~~Non-resonant Higgs boson pair production and self-coupling determination with the ATLAS experiment~~ Di-Higgs status and LAPP involvement

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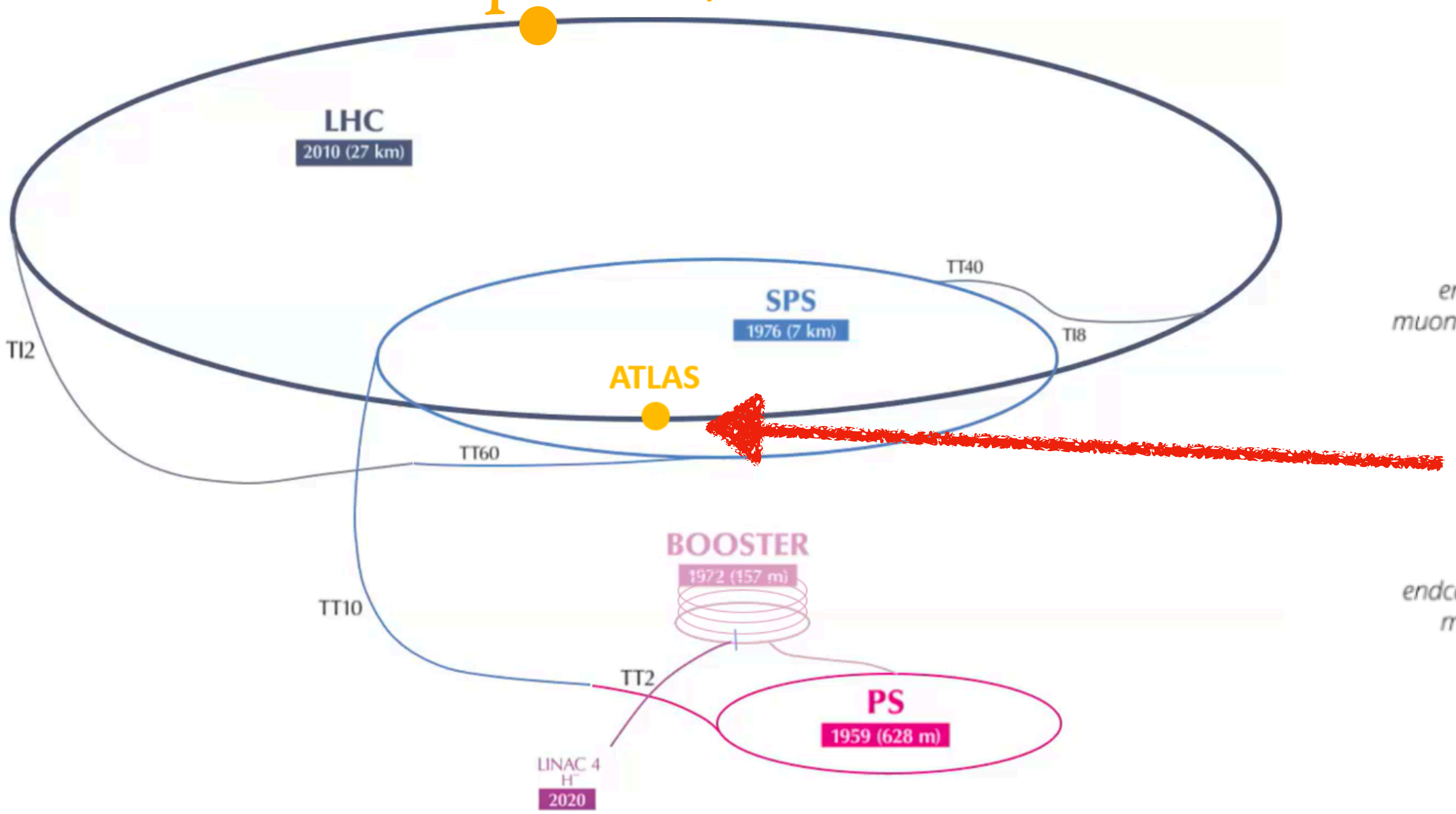
7Nov25 / Assemblée Générale Enigmass+

Experimental apparatus

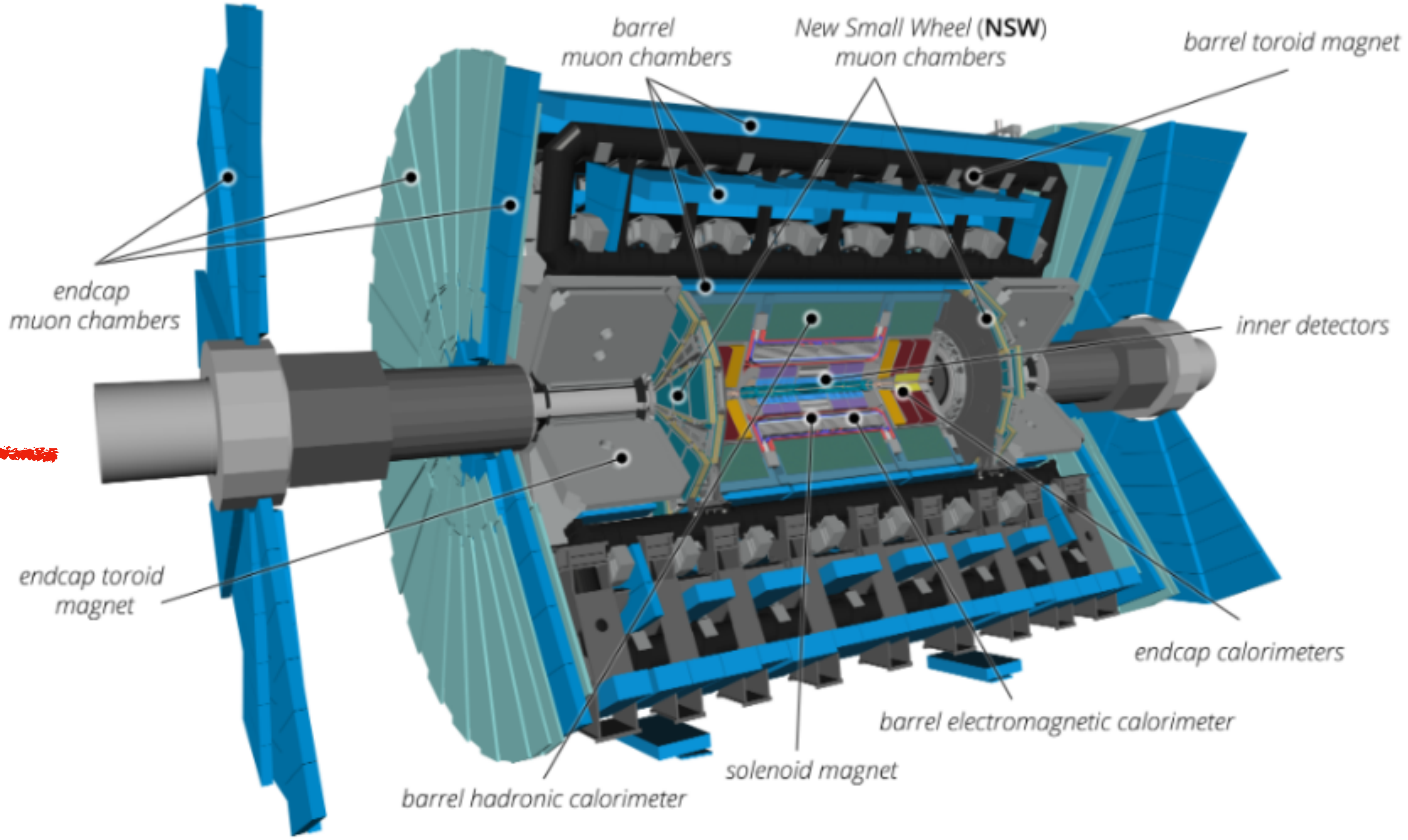
- Most of the data-taking done with proton-proton

Our competitor/friend CMS



- Beam energy 6.8 TeV (now)

- Cylindrical, ~hermetic
- Layers of sub-detectors

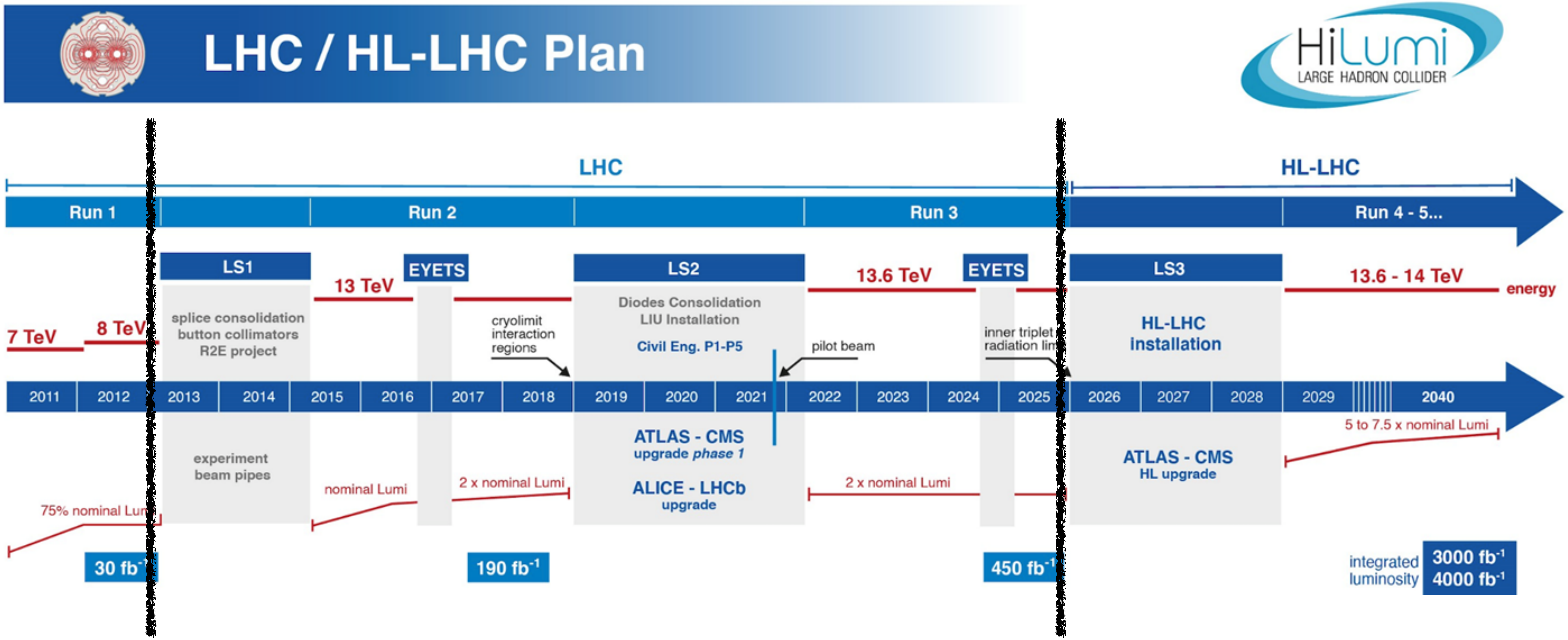


- Reconstruction of all types of objects useful for physics analyses like electrons, muon, jets

Experimental apparatus

- 1987: Workshop on the Physics at Future Accelerators, La Thuile, Italy. The Rubbia “Long-Range Planning Committee“ recommends the LHC as the right choice for CERN’s future

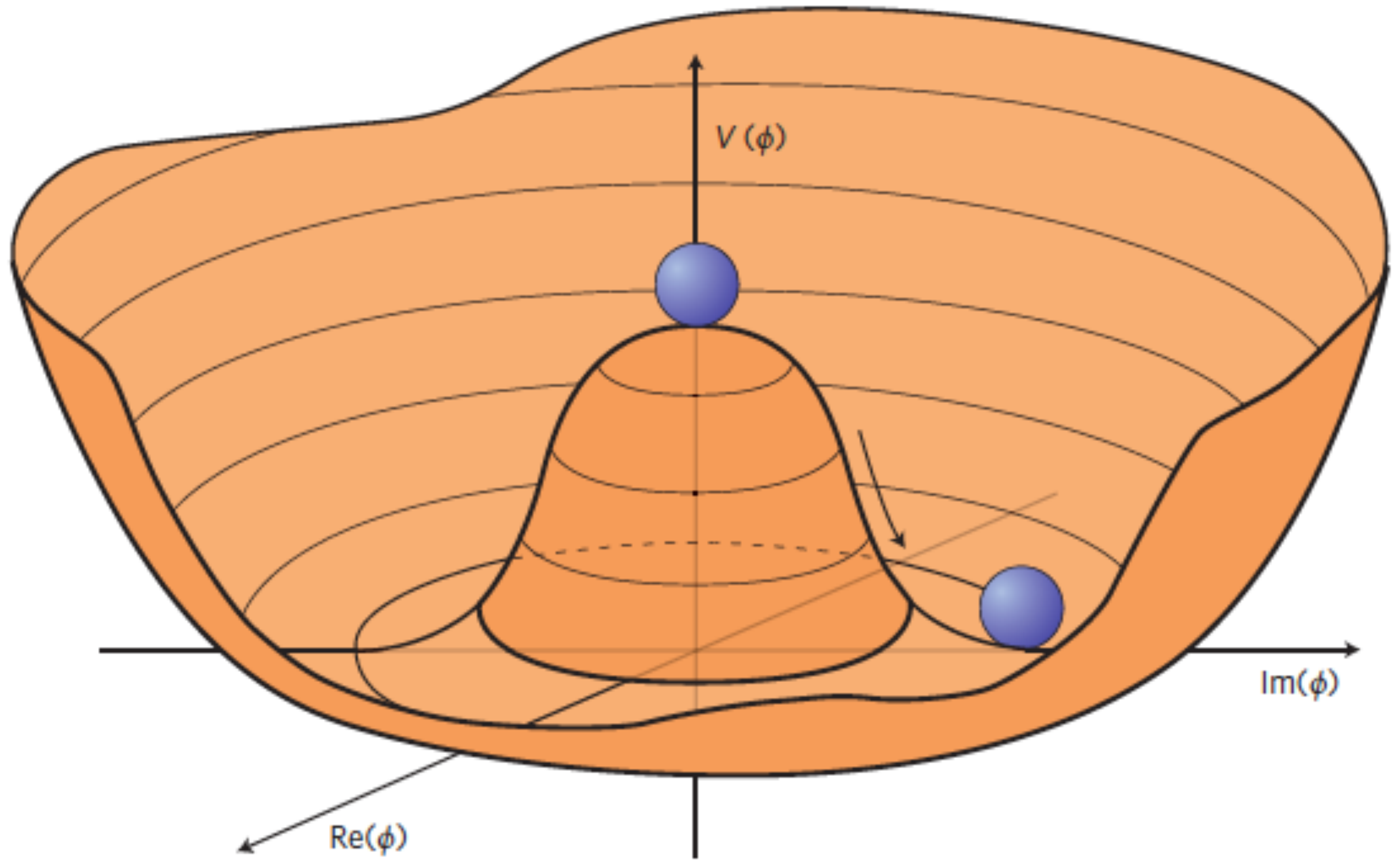
- 2008: first collisions



H discovered HH not discovered

Motivation

- Not so explored part of SM $$V(H) = \frac{1}{2}m_H^2 H^2 + \lambda_{hhh} v H^3 + \ldots$$
- (In SM λ_{hhh}=1)
- Measurement probes the shape of the Higgs potential and hence the Electroweak Symmetry Breaking mechanism



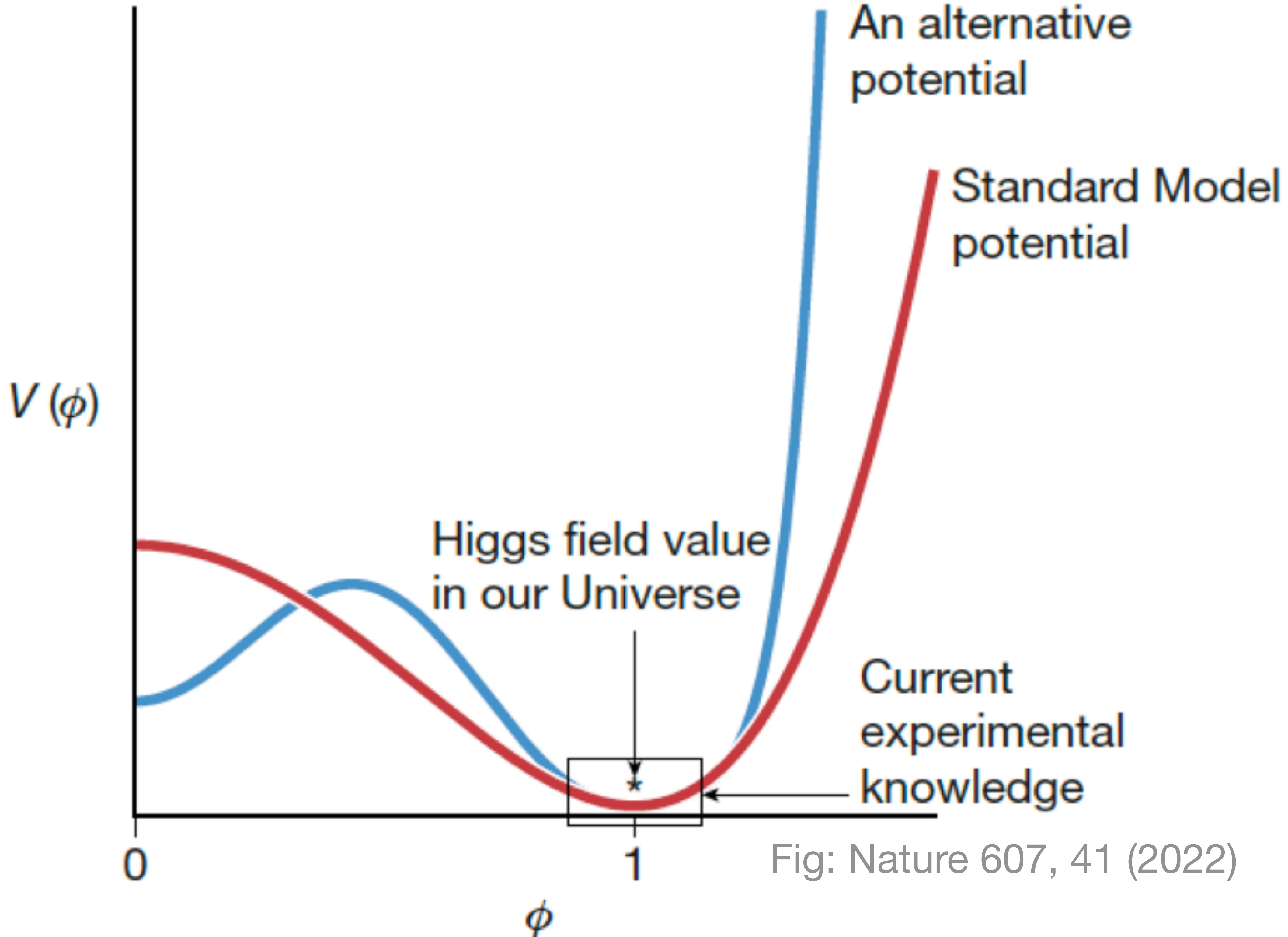
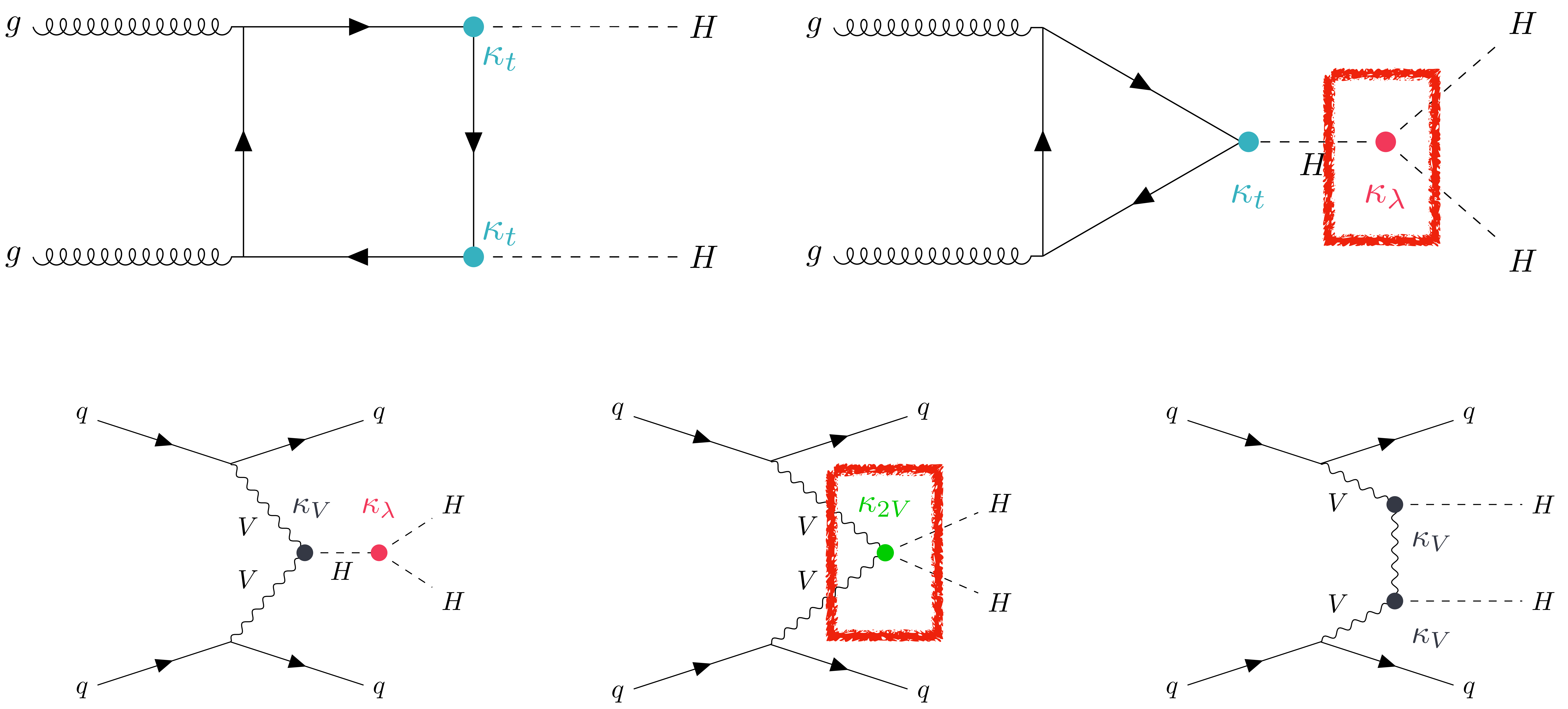


