Combination of HH searches in ATLAS and across LHC

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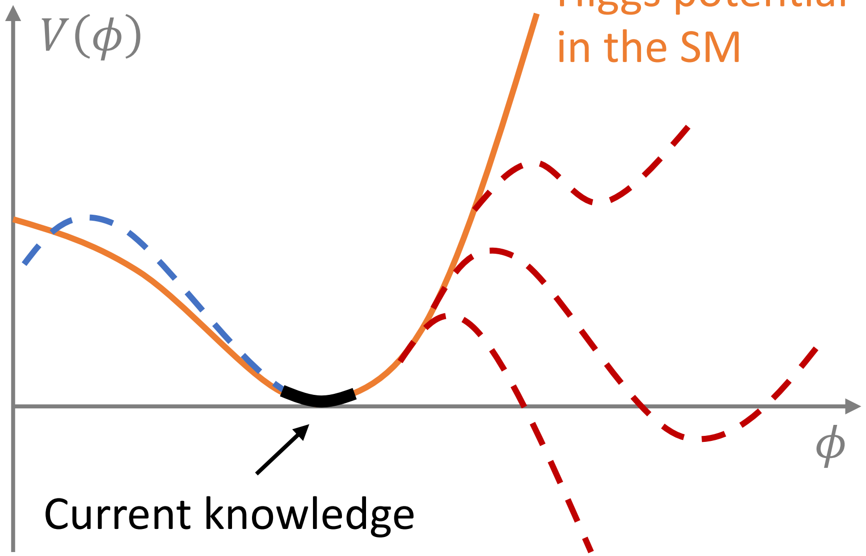
Open questions on universe's history and future

Baryogenesis favors a first-order electroweak phase transition, deviating from the SM prediction



The stability of the electroweak vacuum remains uncertain — our universe may reside in a metastable state rather than the true minimum

Need to directly measure the shape of Higgs potential

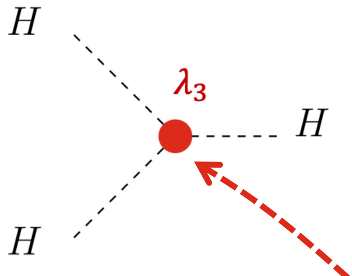
SM predict $$V(H) = \frac{1}{2}m_H^2H^2 + \lambda_3 vH^3 + \frac{1}{4}\lambda_4 H^4 + O(H^5)$$

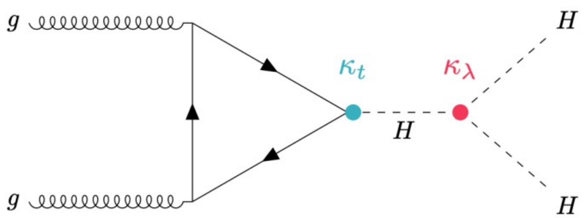
$$\lambda_3 = \lambda_4 = \lambda_{SM} = \frac{m_H^2}{2v^2} \qquad \lambda_i = 0 \text{ for } i \geq 5$$

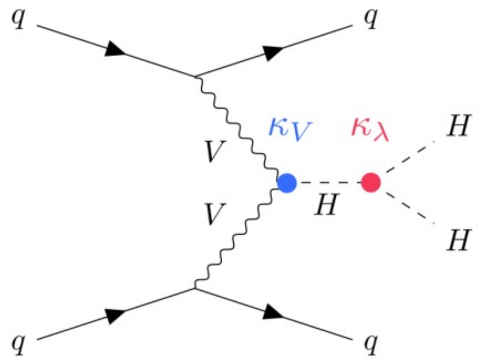
But nature can be more complicate…

Probe Higgs Potential

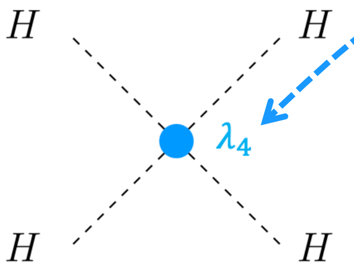
Multi-Higgs production offers a direct handle at LO on the coefficients of Higgs potential

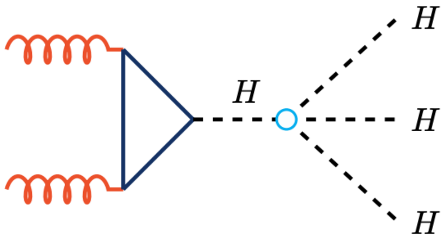






$$V(H) = \frac{1}{2} m_H^2 H^2 + \lambda_3 v H^3 + \frac{1}{4} \lambda_4 H^4 + O(H^5)$$



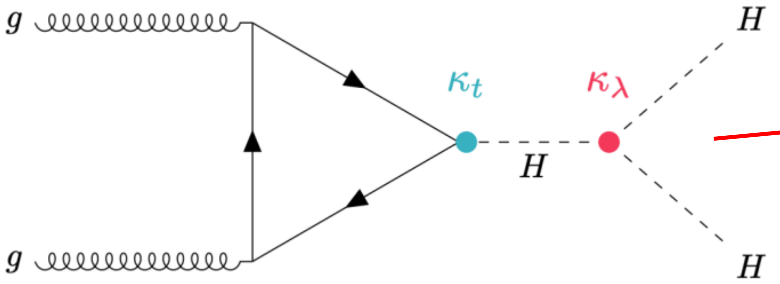


Use κ-framework to interpret results

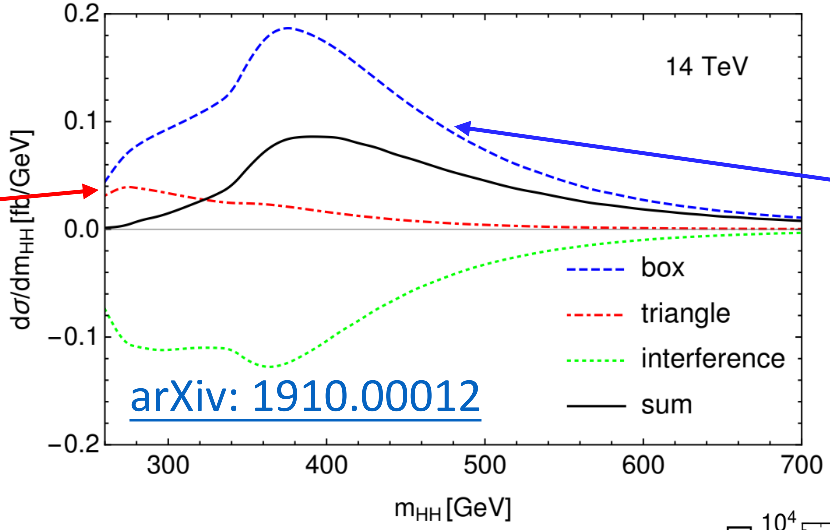
- $\kappa_\lambda = \frac{\lambda}{\lambda_{SM}}, \kappa_{2V} = \frac{g^{HHVV}}{g_{SM}^{HHVV}}$
- Any anomalous value would be a hint for BSM physics

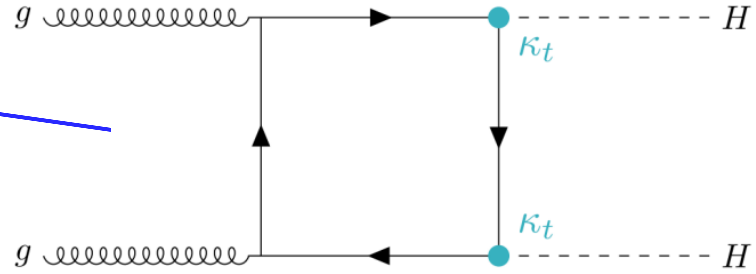
Leading production mode: ggF

Destructive interference between the two diagrams involved in ggF production



"triangle diagram"



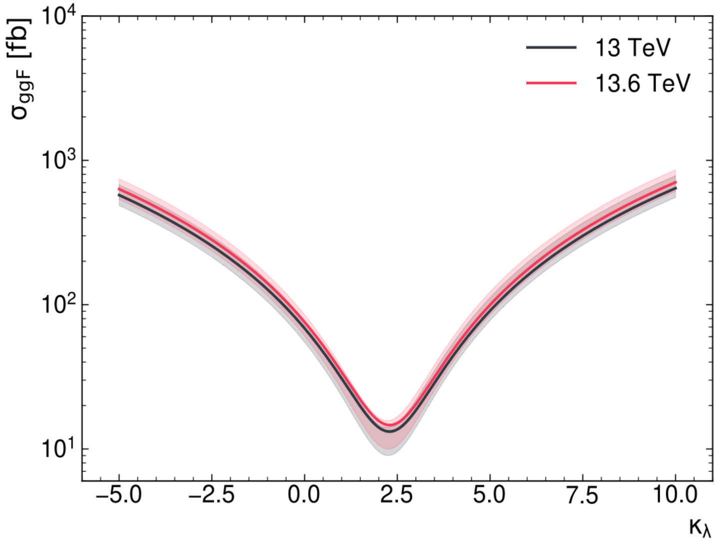


"Box diagram"

