南京大学
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Combination of ATLAS and CMS searches for Higgs boson pair production at 13 TeV

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Motivation

Our universe might be meta-stable

Need direct probe of Higgs potential shape

In the SM

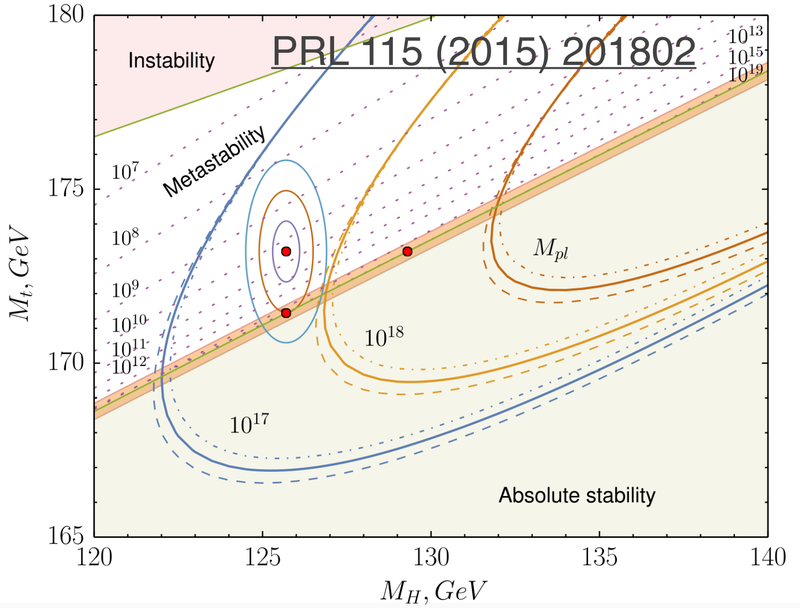
$$V(H) = \frac{1}{2}m_H^2 H^2 + \lambda_3 \nu H^3 + \frac{1}{4}\lambda_4 H^4 + O(H^5)$$

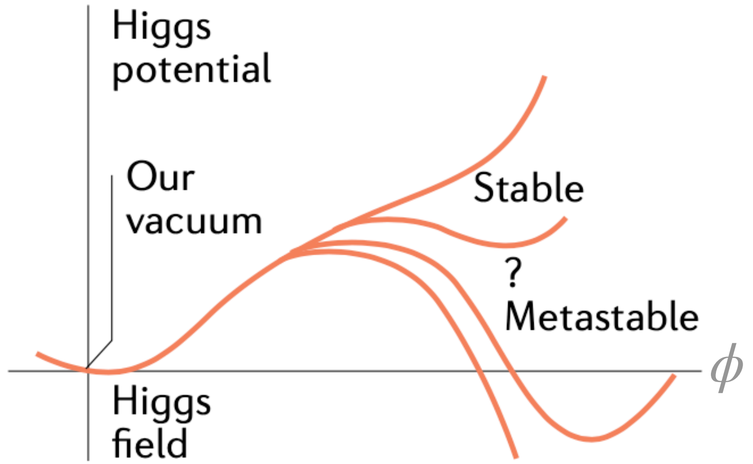
$$\lambda_3 = \lambda_4 = \lambda_{\mathrm{SM}} = \frac{m_H^2}{2\nu^2}, \quad \lambda_{5,6,\ldots} = 0$$

But is it true?

- Limited experimental knowledge
- Alternative shapes are motivated (to allow first order electroweak phase transition)

How to probe the shape?