Fig: Nature 607, 41 (2022)

HH production



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

HH decay

- Three golden channels: bbyy, bbbb, bbtt
- Compromise between statistics (bbbb) and how clean signal is (bbyy)

	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%

ATLAS+CMS Run-2 combination

Combination inputs and goals

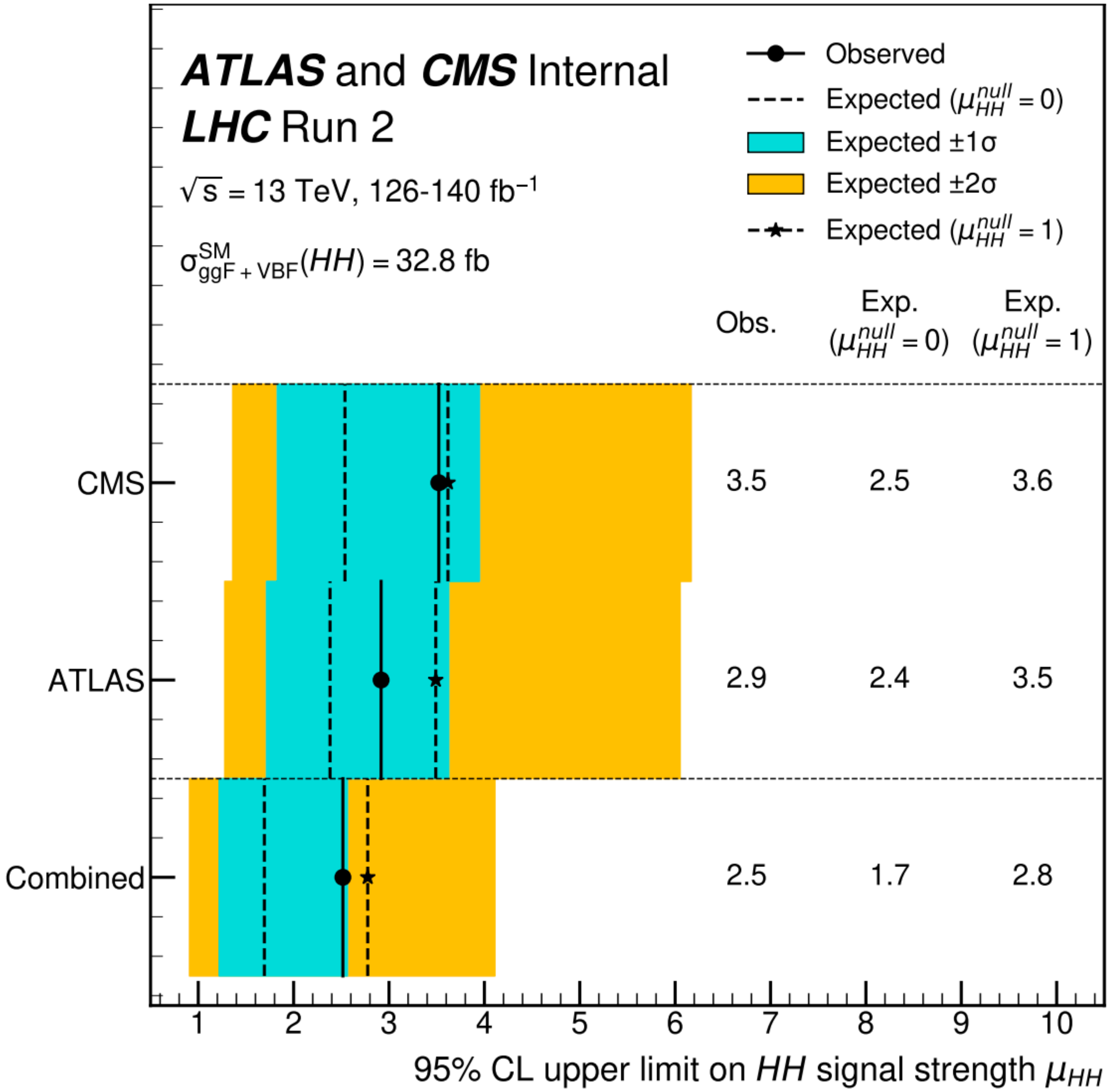
- Run-2 means data was taken in 2015-2018
- Both ATLAS and CMS previously did their own HH combinations
- Combination means make one gigantic statistical model out of several CMS and ATLAS analyses

  between 126 and 140 fb^{-1}, depending on the experiment and the analysis considered. Searches have been performed by both experiments in the bbbb [23–26], bb$\tau\tau$ [27, 28], bb$\gamma\gamma$ [29, 30], bbWW [31, 32] final states, and in topologies with multiple leptons and photons, collectively referred to as Multileptons [33, 34]. Charge conjugation is implied in the notation used throughout this letter.

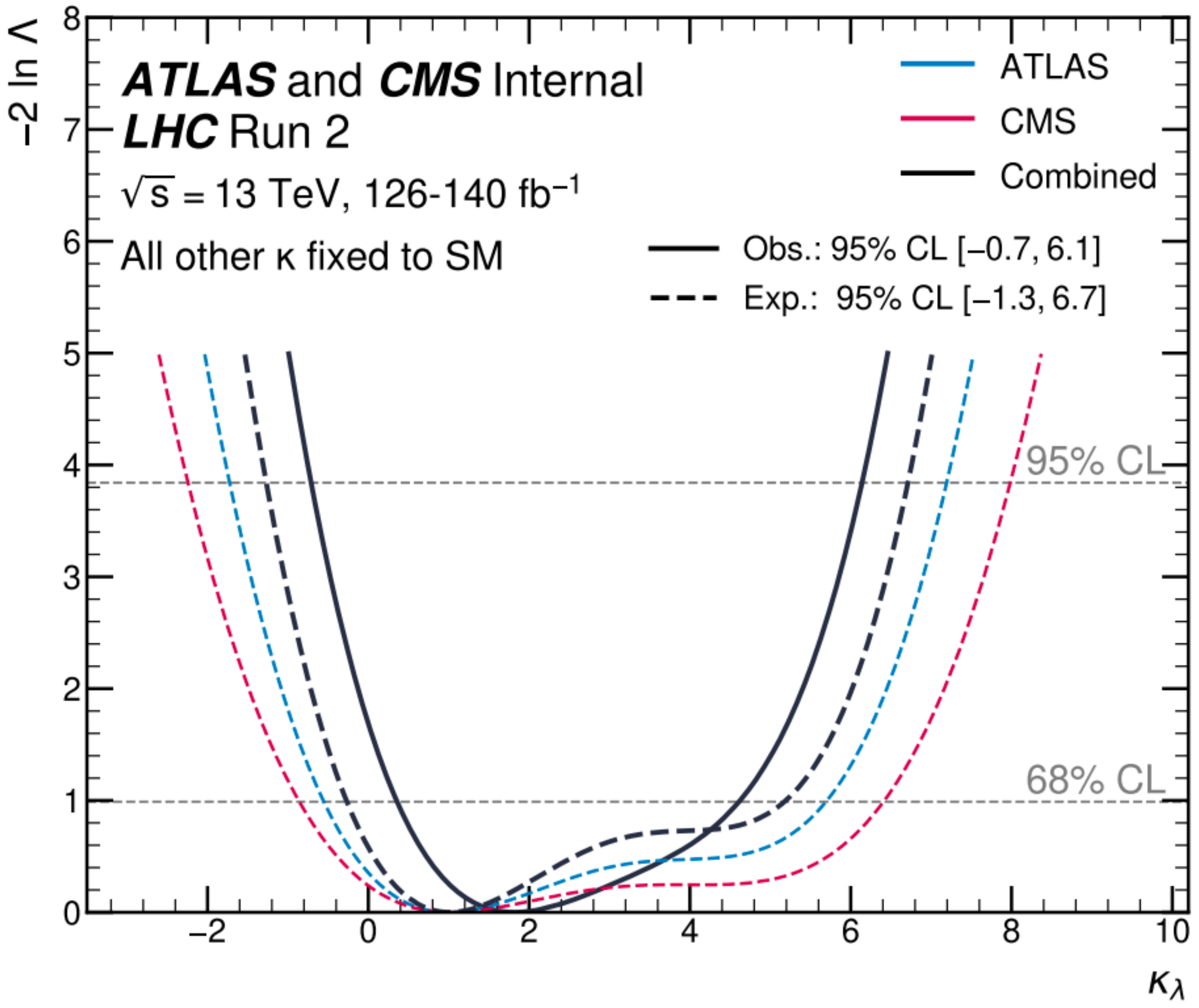
- Want to know
  - Signal strenght (=1 for SM)
  - Significance (want 5 sigma)
  - Which values of $\kappa_\lambda, \kappa_{2V}$ can be excluded

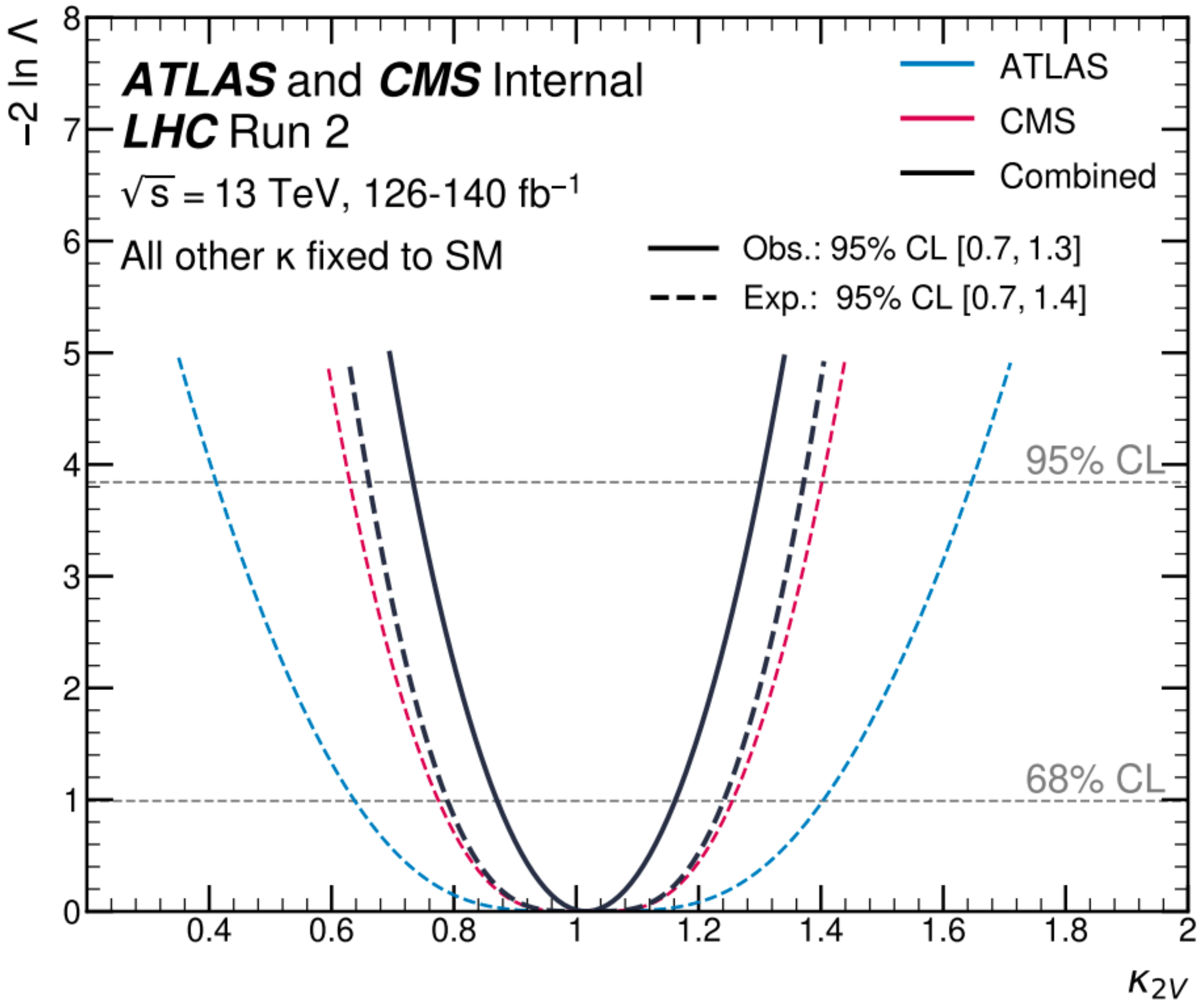
Combination results

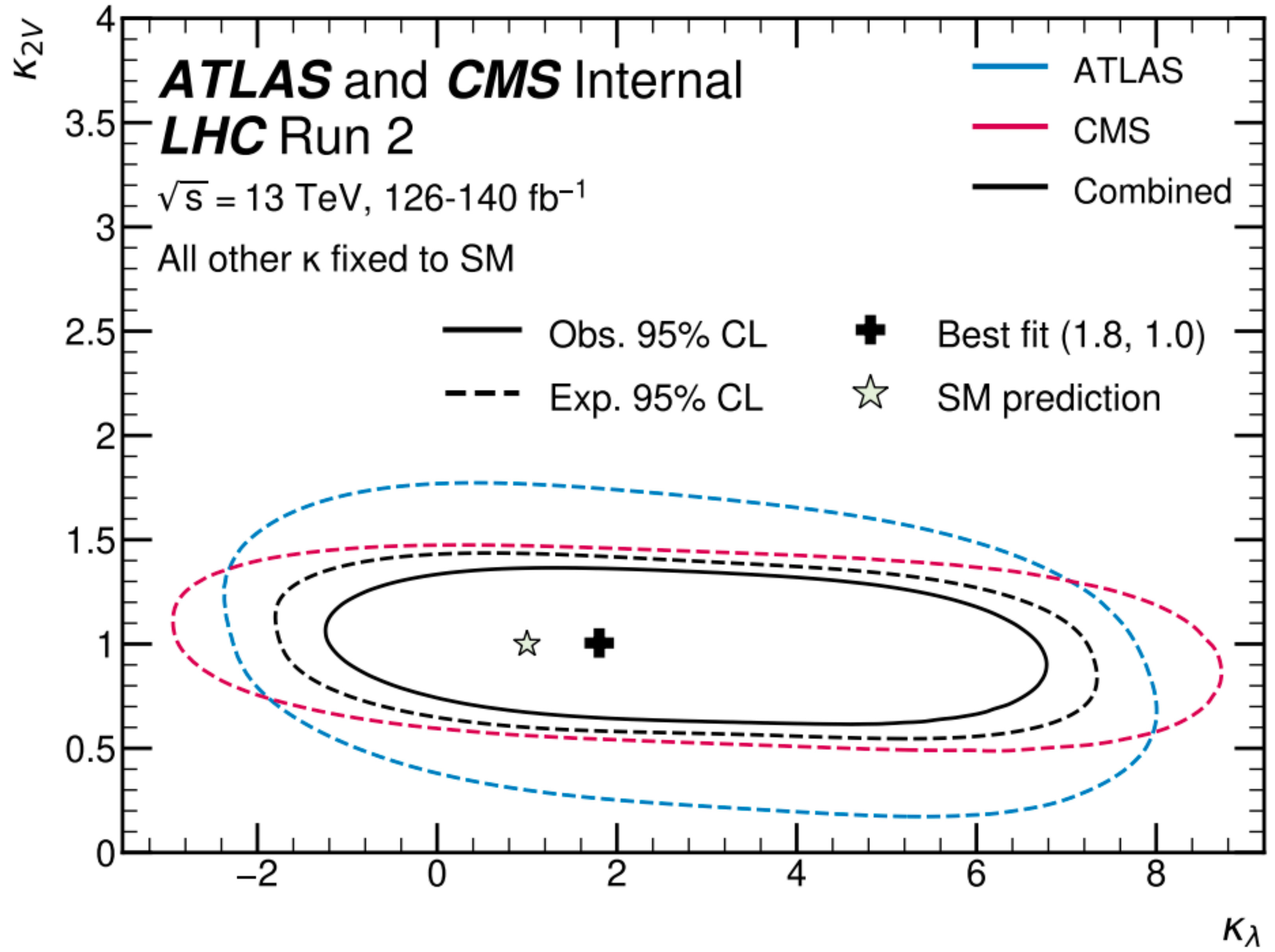
to each set of results, are $\hat{\mu}_{\mathrm{HH}}^{\mathrm{ATLAS}} = 0.5^{+1.2}_{-1.1}$ and $\hat{\mu}_{\mathrm{HH}}^{\mathrm{CMS}} = 1.0^{+1.3}_{-1.0}$. The combined best fit signal strength for HH production is found to be $\hat{\mu}_{\mathrm{HH}} = 0.8^{+0.9}_{-0.7} = 0.8^{+0.7}_{-0.6}(\mathrm{stat.})^{+0.4}_{-0.2}(\mathrm{theory})^{+0.3}_{-0.3}(\mathrm{exp.})$, where the breakdown