- Resulting in a very small cross-section at SM

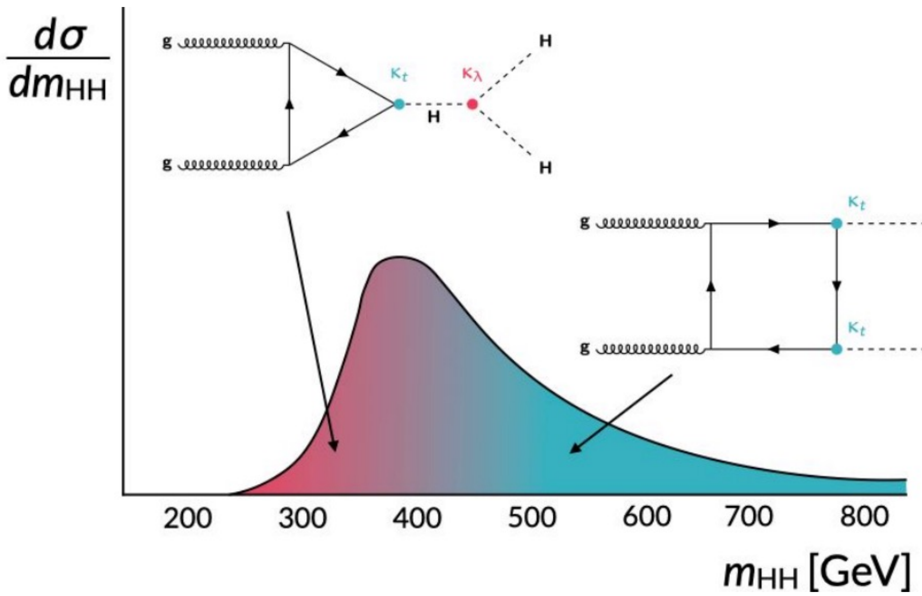
$$\sigma(\mathrm{SM}\ ggF\ HH\ @\ 13\mathrm{TeV}) = 31.05\mathrm{fb}\,{}^{+6\%}_{-23\%}(m_{\mathrm{top}} + \mathrm{scale})\,{}^{+3\%}_{-3\%}(\alpha_s + \mathrm{PDF})$$

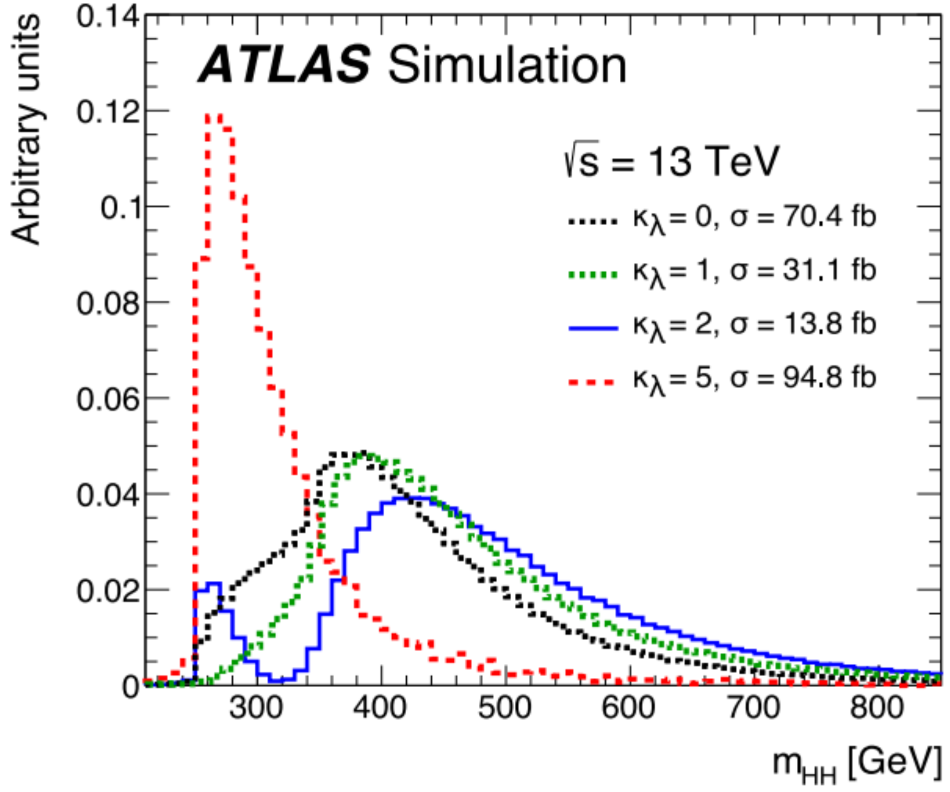
- Maximal destructive interference at $\kappa_\lambda \sim 2$



Leading production mode: ggF

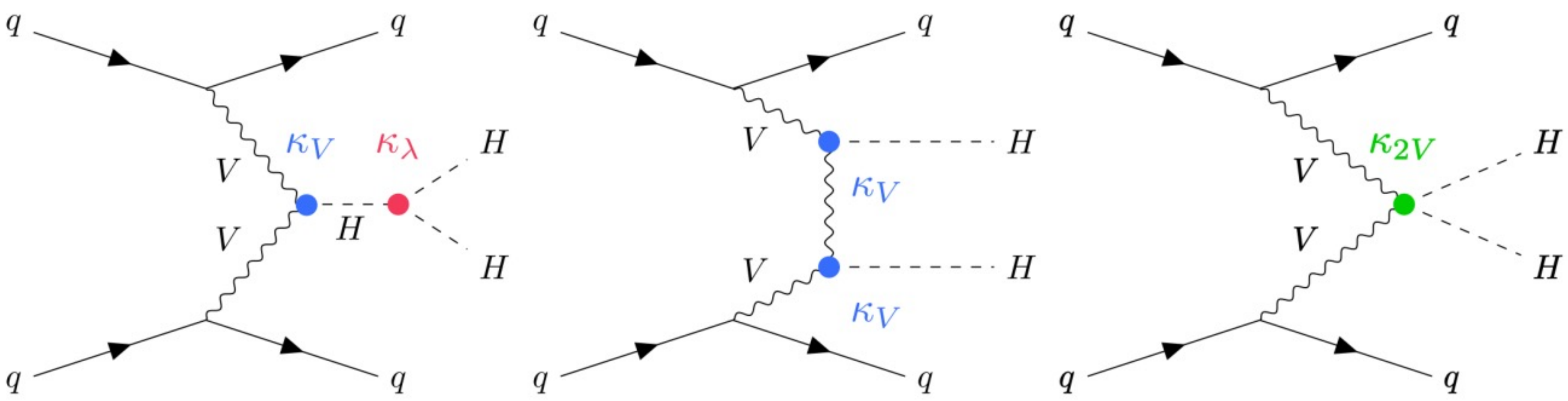
The processes contribute to different kinematic phase space



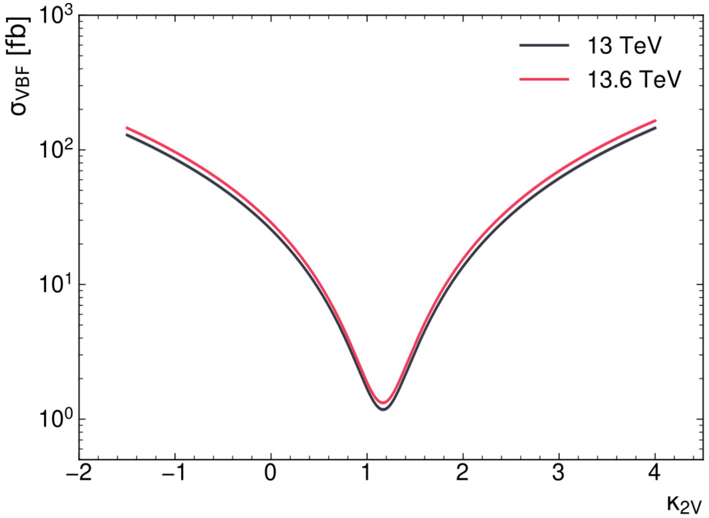


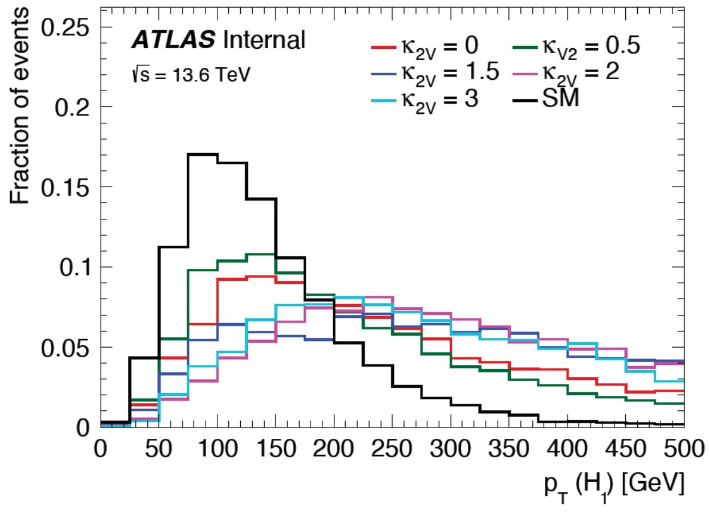
Need attention to softer kinematic events for better constraints on κ_λ

