Studies of new Higgs boson interactions through nonresonant HH production in the bb$\gamma\gamma$ final state in pp collisions at $\sqrt{s}$=13 TeV with the ATLAS detector

Abraham Tishelman-Charny

On behalf of the ATLAS collaboration

Thursday, 31 August 2023

Multi-Boson Interactions - San Diego, California

Brookhaven National Laboratory

ATLAS EXPERIMENT

Outline

I. Introduction
II. SM interpretation
III. EFT interpretation
IV. Summary

Enlightening the beauty of the Higgs

Introduction

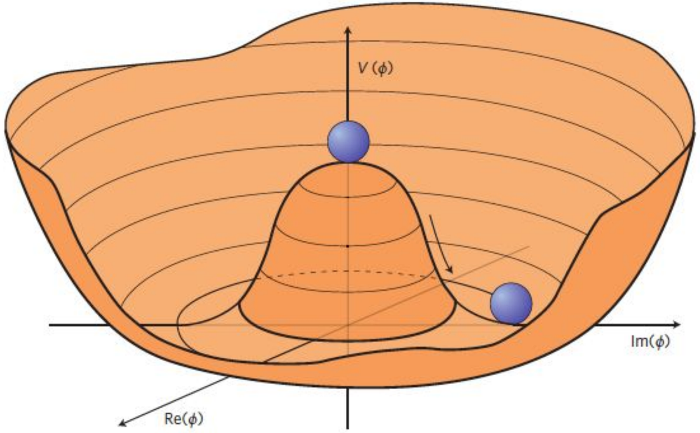
Introduction: Higgs self-coupling

- A particle consistent with the SM **Higgs boson** discovered in 2012 by the **ATLAS** and **CMS** collaborations

- Precise measurements of its properties serve dual purpose:
    - Fundamental test of **SM**, Higgs mechanism
    - Method to search for **BSM**

- Coupling lacking a precise measurement: **Higgs self-coupling (λ)**
    - Determines magnitude of Higgs interaction with itself, shape of the **Higgs potential**

- For more: See Ulascan's talk (Multiboson final states with Higgs bosons in ATLAS and CMS)

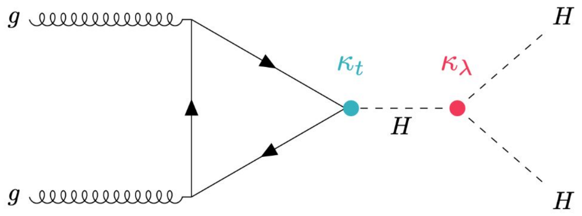


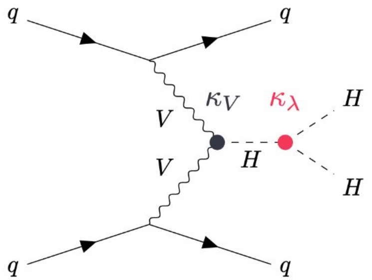
Higgs potential and mechanism

$$V(h) = V_0 + \lambda v^2 h^2 + \lambda v h^3 + \frac{1}{4}\lambda h^4 + \ldots$$

Introduction: Higgs pair production

- Can directly access Higgs self-coupling via **Higgs pair production (HH):**





Gluon fusion: $\sigma_{\text{NNLO, FTapprox}}$ **~ 31.05 fb @ 13 TeV** [1803.02463]
Assuming m_H = 125.0 GeV

Vector boson fusion: $\sigma_{\text{N3LO QCD}}$ **~ 1.73 fb @ 13 TeV** [1811.07906]
Assuming m_H = 125.0 GeV

- Higgs self-coupling affects **cross-section** and **differential distributions** of Higgs pair production in leading production modes: **Gluon fusion, Vector boson fusion**
- **Rare** process - need to select final states with good signal to background ratio

Brookhaven National Laboratory

Introduction: HH→$\gamma\gamma$bb

- HH in H($\gamma\gamma$)H(bb) final state benefits from **clean $\gamma\gamma$** signature, high bb branching ratio

- 2022: Search for HH in $\gamma\gamma$bb with ATLAS **Run 2** dataset published in PRD

- Observed (Expected) upper limit of σ_{HH} 4.2 (5.7) times SM prediction
  - Also constrain higgs self-coupling: observed (expected) [-1.5, 6.7] ([-2.4, 7.7])
  - Resonant search performed

PHYSICAL REVIEW D **106,** 052001 (2022)

Search for Higgs boson pair production in the two bottom quarks plus two photons final state in *pp* collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

G. Aad *et al.*[*]
(ATLAS Collaboration)

(Received 23 December 2021; accepted 1 August 2022; published 6 September 2022)

[Phys. Rev. D 106, 052001]

Introduction: New HH→$\gamma\gamma$bb studies

- Want to **extend** upon this strong Run 2 analysis effort with:
  - Further **EFT** interpretations - way to search for deviations
  - Improved sensitivity for **VBF** results
  - Re-optimized BDT **categorization**
  - Run 3 data still coming in, so consider same **Run 2 dataset**

- New studies via HH→$\gamma\gamma$bb, using Run 2 ATLAS data recently released:

Studies of new Higgs boson interactions through nonresonant HH production in the $b\bar{b}\gamma\gamma$ final state in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

ATLAS-CONF-2023-050

18 August 2023

ATLAS-CONF-2023-050

- Webpage includes public note, figures and tables of the analysis

SM interpretation

SM interpretation: Strategy

- Three physics signatures interplay:
  - HH (Signal)
  - H (Resonant background)
  - Continuum background

- Take advantage of **clean** di-Photon signature

- Need to separate single Higgs and continuum backgrounds from HH

- HH and H modelled with **MC.** Data-driven continuum background using data sidebands