Combination results







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

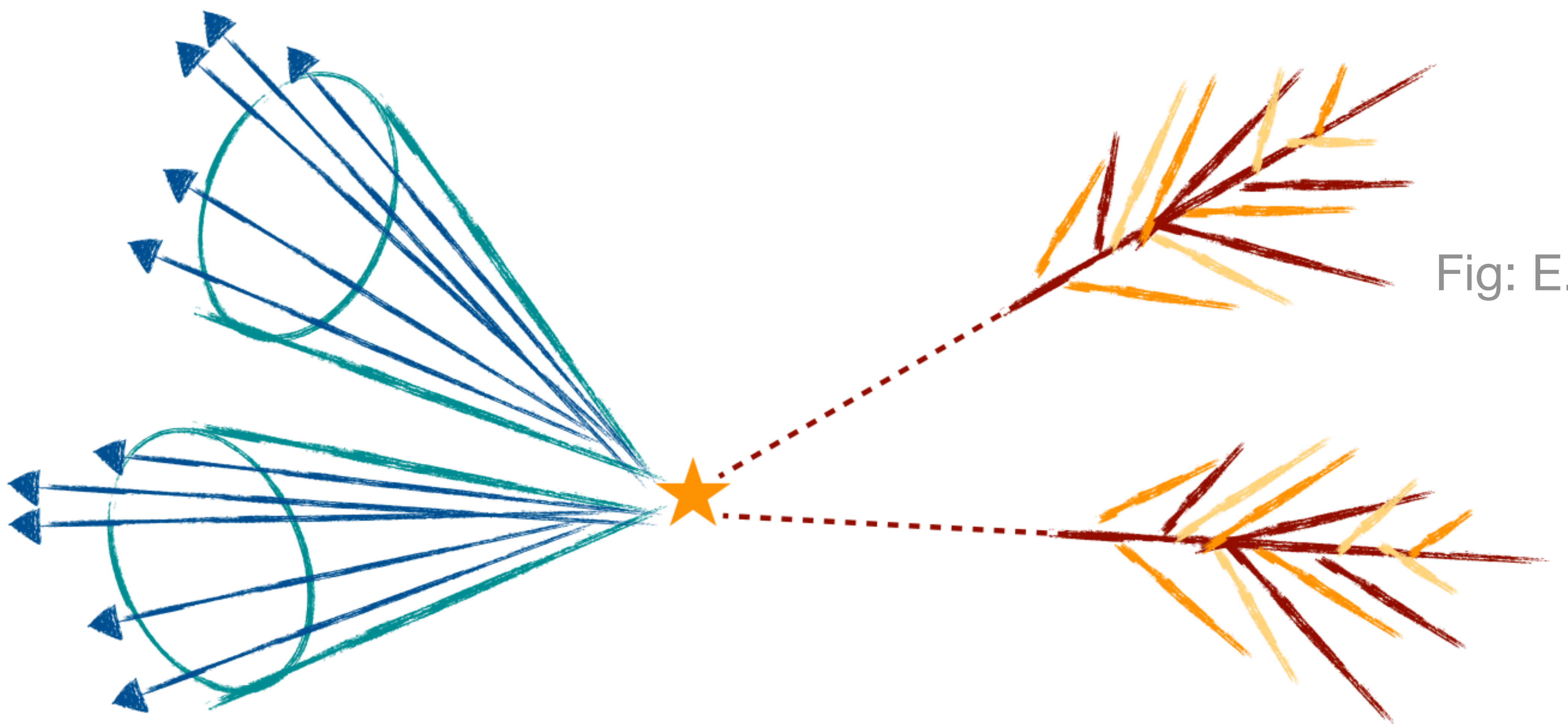


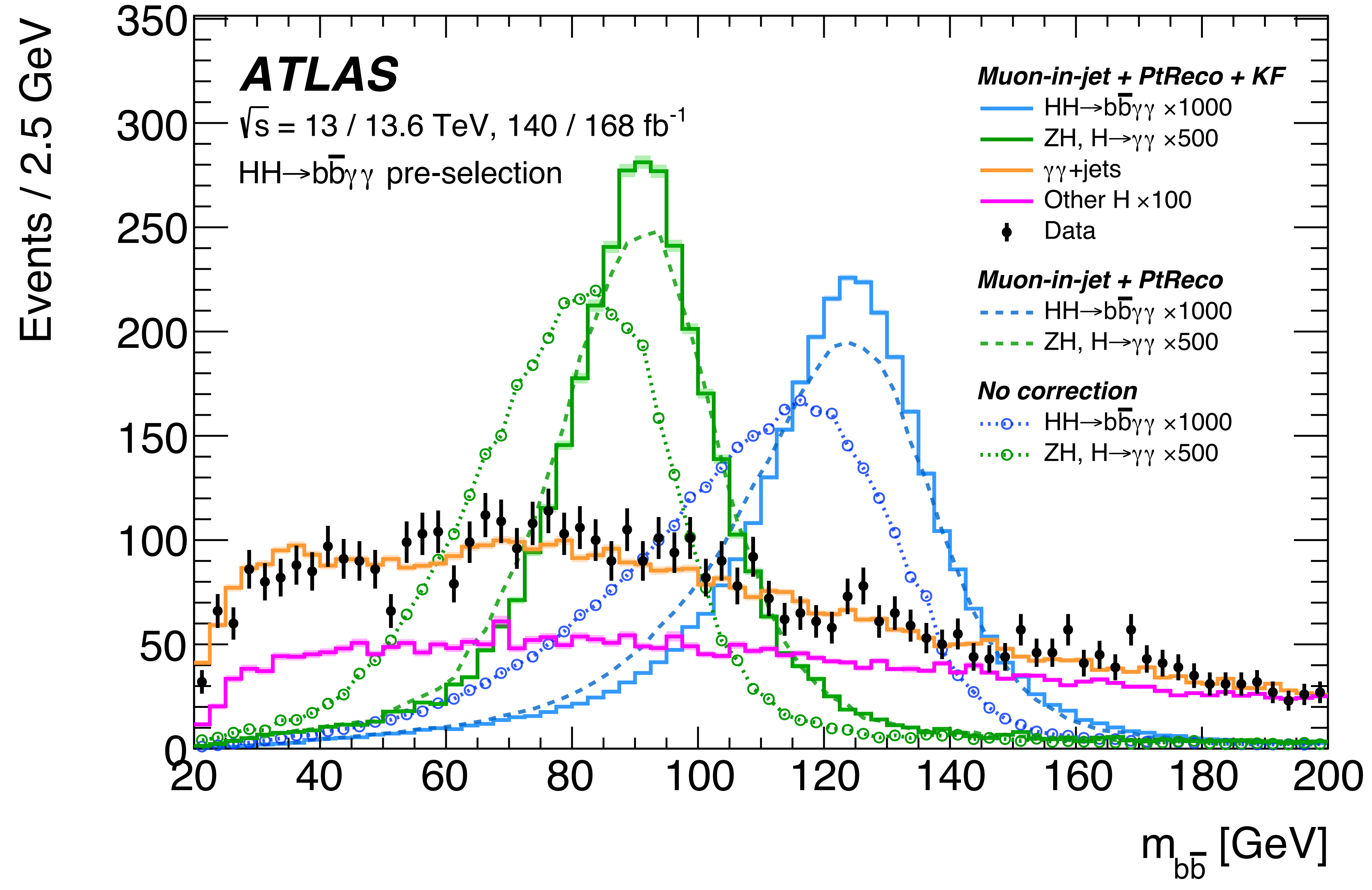
Fig: E. Brost

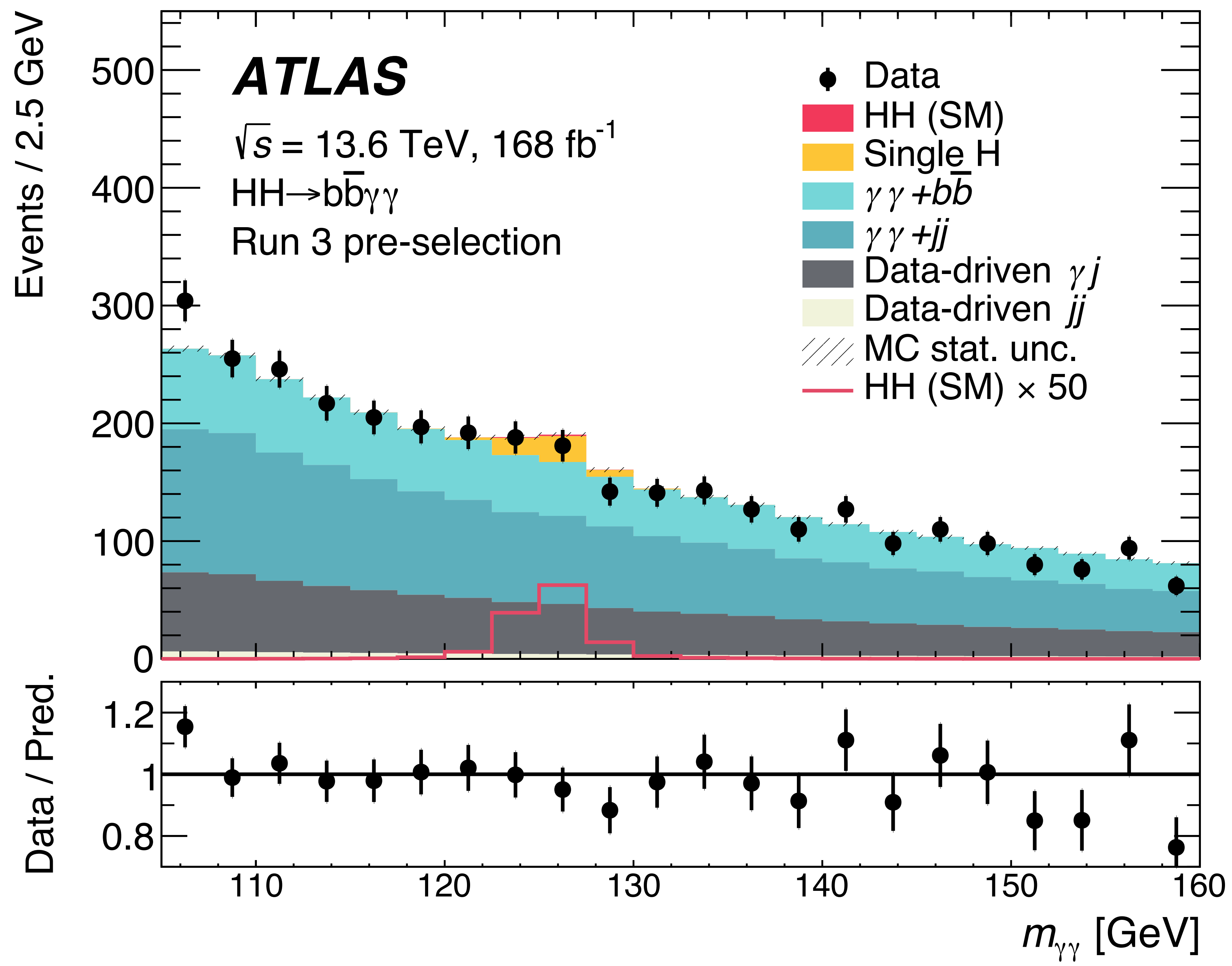
With LAPP contributions (natural continuation of $H \rightarrow \gamma\gamma$ activities done by group since forewer)

bbγγ - pre-selection

2507.03495, Pub.page

- 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





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bbγγ - categorisation

- 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

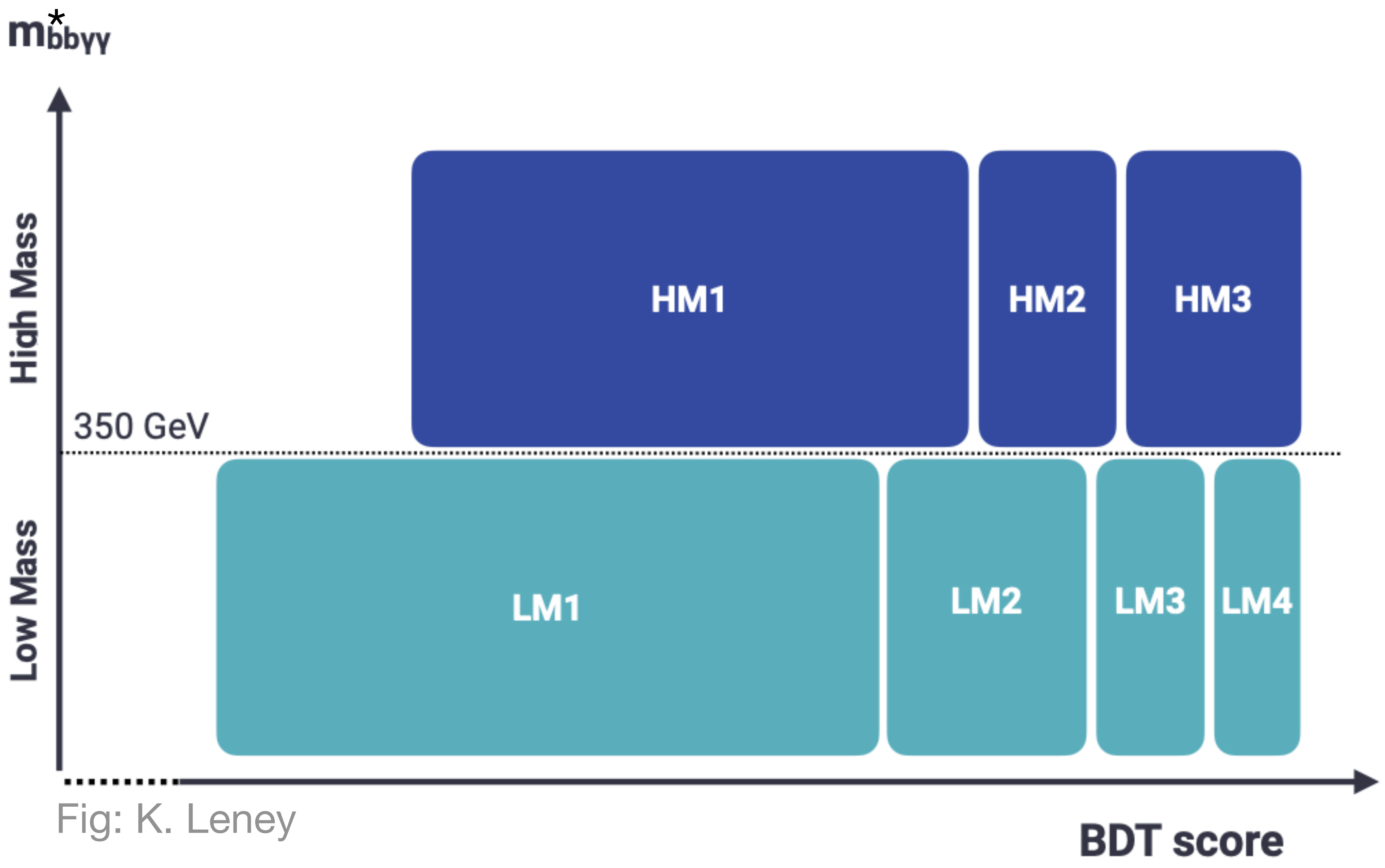
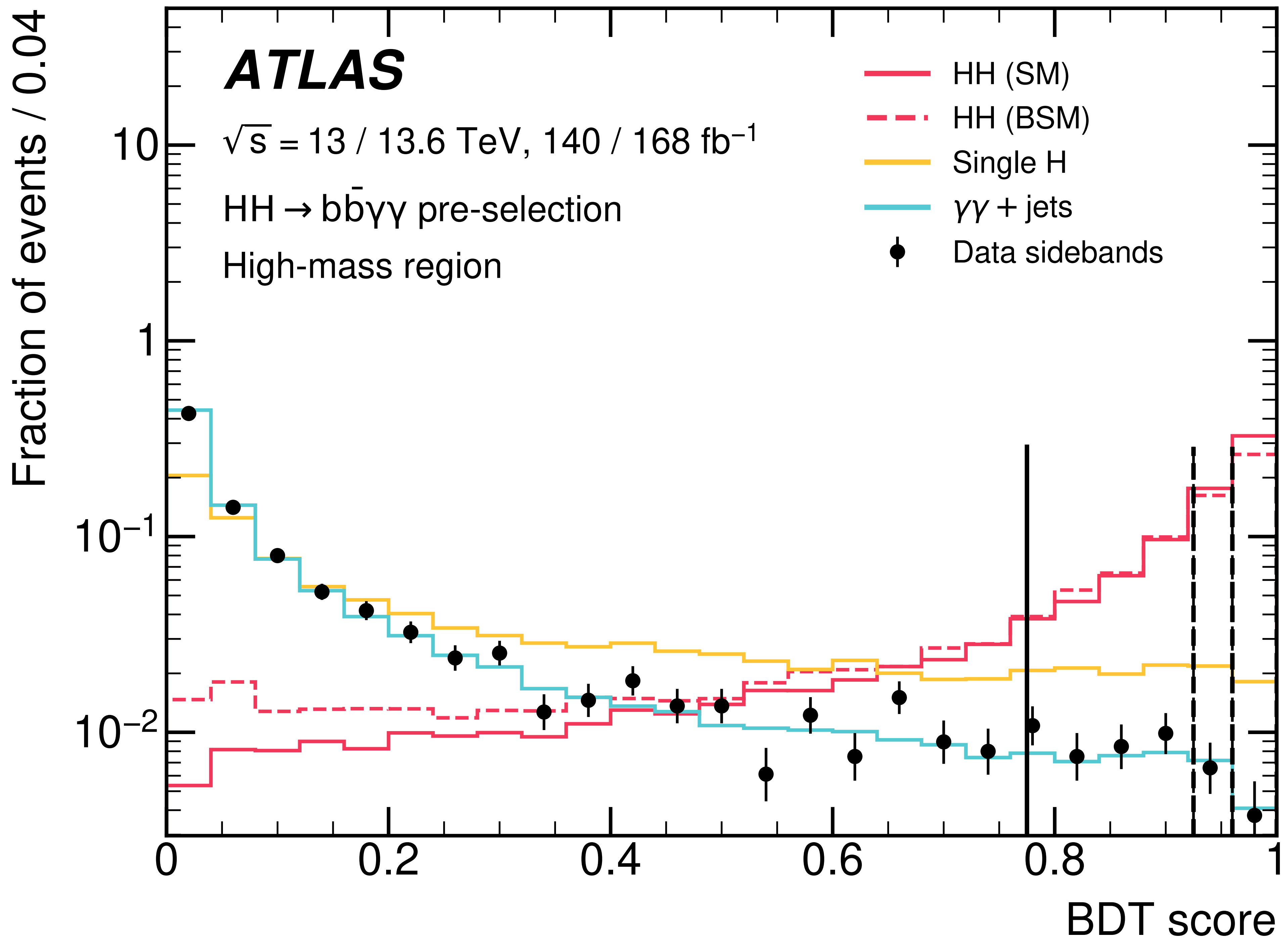


