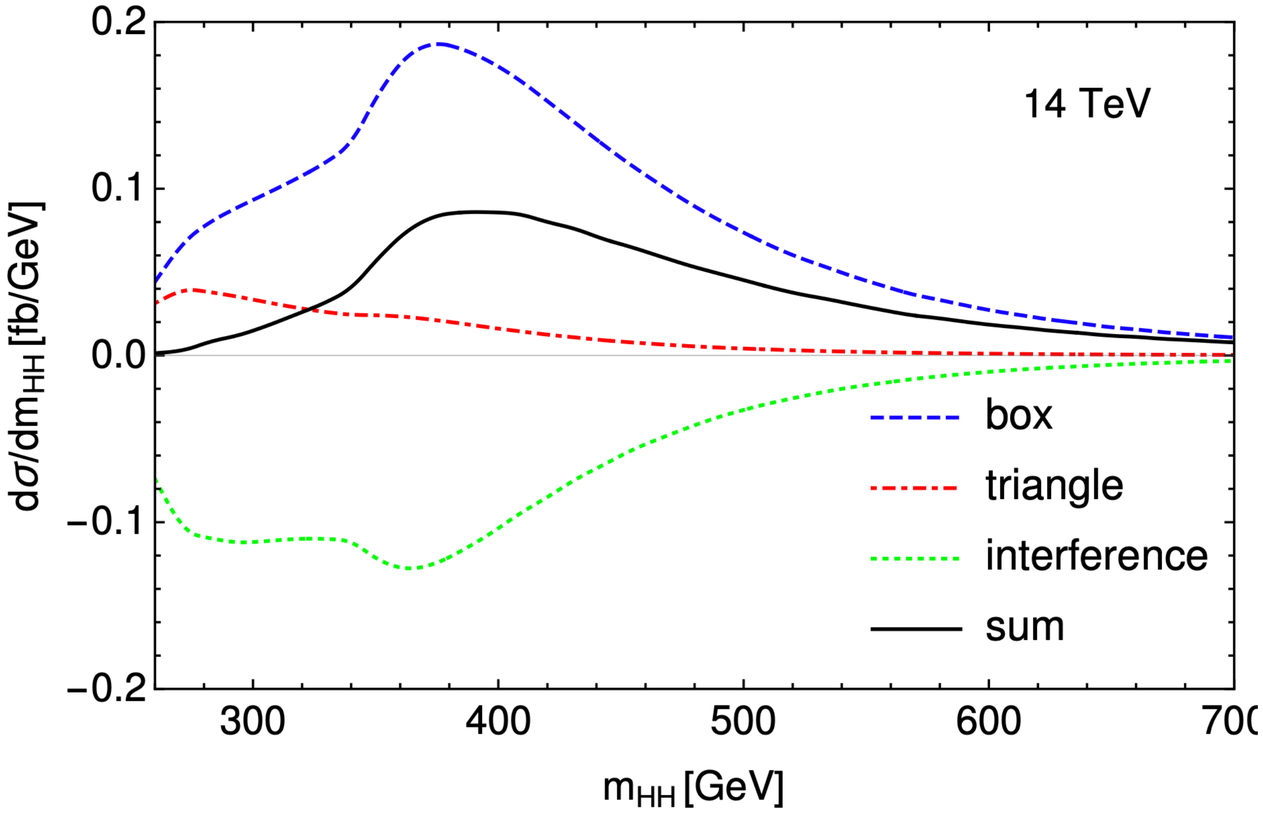
- Fit BDT discriminants in 9 categories plus $m_{\ell\ell}$ in the CR