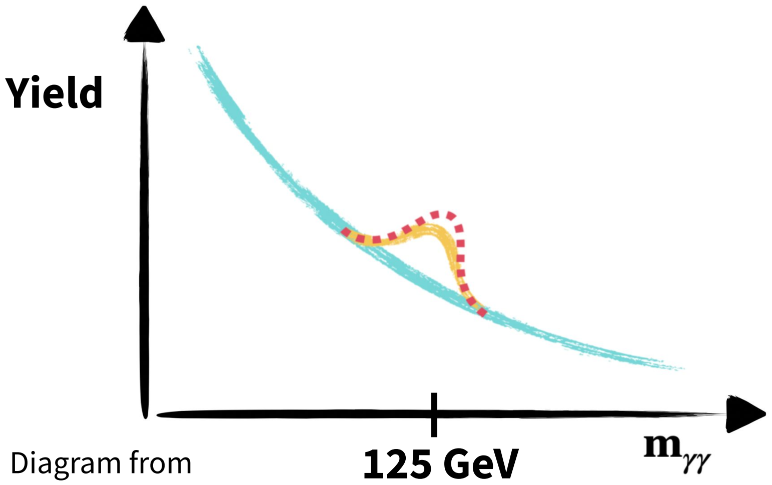


Diagram from
Elena Mazzeo

SM interpretation: Pre-selections

- Make selections on **photons** and **jets** to identify H→$\gamma\gamma$ and H→bb legs:

H→$\gamma\gamma$ selection	H→bb selection	ttH($\gamma\gamma$) reduction
Two high energy, isolated photons Lead (subleading) photon p_T > **35 (25) GeV**	Exactly 2 b-jets	Exactly 0 leptons Less than 6 central jets

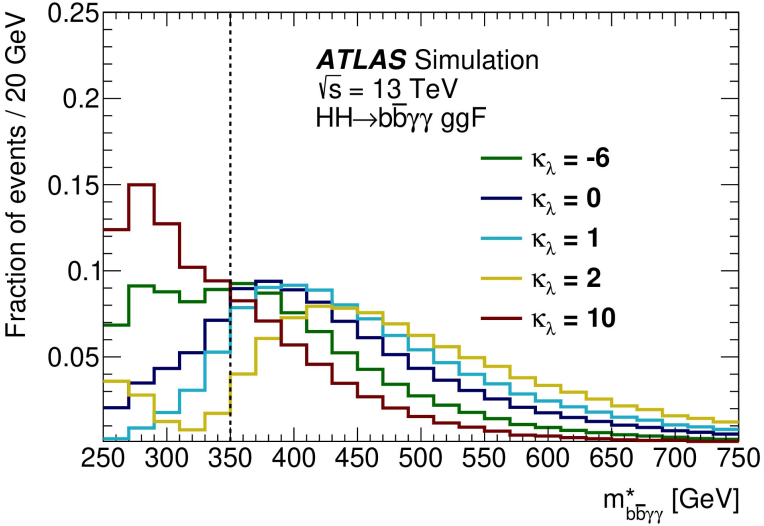
- Jets defined as **anti-kt** jets with R = 0.4
    - Identify “b-jets” with ATLAS “DL1r” algorithm, 77% efficiency working point, low misidentification rate [2211.16345]

- ttH($\gamma\gamma$) is a major single higgs background - reduce based on its final state topology

Brookhaven National Laboratory

SM interpretation: Reduced mass

- Define **reduced mass**: → $m^*_{bb\gamma\gamma} = m_{bb\gamma\gamma} - (m_{bb} - 125 \text{ GeV}) - (m_{\gamma\gamma} - 125 \text{ GeV})$
- Split analysis into 2 regions:
  - Reduced mass less-than or greater-than 350 GeV
  - **High mass:** > 350 GeV: Targets SM HH
  - **Low mass:** < 350 GeV: Targets deviations from self-coupling

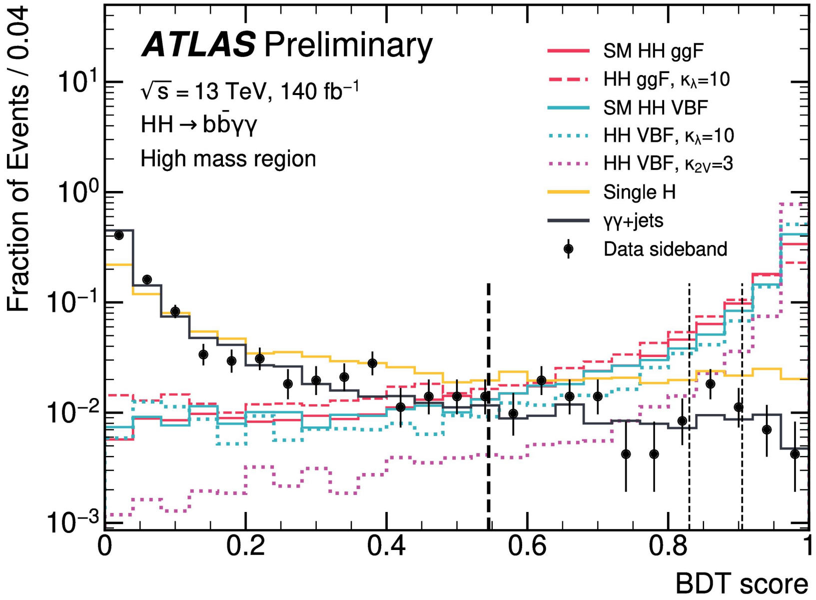


[Phys. Rev. D 106, 052001]

Brookhaven National Laboratory

SM interpretation: BDT

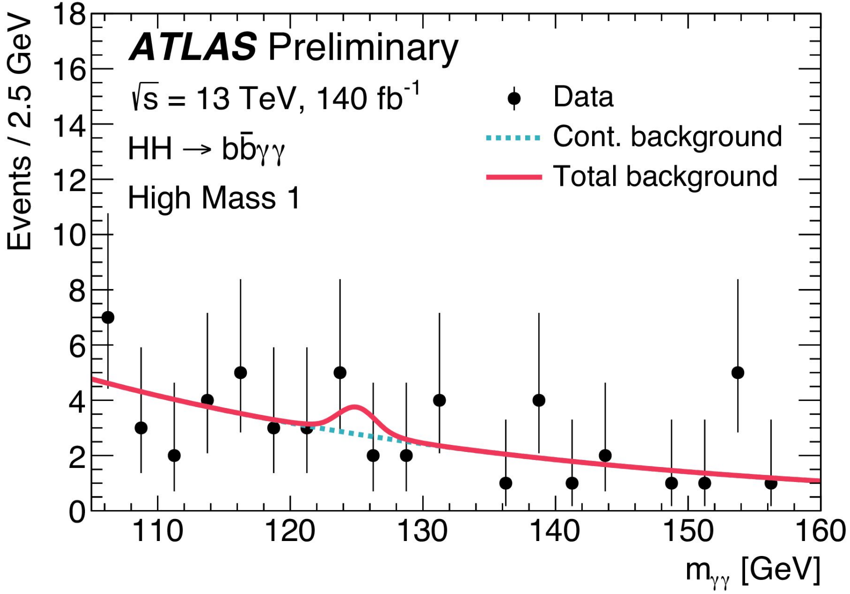
- Train **boosted decision tree** to separate **signal** and **background** signatures
- Use photon, jet kinematics as main inputs. Separate BDT trained to identify **VBF jets**
- Optimize category boundaries based on number-counting significance
- Good separation achieved