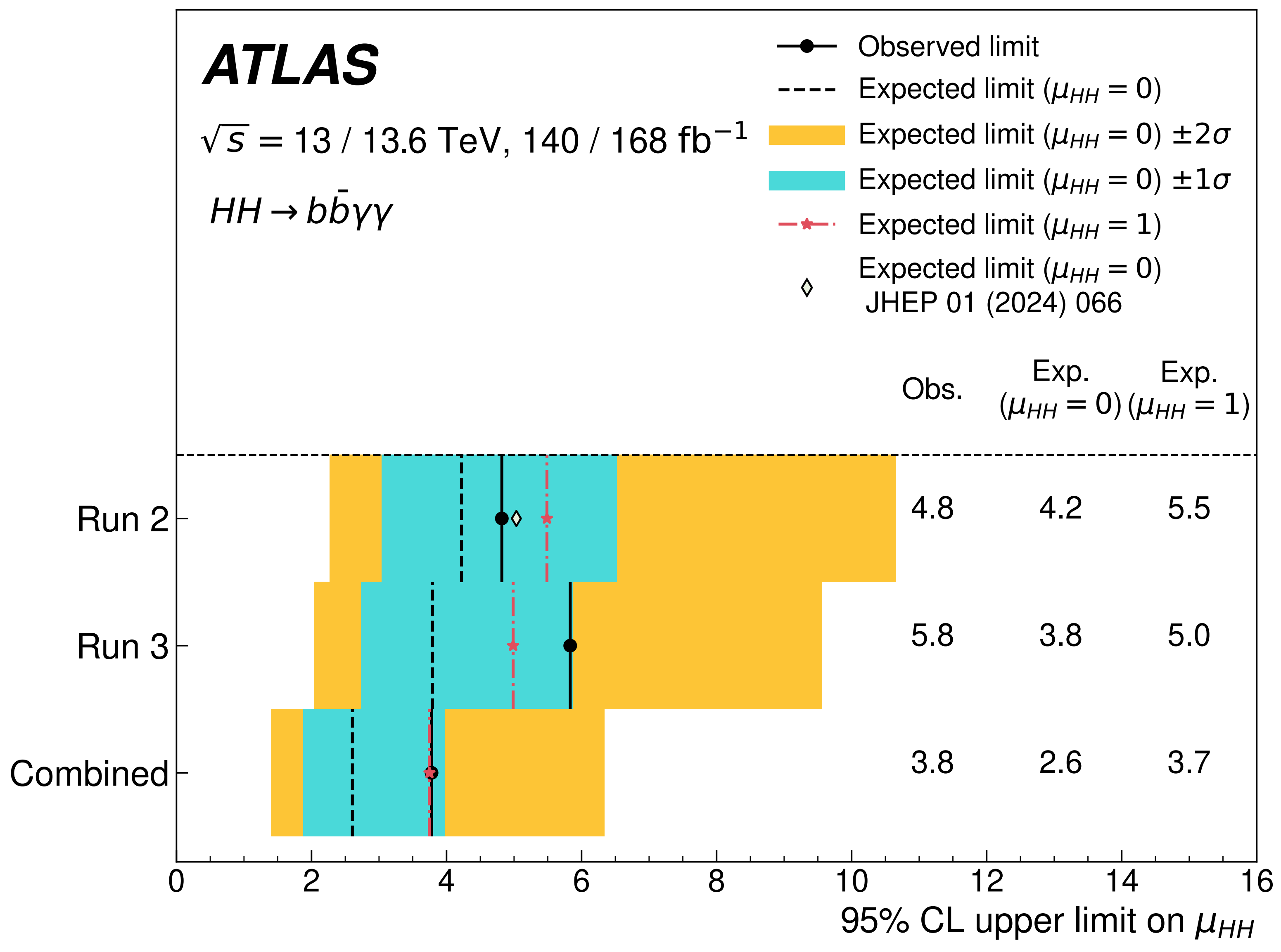
Fig: K. Leney

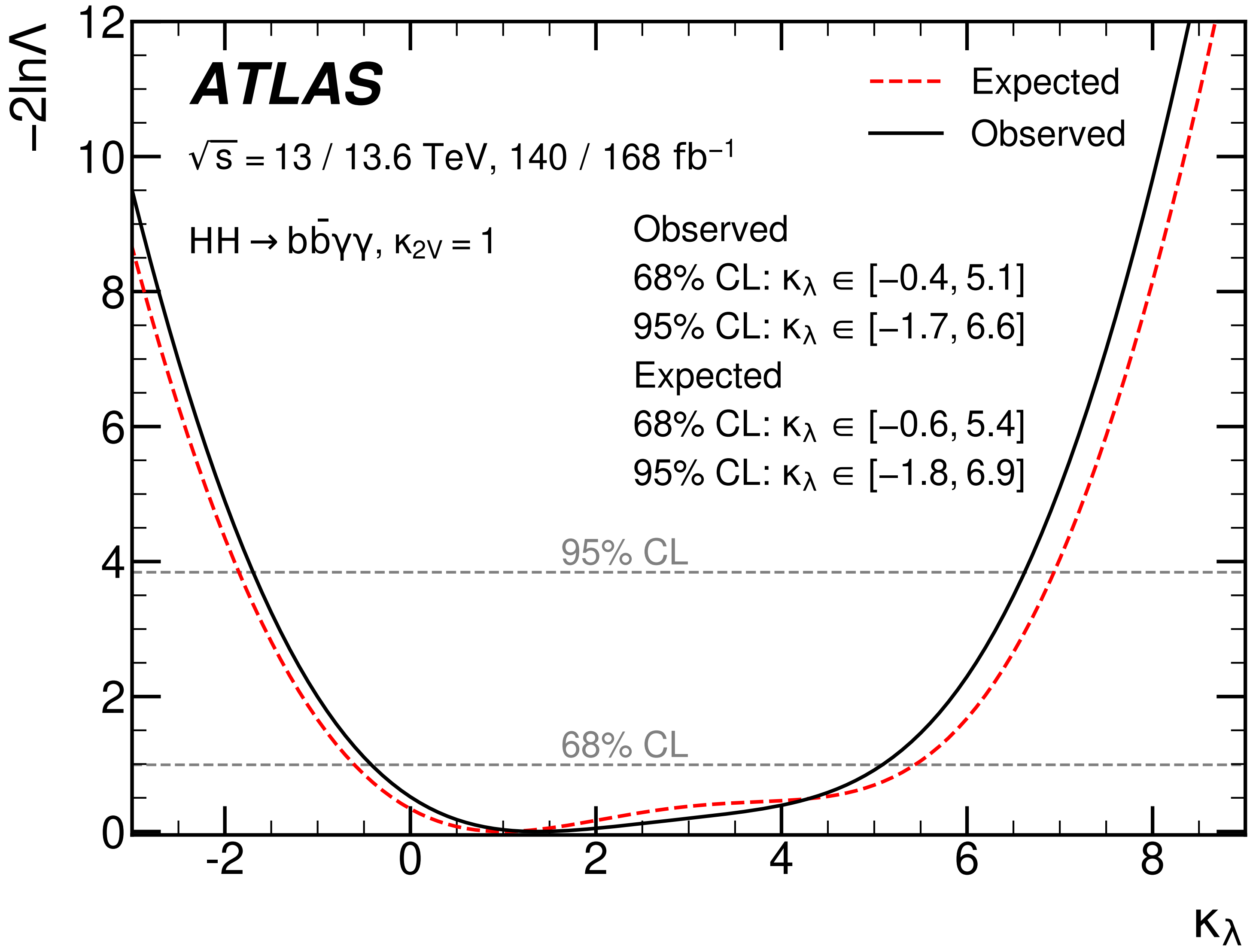


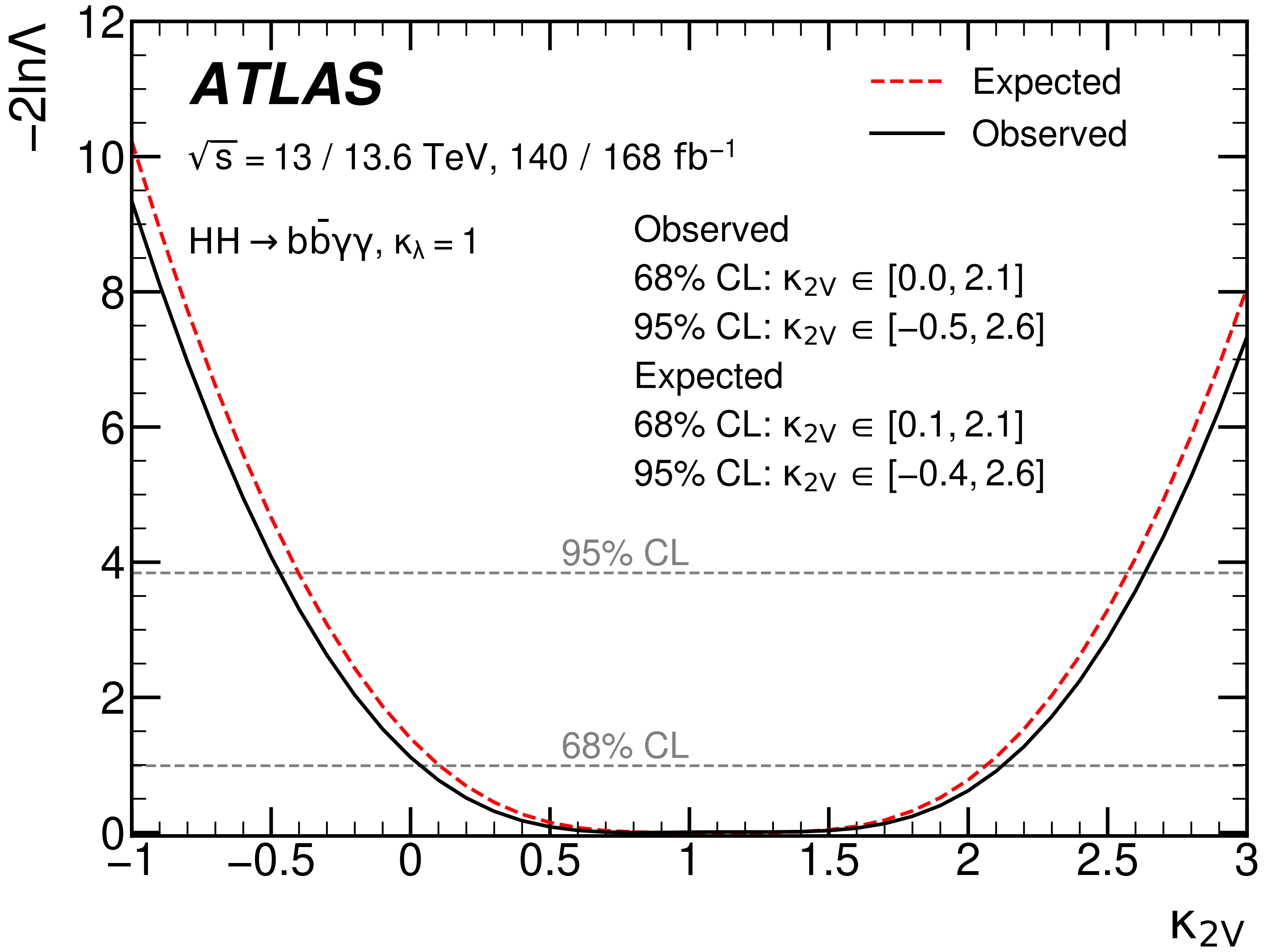
bbγγ - results

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





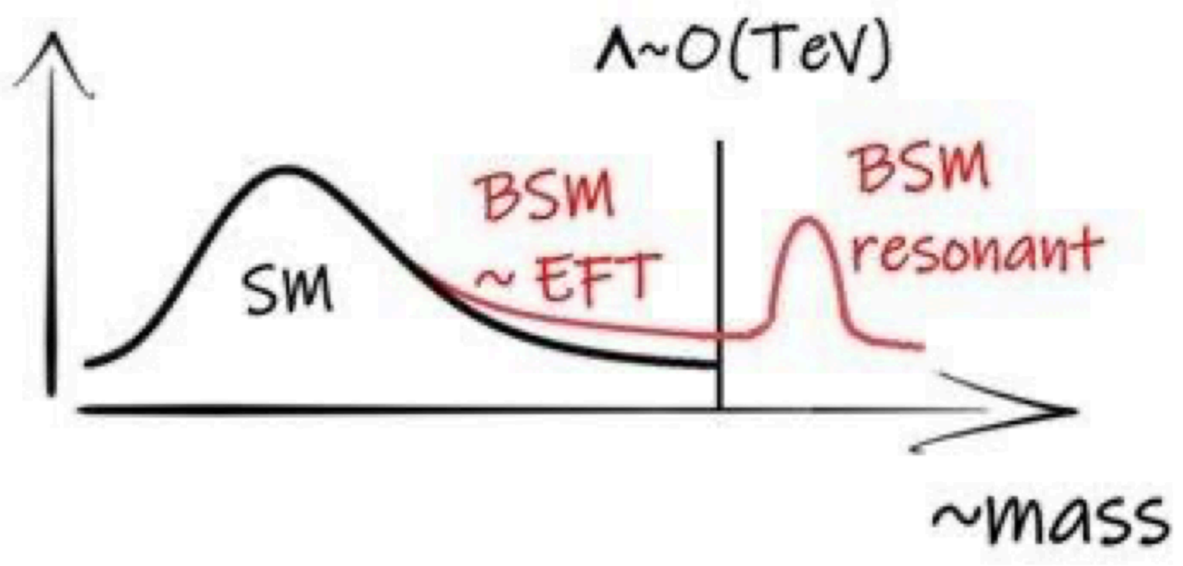


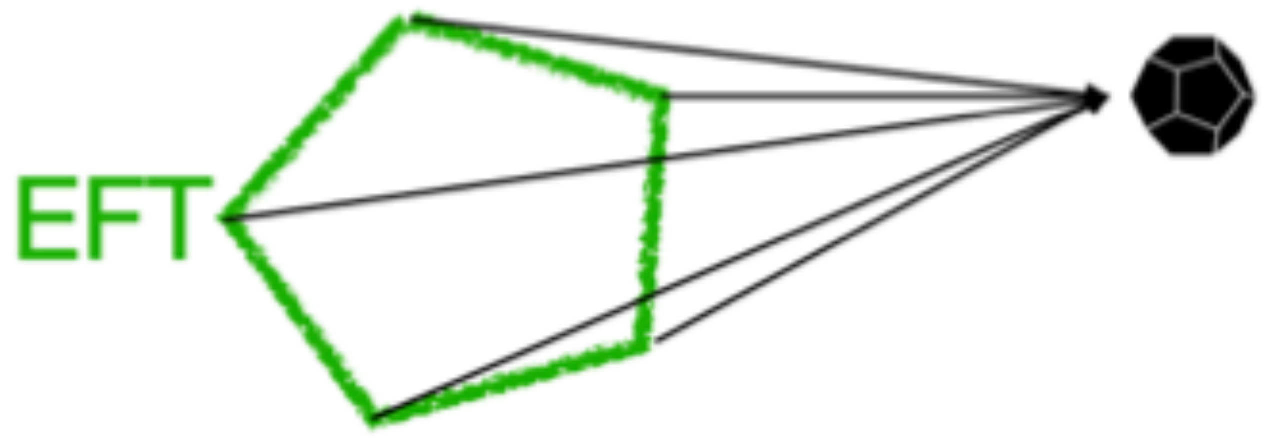
$HH \to bb\gamma\gamma$ EFT

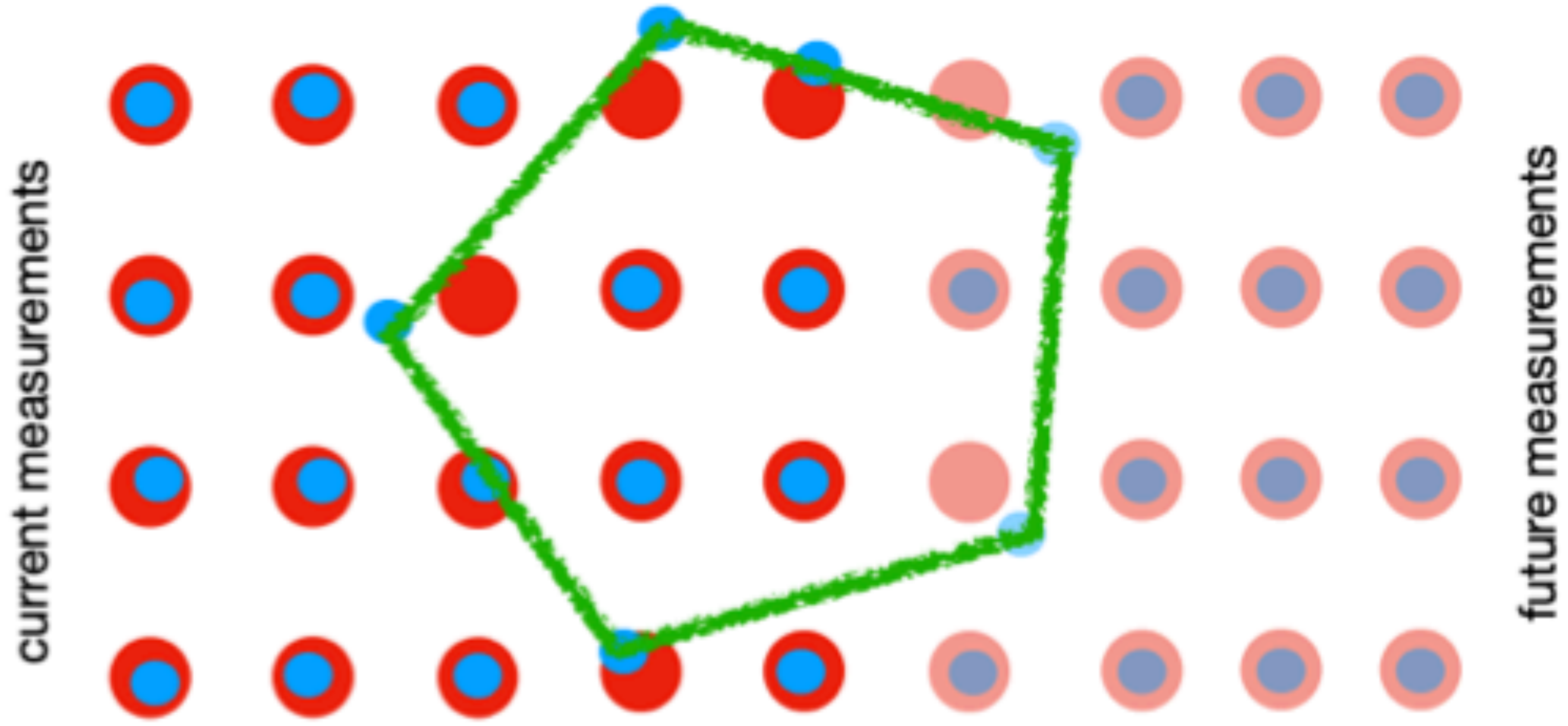
In last round almost single-handedly done by LAPP

EFT introduction

- Consistent parametrization of deviations from SM coming from scales we can't directly reach
- Excluded parts of phase space can help to exlcude concrete models







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If we observe a deviation pattern between theoretical predictions and the experimental data that can be interpreted in terms of something that lives at high energy that we still cannot reach, then it means that we have indirectly discovered new physics.

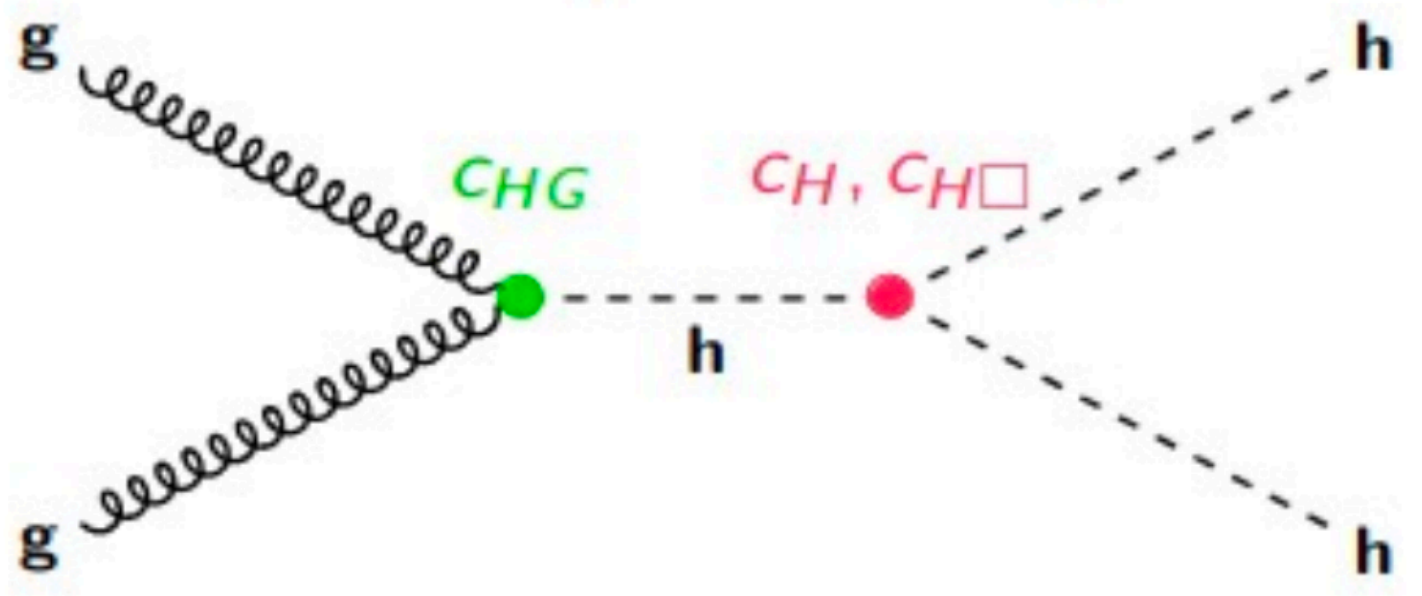
SMEFT introduction

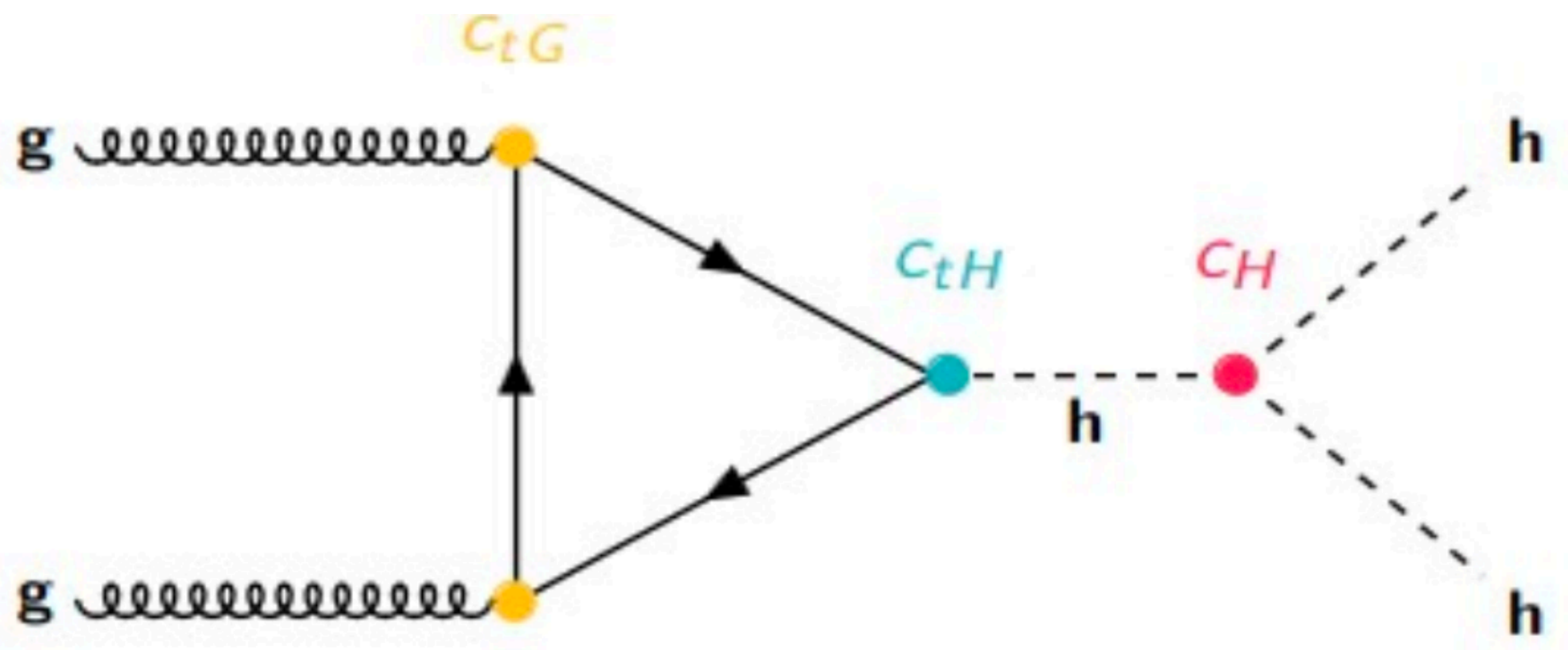
- Augment SM lagrangian with terms allowed by symmetries, expand in energy dimensions

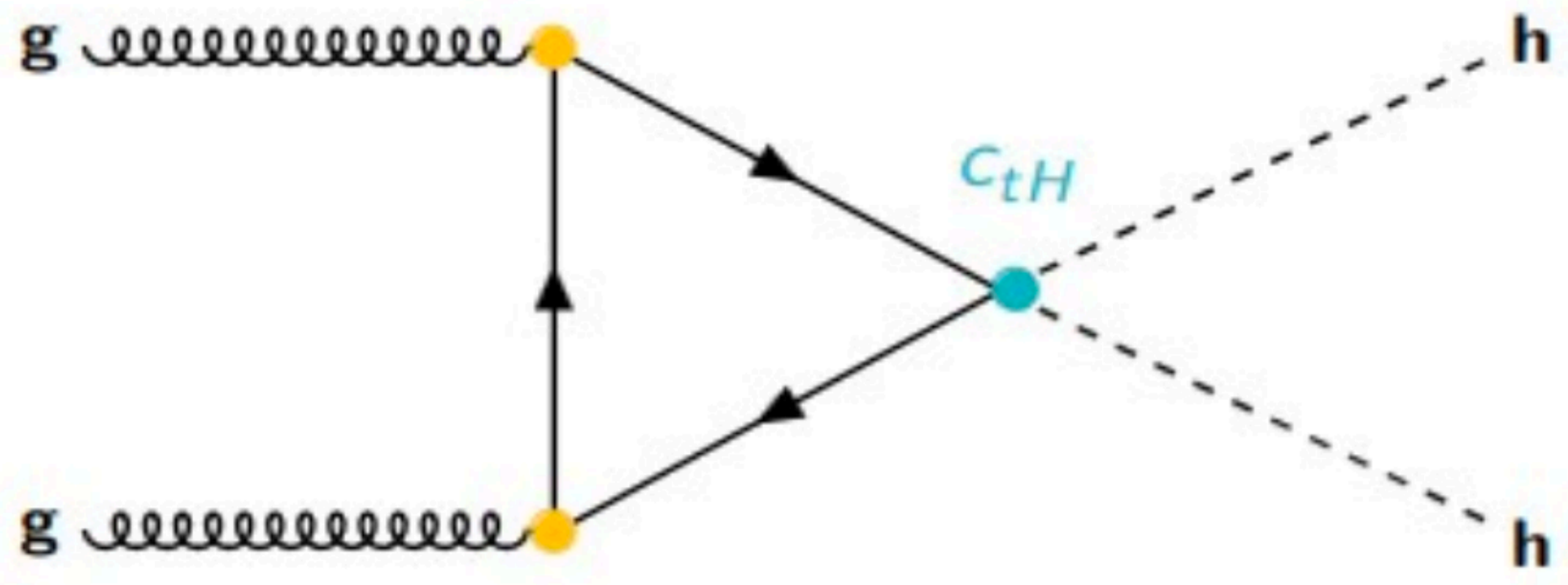
$$\mathscr{L}_{\mathrm{EFT}} = \mathscr{L}_{\mathrm{SM}} + \sum_i \frac{c_i^{(5)}}{\Lambda} O_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} O_i^{(6)} + \dots$$