Sub-leading production mode: VBF



- Also some destructive interference, $\sigma(\mathrm{SM}\ VBF\ HH\ @\ 13\mathrm{TeV}) = 1.726\mathrm{fb}$
- The event kinematic could be much harder when κ_{2V} increase





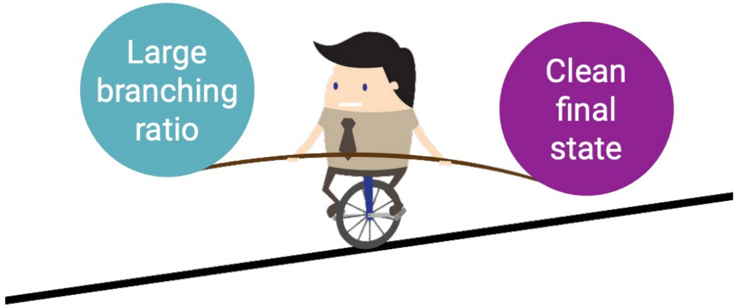
HH searches in ATLAS

Large decay fraction

The other Higgs Boson decay

One Higgs Boson decay	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%

Clean final state



Five orthogonal searches designed for full Run-2, covering most of decays

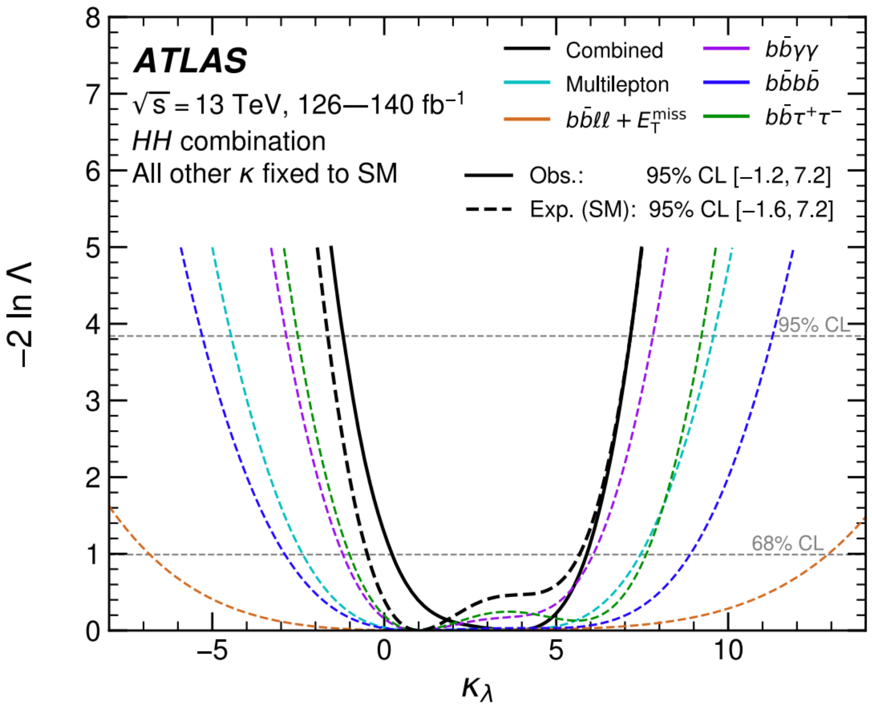
- $bbbb$ (resolved PRD 108 (2023) 052003, boosted VBF PLB 858 (2024) 139007)
- $bb\tau\tau$ PRD 110 (2024) 032012
- $bb\gamma\gamma$ JHEP 01 (2024) 066
- $bb\ell\ell + E_T^{\mathrm{miss}}$ JHEP 02 (2024) 037
- Multilepton JHEP 08 (2024) 164

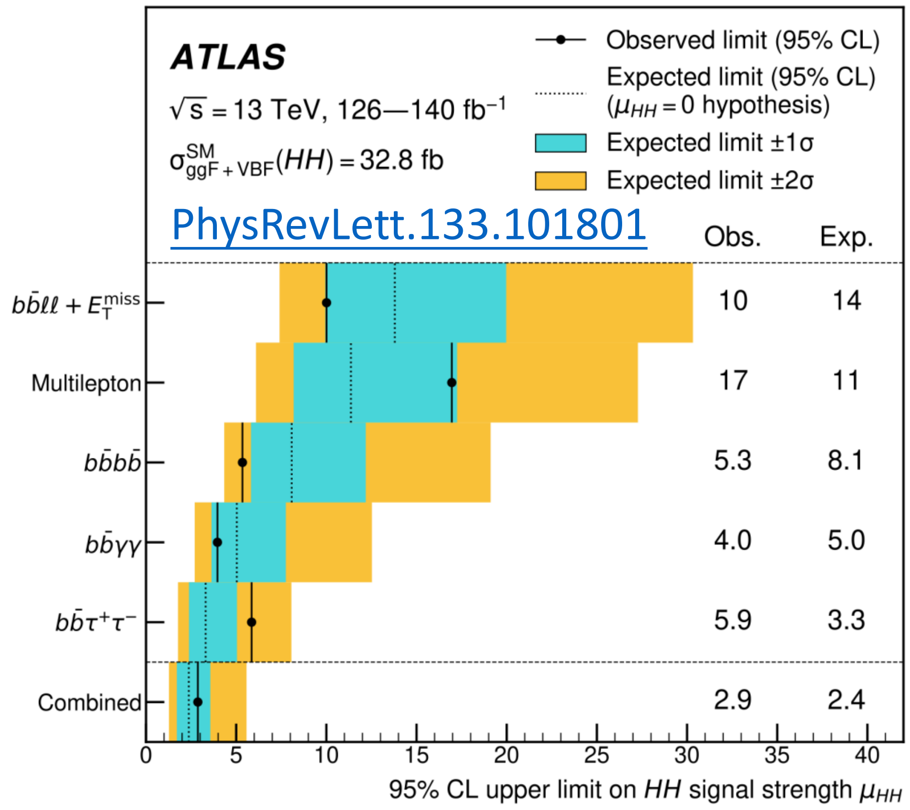
Combination of HH searches in ATLAS

Combining the searches together, we can maximize the sensitivity

- The procedure includes reconstruction of likelihood function, i.e. the correlation in systematics as well as the shape of likelihood curve are carefully studied

$$\mathcal{L}(\mathcal{D},\mathcal{G}|\mu,\alpha)=\prod_c\left(\prod_r Prob\left(x_r|\sum_i S^i(\mu,\alpha)+\sum_j B^j(\alpha)\right)\right)\times\prod_p f_p(a_p|\alpha_p)$$

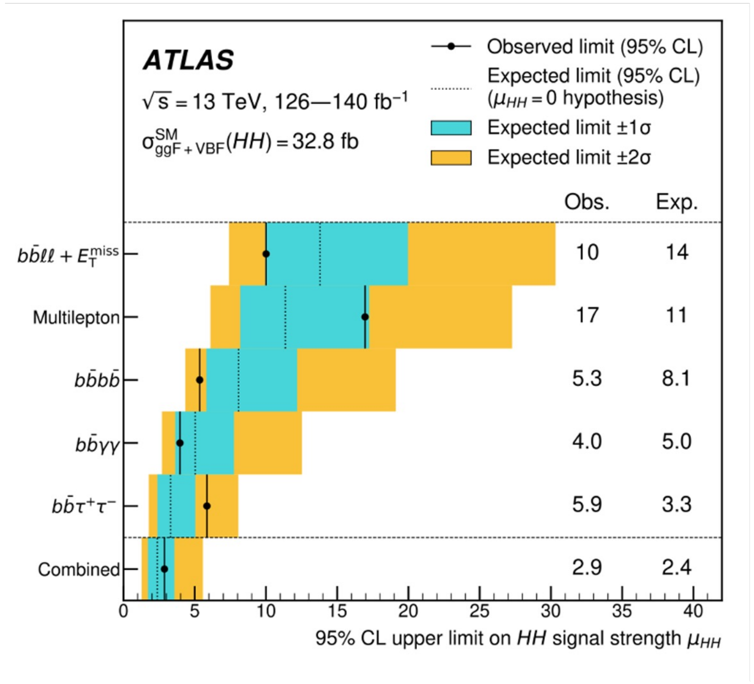




Achieve best sensitivity to HH self-coupling and signal strength

How to maximize the sensitivity in Run-2?

- Remember that there is also a set of excellent HH searches in CMS
  - Using statistically independent datasets
- Get twice data if we combine the two experiments together!



