Non-resonant Higgs boson pair production and self-coupling determination with the ATLAS experiment

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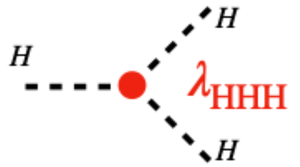
on behalf of the ATLAS collaboration

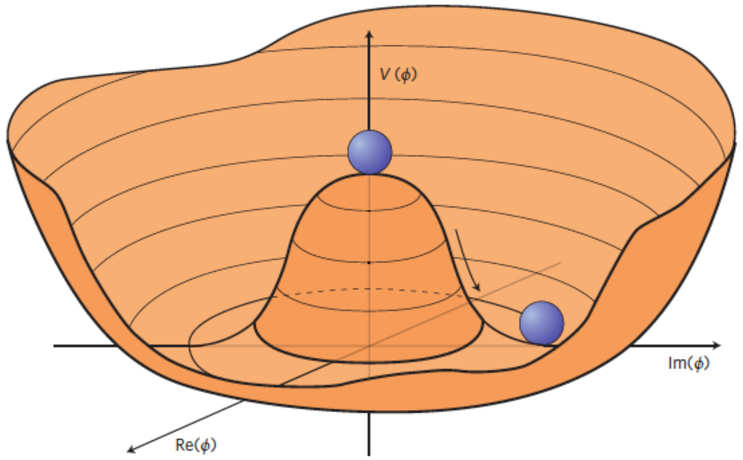
8July25 / EPS-HEP @ Marseille

Motivation



- Not so explored part of SM $\quad V(H) = \frac{1}{2} m_H^2 H^2 + \lambda_{hhh} v H^3 + \ldots$

- Measurement probes the shape of the Higgs potential and hence the Electroweak Symmetry Breaking mechanism



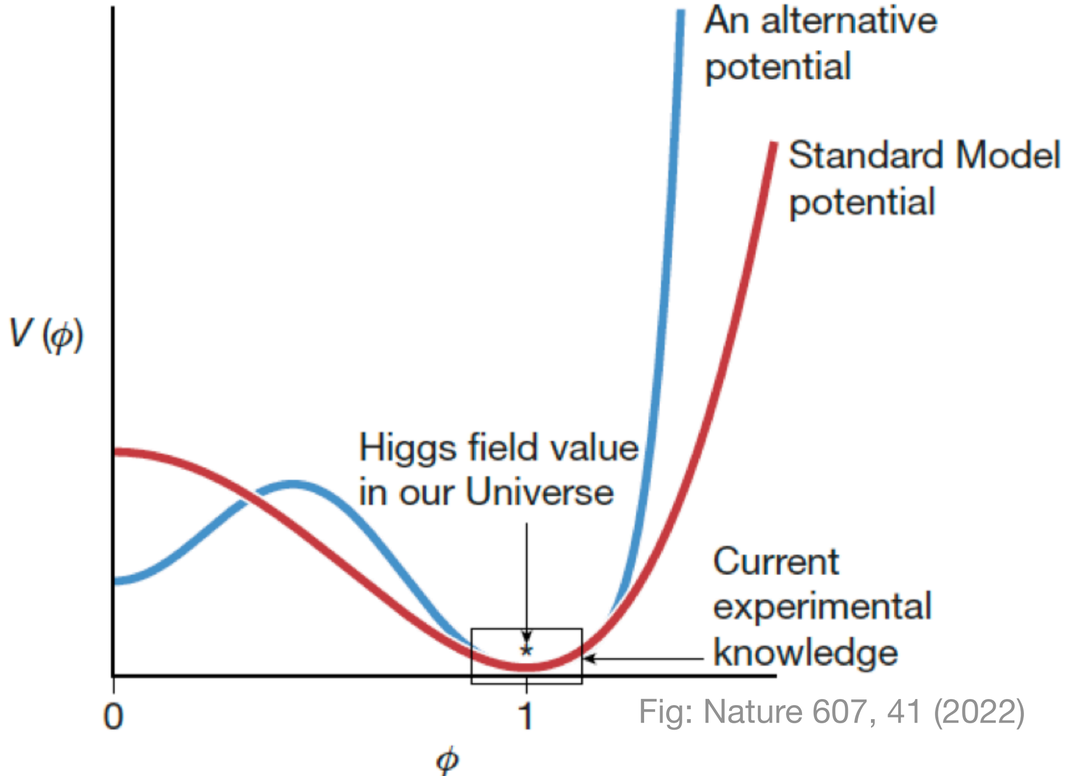
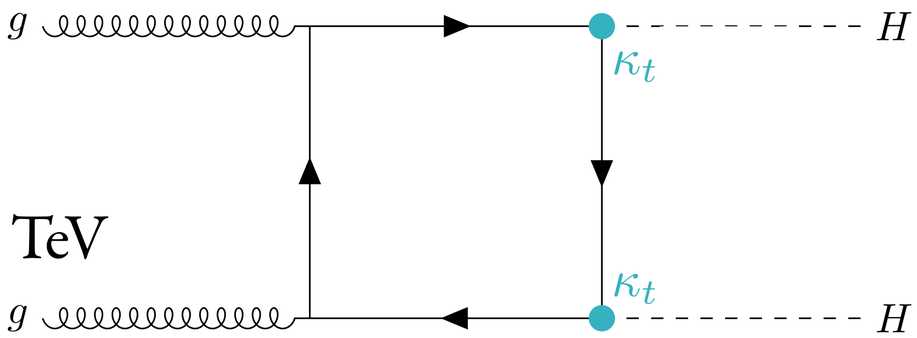


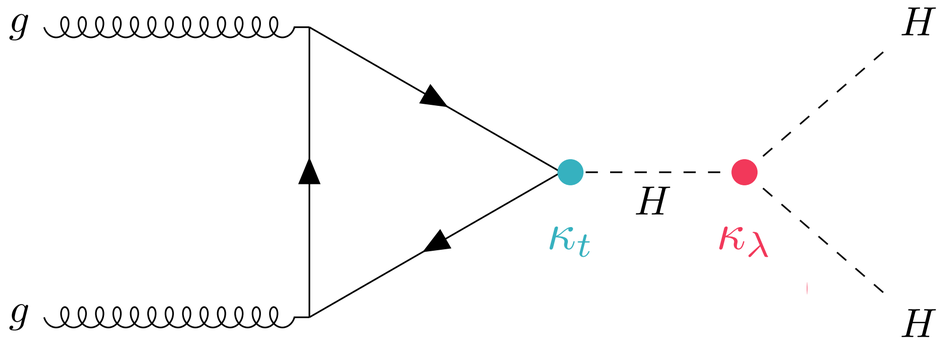
Fig: Nature 607, 41 (2022)