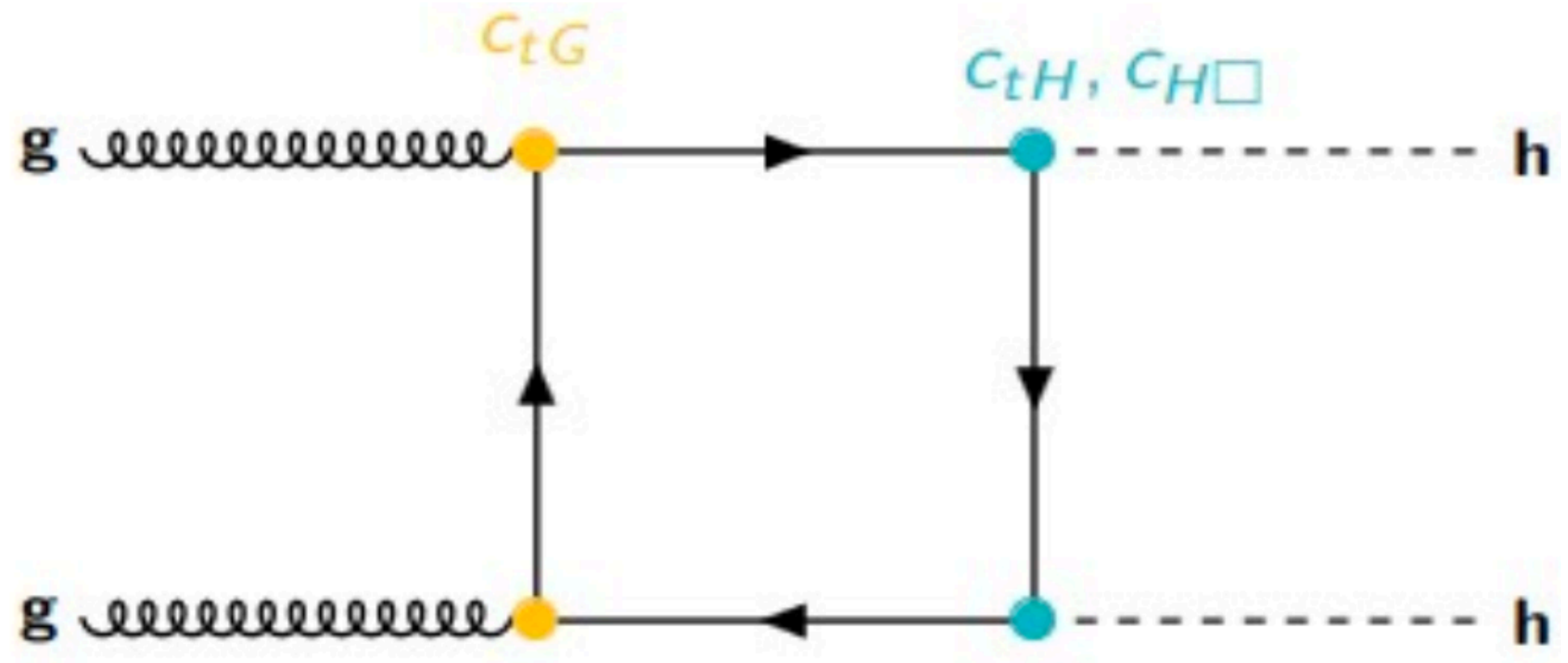
- Leading relevant terms for HH arise at dim-6

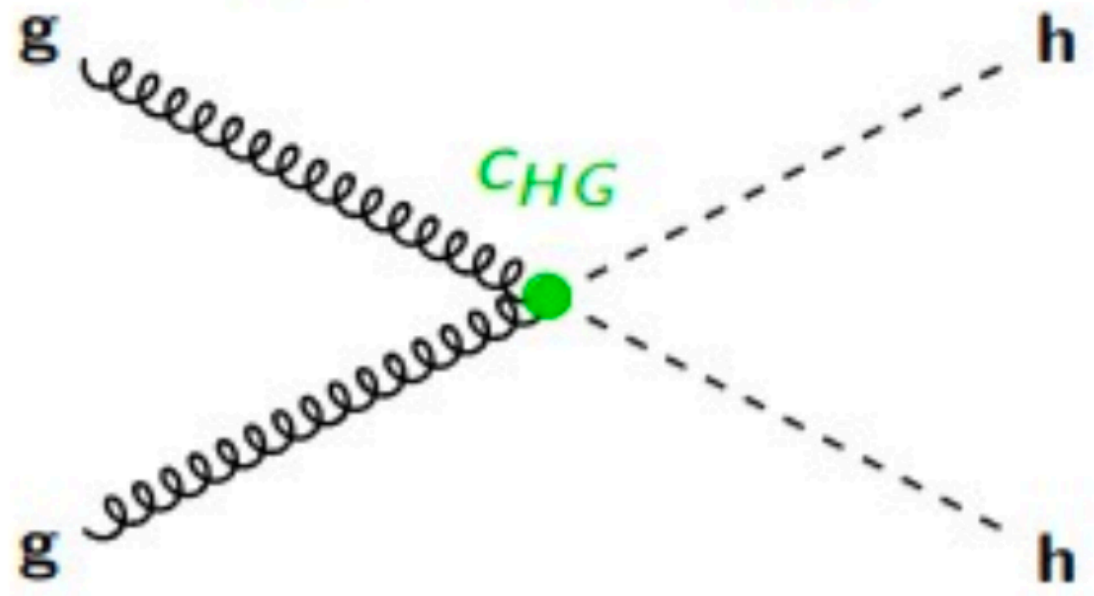
$$\Delta\mathscr{L}_{\mathrm{Warsaw}} = \frac{C_{H,\Box}}{\Lambda^2}(\phi^\dagger\phi)\Box(\phi^\dagger\phi) + \frac{C_{HD}}{\Lambda^2}\left(\phi^\dagger D_\mu \phi\right)^*(\phi^\dagger D^\mu \phi) + \frac{C_H}{\Lambda^2}(\phi^\dagger\phi)^3$$
$$+\left(\frac{C_{uH}}{\Lambda^2}\phi^\dagger\phi \bar{q}_L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











bbγγ SMEFT results

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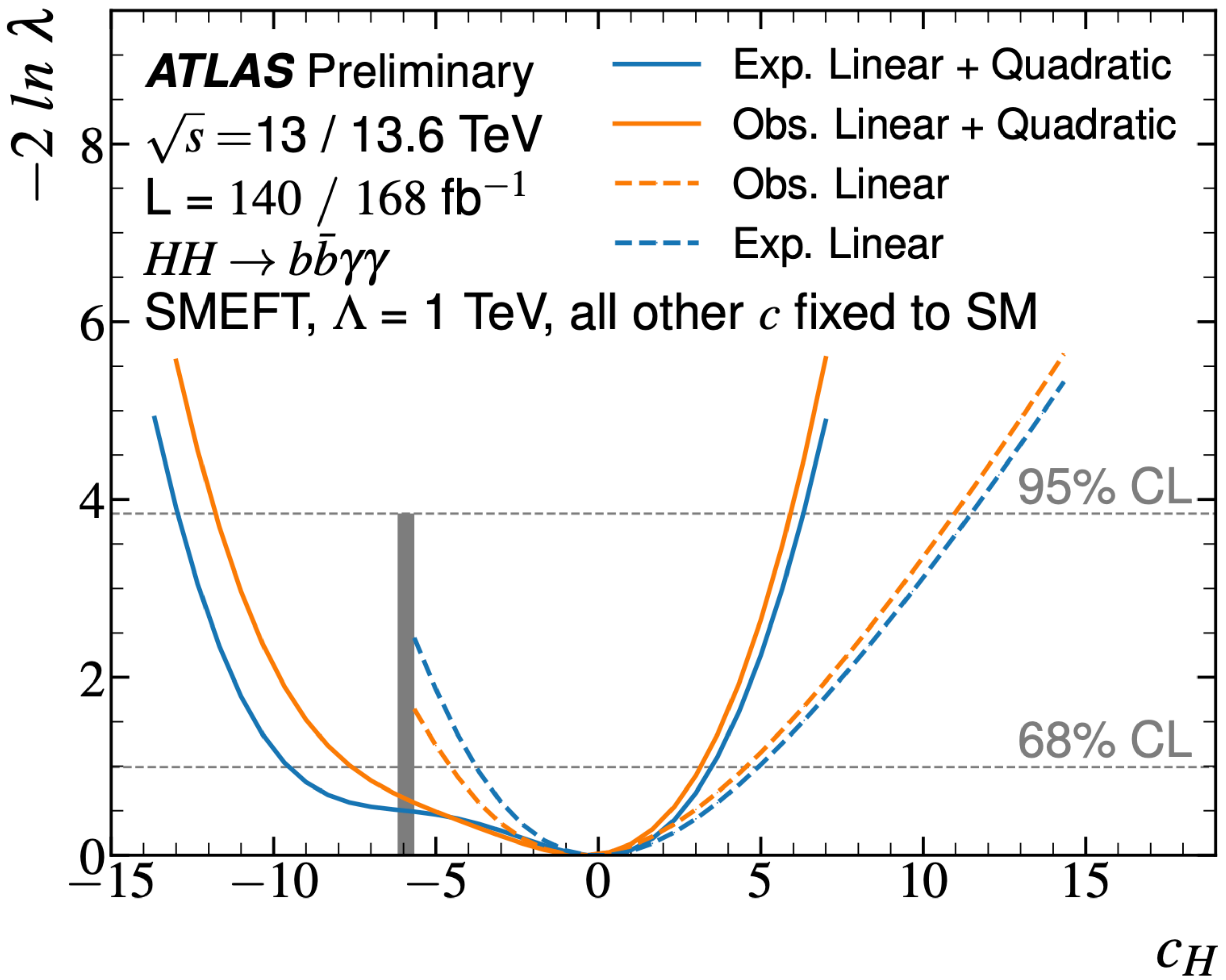
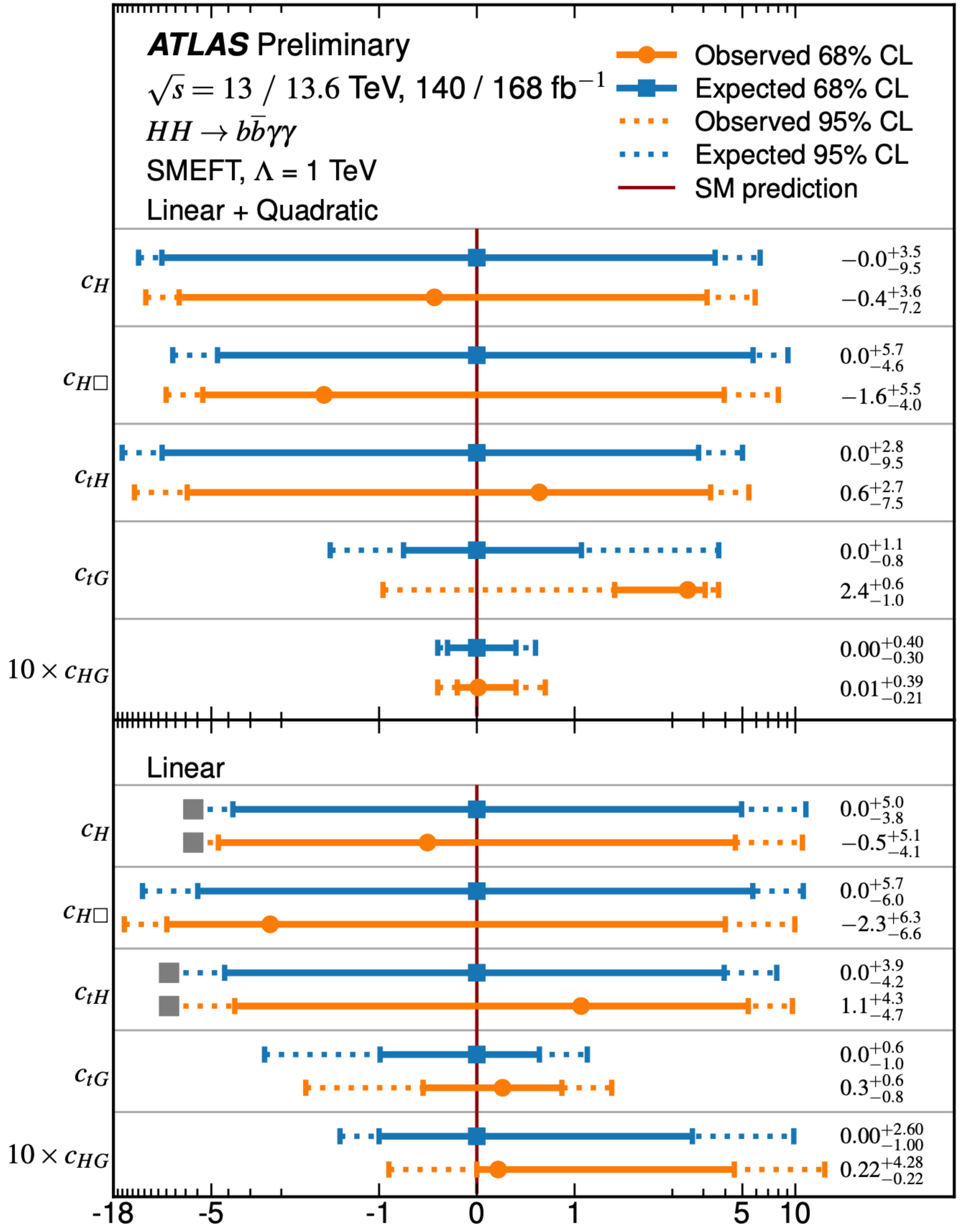
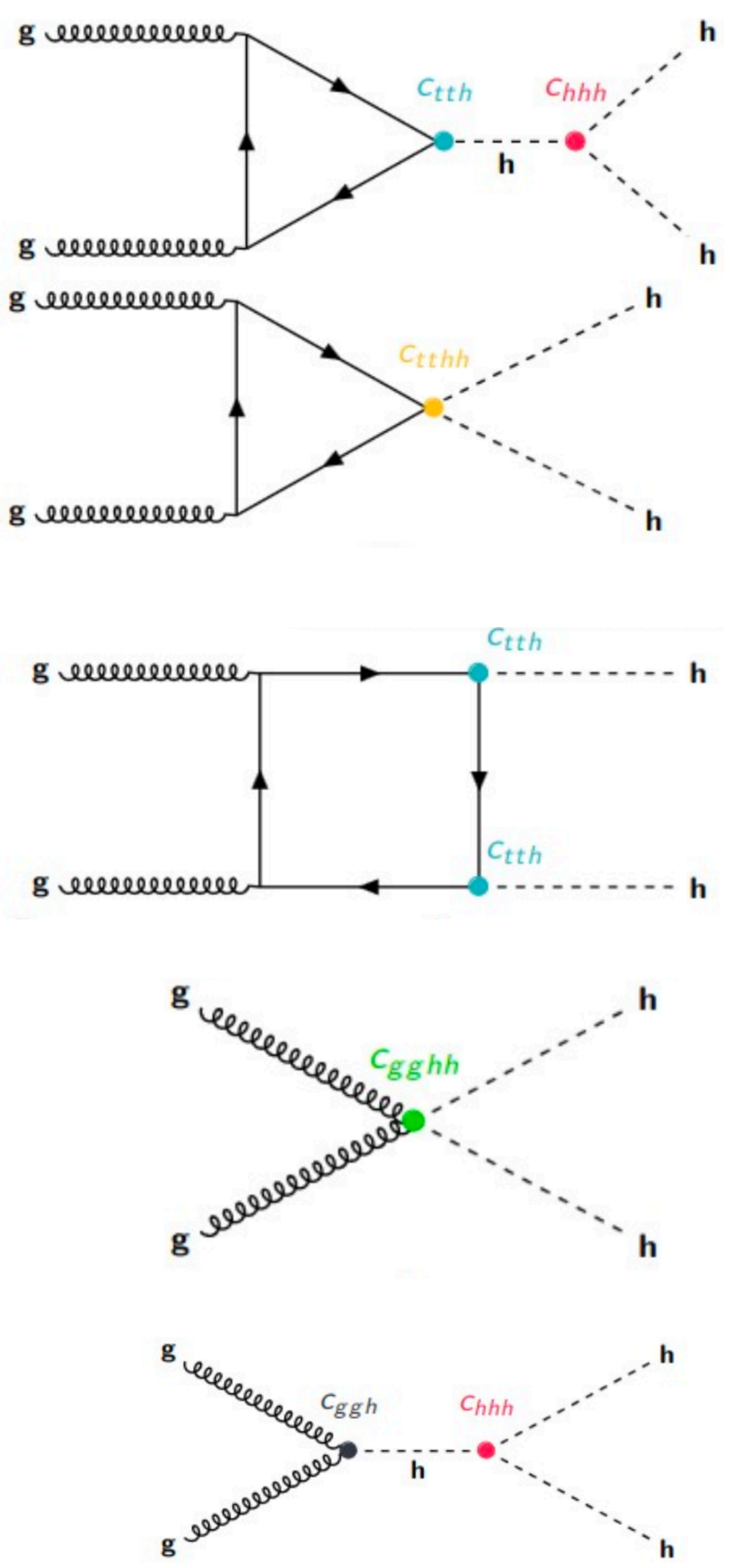
- Depending on where expansion is truncated (debatable) get linear or linear+quadratic limits, provided both
- CH is only directly doable in HH, others can be done (better) from single-H
- 



HEFT introduction

- Another type of EFT only doable in HH, operators introduced
  - chhh
  - cgghh
  - ctthh
- H operators decoupled from HH
  - cggh
  - ct
- Not SMEFT
- Cannot be easily mapped to SMEFT