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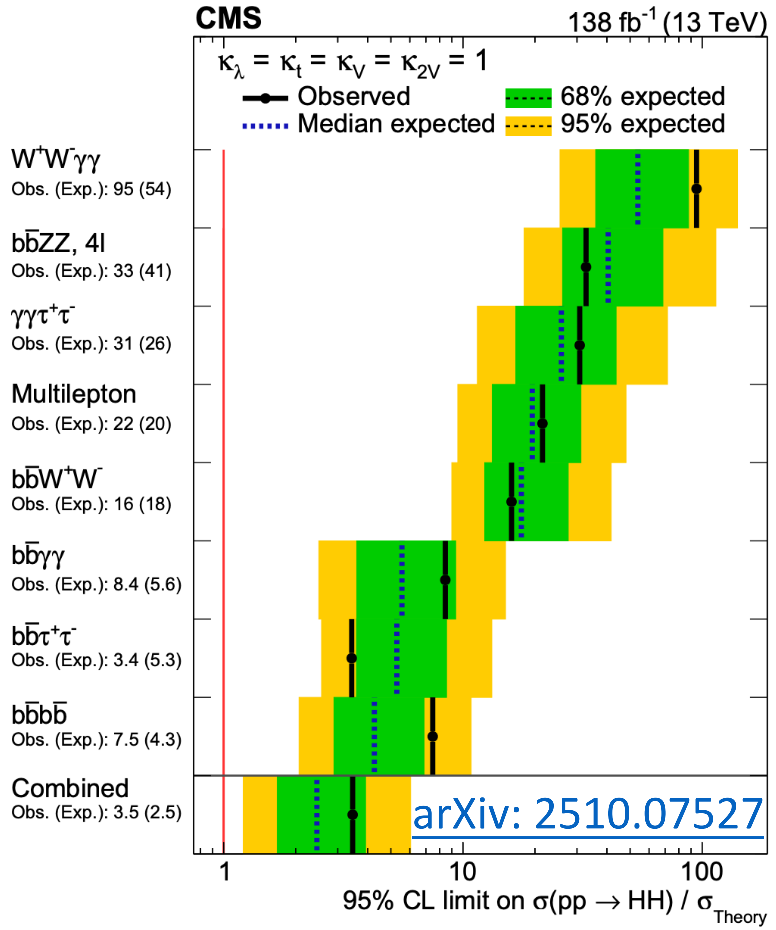


= ?

Will definitely represent a critical step toward constraining the nature of Higgs self-coupling

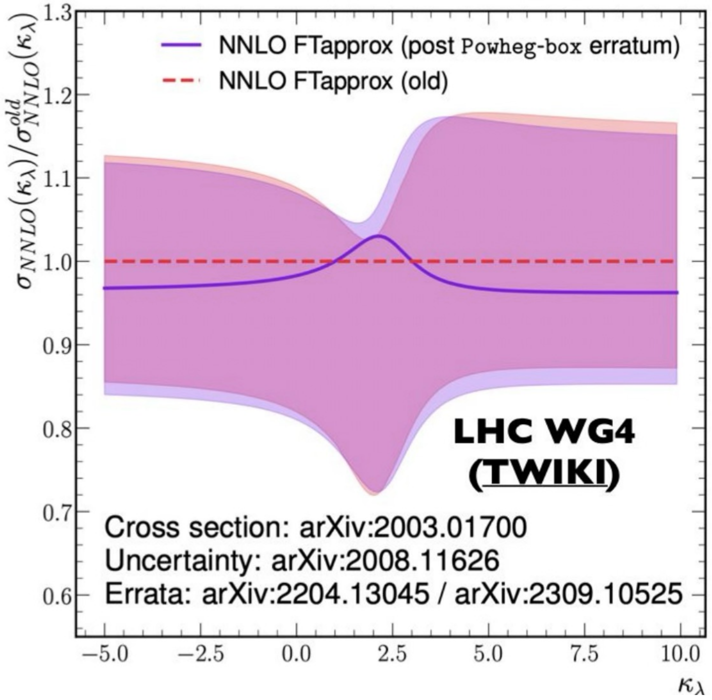
Harmonization between ATLAS and CMS

All Run-2 HH analyses were affected by a bug in the production stage

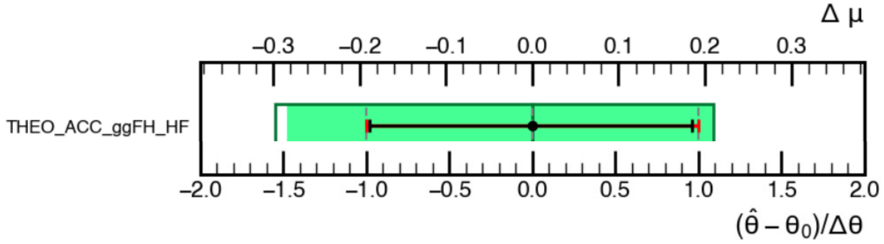
- A term missing in two-loop amplitude calculation of Powheg box
- Will affect both distribution and cross section for $\kappa_\lambda \neq 1$

A correction on xsec was agreed to address this issue

- Update both κ_λ-dependent central value and uncertainty
- Didn't correct shape as it requires re-run of analysis



ATLAS usually considers a big normalization uncertainty for H + heavy flavor jets background (arXiv: 2307.09992)



Included in CMS in the individual combination

Harmonization between ATLAS and CMS

CMS always considers the κ_λ impact on Higgs decay branching ratio and single-H production cross-section

$$\mu_i(\kappa_\lambda, \kappa_i) = \frac{\sigma^{\mathrm{BSM}}}{\sigma^{\mathrm{SM}}} = Z_H^{\mathrm{BSM}}(\kappa_\lambda)\left[\kappa_i^2 + \frac{(\kappa_\lambda - 1)C_1^i}{K_{\mathrm{EW}}^i}\right]$$

$$\mu_f(\kappa_\lambda, \kappa_f) = \frac{\mathrm{BR}_f^{\mathrm{BSM}}}{\mathrm{BR}_f^{\mathrm{SM}}} = \frac{\kappa_f^2 + (\kappa_\lambda - 1)C_1^f}{\sum_j \mathrm{BR}_j^{\mathrm{SM}}\left[\kappa_j^2 + (\kappa_\lambda - 1)C_1^j\right]}$$

Initially considered only in $bb\tau\tau$ in ATLAS, now also introduced into $bbbb$ and $bb\gamma\gamma$, will serve as the baseline strategy in future ATLAS HH analyses

HistFactory-based tools

in CMS v.s. ... in ATLAS

The two experiments have diverged in the fitting tool developments

- Many dedicated classes and features are incompatible across experiments

With recent developments, we can reliably process each other's workspaces

- Will benefit future ATLAS+CMS combination

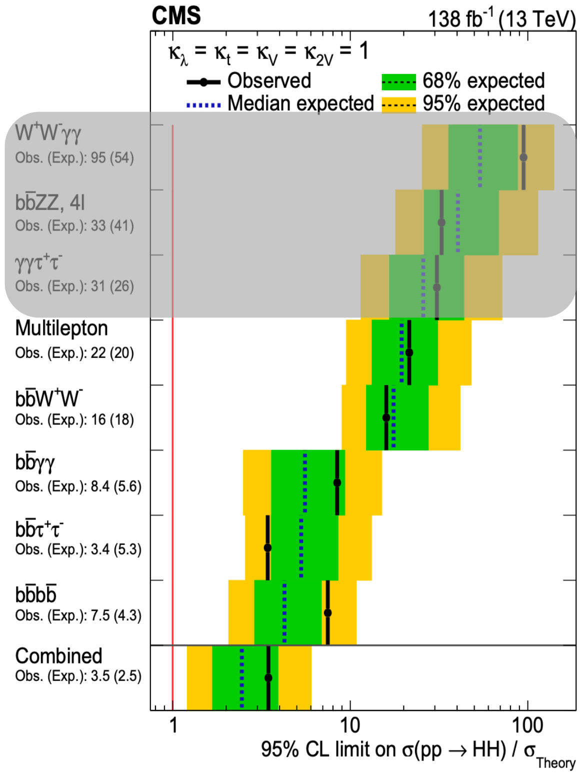
Combination procedure

Correlation scheme:

- Correlate HH and H theory cross-section and BR systematics
- The only possible experimental systematic — luminosity — remain uncorrelated because of the difference in year-dependence