HH production

ggF

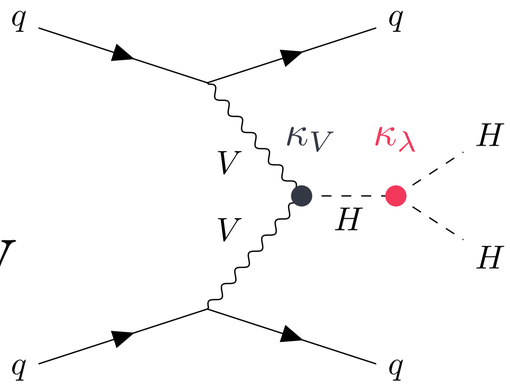
$\sigma \approx 30.8$ fb @ 13 TeV

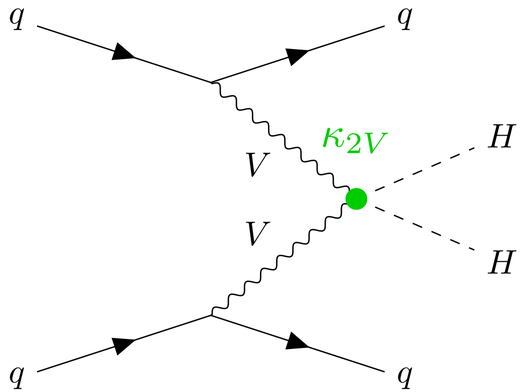


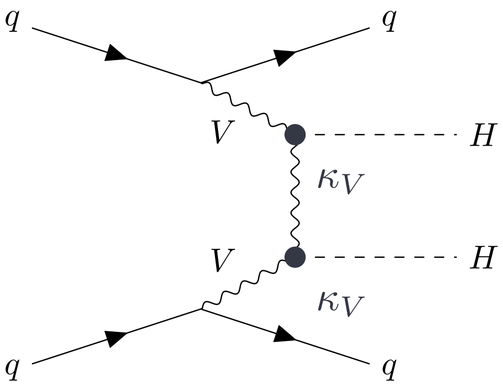


VBF

$\sigma \approx 1.69$ fb @ 13 TeV







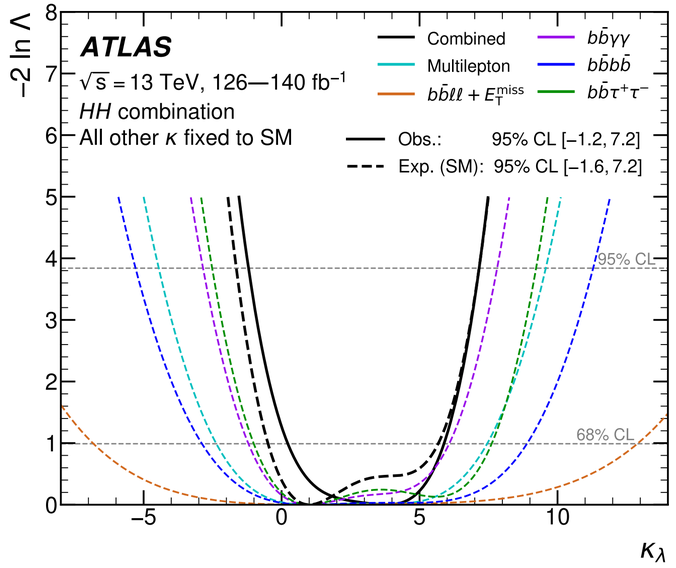
Unique direct access to Higgs boson self-coupling and quartic HHVV coupling modifier

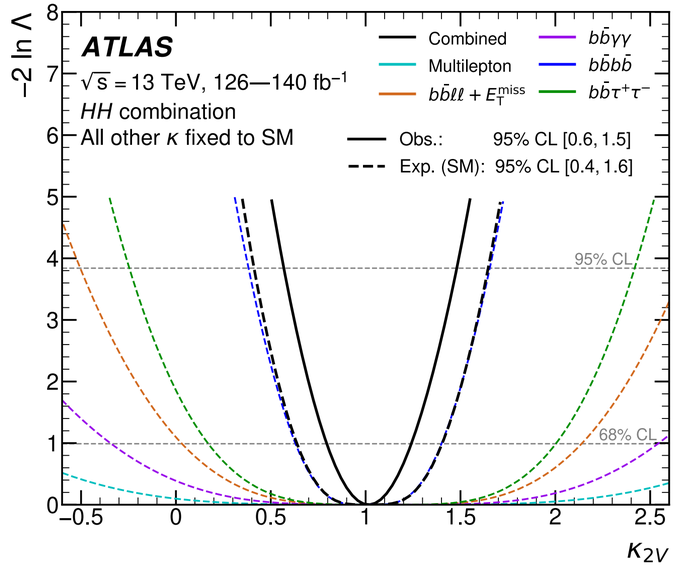
Run-2 combinations

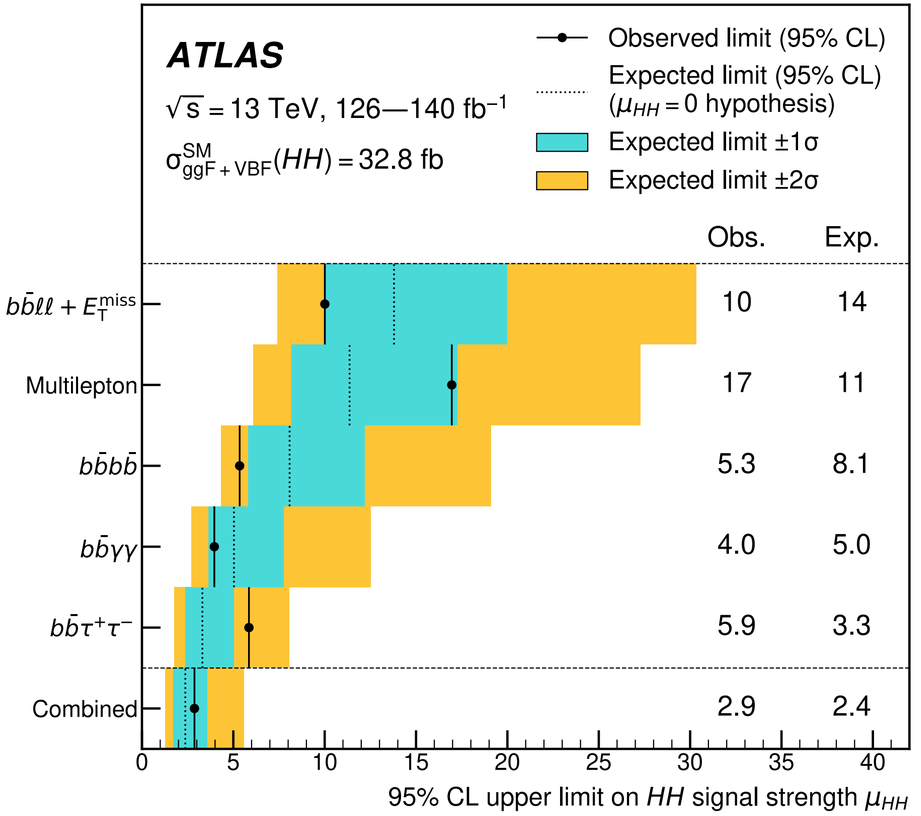
κ-framework/HEFT HH combination

Phys. Rev. Lett. 133, 101801

- All Run-2 HH channels are combined
- Gaining from combination, obtain:
  - Obs. (exp.) 95% CL production limit is 2.9 (2.4) × SM
  - Observed 95% CL limit $-1.2 < \kappa_\lambda < 7.2$
  - Observed 95% CL limit $0.6 < \kappa_{2V} < 1.5$