bbγγ HEFT results

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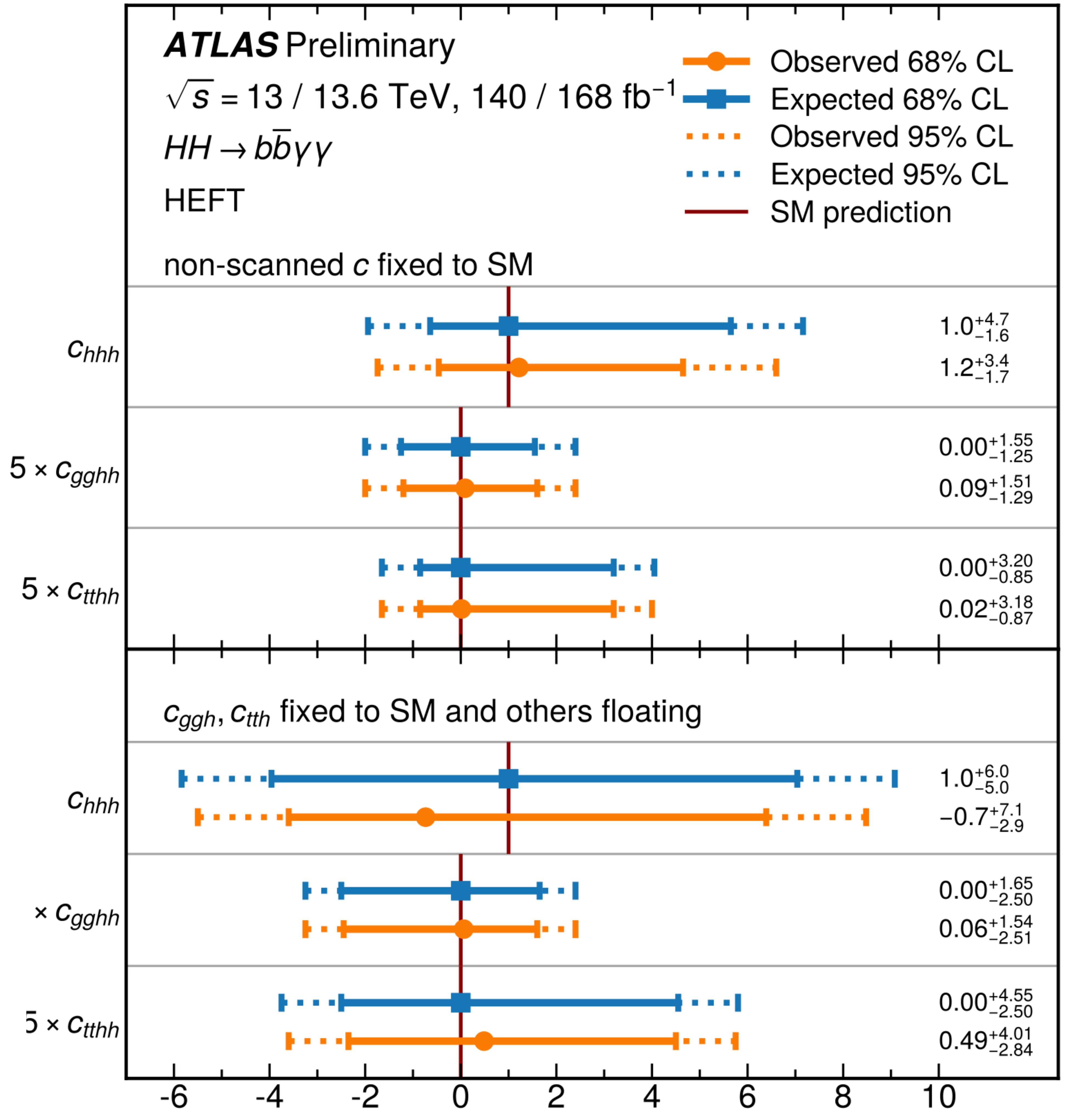
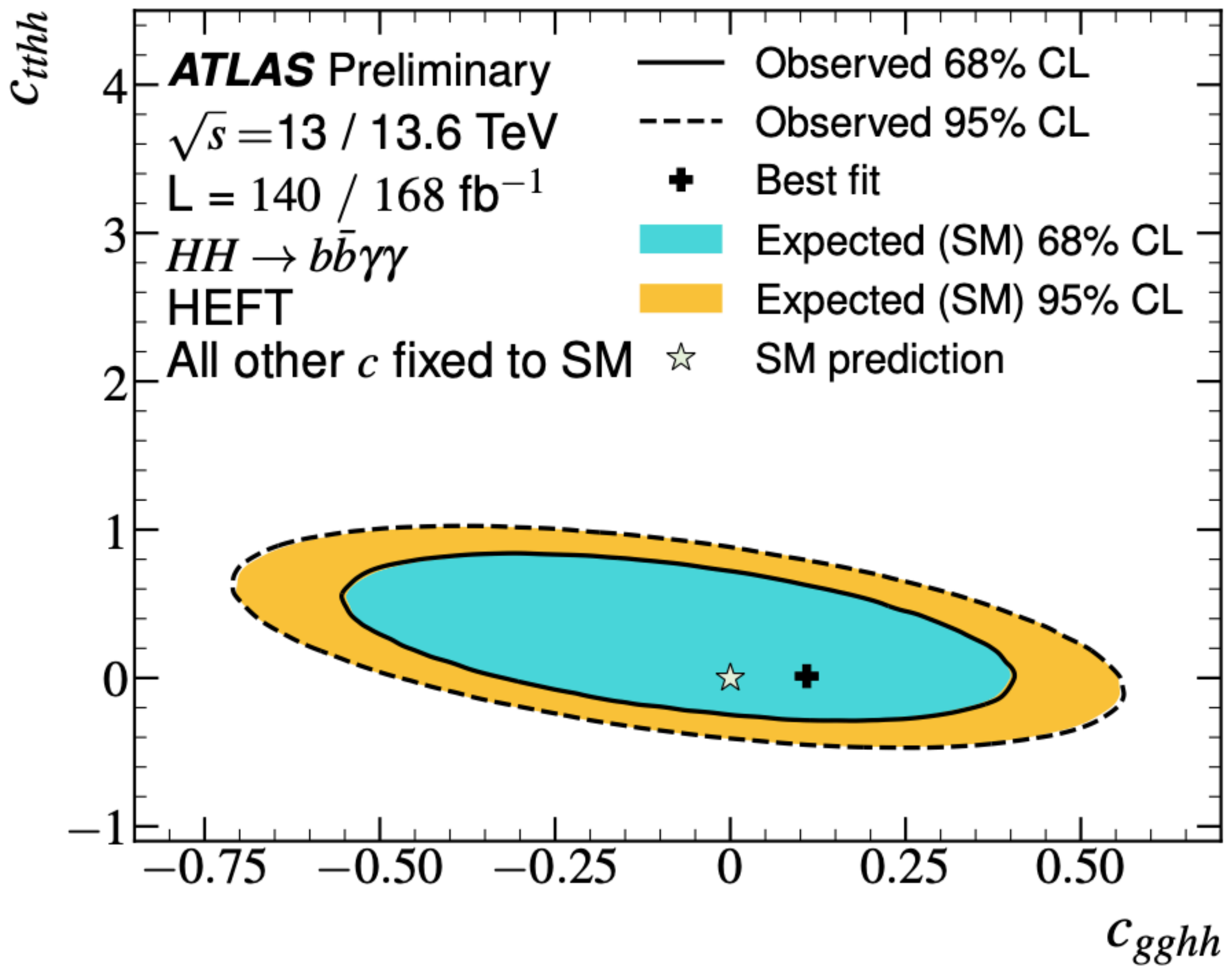
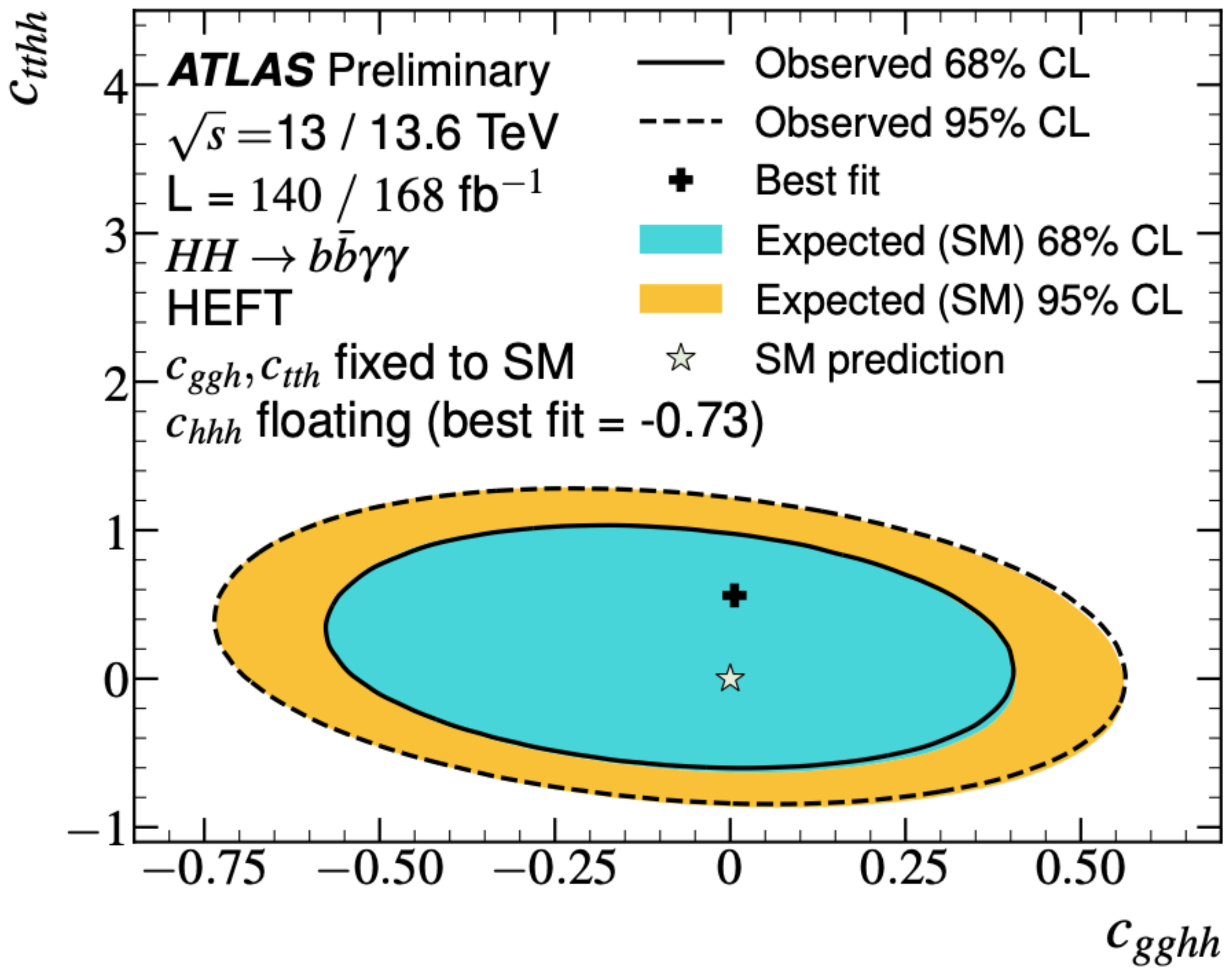
- Provided limits when fixing non-scanned ones and not (theory correlations from triple operator terms)
- Provided limits involving pairs of operators in similar way







HL-LHC Projections

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

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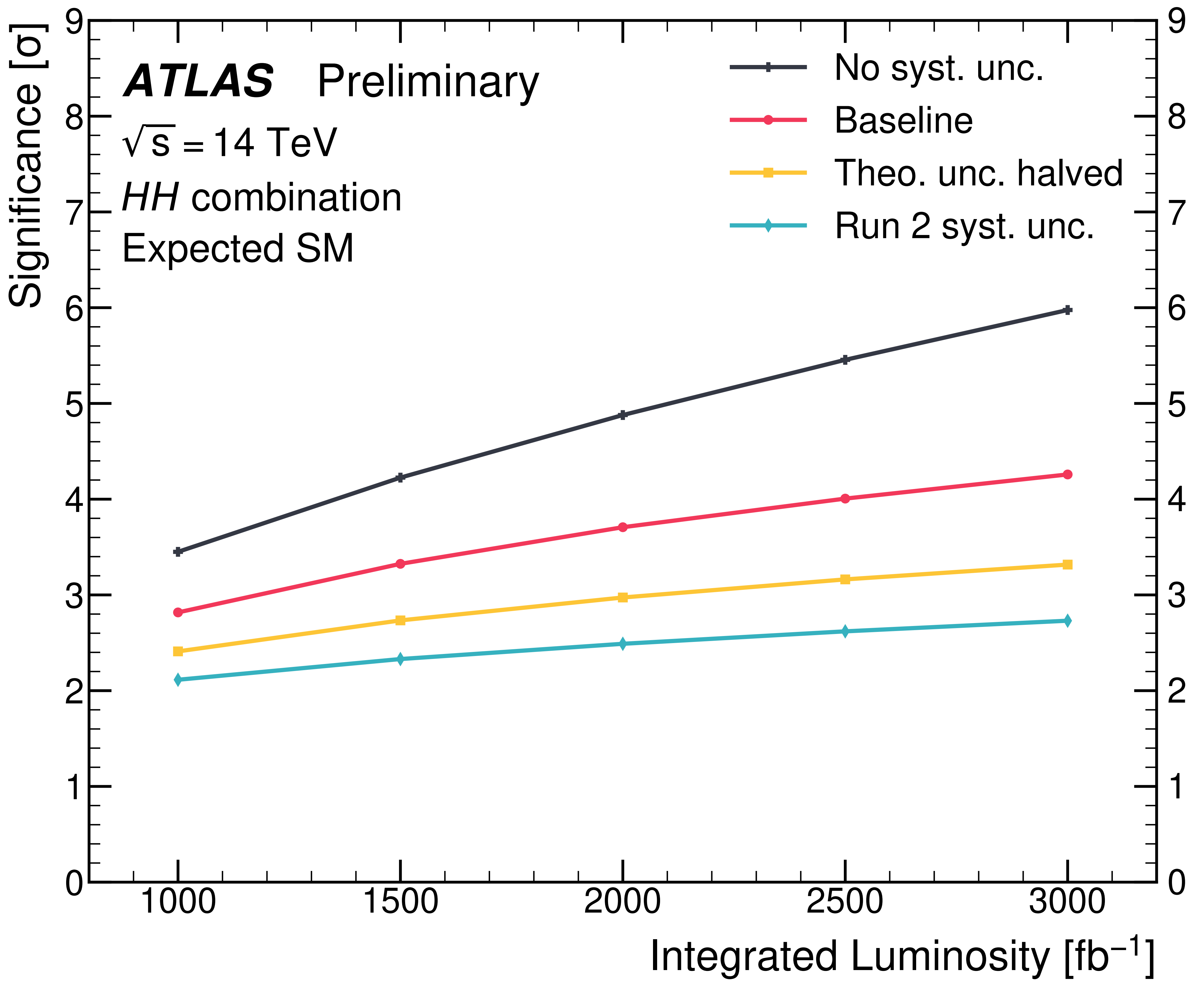
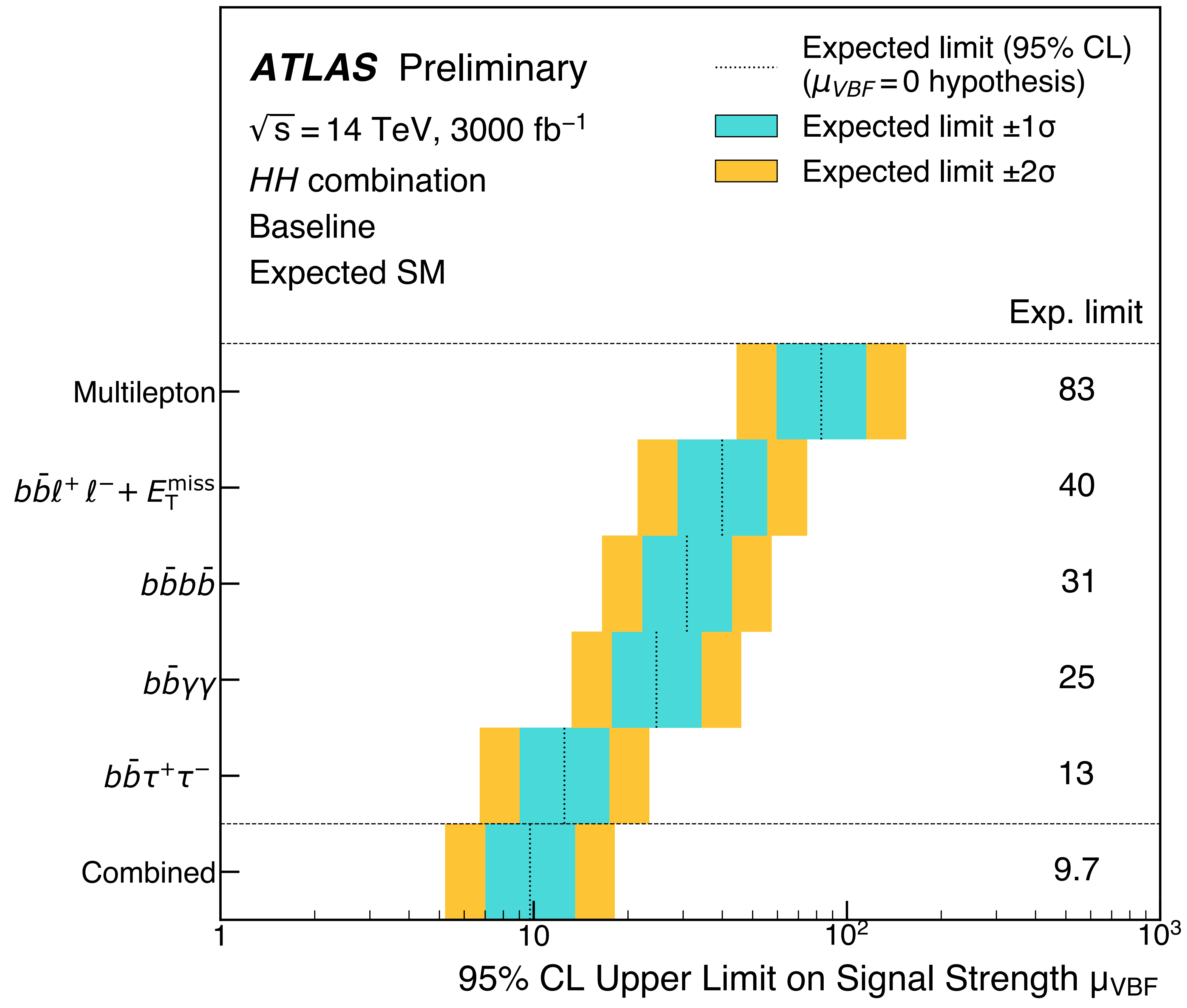
- 5 analysis considered as reference, projected to up 3000 1/fb



- Expected 4.3σ significance with full HL-LHC data

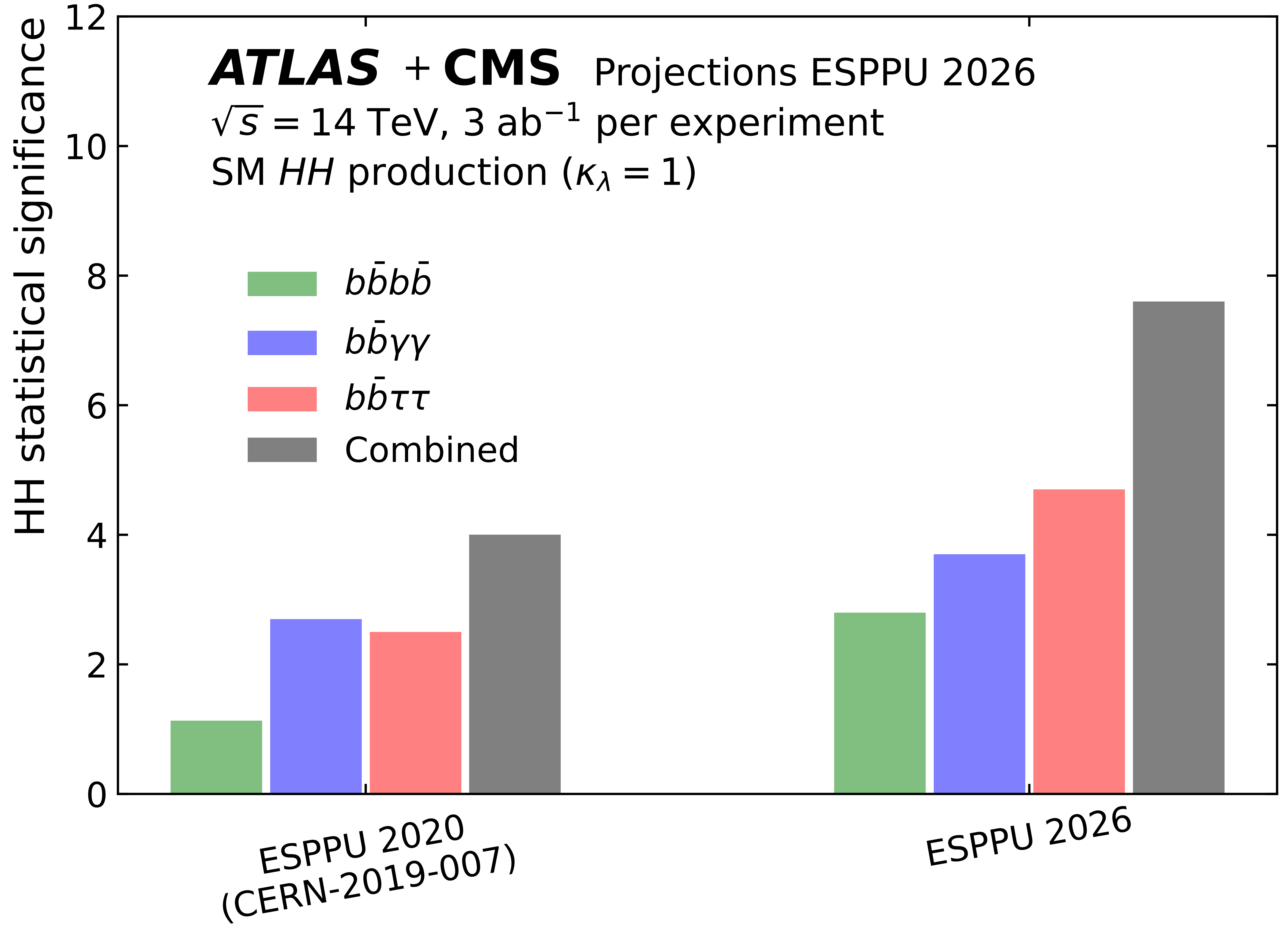
- Expected 95% μ_{VBF} limit: $9.7 \times$ SM



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



Conclusion

- HH measurements is a fundamental test of the SM
- ATLAS+CMS Run-2 combined observed 95% CL limit: 2.5
- HL-LHC ATLAS projection: 4.3σ at the end of HL-LHC (baseline uncertainty scenario)
- HL-LHC ATLAS+CMS projection: observation significance should be reached

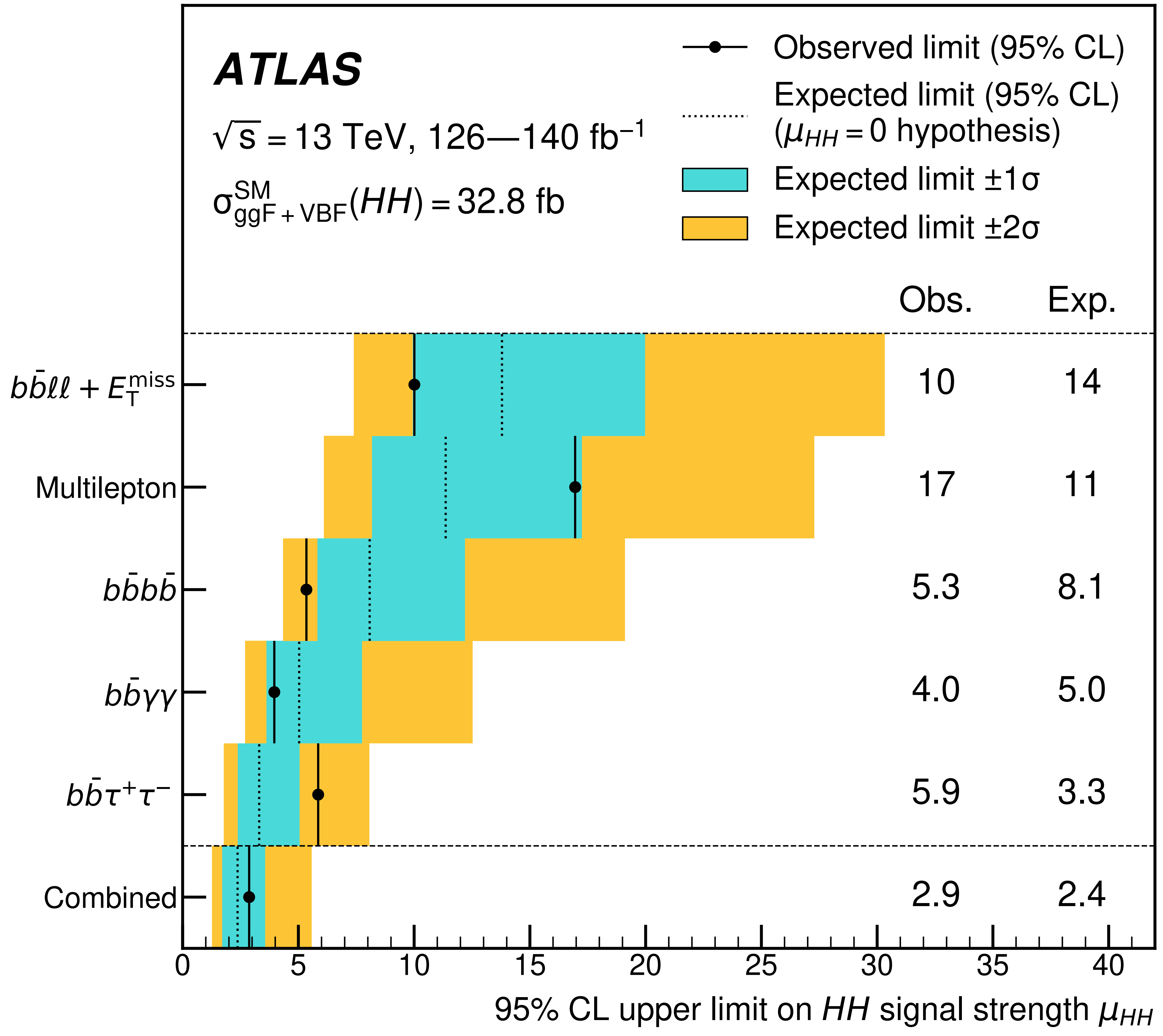
- HH→bbγγ is the first analysis with 308 1/fb of data (inc. 2024 data) published: obs. 95% CL limit 3.8
- HH→bbγγ EFT for the first time provided
  - Linear-only SMEFT limits
  - SMEFT effect on decays
  - Quantified sentivity to SMEFT “single-H” operators
  - HEFT limits which are not excluding correlations
  - Included VBFHH