Only five channels from CMS are included

- The missing channels have impact of < 1%

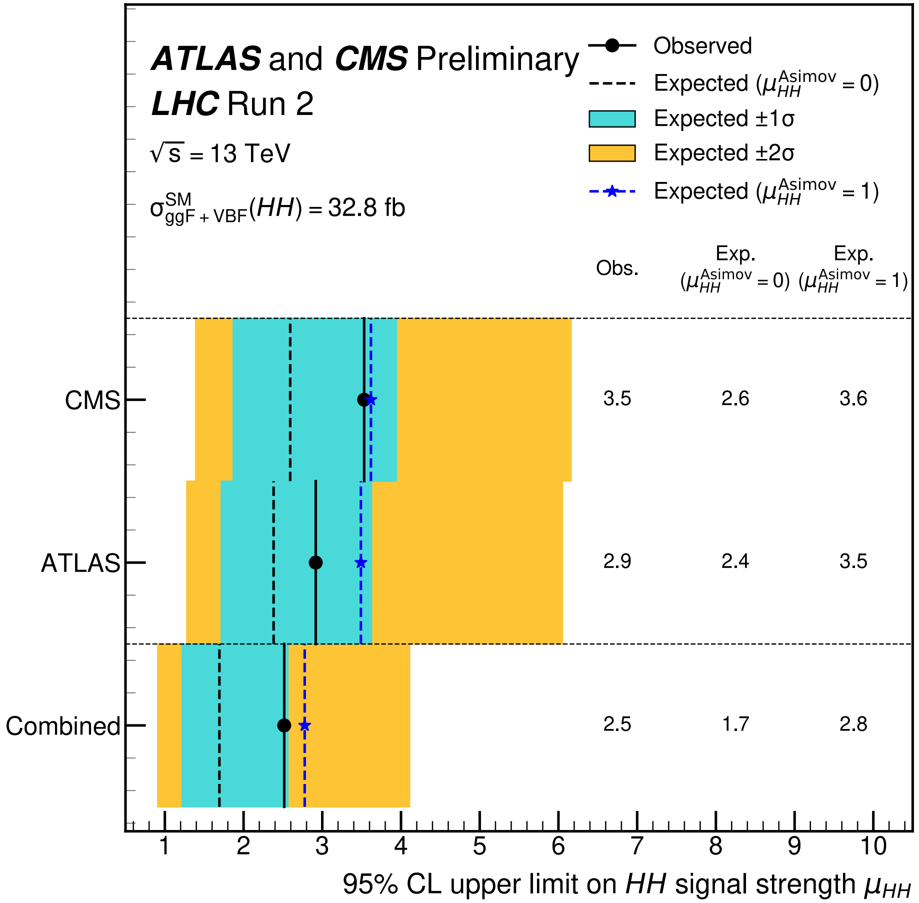


Each experiment share the individual combined workspace and obtain the results independently using own statistical framework

- Excellent agreement in results overall

LHC HH combination: upper limit

ATLAS-CONF-2025-012/CMS-PAS-HIG-25-014



Fitting results:

- Observed: $\hat{\mu}_{\mathrm{HH}} = 0.8^{+0.9}_{-0.7} = 0.8^{+0.7}_{-0.6}(\mathrm{stat.})^{+0.4}_{-0.2}(\mathrm{theory})^{+0.3}_{-0.3}(\mathrm{exp.})$
- Expected: $\hat{\mu}^{\mathrm{exp}}_{\mathrm{HH}} = 1.0^{+0.9}_{-0.8} = 1.0^{+0.7}_{-0.6}(\mathrm{stat.})^{+0.5}_{-0.3}(\mathrm{theory})^{+0.3}_{-0.3}(\mathrm{exp.})$
- Statistical uncertainty still dominates, theoretical uncertainty is also sizable

The observed (expected) local significance:

- 1.1σ (1.3σ)

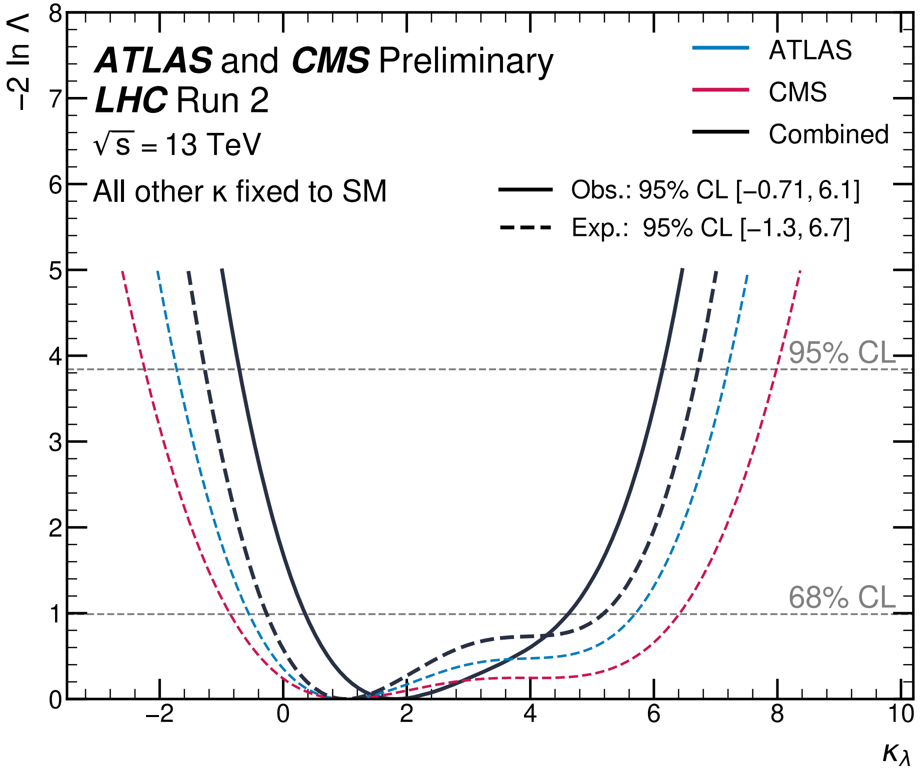
Expected 95% CL upper limit reach 1.7

- ~30% improvement w.r.t. single experiment

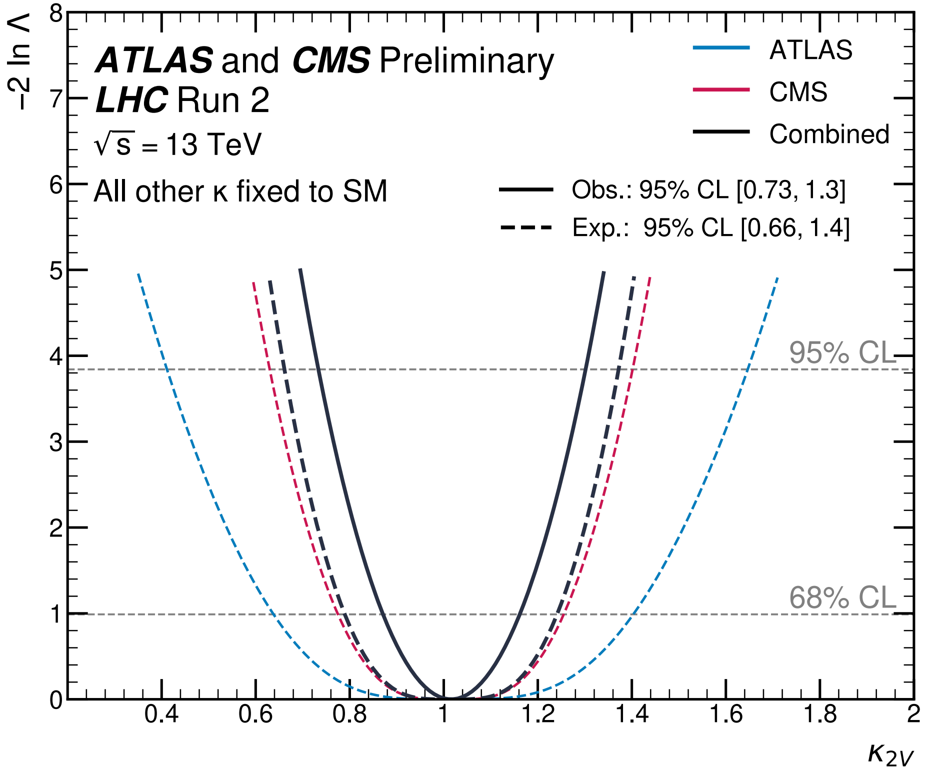
Expected limit assuming SM HH production (2.8) is closer to the observed limit (2.5)

LHC HH combination: coupling

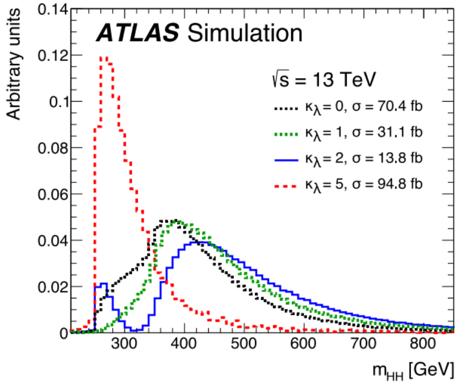
κ_λ interval driven by $bb\gamma\gamma$ and $bb\tau\tau$