BDT score in high mass region, **data sideband**

SM interpretation: Di-Photon mass

- Di-Photon mass distribution in High Mass 1 category
- HH and H signatures modelled with **double sided crystal ball**
- Continuum background modelled by **fit to data sidebands**
  - Fit exponential functions. Normalization and shape obtained from fit to data



Di-Photon mass distribution in High Mass 1 category

Brookhaven National Laboratory

SM interpretation: Results

- Perform simultaneous **unbinned** maximum likelihood fit in all categories
- Not near evidence level (yet!) so compute **upper limits**
- 95% CL_S upper limit extracted on HH signal strength
- Combining gluon fusion and VBF channels, upper limit on HH signal strength of **4.0** times the SM prediction
    - Improvement over previous analysis **observed (expected)** 95% UL on signal strength of **4.2 (5.7)** times SM due to updated event classification

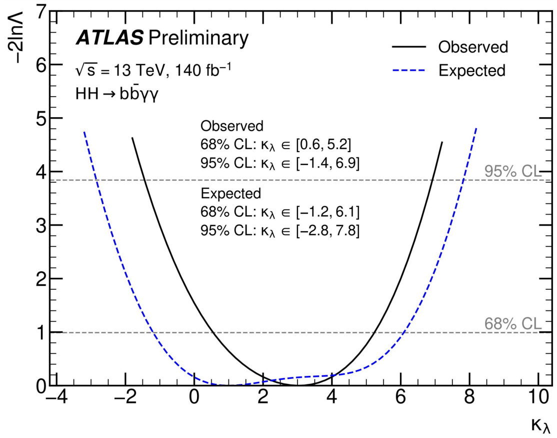
	Observed	**Median expected**
μ_{VBF}	≲ 96	≲ 145
μ_{ggF}	≲ 4.1	≲ 5.3
$\mu_{(ggF+VBF)}$	≲ 4.0	≲ 5.0 (Background only hypothesis)

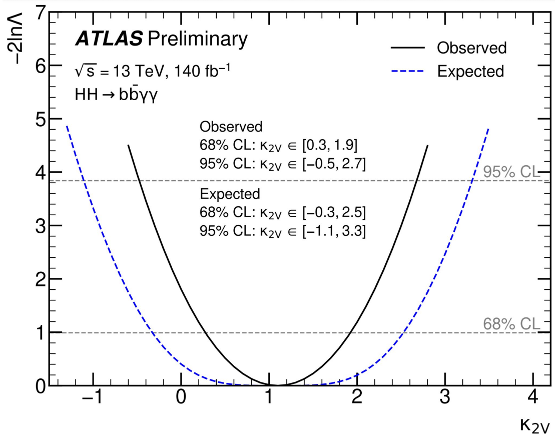
95% CL upper limits on **signal strength** (μ)

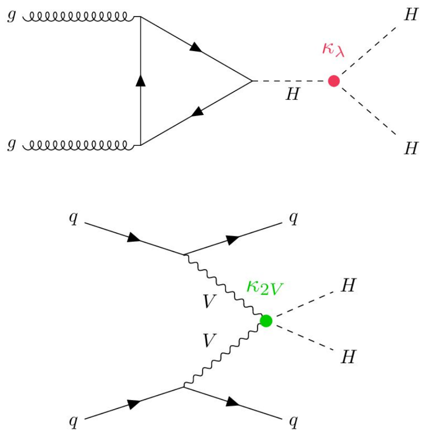
Brookhaven National Laboratory

Coupling modifier exclusion

- **Kappa framework**: Perform r**eweighting of SM sample** using m_{HH} information to estimate **shape** and **yields** on non-SM Higgs self-coupling, HHVV couplings → See Andrew's talk
- Fit to data, extract likelihood at each point:







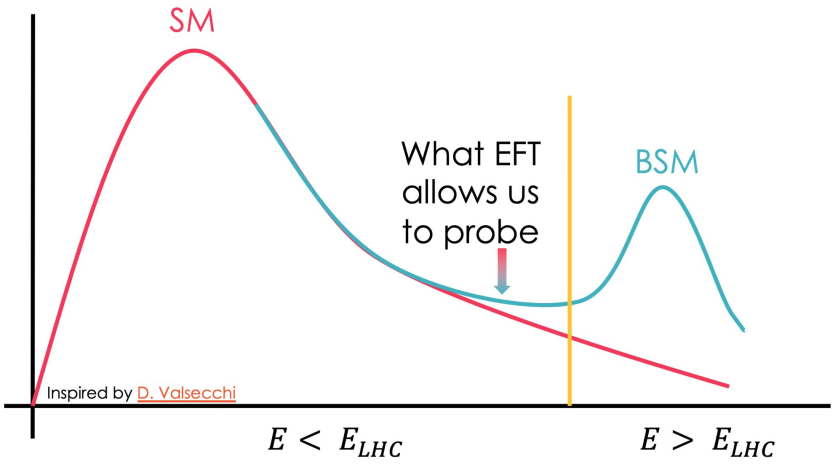
- Compare to one and two sigma deviations via likelihood, leads to 2D exclusion lines
- Best fit agrees with SM prediction within 1 sigma
- Improvement on **expected** κ_λ range, **part** of observed range w.r.t. previous analysis: **[-2.4, 7.7] ([-1.5, 6.7])** Expected (observed) @ 95% CL

Brookhaven National Laboratory

EFT interpretation

EFT: Introduction

- Effective field theory: A **QFT** which holds true up to a given **energy scale**
- Allows for **re-interpretation** of results using this framework - search for **non-SM** effects in results
- May allow us to see **BSM** effects, if they exist, at **LHC energy**