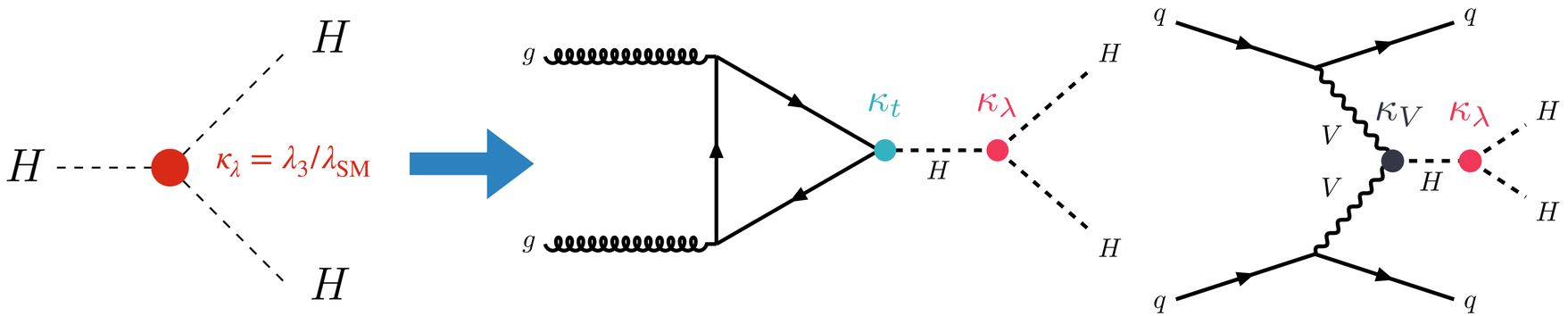




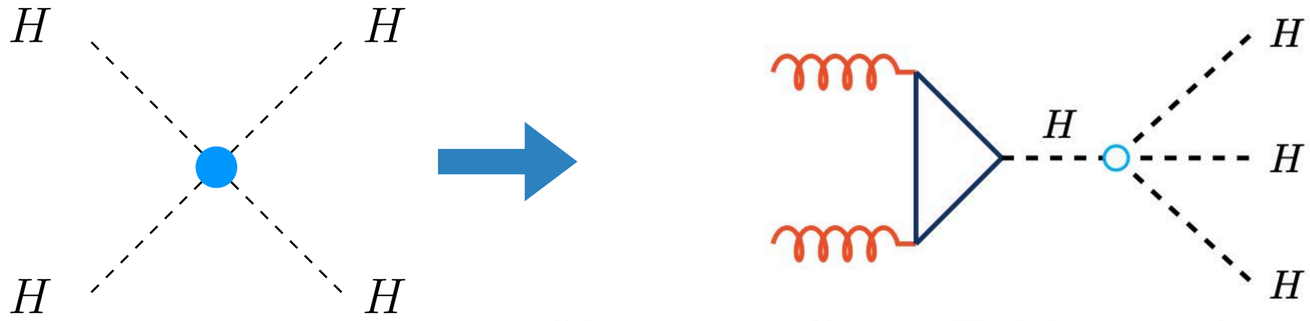
Nature Reviews Physics 3.9 (2021)