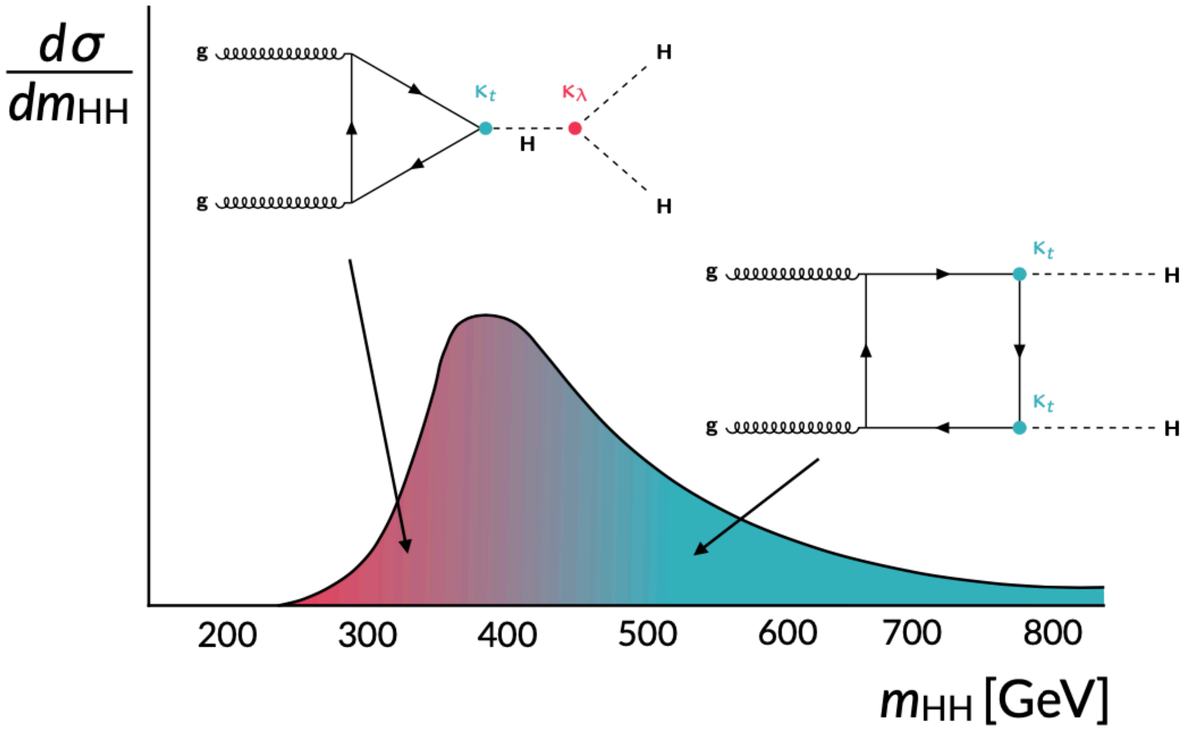


- Mild excess in the last BDT bin of the high-m_{HH} category of the $\tau_{\text{lep}}\tau_{\text{had}}$ SLT SR



mHH distributions

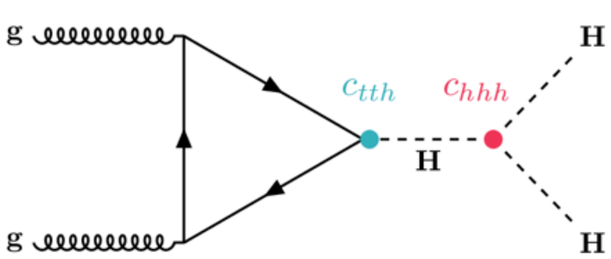


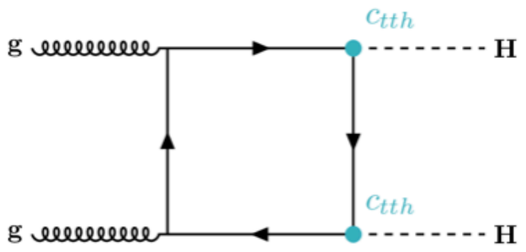


HEFT in HH

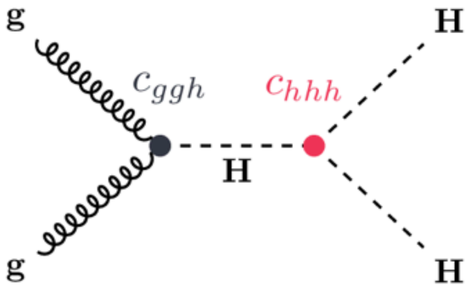
- 5 independent effective coupling coefficients, where $c_{hhh} = \kappa_\lambda$ and $c_{tth} = \kappa_t$

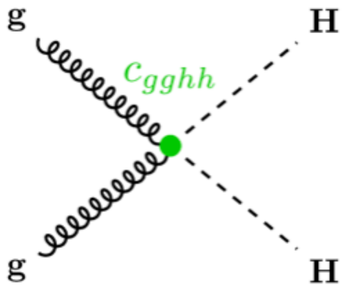
$$\mathscr{L}_{\text{HEFT}} \supset -m_t \left(c_{tth} \frac{h}{v} + c_{tthh} \frac{h^2}{v^2} \right) \bar{t}t - c_{hhh} \frac{m_h^2}{2v} h^3 + \frac{\alpha_s}{8\pi} \left(c_{ggh} \frac{h}{v} + c_{gghh} \frac{h^2}{v^2} \right) G^a_{\mu\nu} G^{a,\mu\nu}$$

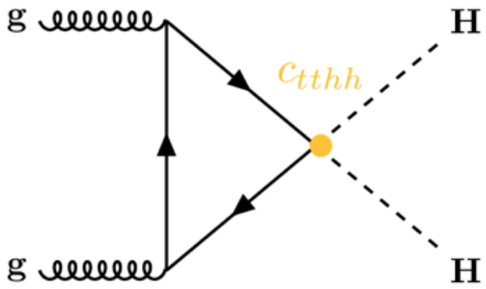




SM







BSM

HEFT in HH

- 7 benchmarks