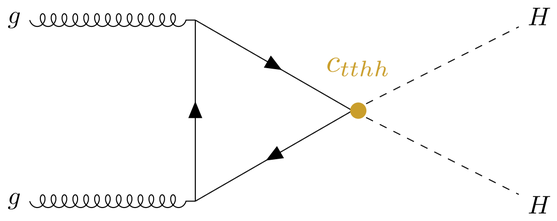


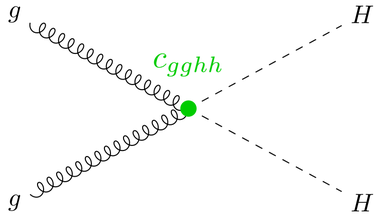


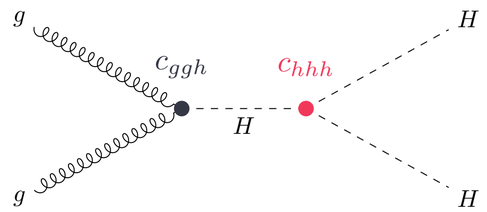
κ-framework/HEFT HH combination

Phys. Rev. Lett. 133, 101801

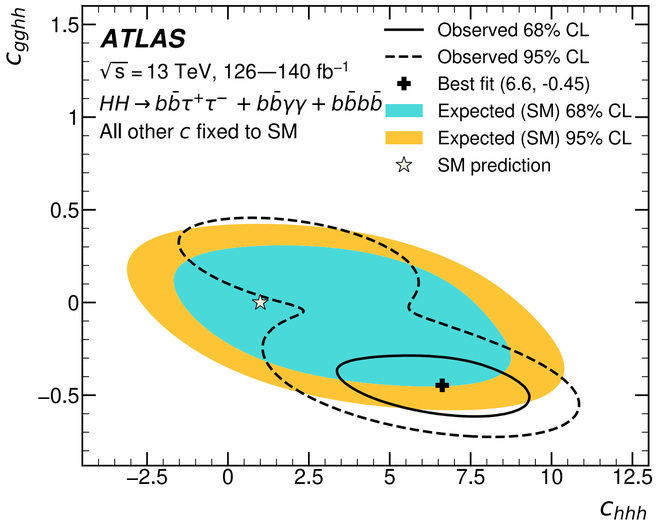
- Higgs Effective Field Theory introduces non-SM couplings c_{tthh}, c_{gghh}, c_{ggh}
- c_{hhh}, c_t in SM have value 1

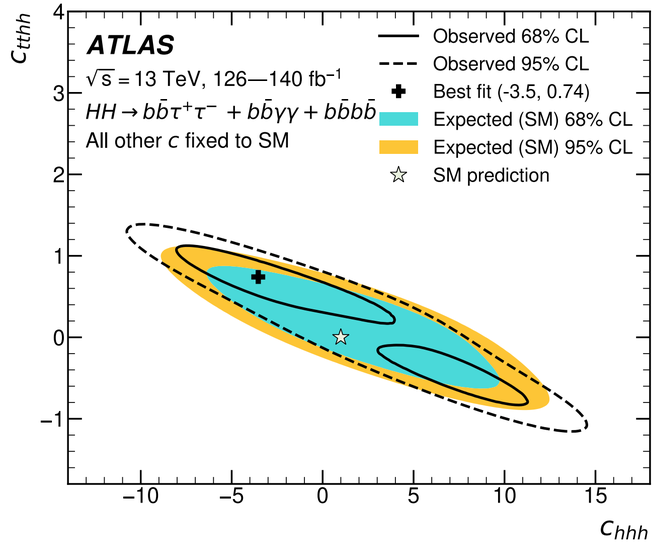


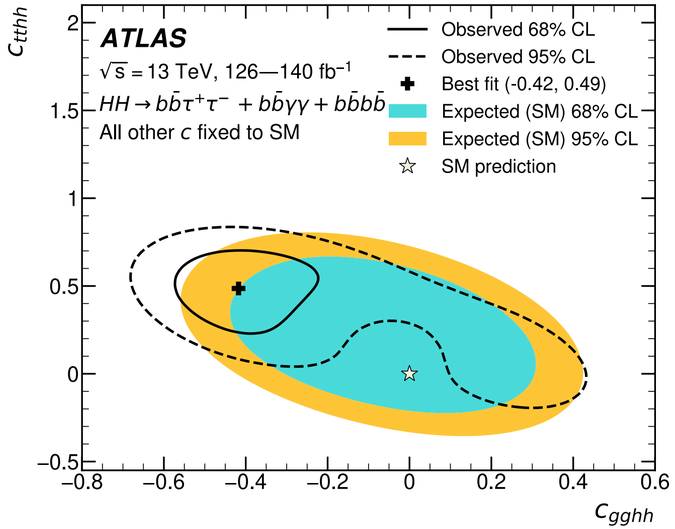




- 2D constraints are obtained, while fixing other values to SM



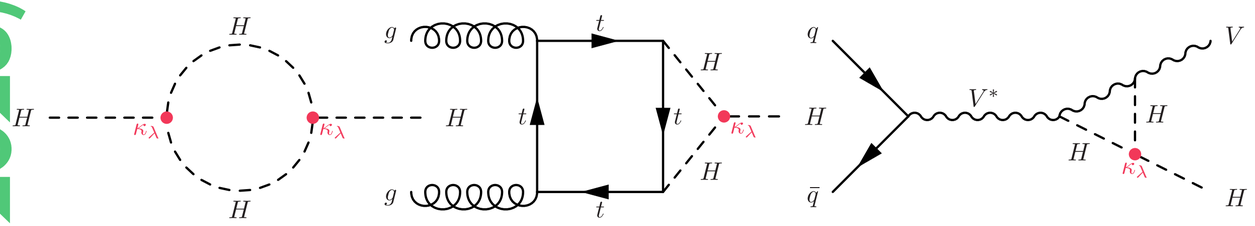




H+HH(partial) combination

Phys. Lett. B 843 (2023) 137745

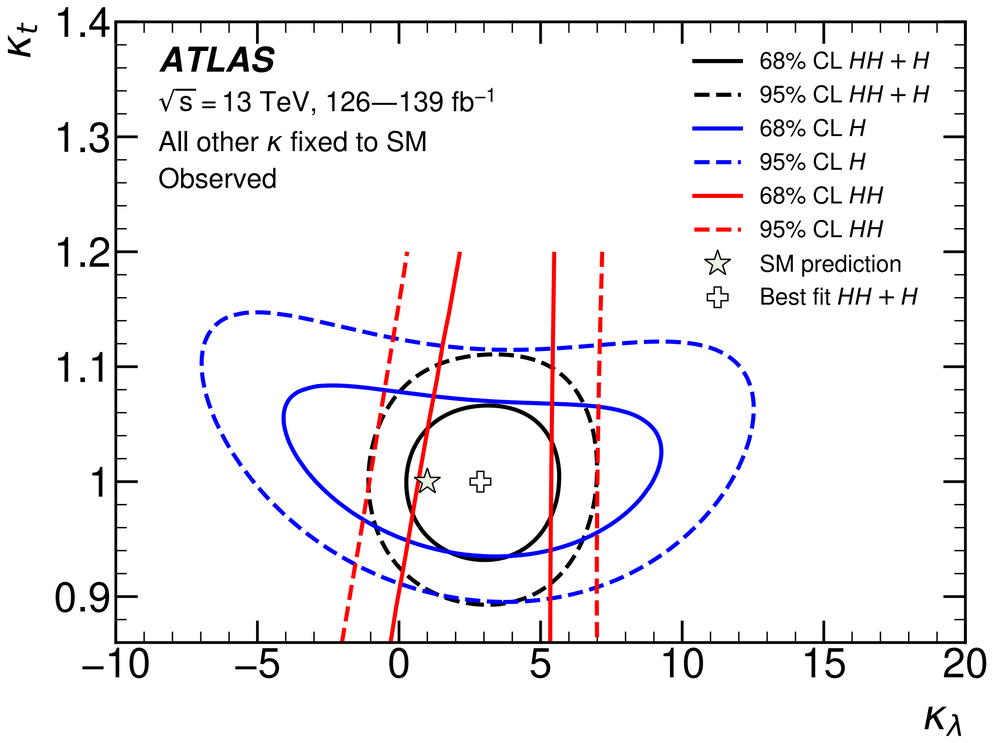
- Sensitive to Higgs self-coupling through EW corrections: single Higgs boson production and decay rates → combine with HH



- H parametrized in STXS bins
- Including H brings 5-7% improvement on κ_λ

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	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.6$