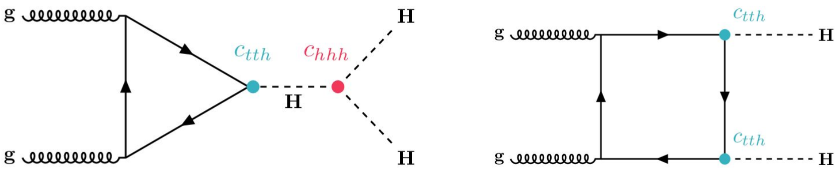
From Valentina Cairo [Lepton Photon 2023]

EFT: HEFT

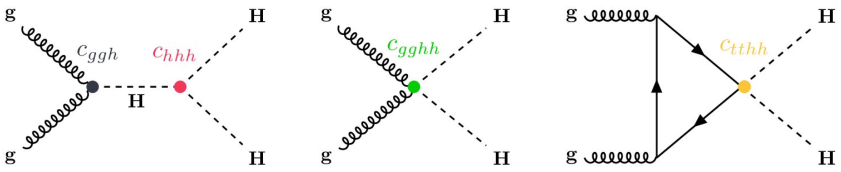
- **HEFT**: Higgs effective field theory. **Parameterized** lagrangian allowing for deviations from SM
- Useful for **HH** re-interpretation: Higgs field is singlet, c_{gghh} and c_{tthh} do not affect the **background**

$$\mathcal{L}_{BSM} = -c_{hhh}\lambda^{SM}_{HHH} v h^3 - \frac{m_t}{v}\left(c_{tth} h + \frac{c_{tthh}}{v} h^2\right)(\bar{t}_L t_R + h.c.) + \frac{\alpha_S}{12\pi v}\left(c_{ggh} h - \frac{c_{gghh}}{2v} h^2\right) G^a_{\mu\nu} G^{a,\,\mu\nu}$$

$$c_{hhh} = \kappa_\lambda = \frac{\lambda_{HHH}}{\lambda^{SM}_{HHH}}, \quad \lambda^{SM}_{HHH} = \frac{m_H^2}{2v^2}, \quad c_{tth} = \frac{y_t}{y_t^{SM}}, \quad y_t^{SM} = \frac{\sqrt{2}m_t^2}{v}$$



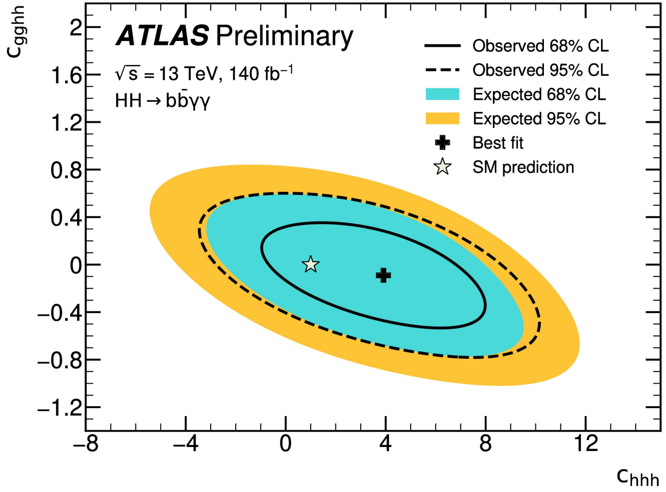
SM-like processes (modified by couplings)

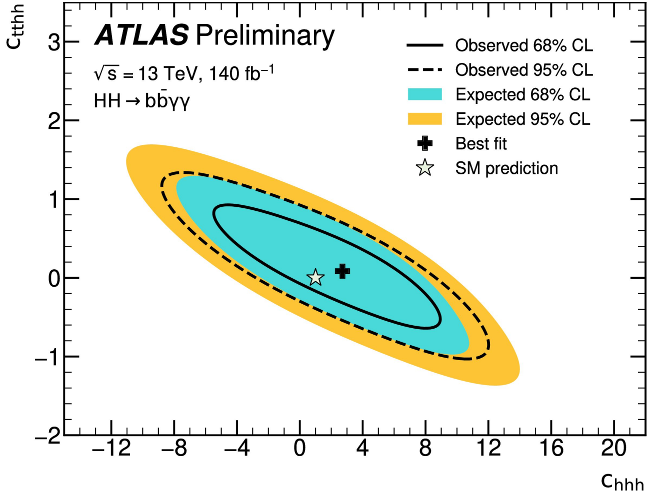


BSM processes

EFT: HEFT scan results

- Simultaneously vary $\mathbf{c_{hhh}}$, and modifier of HH coupling to **gg/tt**:
- **Implementation** difference from κ_λ: Reweight **SM** samples. κ_λ results use **sum of three** samples to estimate shape and yields for non-SM values





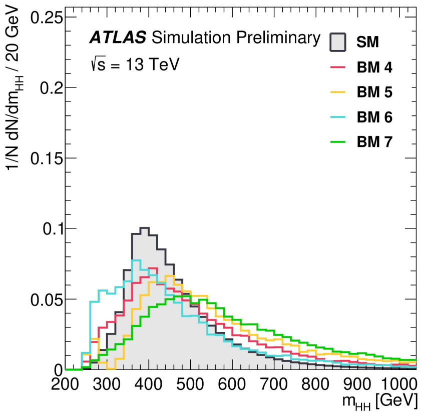
- **No significant deviations** from SM seen. Best fit agrees with SM within $\mathbf{1\sigma}$

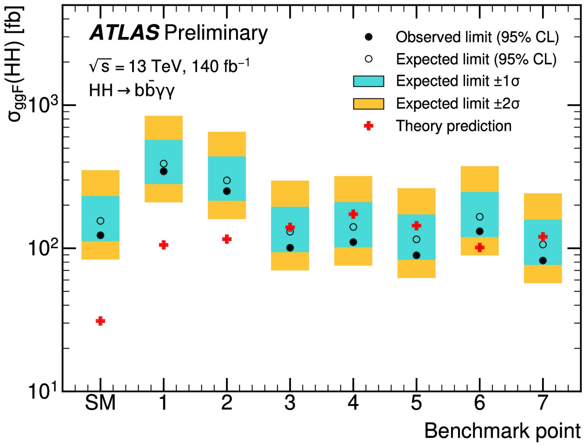
Brookhaven National Laboratory

EFT: HEFT benchmark results

- Additionally search for HEFT **benchmarks** which represent **distinct, representative kinematic shapes** in 5D HEFT phase space [1908.09923], [CDS]:

Benchmark	c_{hhh}	c_{tth}	c_{ggh}	c_{gghh}	c_{tthh}
SM	1	1	0	0	0
1	5.11	1.10	0	0	0
2	6.84	1.03	-1/3	0	1/6
3	2.21	1.05	1/2	1/2	-1/3
4	2.79	0.90	-1/3	-1/2	-1/6
5	3.95	1.17	1/6	-1/2	-1/3
6	-0.68	0.90	1/2	0.25	-1/6
7	-0.10	0.94	1/6	-1/6	1



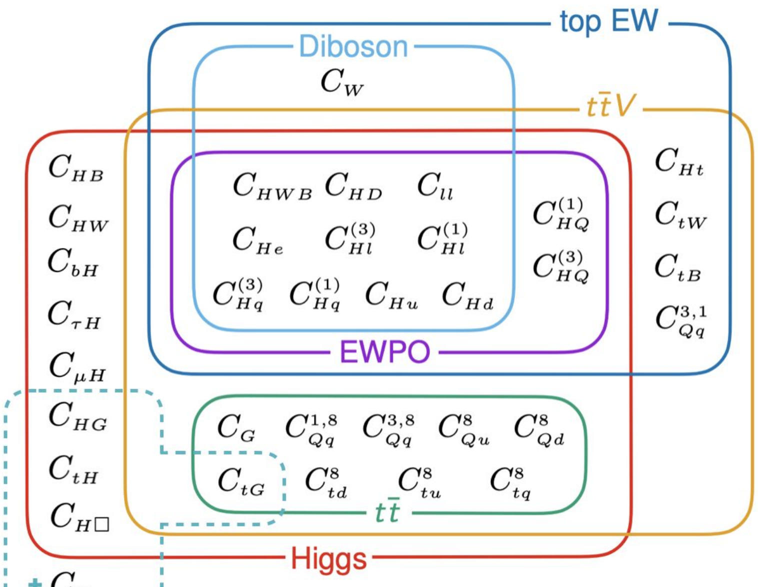


- Benchmarks **3, 4, 5, 7** excluded at a 95% CL - partially due to **harder m_{HH} spectrum**

Brookhaven National Laboratory

EFT: SMEFT

- **SMEFT**: Standard model effective field theory
- Expansion of SM lagrangian with dim-6 operators, includes 5 Wilson Coefficients
- This analysis uses **linear + quadratic** truncation scheme (not sensitive to linear only)
- **Operators** considered in this analysis:
  C_H $C_{H\Box}$ C_{tH} C_{tG} C_{HG} → [LHCWG-2022-004]
- Compared to **HEFT**:
  - Less general. h is contained in SU(2) doublet (same as SM).
  - More useful for **global combination** - many other LHC searches use SMEFT



Adapted from J. Ellis et al JHEP 04 (2021) 279

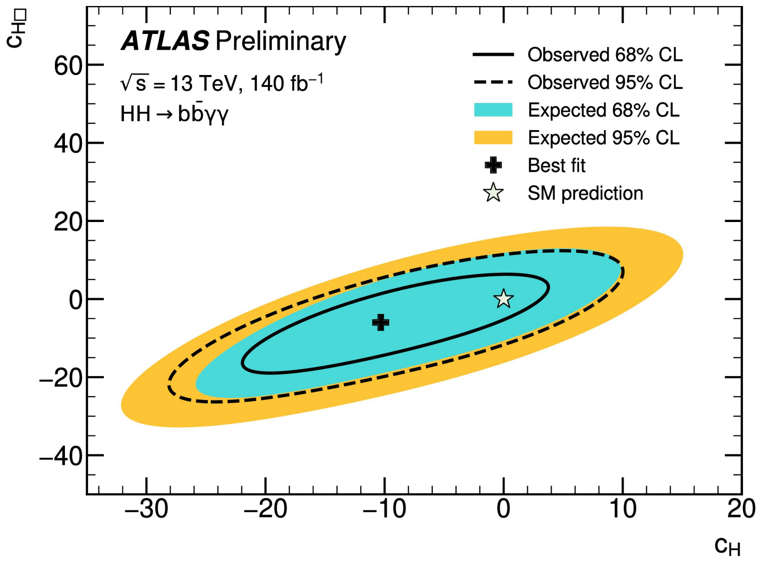
EFT: SMEFT

- Simultaneously vary **two** SMEFT parameters, effect on **single Higgs** backgrounds

- Similar to κ_λ, κ_{2V}, HEFT interpretations, reweight **SM signal** based on expected cross-section and branching ratios of given point
  - c_H at tree level, and $c_{H\square}$ do not affect branching fractions

- Fit to **data**, compute **likelihood**

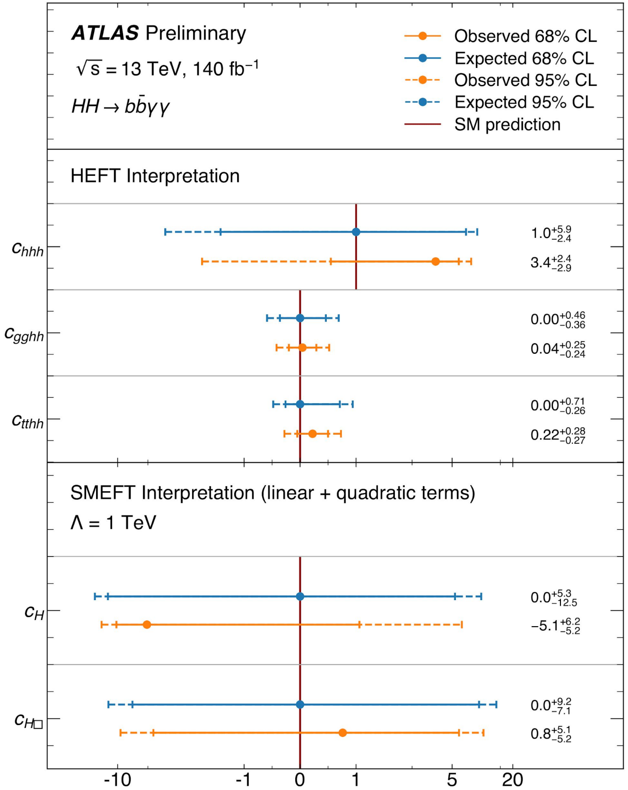
- Again, no deviation seen w.r.t. SM. Agrees within 1 sigma



EFT: Results summary

- **Summary** of EFT results varying one parameter at a time, keeping others **fixed** to SM values