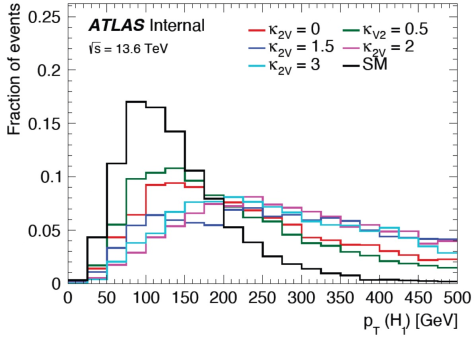


κ_{2V} interval driven by $bbbb$



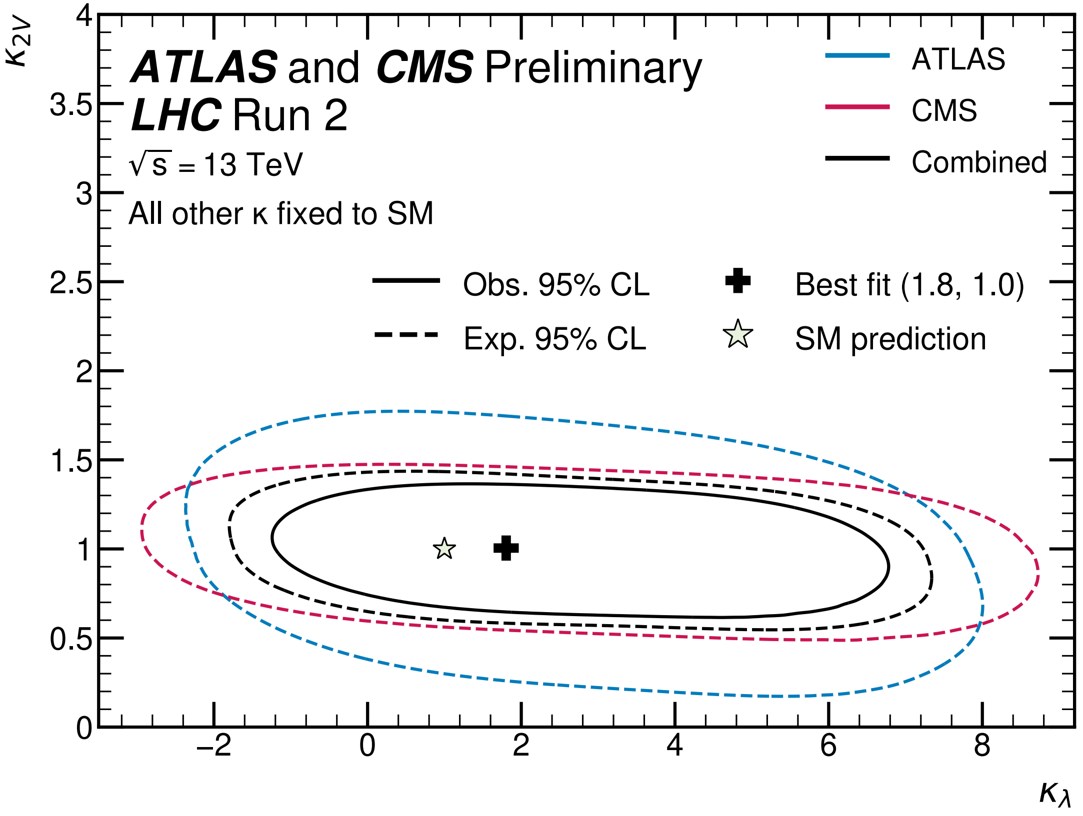
Recall the kinematic dependence on coupling





Improve the constraints by 10% on κ_λ and 8% on κ_{2V} w.r.t. the best constraints to date

LHC HH combination: coupling

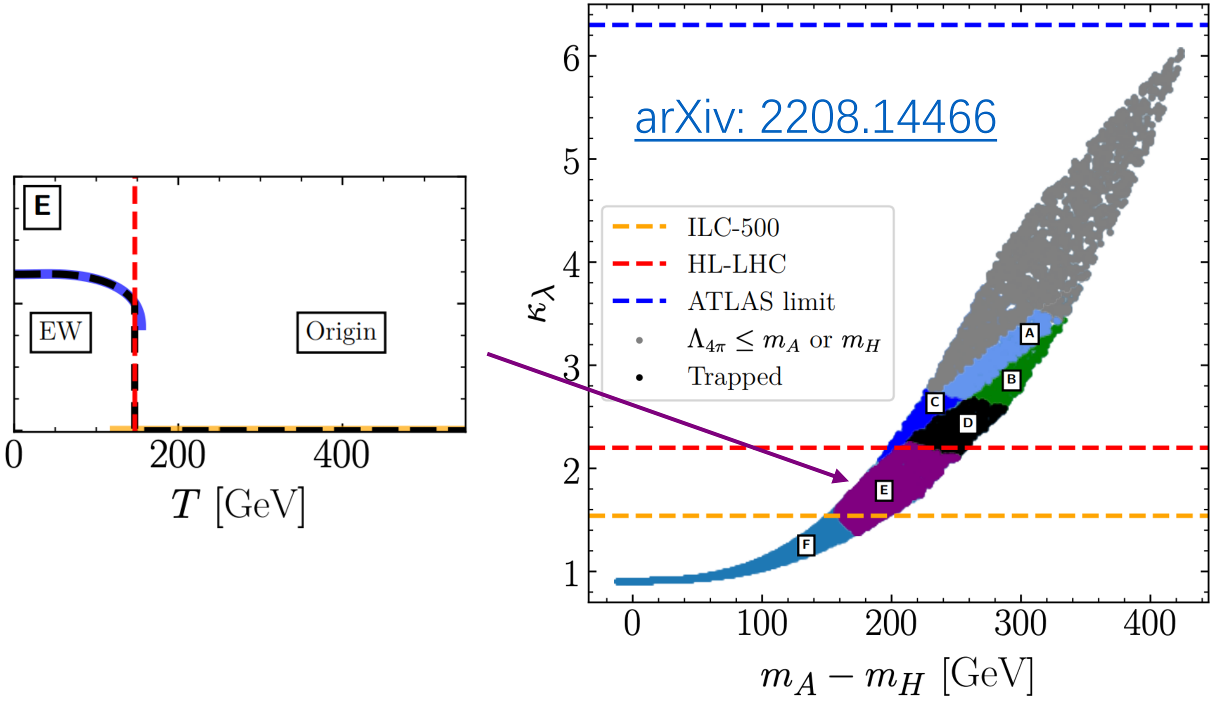


Best-fit in the $\kappa_\lambda - \kappa_{2V}$ plane set to $(1.8, 1.0)$

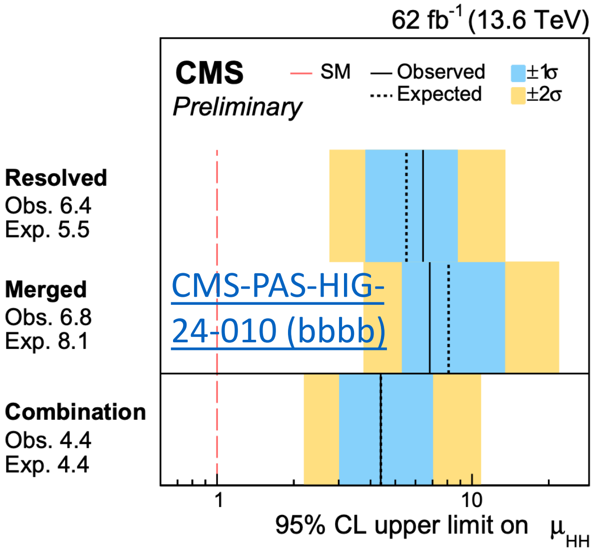
- Compatible with the SM

The value 1.8 of κ_λ is preferred by SFOEWPT?