- Beautiful combination example: combined H+HH fit allows to break $\kappa_\lambda : \kappa_t$ degeneracy



*see also talk of Yimin

HL-LHC Projections from Run-2

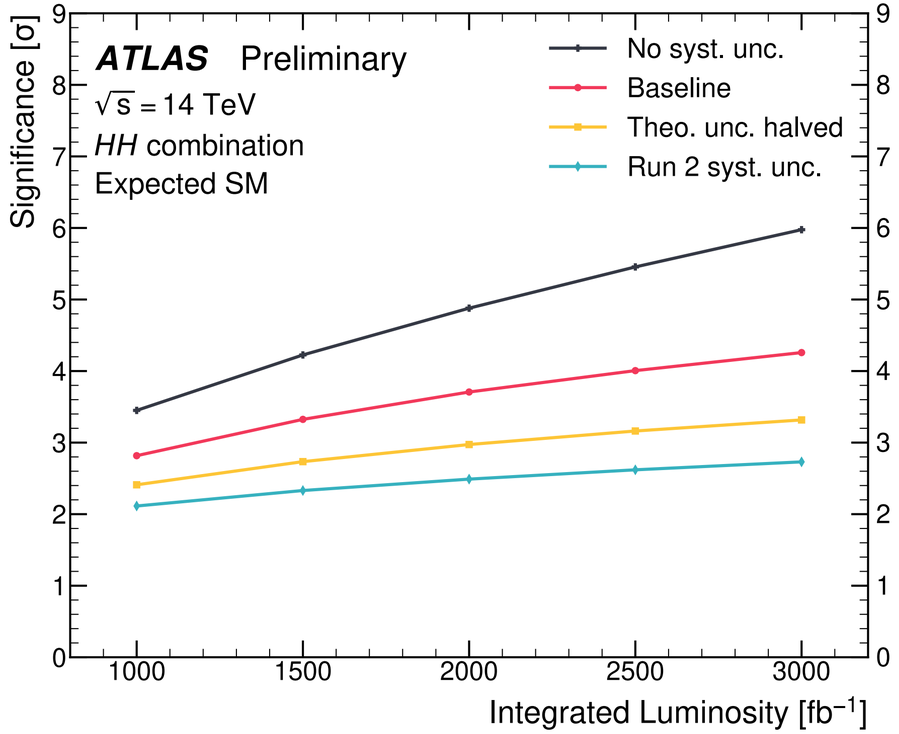
Assume same nominal selection efficiency as in Run-2 which is likely conservative

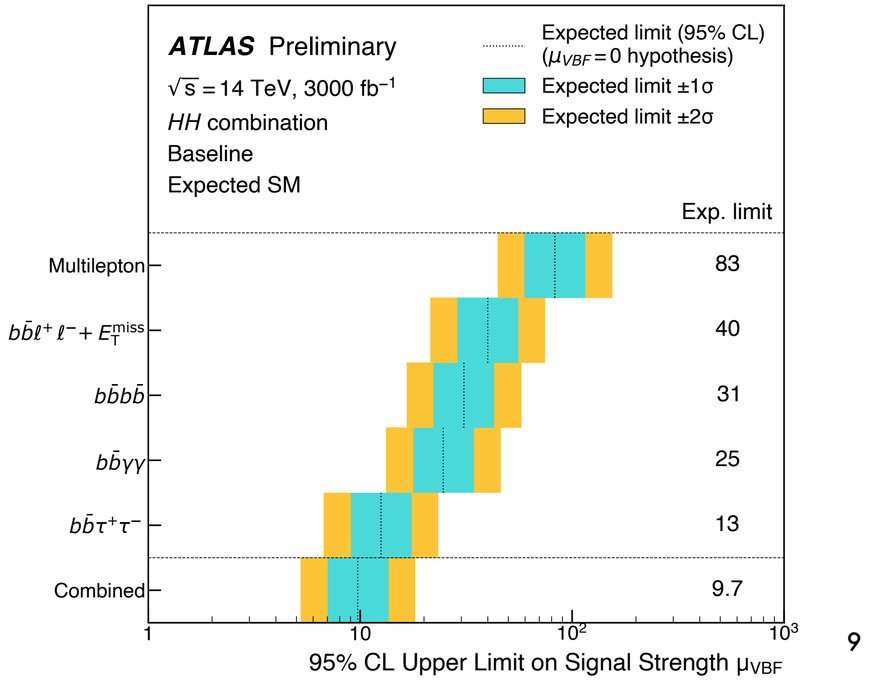
Yields are scaled by overall luminosity factor and process-dependent factor for $\sigma = f(E_{CM})$

ATLAS HH projection

ATL-PHYS-PUB-2025-006

- 5 analysis considered as reference, projected to up 3000 1/fb
- Systematics scenarios:
  - Run-2 level
  - All (signal and background) theoretical ones halved
  - Baseline: theoretical halved and CP ones reduced according to HL-LHC expectation
  - No systematics
- Expected 4.3σ significance with full HL-LHC data
- Expected 95% μ_{VBF} limit: 9.7 × SM