- **No deviations** w.r.t. SM predictions observed

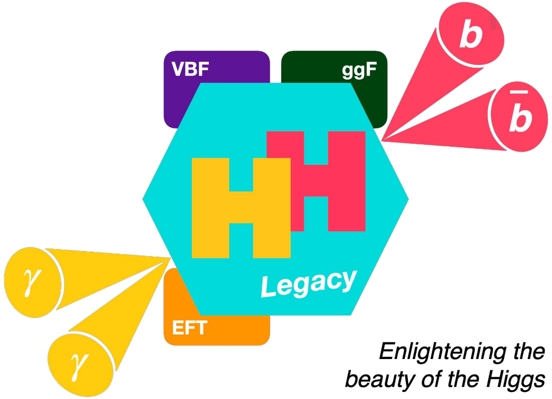


Brookhaven National Laboratory

Summary

Summary

- **Higgs pair production** is a versatile tool towards studying the Higgs, electroweak symmetry breaking, and bridges to **BSM**
- **<u>New</u>** ATLAS HH→$\gamma\gamma$bb analysis builds upon existing publication:
    - Improved **VBF** sensitivity
    - **EFT** interpretations
- Results consistent with **SM**
- Observed upper limit on $\boldsymbol{\mu_{HH}}$**: < 4.0** at 95% CL - Improvement over previous analysis (< 4.2 observed)
    - Observed (expected) constraint on **self-coupling** at 95% CL: [-1.4, 6.9] (-2.8, 7.8) → **Improvement** in **expected** over previous analysis
    - Observed (expected) constraint on **HHVV coupling** at 95% CL: [-0.5, 2.7] (-1.1, 3.3)
- **HEFT** and **SMEFT** parameter constraints extracted, no deviations observed



Enlightening the beauty of the Higgs

Brookhaven National Laboratory

Backup

Introduction: Full top approximation

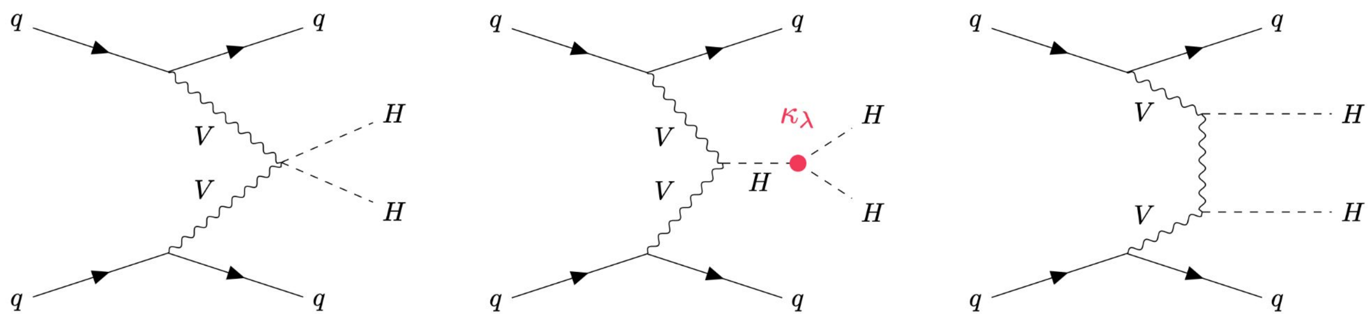
- FT approx (Full Top approximation) definition from https://arxiv.org/pdf/1803.02463.pdf:

In Refs. [4, 22] an approximation for Higgs boson pair production at NLO, labelled "FT_{approx}", was introduced, in which the real radiation matrix elements contain the full top quark mass dependence, while the virtual part is calculated at NLO in the HEFT approximation and rescaled at the event level by the re-weighting factor B_{FT}/B_{HEFT}. At the inlusive cross section level this approximation suggests at the LHC a correction with respect to the "Born-improved HEFT" approximation of about -10%, close to the corresponding correction of -14% later obtained in the full NLO calculation [16, 17].

Brookhaven National Laboratory

Introduction: VBF diagrams

- HH VBF diagrams from [2112.11876]:



(a) $HHVV$ vertex (b) Trilinear coupling (c) VVH Production mode

- All diagrams and figures [here]

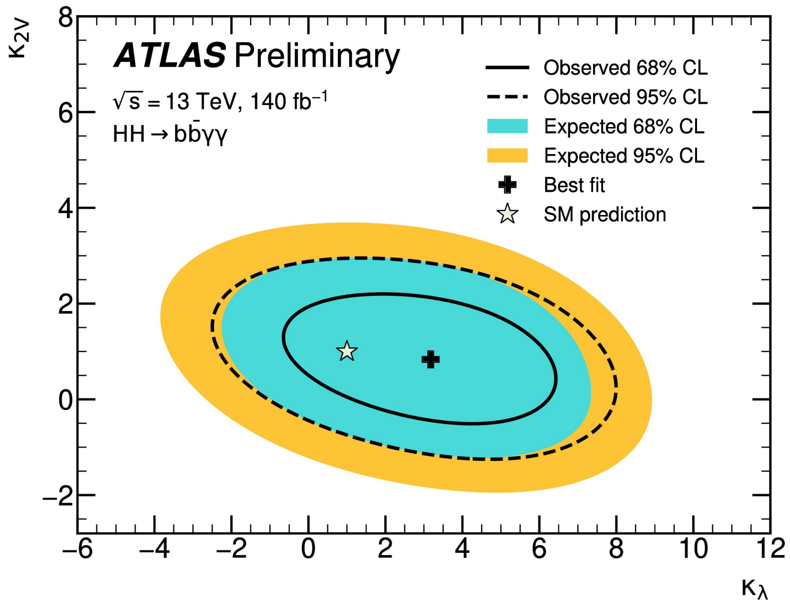
Per-category yields

- Number of **expected events** per category
- For comparison, number of **observed data events** ($120 < m_{\gamma\gamma} < 130$) GeV