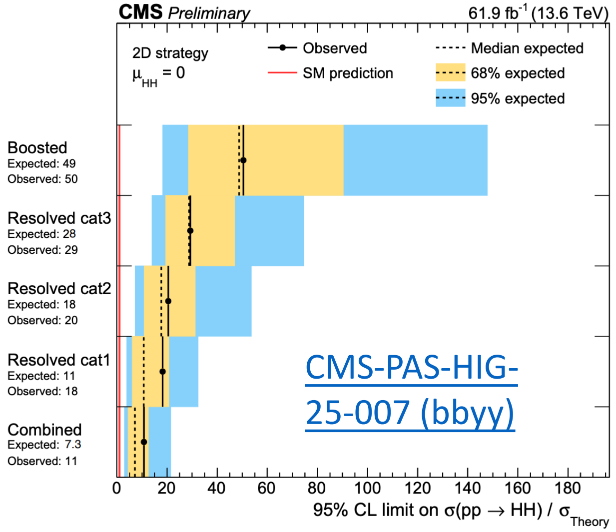
- Still too early to draw conclusions



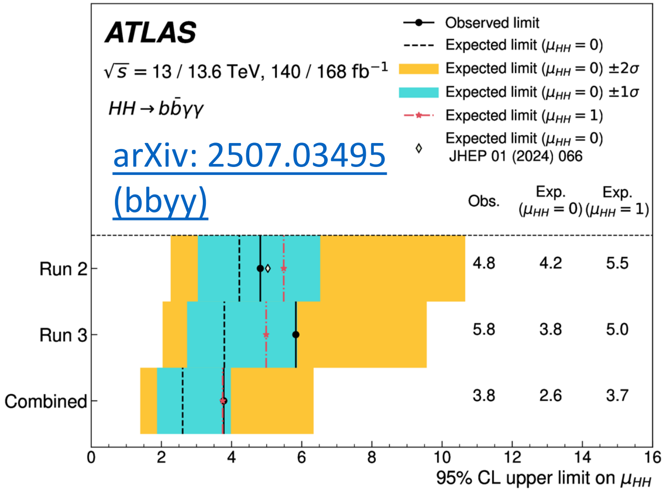
Exciting Run-3 results came/coming



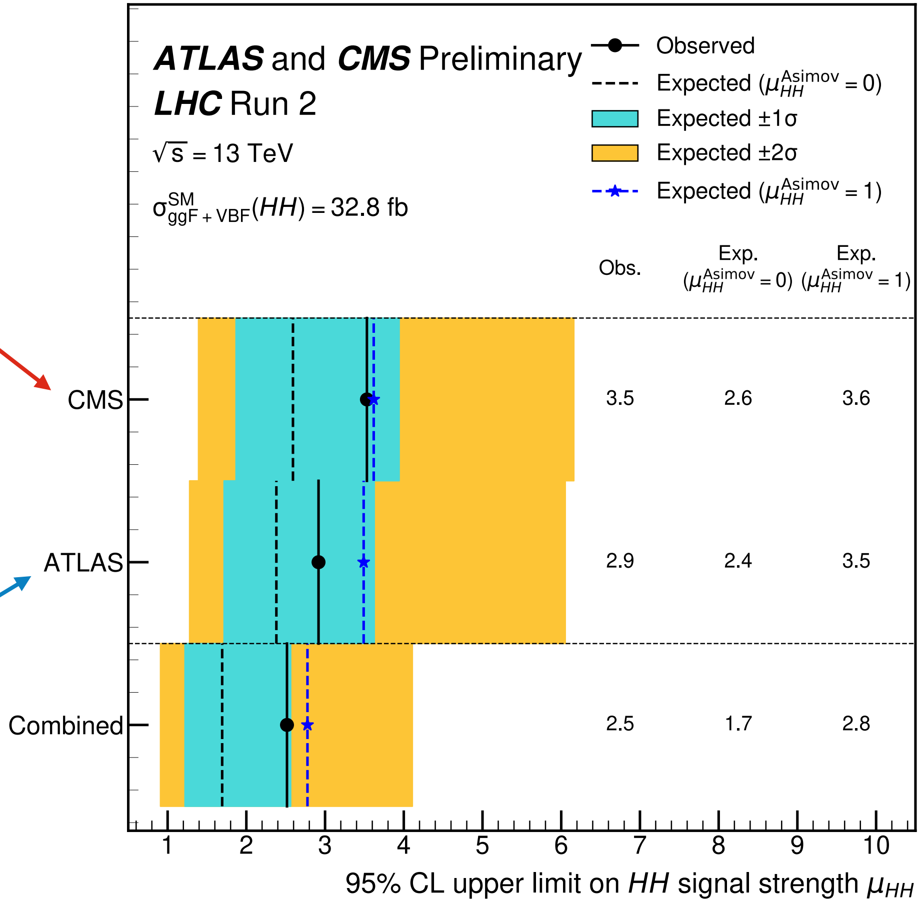
CMS-PAS-HIG-24-010 (bbbb)



CMS-PAS-HIG-25-007 (bbyy)



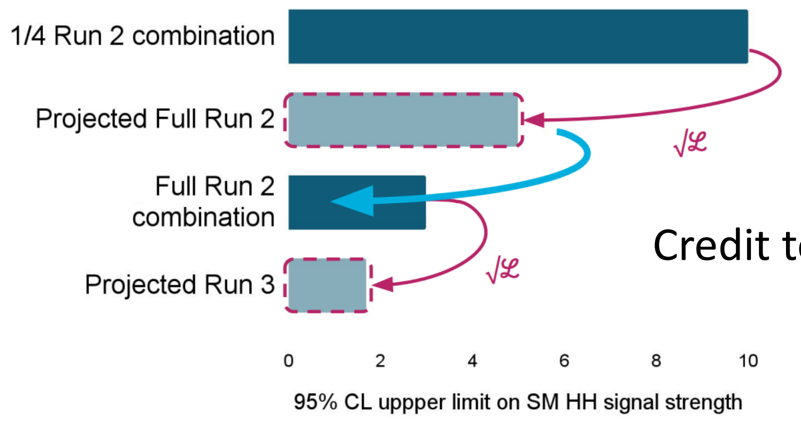
arXiv: 2507.03495 (bbyy)



Can expect upper limit of 1.4 by a simple computation!

Summary

- Final and best results of HH search in LHC Run-2:
  - 95% CL U.L.: $\mu_{HH} < 2.5\ (1.7\ exp)$
  - 95% CI on κ_λ: $[-0.71, 6.1]\ ([-1.3, 6.7]\ exp)$
  - 95% CI on κ_{2V}: $[0.73, 1.3]\ ([0.66, 1.4]\ exp)$
- Keep optimizing the analysis and iterating the combination with Run-3 data
  - We always get better improvement than a simple luminosity scaling
  - Very likely to achieve evidence of HH with LHC combination at Run-3 if $\kappa_\lambda = 1$



Credit to [Liza]