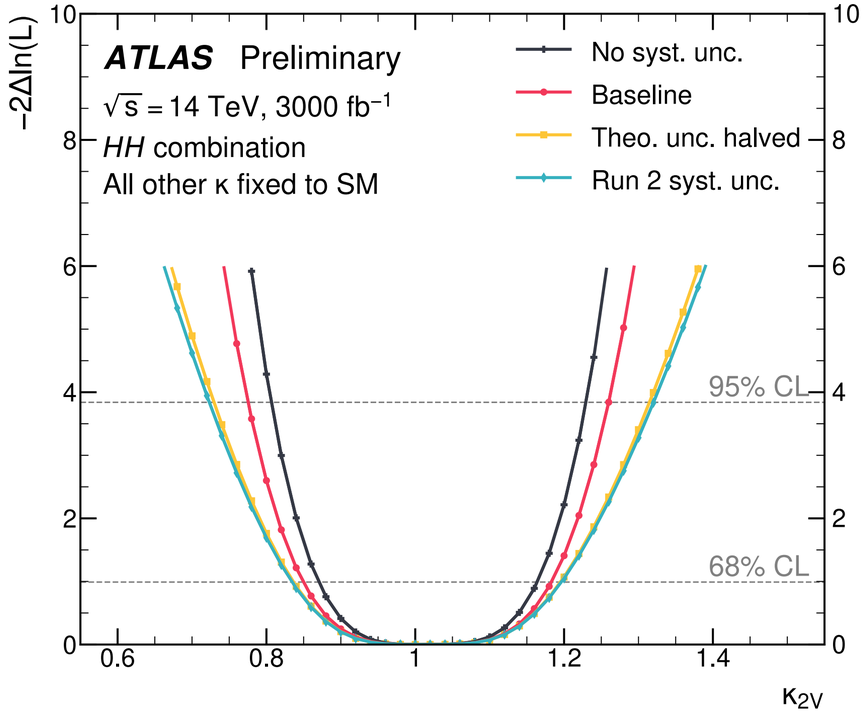


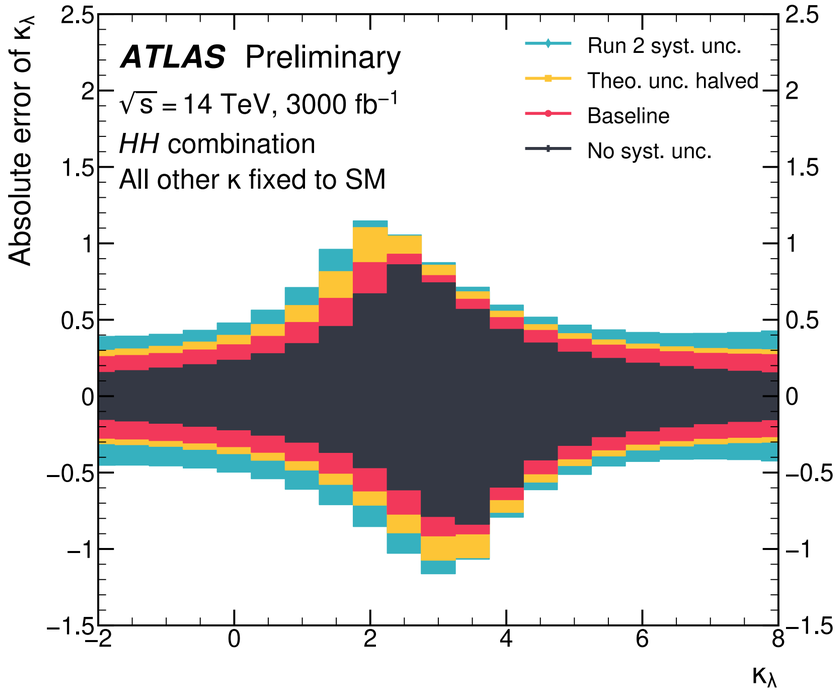


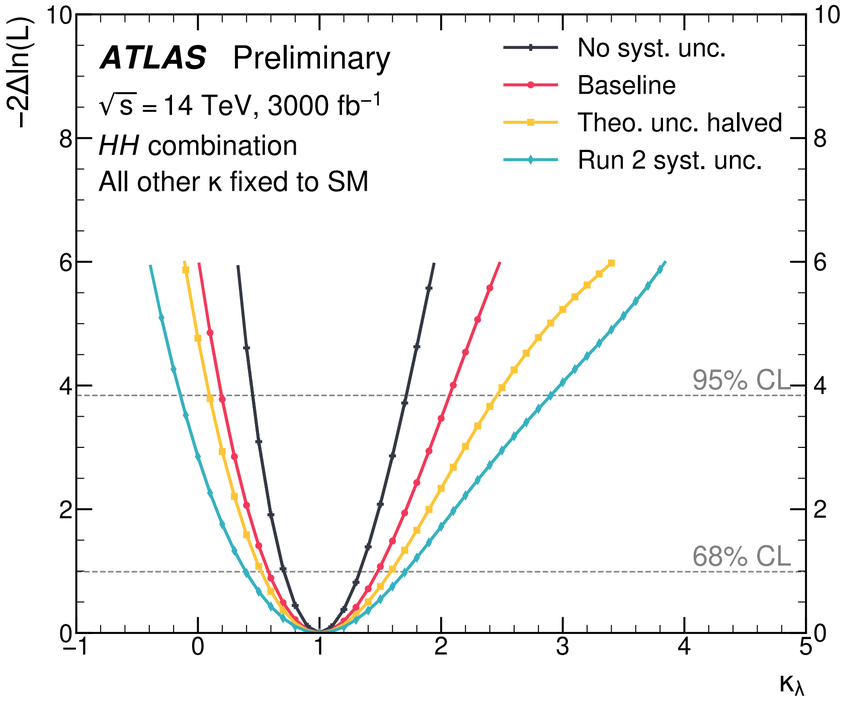
ATLAS HH projection

ATL-PHYS-PUB-2025-006

- Improvement on both κ_λ, κ_{2V} limits, project to get
  - 68% CL limit $0.58 < \kappa_\lambda < 1.48$ (75% improvement compared to previous projection)
  - 68% CL limit $0.85 < \kappa_{2V} < 1.18$
- Good precision for any value of the self-coupling strength nature might prefer



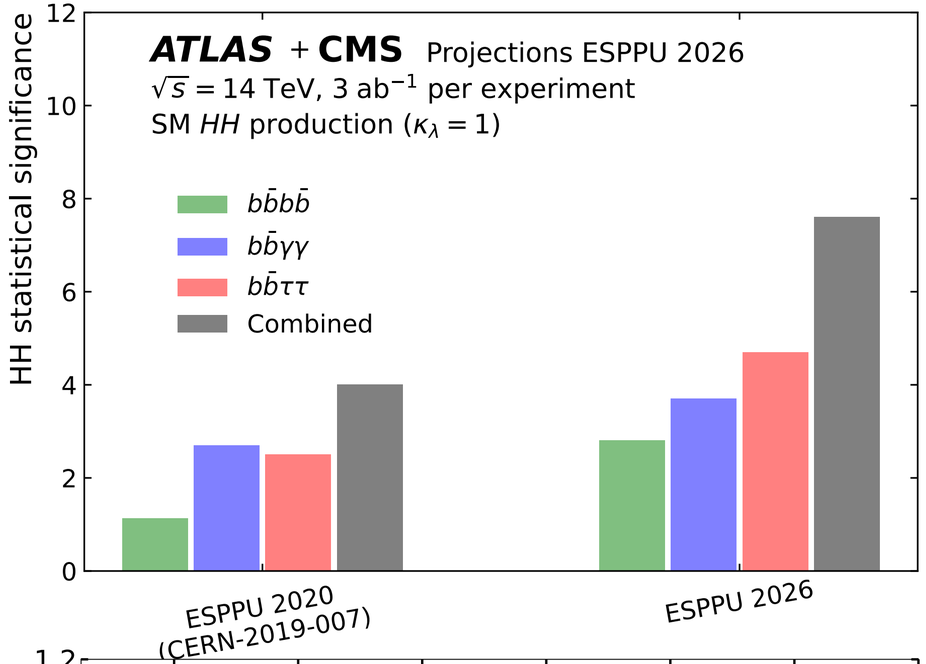


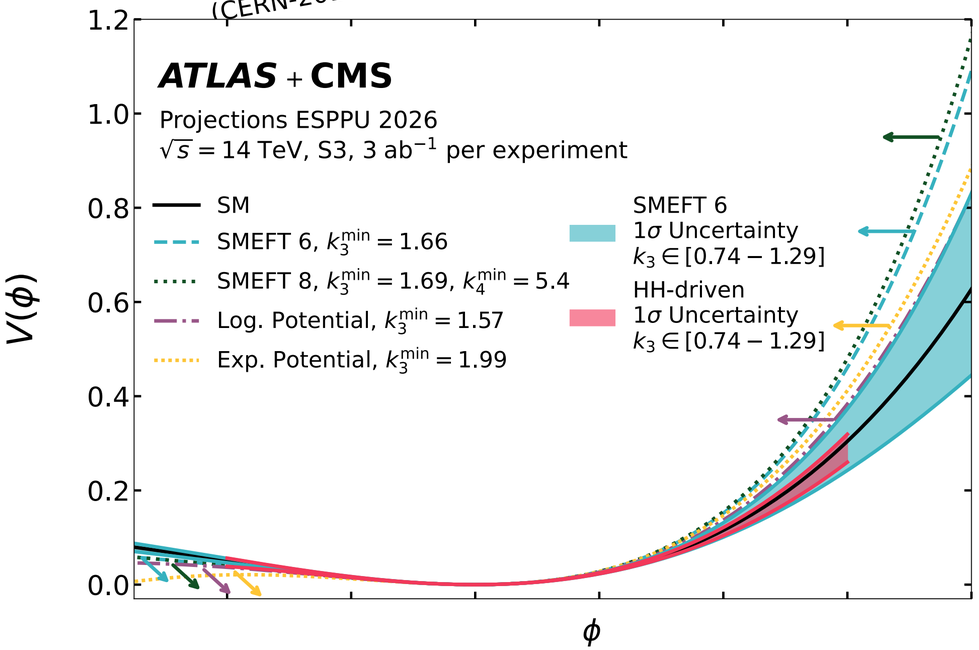


ATLAS+CMS HH projection (ESPPU)