	High Mass 1	High Mass 2	High Mass 3	Low Mass 1	Low Mass 2	Low Mass 3	Low Mass 4
SM $HH(\kappa_\lambda = 1)$ signal	$0.26^{+0.03}_{-0.04}$	$0.194^{+0.021}_{-0.032}$	$0.84^{+0.10}_{-0.14}$	$0.048^{+0.007}_{-0.008}$	$0.038^{+0.004}_{-0.006}$	$0.039^{+0.004}_{-0.006}$	$0.032^{+0.004}_{-0.004}$
ggF	$0.25^{+0.03}_{-0.04}$	$0.188^{+0.021}_{-0.032}$	$0.81^{+0.10}_{-0.14}$	$0.046^{+0.007}_{-0.008}$	$0.036^{+0.004}_{-0.006}$	$0.037^{+0.004}_{-0.006}$	$0.025^{+0.004}_{-0.004}$
VBF $\times 10^3$	$7.9^{+0.6}_{-0.5}$	$5.3^{+0.5}_{-0.4}$	29^{+4}_{-3}	$1.98^{+0.28}_{-0.24}$	$1.71^{+0.16}_{-0.14}$	$1.96^{+0.21}_{-0.19}$	$7.4^{+0.6}_{-0.5}$
Alternative $HH(\kappa_\lambda = 10)$ signal	$2.5^{+0.4}_{-0.3}$	$1.81^{+0.25}_{-0.20}$	$6.2^{+0.8}_{-0.6}$	$5.0^{+1.2}_{-0.9}$	$3.8^{+0.7}_{-0.5}$	$3.7^{+0.7}_{-0.6}$	$3.6^{+0.4}_{-0.4}$
ggF	$2.3^{+0.4}_{-0.3}$	$1.64^{+0.25}_{-0.19}$	$4.9^{+0.8}_{-0.6}$	$4.7^{+1.0}_{-0.8}$	$3.6^{+0.7}_{-0.6}$	$3.3^{+0.7}_{-0.5}$	$2.04^{+0.34}_{-0.27}$
VBF	$0.231^{+0.019}_{-0.017}$	$0.170^{+0.019}_{-0.017}$	$1.29^{+0.15}_{-0.14}$	$0.28^{+0.20}_{-0.11}$	$0.23^{+0.23}_{-0.12}$	$0.36^{+0.10}_{-0.08}$	$1.57^{+0.17}_{-0.16}$
Alternative VBF $HH(\kappa_{2V} = 3)$ signal	$0.23^{+0.04}_{-0.04}$	$0.20^{+0.05}_{-0.04}$	$3.8^{+0.7}_{-0.6}$	$0.03^{+0.04}_{-0.02}$	$0.03^{+0.06}_{-0.02}$	$0.048^{+0.023}_{-0.015}$	$0.17^{+0.04}_{-0.03}$
Single Higgs boson background	$1.5^{+0.5}_{-0.3}$	$0.48^{+0.21}_{-0.10}$	$0.57^{+0.25}_{-0.14}$	$1.72^{+0.31}_{-0.19}$	$0.53^{+0.08}_{-0.06}$	$0.29^{+0.14}_{-0.07}$	$0.16^{+0.06}_{-0.03}$
ggH	$0.5^{+0.5}_{-0.2}$	$0.14^{+0.21}_{-0.09}$	$0.25^{+0.25}_{-0.12}$	$0.29^{+0.31}_{-0.15}$	$0.08^{+0.08}_{-0.04}$	$0.07^{+0.13}_{-0.06}$	$0.04^{+0.06}_{-0.03}$
$t\bar{t}H$	$0.302^{+0.034}_{-0.032}$	$0.069^{+0.009}_{-0.008}$	$0.063^{+0.008}_{-0.007}$	$0.77^{+0.09}_{-0.08}$	$0.214^{+0.029}_{-0.026}$	$0.100^{+0.012}_{-0.012}$	$0.048^{+0.005}_{-0.005}$
ZH	$0.61^{+0.06}_{-0.05}$	$0.174^{+0.020}_{-0.016}$	$0.188^{+0.035}_{-0.029}$	$0.49^{+0.05}_{-0.04}$	$0.149^{+0.028}_{-0.025}$	$0.069^{+0.033}_{-0.023}$	$0.028^{+0.010}_{-0.007}$
Rest	$0.17^{+0.08}_{-0.04}$	$0.089^{+0.030}_{-0.016}$	$0.07^{+0.04}_{-0.02}$	$0.181^{+0.030}_{-0.019}$	$0.089^{+0.016}_{-0.009}$	$0.046^{+0.007}_{-0.004}$	$0.039^{+0.008}_{-0.004}$
Continuum background	$11.3^{+1.5}_{-1.6}$	$3.2^{+0.8}_{-0.8}$	$2.8^{+0.8}_{-0.8}$	$37.2^{+2.9}_{-2.9}$	$10.8^{+1.5}_{-1.5}$	$4.4^{+0.9}_{-1.0}$	$1.1^{+0.5}_{-0.5}$
Total background	$12.8^{+1.6}_{-1.6}$	$3.7^{+0.9}_{-0.8}$	$3.4^{+0.8}_{-0.8}$	$38.9^{+2.9}_{-2.9}$	$11.3^{+1.5}_{-1.5}$	$4.7^{+0.9}_{-1.0}$	$1.3^{+0.5}_{-0.5}$
Data	12	4	1	29	8	5	4