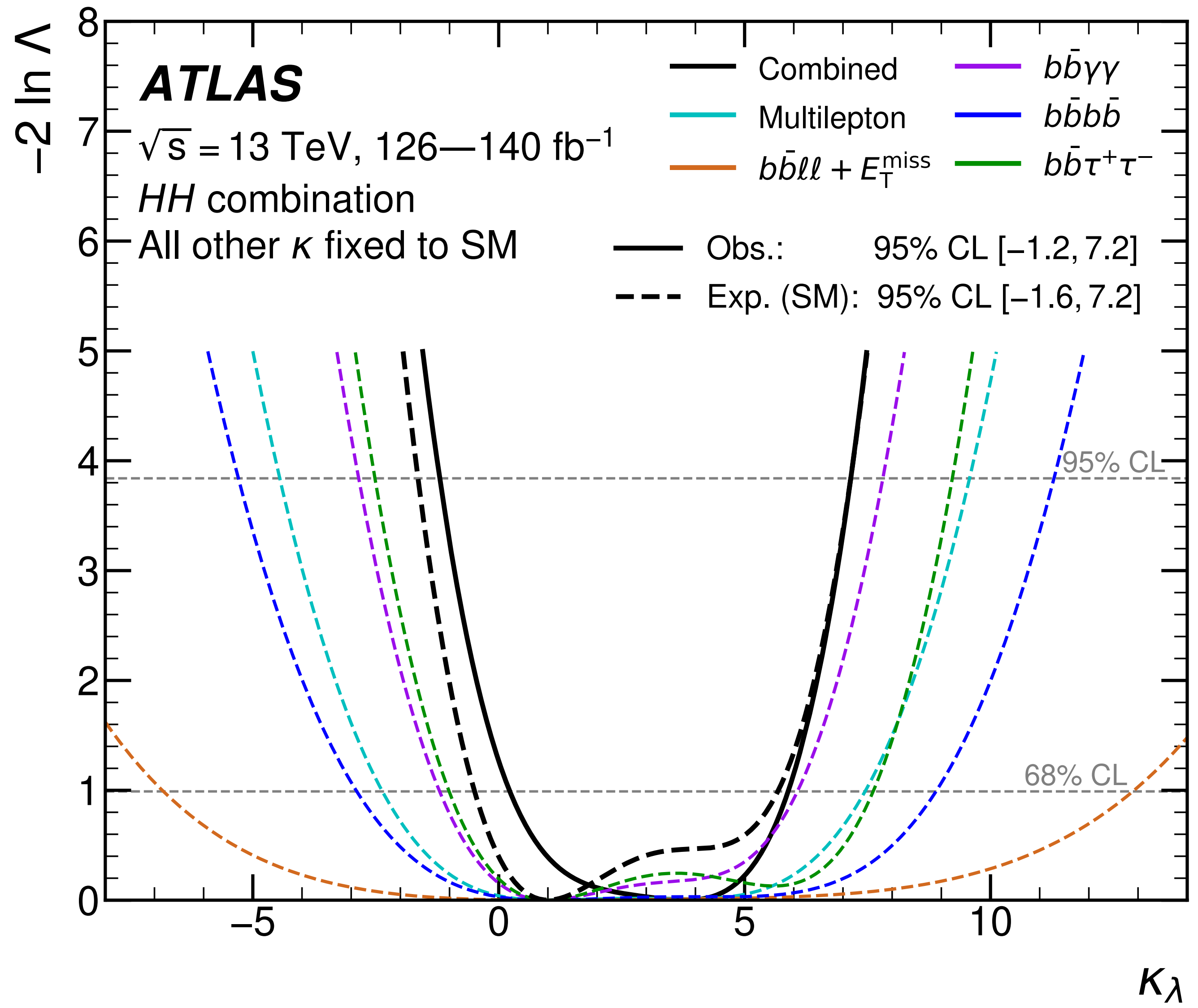
The End

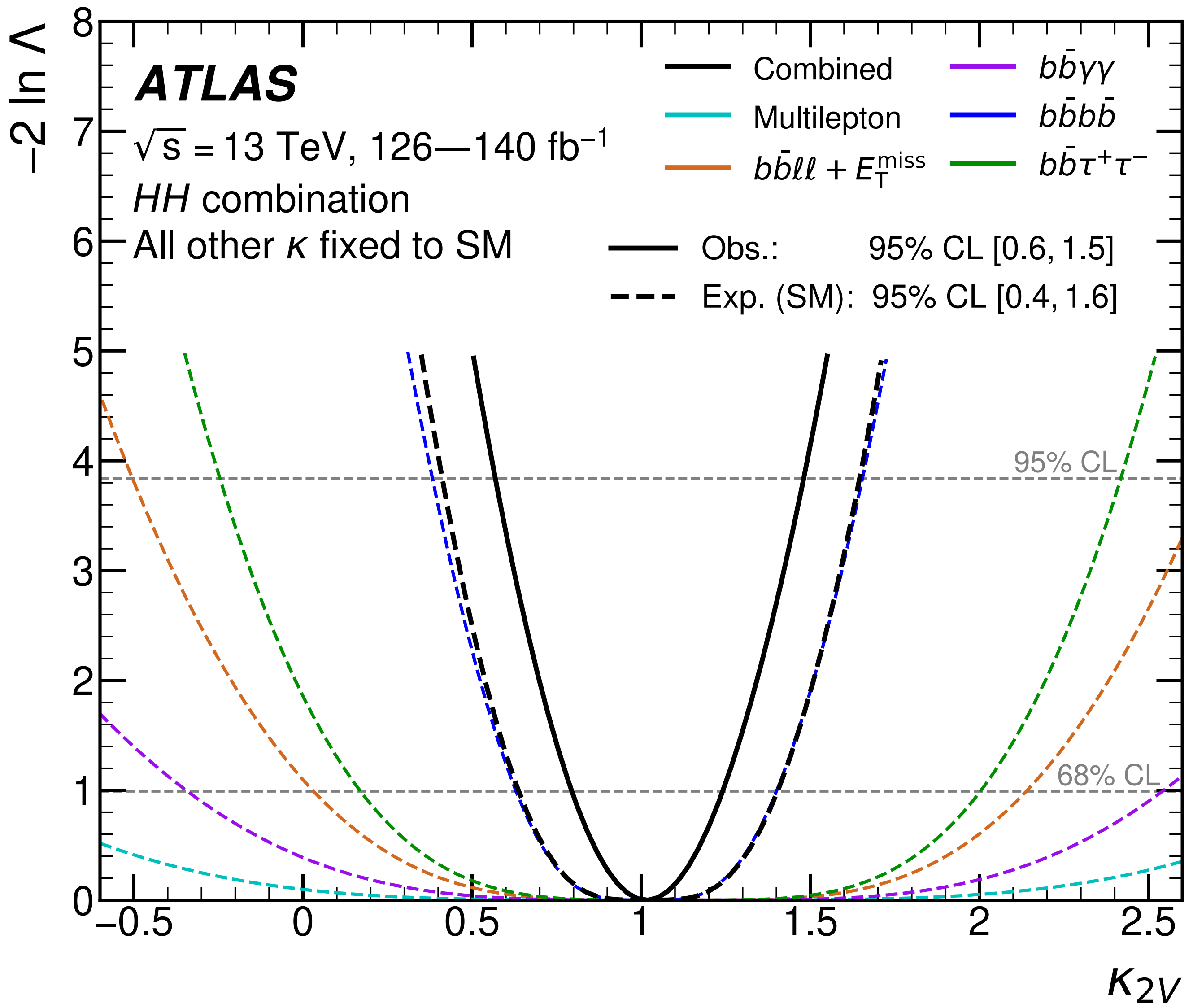
κ-framework/HEFT HH combination

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 $0.6 < \kappa_{2V} < 1.5$



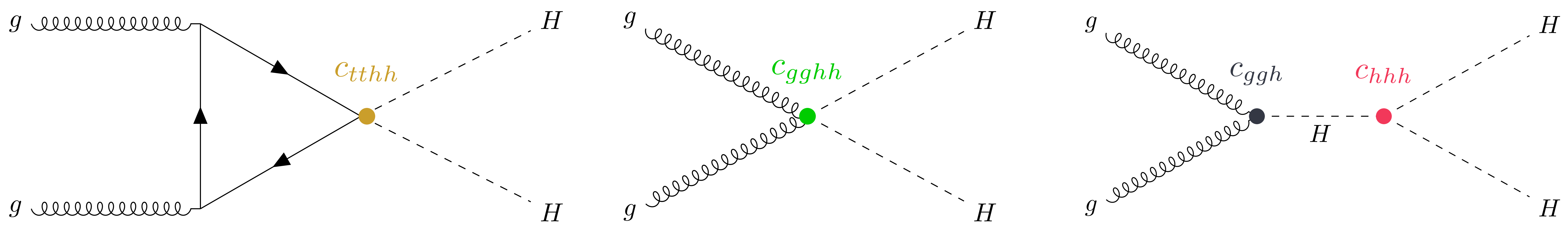




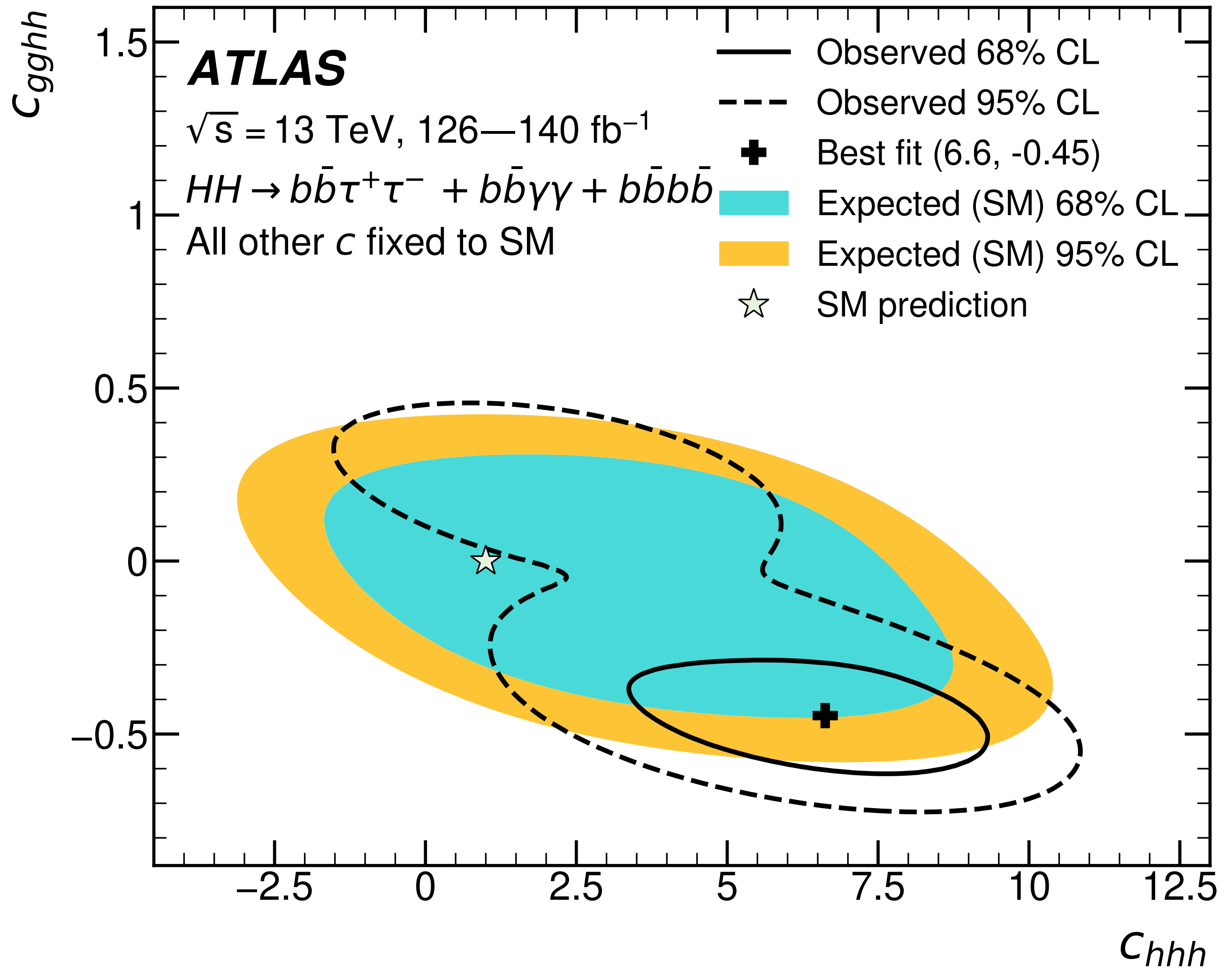
κ-framework/HEFT HH combination

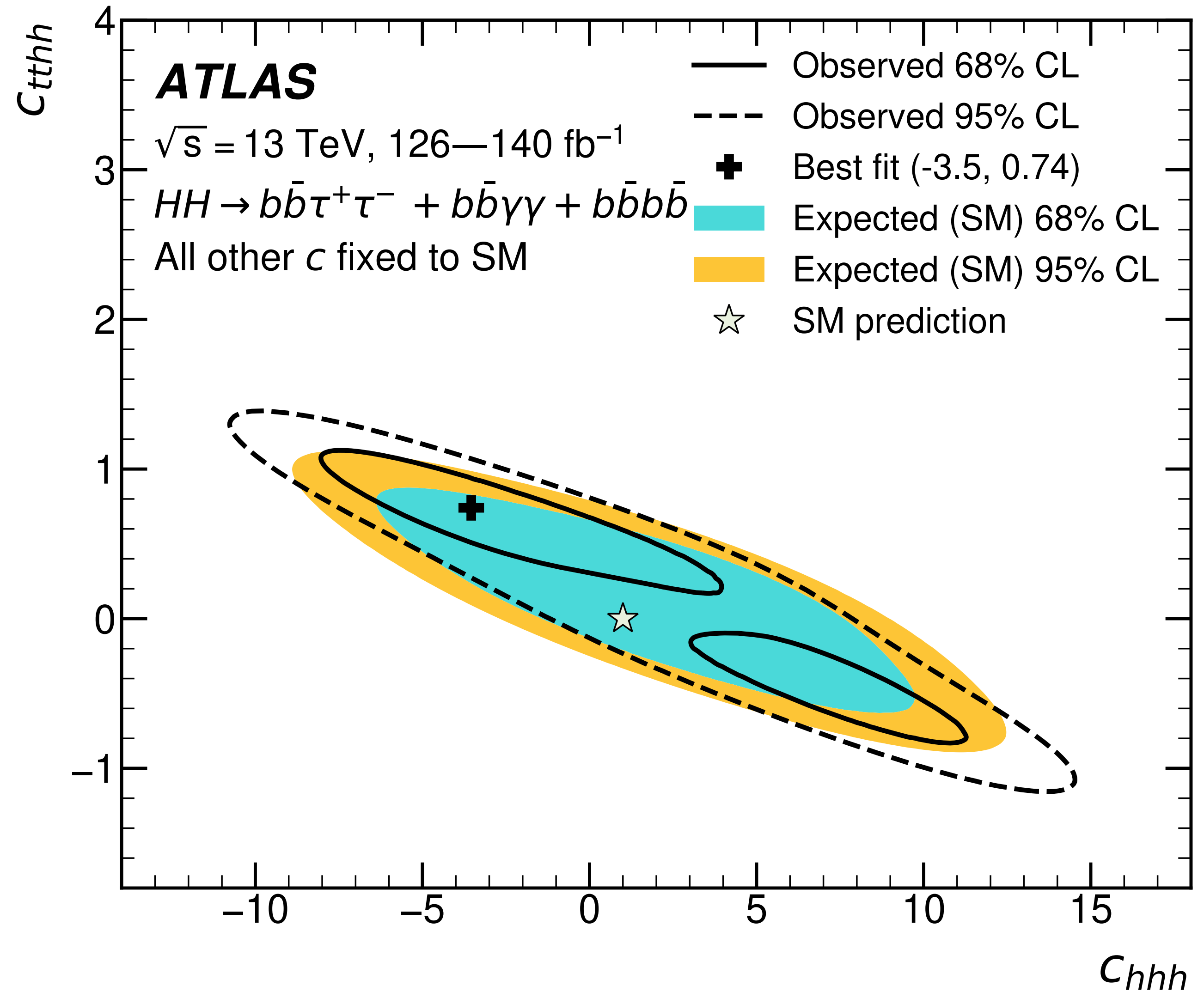
Phys. Rev. Lett. 133, 101801

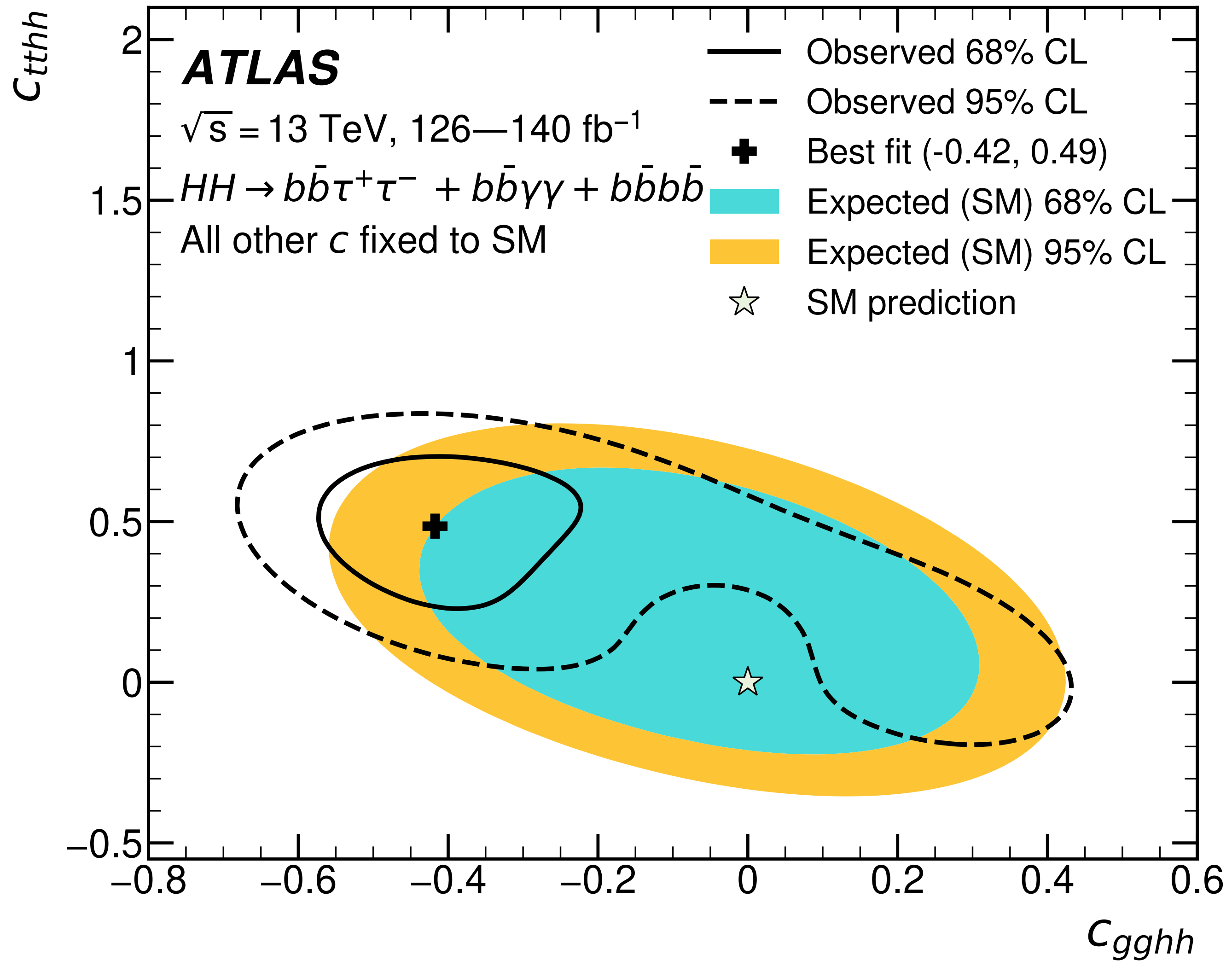
- Higgs Effective Field Theory introduces non-SM couplings c_{tthh}, c_{gghh}, c_{ggh}
- c_{hhh}, c_t in SM have value 1