ATL-PHYS-PUB-2025-018

- From recent (2020) history, results will be better then we can think of now
- Significance > 7σ with full HL-LHC dataset collected by ATLAS+CMS, nearly observation by single experiment
- BEH potential of models allowing strong first-order phase transition compared to SM BEH potential
- SMEFT 6 and HH-driven approaches are used to show uncertainties on Higgs self-coupling
- Exclude strong FOPT @ SMEFT dim-6





One of HH golden channels due to $m_{\gamma\gamma}$ resolution, despite low BR

Run-2 + partial Run-3 HH→bbγγ

First ATLAS result with 2024 data

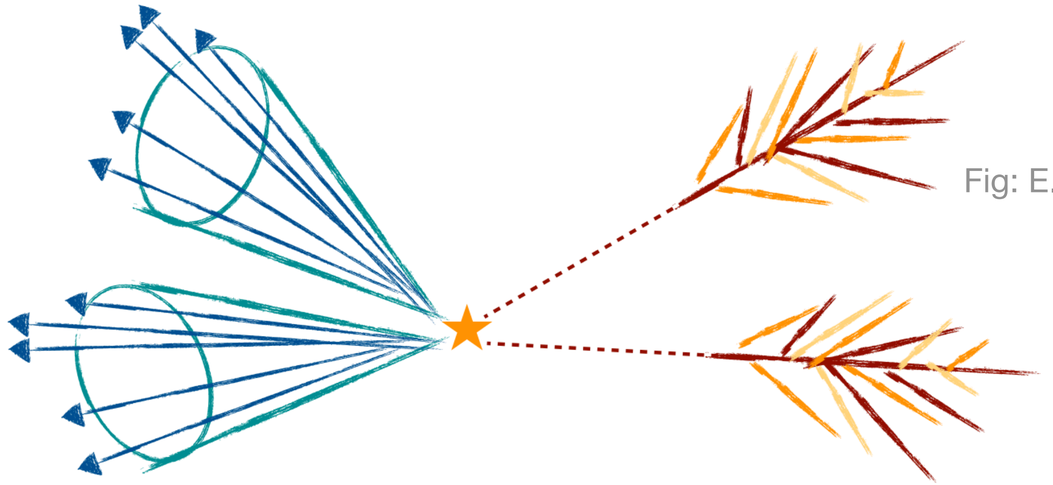


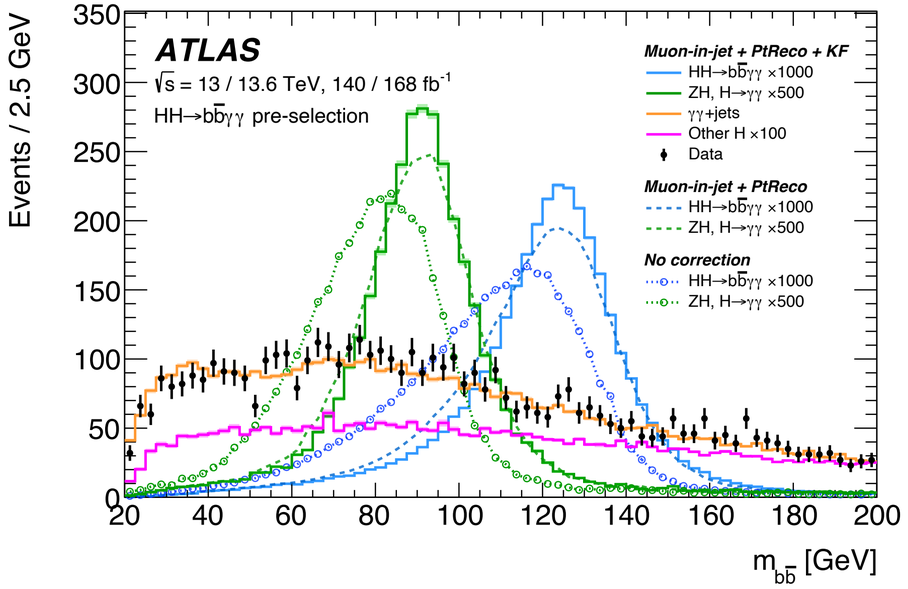
Fig: E. Brost

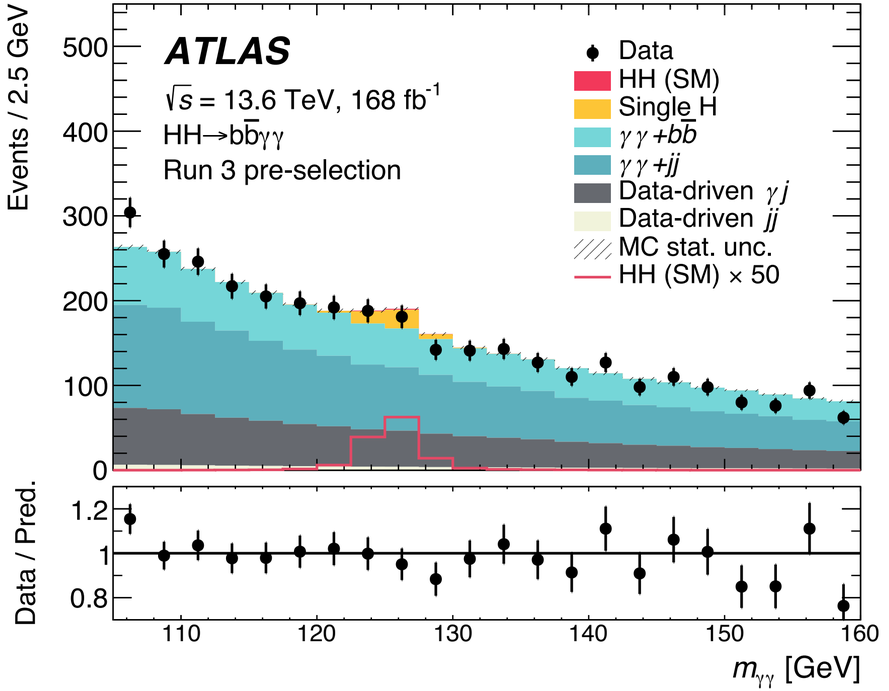
*see also poster of Alexandra

bbγγ - pre-selection

Pub.page 2507.03495,

- Photon-related: diphoton triggers, 2 tight and isolated photons, relative leading (subleading) $p_T > 0.35$ (0.25), $105 < m_{\gamma\gamma} < 160$ GeV
- ttH suppression: $N_{leptons} = 0$, $N_{central\ jets} < 6$
- B-jets
  - (new) GN2 tagger @ 85% WP
  - (new) Kinematic Fit for improved m_{bb}, m^*_{bbyy} resolution
- Further categorized with BDT





bbγγ - categorisation

2507.03495, Pub.page

- Split into two regions based on $m^*_{bb\gamma\gamma} = m_{bb\gamma\gamma} - (m_{bb} - 125) - (m_{\gamma\gamma} - 125)$
- Train two BDTs based on score define categories
- Simultaneous fit is done in 7 (number of regions) * 2 (Run-2, Run-3) categories