Coupling modifier exclusion

- 2D version of kappa framework result - simultaneously vary **two parameters**



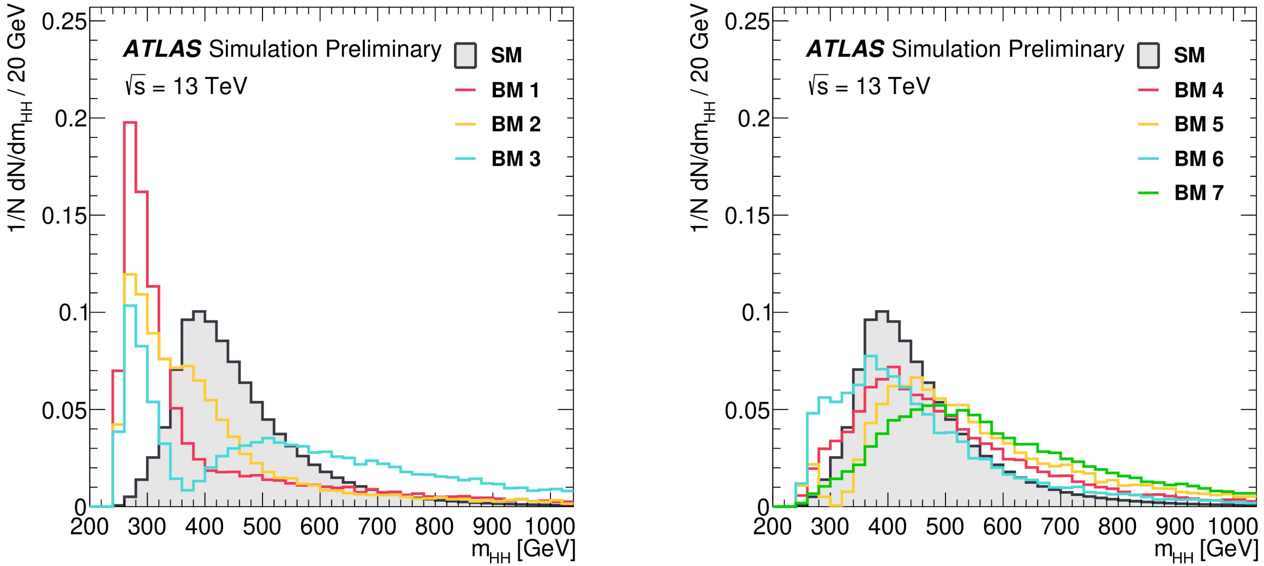
Brookhaven National Laboratory

EFT: References

- Diagrams from public result:
  - https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HDBS-2022-03/
- PUB note from ATLAS:
  - https://cds.cern.ch/record/2806411/files/ATL-PHYS-PUB-2022-019.pdf
  - Public website
- Published yybb result:
  - https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HDBS-2018-34/

EFT: HEFT benchmarks

- m_{HH} distributions of 7 benchmarks [reference]:



Brookhaven National Laboratory

EFT: SMEFT matrix element squared

- Matrix element squared of **SMEFT**:

$$|\mathcal{M}_{\rm SM}|^2 + \underbrace{\sum_i \frac{c_i^{(6)}}{\Lambda^2} 2\,\mathrm{Re}\left(\mathcal{M}_i^{(6)}\mathcal{M}_{\rm SM}^*\right)}_{\text{linear model}} + \underbrace{\sum_i \frac{\left(c_i^{(6)}\right)^2}{\Lambda^4}\left|\mathcal{M}_i^{(6)}\right|^2}_{\text{quadratic terms}} + \underbrace{\sum_{i<j} \frac{c_i^{(6)}c_j^{(6)}}{\Lambda^4} 2\,\mathrm{Re}\left(\mathcal{M}_i^{(6)}\mathcal{M}_j^{(6)*}\right)}_{\text{cross terms}} + \ldots$$

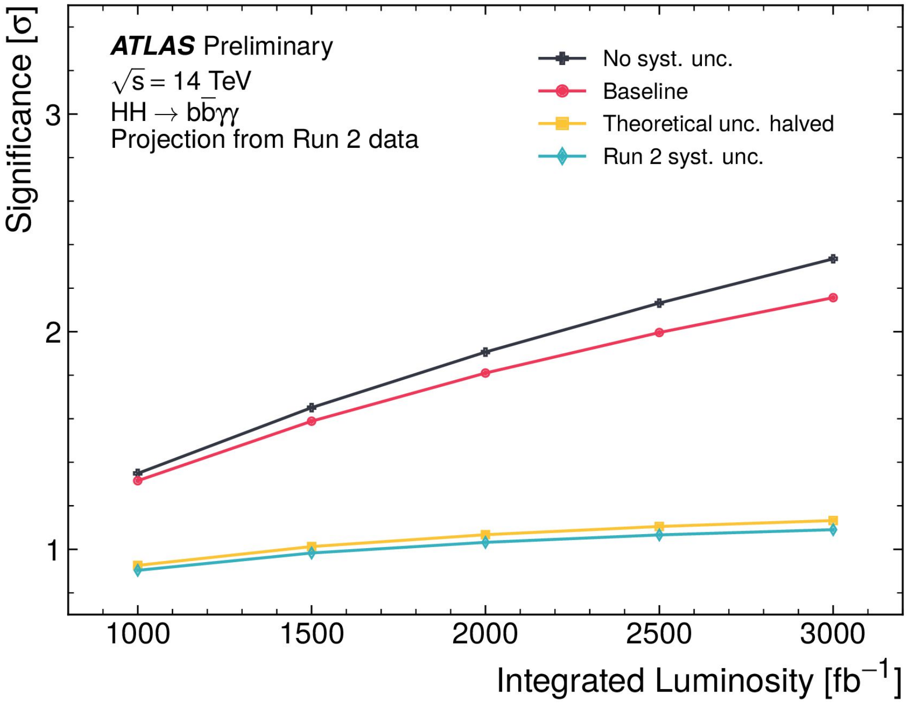
- And lagrangian in Warsaw basis:

$$\begin{aligned}\Delta\mathcal{L}_{\rm Warsaw} = {} & \frac{C_{H,\Box}}{\Lambda^2}(\phi^\dagger\phi)\Box(\phi^\dagger\phi) + \frac{C_{HD}}{\Lambda^2}(\phi^\dagger D_\mu\phi)^*(\phi^\dagger D^\mu\phi) + \frac{C_H}{\Lambda^2}(\phi^\dagger\phi)^3 \\ & + \left(\frac{C_{uH}}{\Lambda^2}\phi^\dagger\phi\bar{q}_L\tilde{\phi}\,t_R + h.c.\right) + \frac{C_{HG}}{\Lambda^2}\phi^\dagger\phi G^a_{\mu\nu}G^{\mu\nu,a} \\ & + \frac{C_{uG}}{\Lambda^2}(\bar{q}_L\sigma^{\mu\nu}T^a G^a_{\mu\nu}\tilde{\phi}\,t_R + \mathrm{h.c.})\,.\end{aligned}$$

Brookhaven National Laboratory

HL-LHC extrapolation

- Measurement prospects of Higgs boson pair production in the $b\bar{b}\gamma\gamma$ final state with the ATLAS experiment at the HL-LHC:
  - https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2022-001/
- **Extrapolated** precision on signal strength measurement of ~ **50%**, significance ~ **2.2-2.3 sigma** with no syst. unc.
- With (without) systematic uncertainties, κλ, the modifier of the trilinear Higgs boson self-coupling, is projected to be constrained to the 1σ confidence interval [0.3,1.9] ([0.4,1.8])
- With $bb\tau\tau$:
  - https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2022-005/



Brookhaven National Laboratory