Backup

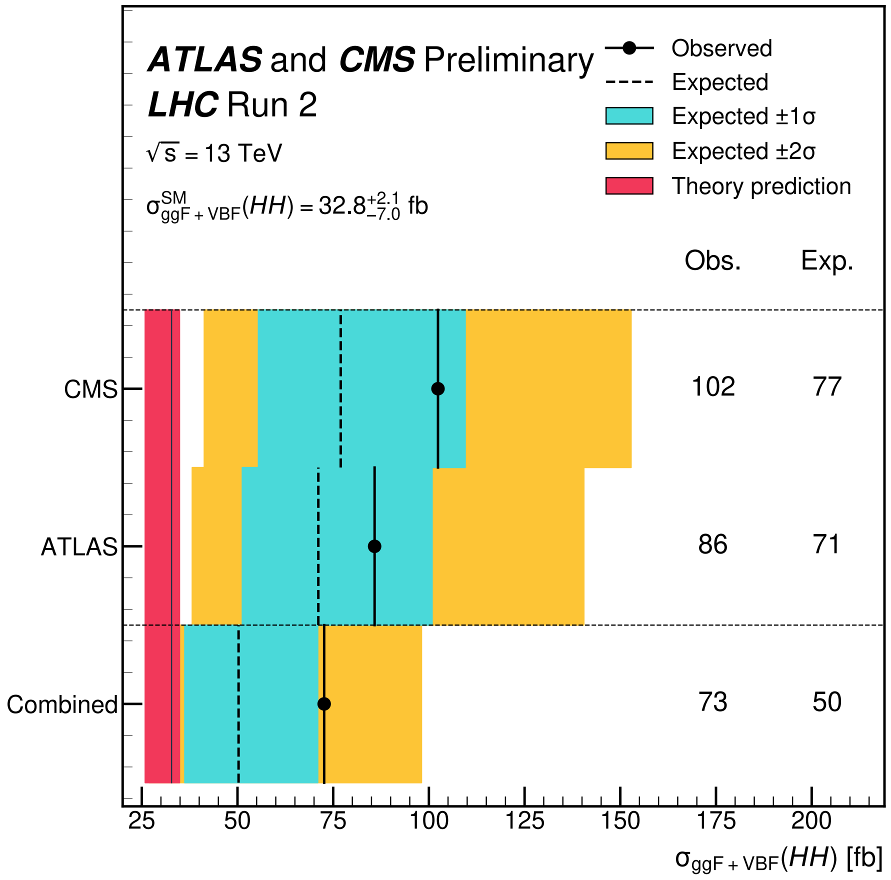
LHC HH combination results

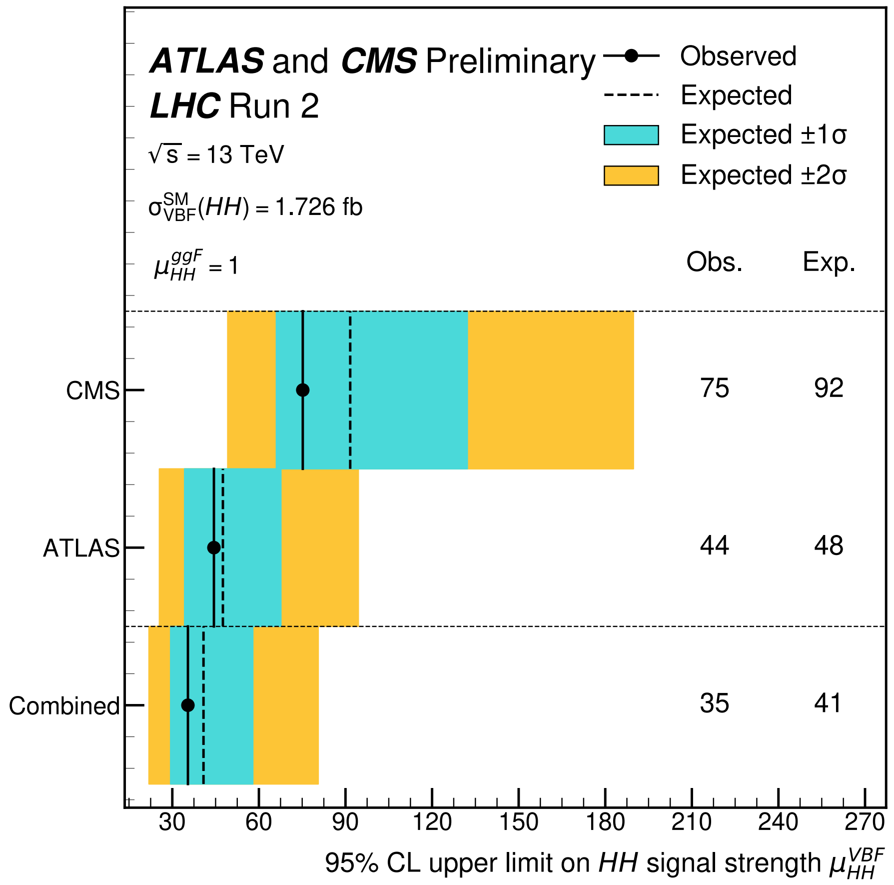
	Channel	Details	Expected			Observed		
			μ_{HH}	κ_λ	κ_{2V}	μ_{HH}	κ_λ	κ_{2V}
ATLAS	bbbb	[30, 32]	< 8.1	[−5.3, 12]	[0.38, 1.7]	< 5.4	[−3.4, 11]	[0.55, 1.5]
ATLAS	$bb\tau\tau$	[34]	< 3.3	[−2.6, 9.2]	[−0.24, 2.4]	< 5.8	[−3.3, 9.1]	[−0.51, 2.7]
ATLAS	$bb\gamma\gamma$	[36]	< 5.2	[−3.0, 7.9]	[−1.1, 3.3]	< 4.1	[−1.6, 7.0]	[−0.48, 2.7]
ATLAS	$bb\ell\ell + E_T^{miss}$	[38]	< 14	[−11, 17]	[−0.50, 2.7]	< 9.6	[−6.5, 13]	[−0.19, 2.4]
ATLAS	Multileptons	[40]	< 11	[−4.5, 9.6]	[−1.9, 4.1]	< 17	[−6.4, 12]	[−2.5, 4.7]
ATLAS	Combined	[41]	< 2.4	[−1.7, 7.2]	[0.41, 1.7]	< 2.9	[−1.3, 7.2]	[0.57, 1.5]
CMS	bbbb	[29, 31]	< 4.3	[−4.6, 12]	[0.63, 1.4]	< 7.0	[−5.0, 12]	[0.66, 1.4]
CMS	$bb\tau\tau$	[33]	< 5.4	[−4.2, 11]	[−0.64, 2.8]	< 3.5	[−1.9, 8.9]	[−0.32, 2.5]
CMS	$bb\gamma\gamma$	[35]	< 5.7	[−3.5, 8.8]	[−0.94, 3.1]	< 8.7	[−3.5, 8.0]	[−1.4, 3.6]
CMS	bbWW	[37]	< 19	[−9.4, 16]	[−1.4, 3.5]	< 15	[−6.1, 13]	[−1.0, 3.1]
CMS	Multileptons	[39]	< 20	[−8.0, 12]	[−2.5, 4.6]	< 22	[−5.8, 10]	[−3.4, 5.6]
CMS	Combined	[42]	< 2.6	[−2.2, 8.0]	[0.63, 1.4]	< 3.5	[−1.4, 6.6]	[0.66, 1.4]
ATLAS + CMS combined			< 1.7	[−1.3, 6.7]	[0.66, 1.4]	< 2.5	[−0.71, 6.1]	[0.73, 1.3]

LHC HH combination results

		κ_λ			κ_{2V}		
		Best fit	68% CL	95% CL	Best fit	68% CL	95% CL
ATLAS	Observed	3.5	[0.11, 5.9]	[-1.3, 7.2]	1.0	[0.80, 1.2]	[0.57, 1.5]
	Expected	1.0	[-0.55, 5.7]	[-1.7, 7.2]	1.0	[0.64, 1.4]	[0.41, 1.7]
CMS	Observed	1.6	[-0.04, 4.6]	[-1.4, 6.6]	1.0	[0.83, 1.2]	[0.66, 1.4]
	Expected	1.0	[-0.86, 6.4]	[-2.2, 8.0]	1.0	[0.78, 1.3]	[0.63, 1.4]
Combination	Observed	1.8	[0.36, 4.6]	[-0.71, 6.1]	1.0	[0.87, 1.2]	[0.73, 1.3]
	Expected	1.0	[-0.27, 5.2]	[-1.3, 6.7]	1.0	[0.79, 1.2]	[0.66, 1.4]

LHC HH combination results





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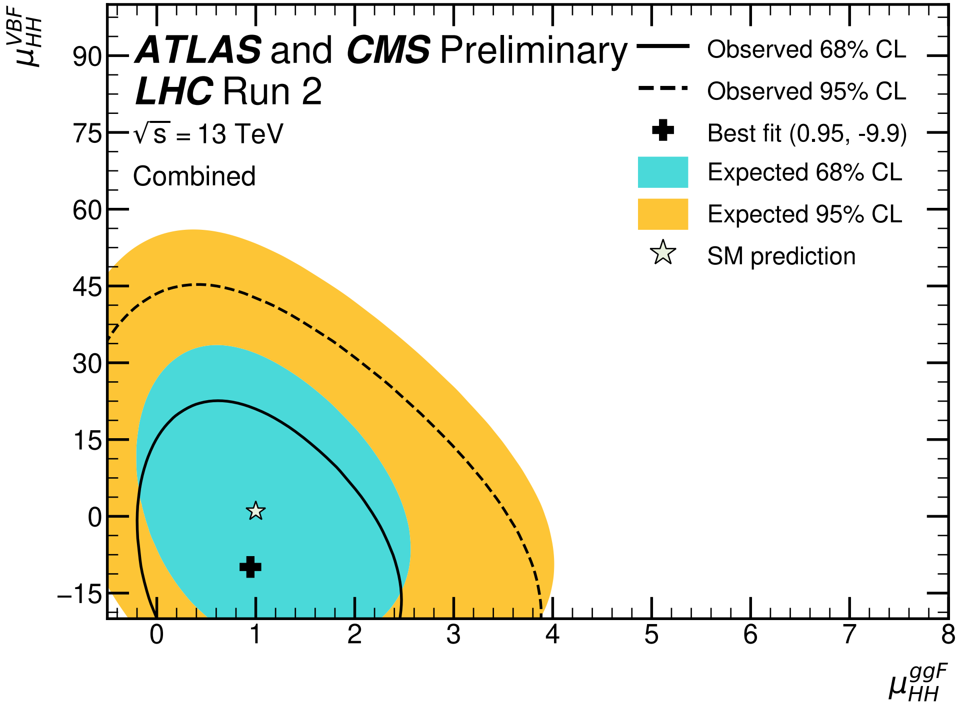

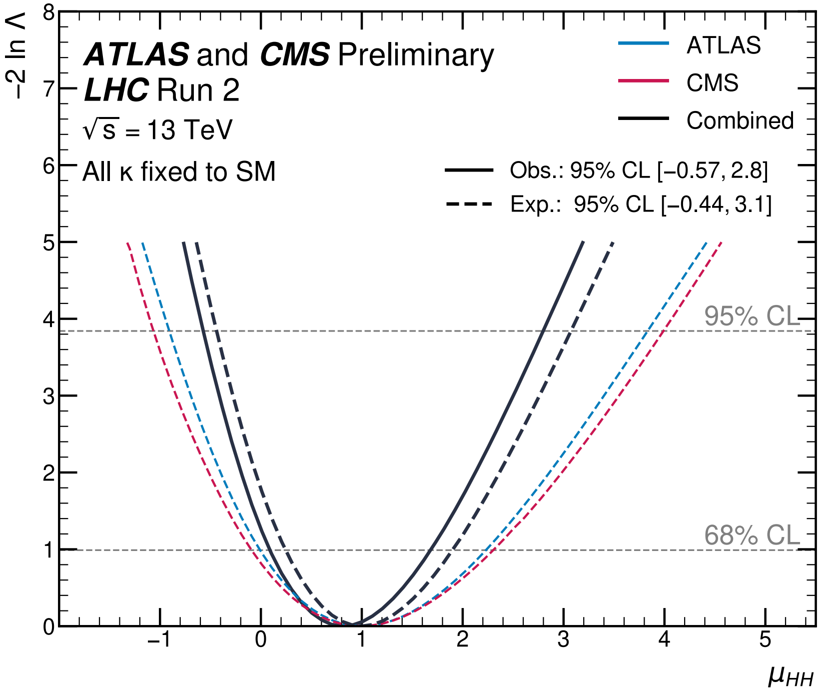

LHC HH combination results