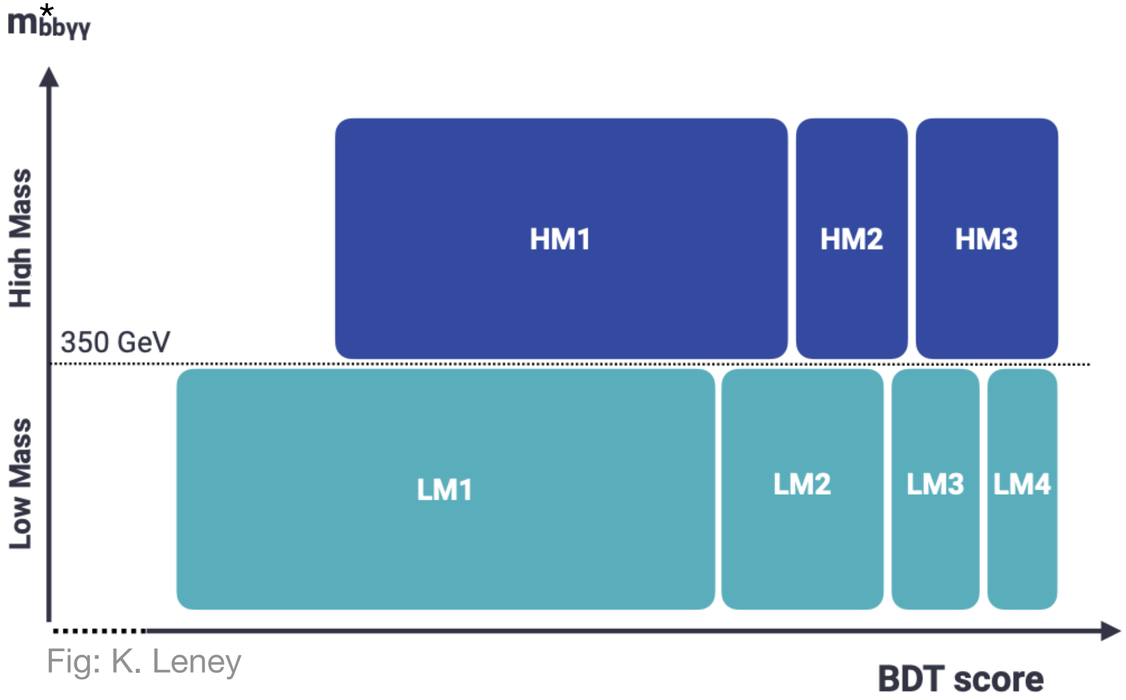
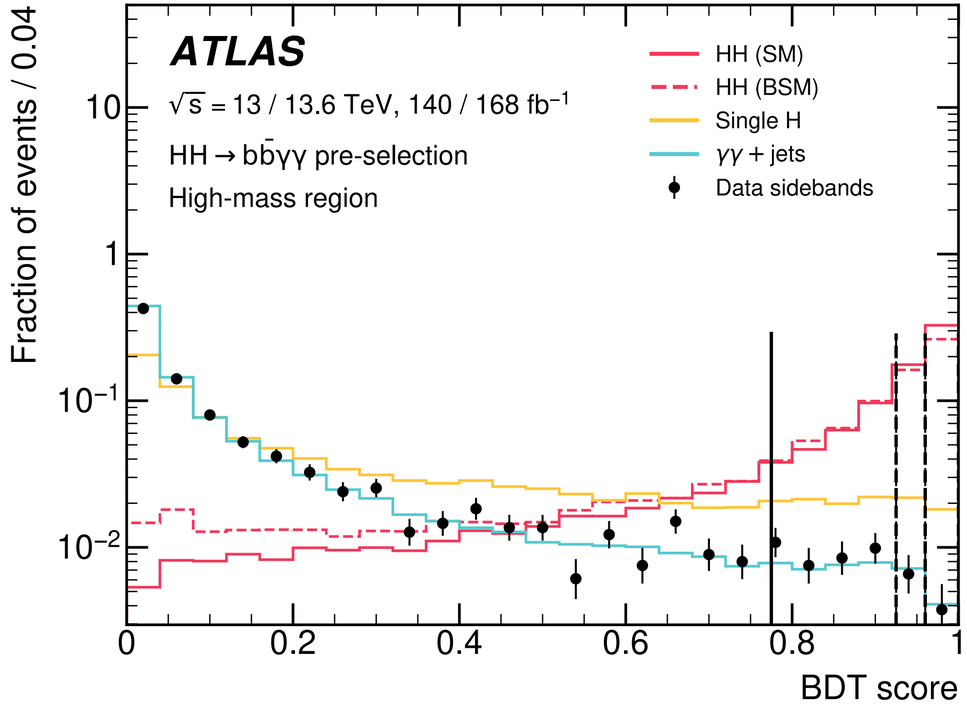