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

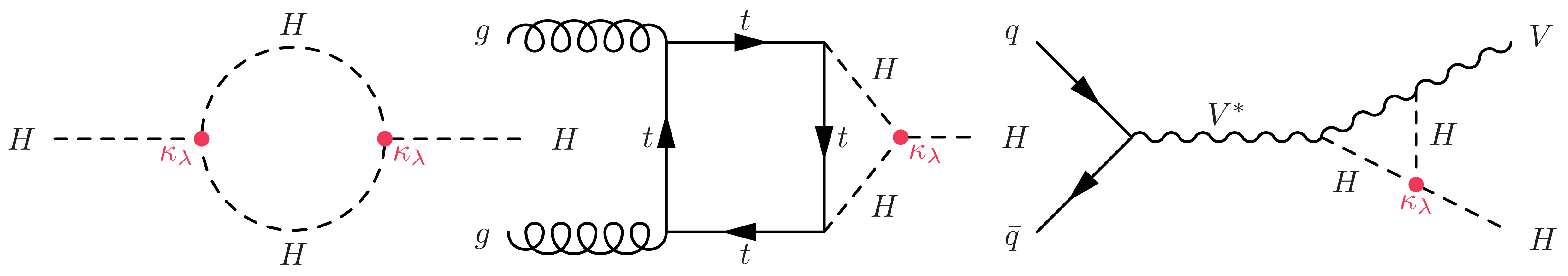






H+HH(partial) combination

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

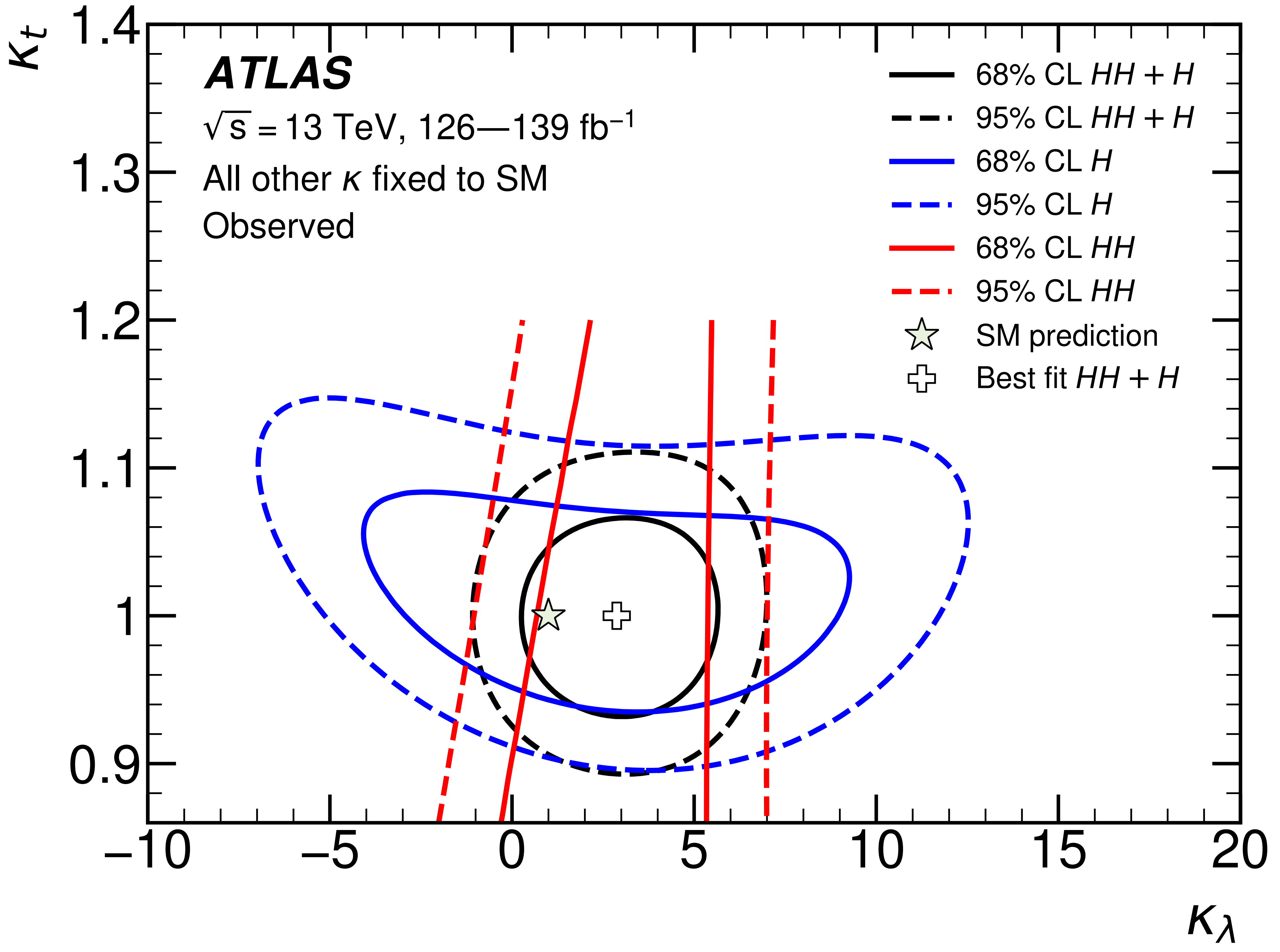


- H parametrized in STXS bins

- 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



ATLAS HH projection

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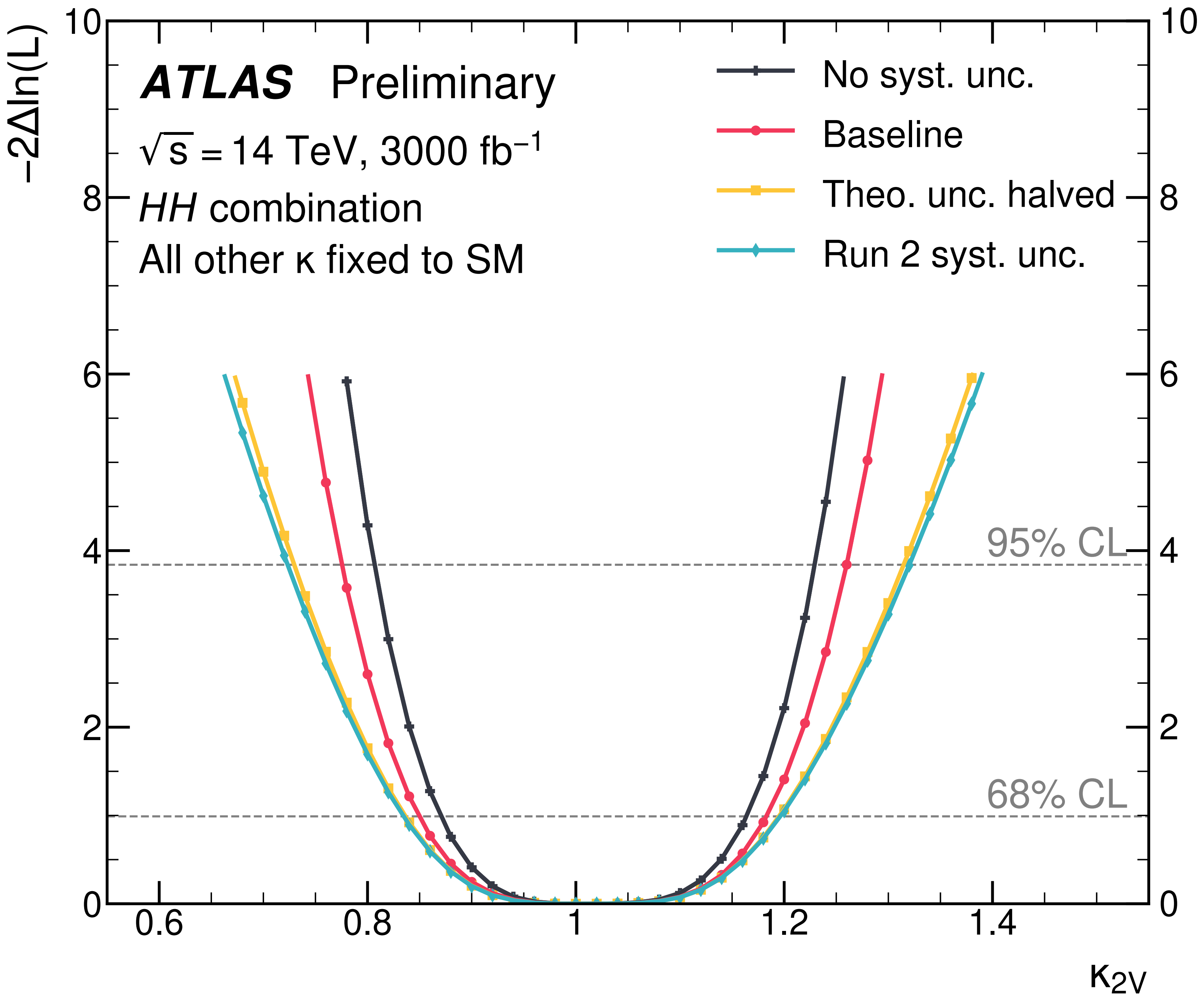
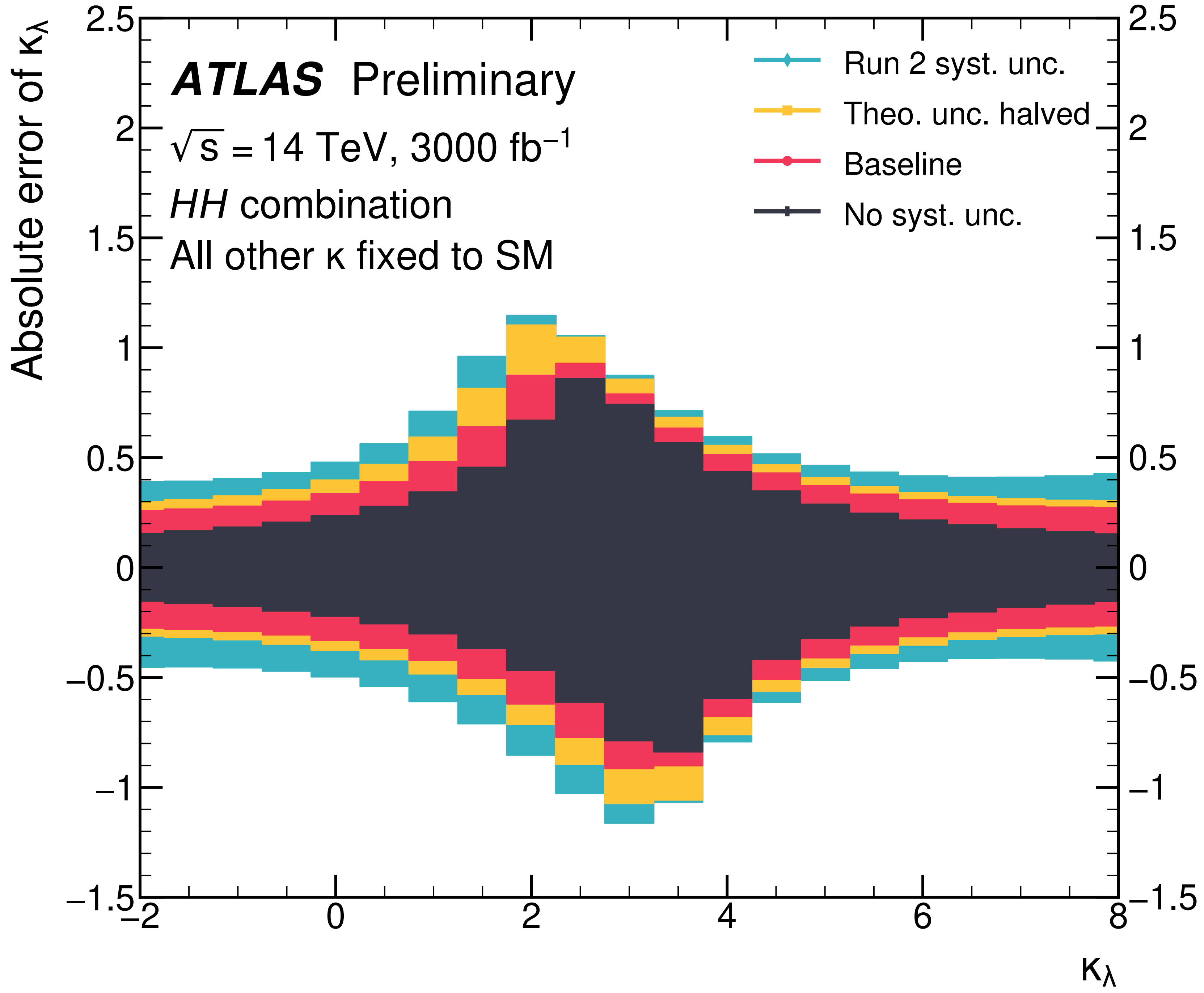
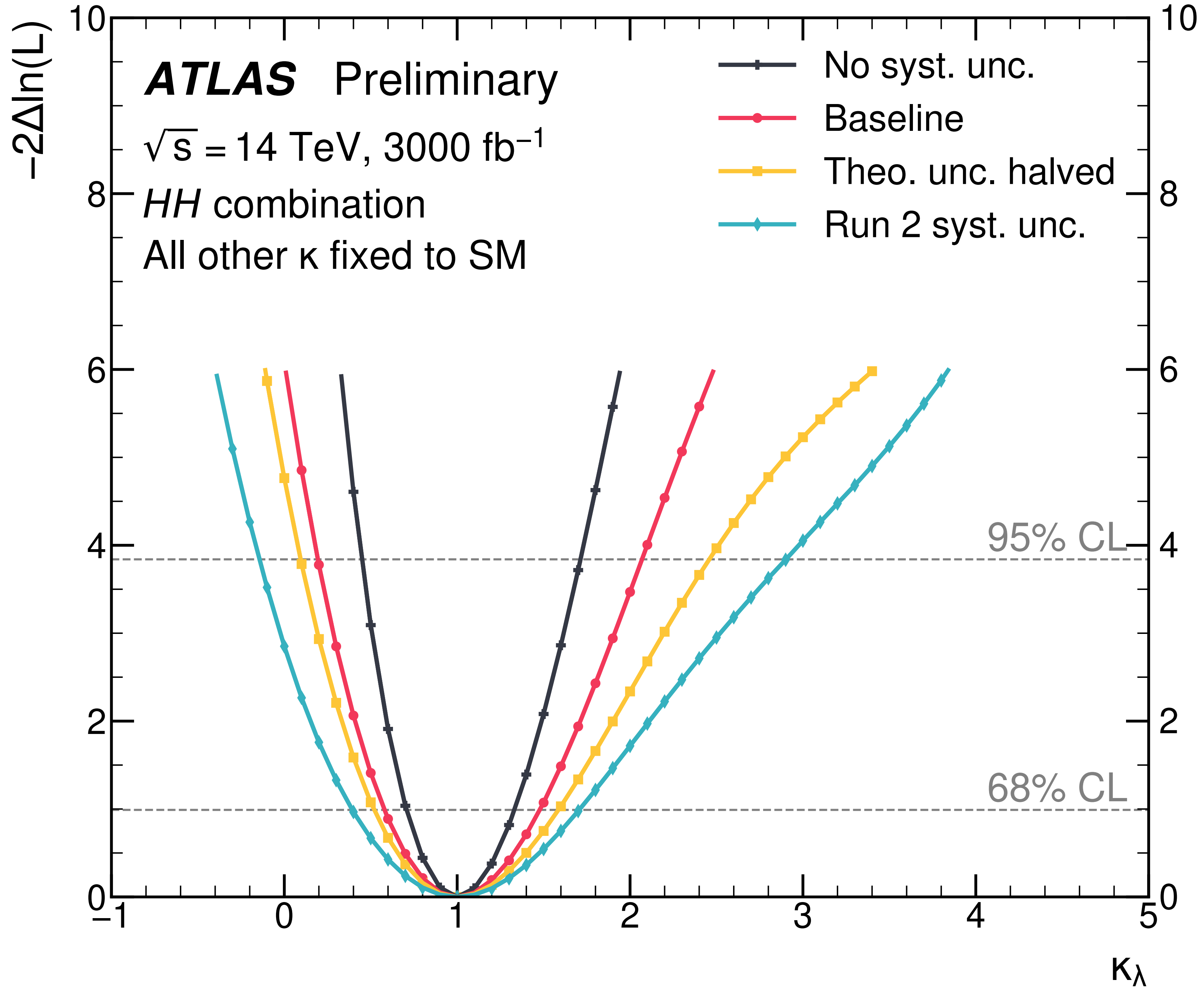
- Improvement on both $\kappa_\lambda, \kappa_{2V}$ limits, project to get
  - 68% CL limit $0.58 < \kappa_\lambda < 1.48$ (75% improvement compared to previous projection)
  - 68% CL limit $0.85 < \kappa_{2V} < 1.18$
- Good precision for any value of the self-coupling strength nature might prefer



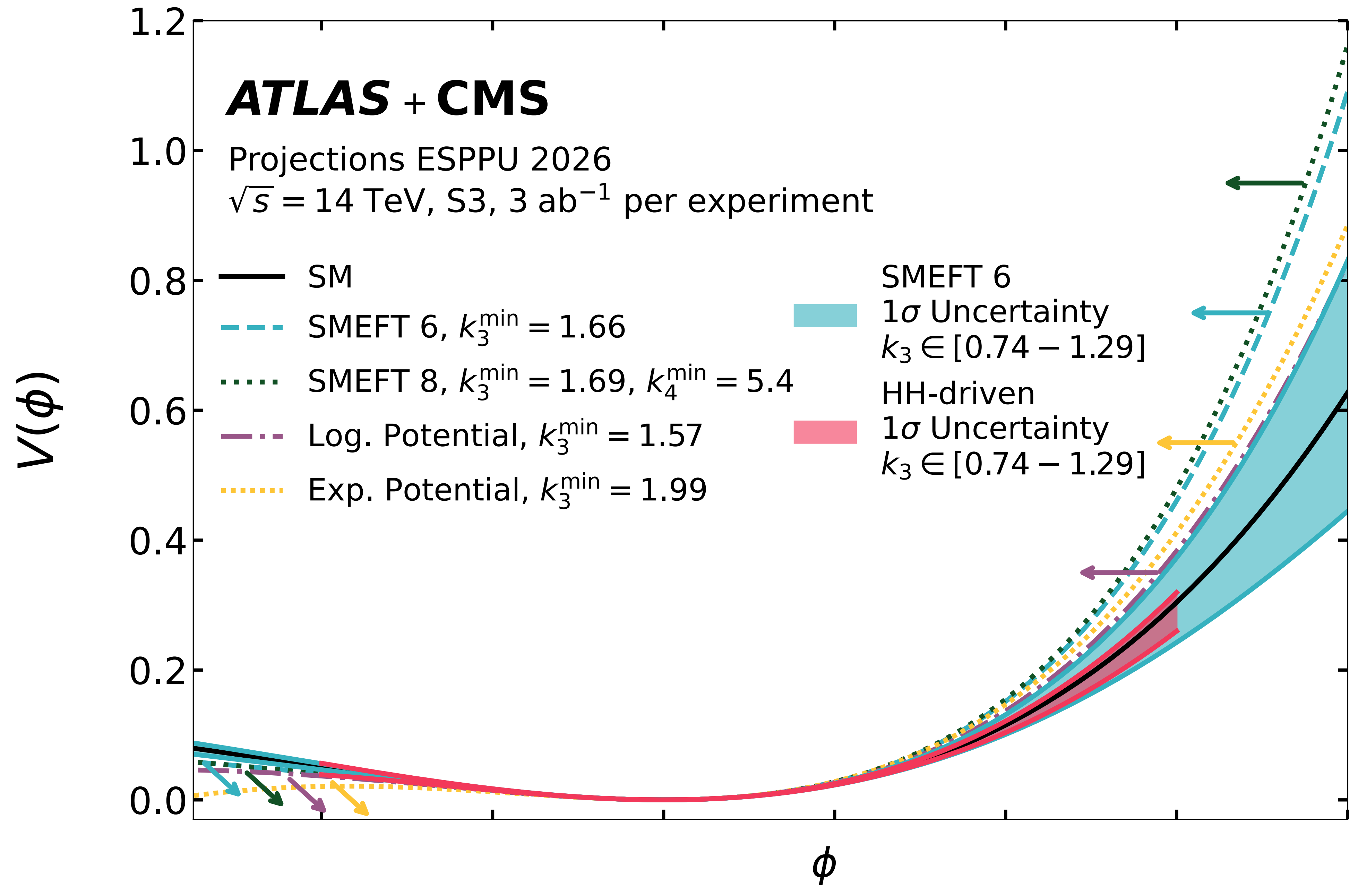




ATLAS+CMS HH projection (ESPPU)

ATL-PHYS-PUB-2025-018

- 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



Bbyy uncertainties

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 impacts are found to be compatible within 30%, the values are symmetrised in the table for better readability. Asymmetric impacts primarily result from the asymmetric QCD scale + m_{top} signal uncertainty, and the fact that the lower endpoint of the 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 impact [%]**	
	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
Theory		
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	

HEFT/SMEFT tricky conversion

Such a translation is given in Table 2.1. However, it has to be used with great care, as the different EFT descriptions rely on different assumptions and therefore are not necessarily translatable into each other. As a consequence, an anomalous coupling configuration which is perfectly valid in HEFT can lie outside the validity range of SMEFT upon such a naive translation. Examples are given in Chapter 3.

HEFT	SILH	Warsaw
c_{hhh}	$1 - \frac{3}{2}\bar{c}_H + \bar{c}_6$	$1 - 2\frac{v^2}{\Lambda^2}\frac{v^2}{m_h^2} C_H + 3\frac{v^2}{\Lambda^2} C_{H,\text{kin}}$
c_t	$1 - \frac{\bar{c}_H}{2} - \bar{c}_u$	$1 + \frac{v^2}{\Lambda^2} C_{H,\text{kin}} - \frac{v^2}{\Lambda^2}\frac{v}{\sqrt{2}m_t} C_{uH}$
c_{tt}	$-\frac{\bar{c}_H + 3\bar{c}_u}{4}$	$-\frac{v^2}{\Lambda^2}\frac{3v}{2\sqrt{2}m_t} C_{uH} + \frac{v^2}{\Lambda^2} C_{H,\text{kin}}$
c_{ggh}	$128\pi^2\bar{c}_g$	$\frac{v^2}{\Lambda^2}\frac{8\pi}{\alpha_s} C_{HG}$
c_{gghh}	$64\pi^2\bar{c}_g$	$\frac{v^2}{\Lambda^2}\frac{4\pi}{\alpha_s} C_{HG}$

Table 2.1: Leading order translation between different operator basis choices.