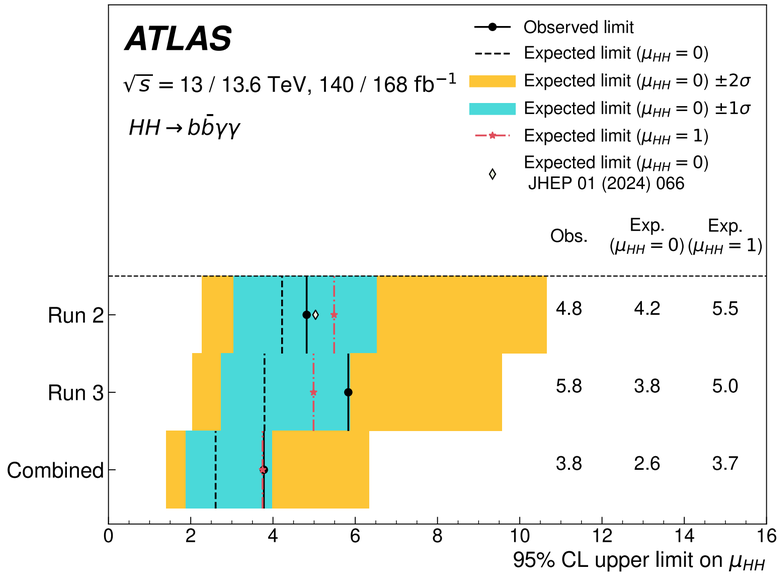
Fig: K. Leney

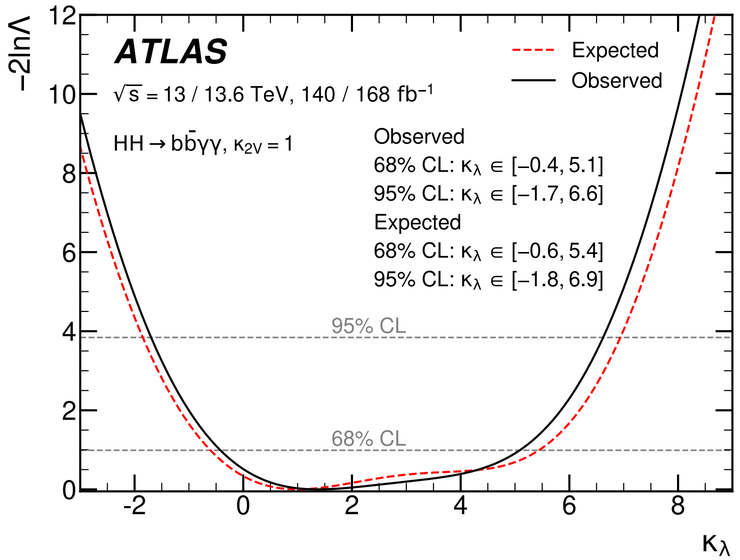


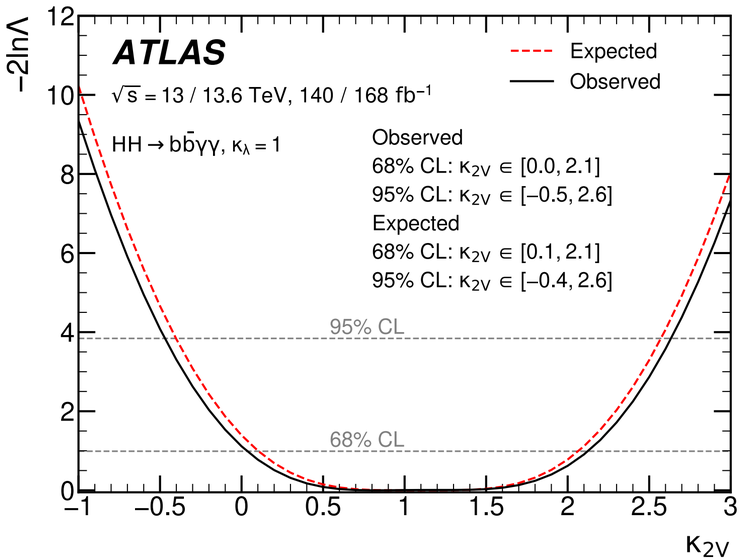
bbγγ - results

2507.03495, Pub.page

- Observed (expected) significance of SM HH: 0.8 (1.0) σ
- Improvement wrt to previous analysis: 50% from more data, 50% from GN2, KF, combined Run-2, Run-3 categories
- Obs. (exp.) 95% CL upper limit: 3.8 (2.6) × SM: expected limit comparable with Run-2 combination
- 95% CL expected limits wrt to previous analysis ~20% better k_λ limit, ~30% better k_{2V} limit







Conclusion

- HH measurements is a fundamental test of the SM
- All decays channels are covered by ATLAS
- Explored within κ-framework, HEFT, SMEFT approaches and combination with H

- Run-2 combined observed 95% CL limit: 2.9
- HL-LHC ATLAS projection: 4.3σ at the end of HL-LHC (baseline uncertainty scenario)
- HL-LHC ATLAS+CMS projection: observation significance reached!

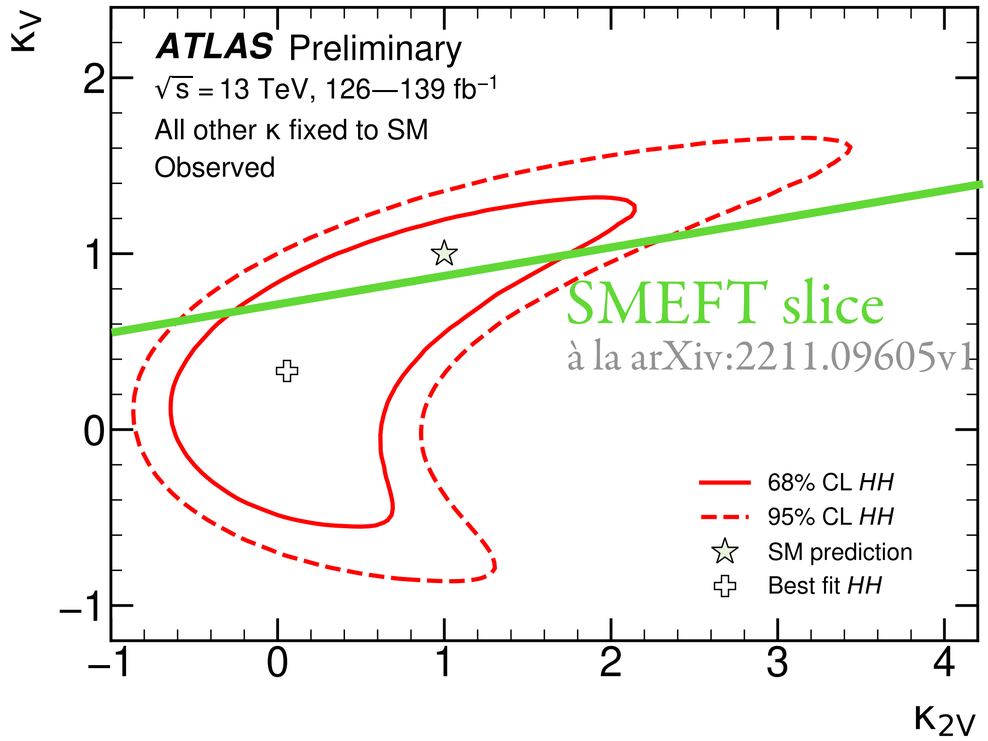
- HH→bb$\gamma\gamma$ is the first analysis with 308 1/fb of data (inc. 2024 data) published: obs. 95% CL limit 3.8

The End

H+HH(partial) combination

Phys. Lett. B 843 (2023) 137745

- With HH only $\kappa_V : \kappa_{2V}$ constraint was derived
- In HEFT parameters are decorrelated
- In SMEFT they are correlated, slice parallel to one of the "branches" of experimental bounds



H+HH(partial) combination

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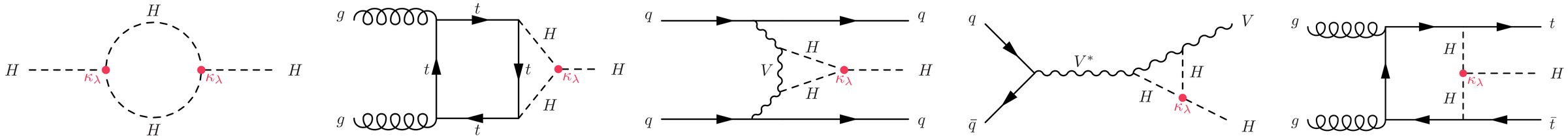

Channel	Integrated luminosity [fb^{-1}]	Ref.
$HH \to b\bar{b}\gamma\gamma$	139	[17]
$HH \to b\bar{b}\tau^+\tau^-$	139	[18]
$HH \to b\bar{b}b\bar{b}$	126	[19]
$H \to \gamma\gamma$	139	[58]
$H \to ZZ^* \to 4\ell$	139	[59]
$H \to \tau^+\tau^-$	139	[60]
$H \to WW^* \to e\nu\mu\nu$ (ggF,VBF)	139	[61]
$H \to b\bar{b}$ (VH)	139	[62]
$H \to b\bar{b}$ (VBF)	126	[63]
$H \to b\bar{b}$ ($t\bar{t}H$)	139	[64]

bbγγ - uncertainties

2507.03495, Pub.page

$$\mu_{HH} = 0.9^{+1.3}_{-1.0}\,(\text{stat.})\,^{+0.6}_{-0.5}\,(\text{syst.})$$

Table 1: Impact of the various systematic uncertainties in the observed μ_{HH} measurement. For each uncertainty group, the error on μ_{HH} is obtained from a fit with only those corresponding nuisance parameters floating and all others fixed to their best-fit values. The impact is then calculated from the subtraction in quadrature of this error and the error when all nuisance parameters are fixed. The up (down) columns indicate the impact on the upper (lower) μ_{HH} error. When the up and down variations are found to be compatible within 30%, the uncertainties are symmetrised. Asymmetric impacts primarily result from the asymmetric QCD scale + m_{top} signal uncertainty, and the fact that the lower 68% CL error on the signal strength is close to 0. The heavy-flavour content uncertainty in the table refers to single Higgs boson production.

Source of systematic uncertainty	**Relative uncertainty [%]**	
	Up	**Down**
Experimental		
Photon energy scale	+20	−30
Photon energy resolution	+13	−6.8
Photon efficiency	+13	−2.5
Jet	+9.6	−6.4
Luminosity	+6.3	−1.1
Theoretical		
QCD scale + m_{top}, PDF+α_S	+34	−4.5
$\mathcal{B}(H \to \gamma\gamma, b\bar{b})$	+9.9	−2.1
Parton showering model	±15	
Heavy-flavour content	±29	
Background model		
Spurious signal	±6.5	