Higgs self-coupling

Multi-Higgs production offers a direct handle of the shape at leading order



SM σ_{HH} @ 13 TeV ~ 33 fb



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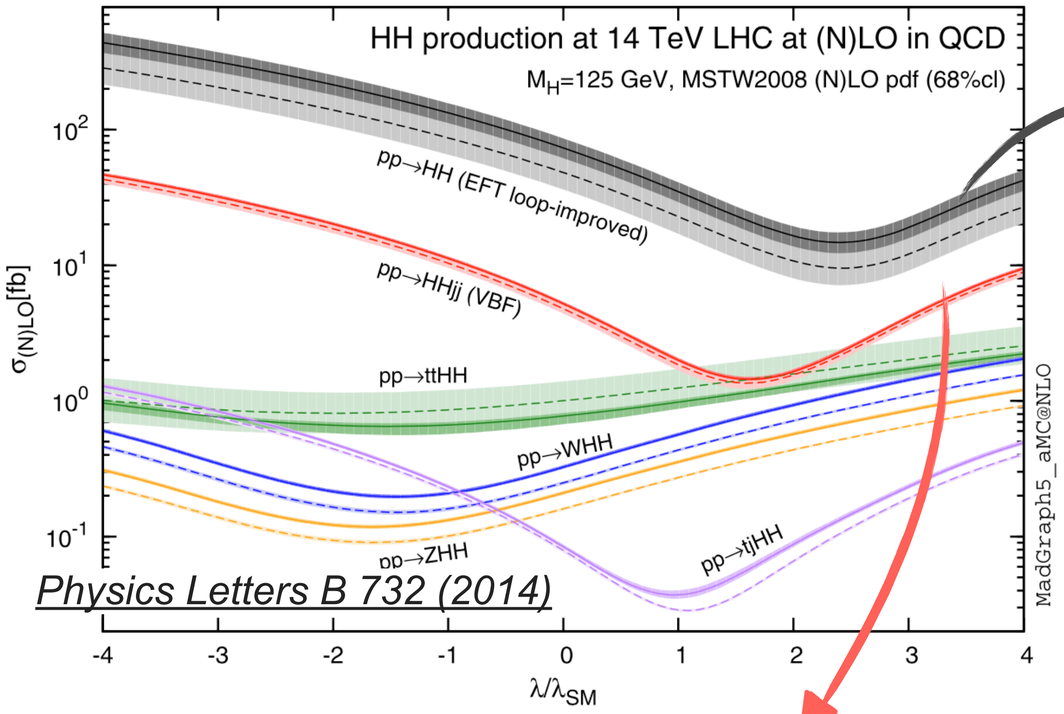
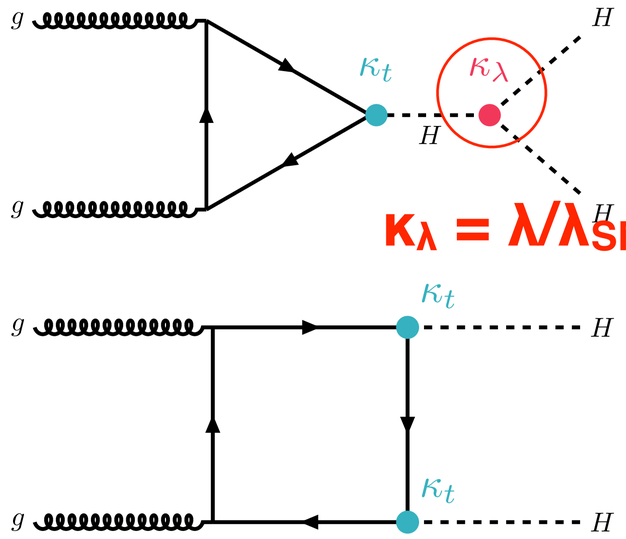
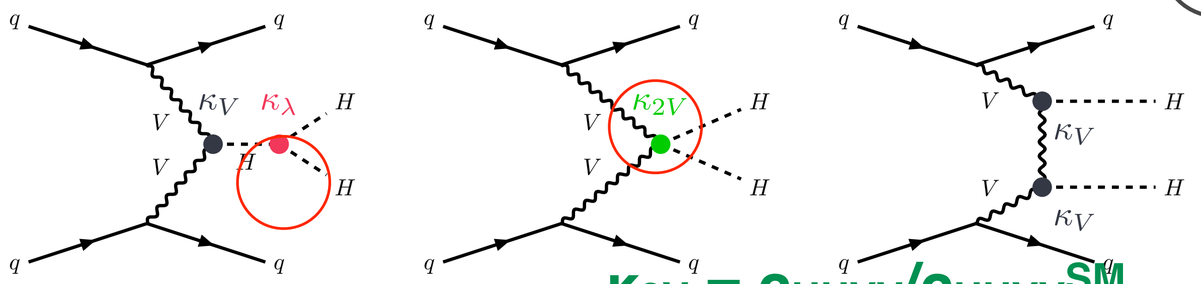
Higgs self-coupling



Gluon-gluon Fusion production (ggF)



$$\sigma^{\mathrm{SM}}_{\mathrm{ggF}}(HH) = 31.05^{+6\%}_{-23\%}\,(\mathrm{scale} + m_{\mathrm{top}}) \pm 3.0\,\%\,(\mathrm{PDF} + \alpha_s)\ \mathrm{fb}$$



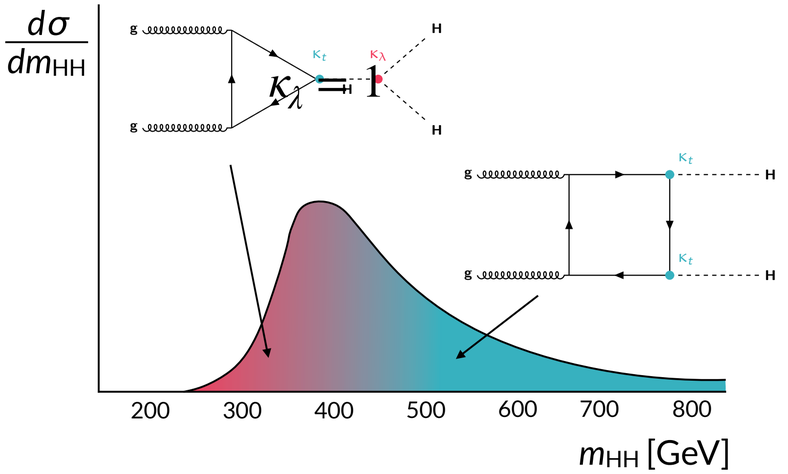
$\kappa_{2V} = c_{HHVV}/c_{HHVV}^{SM}$

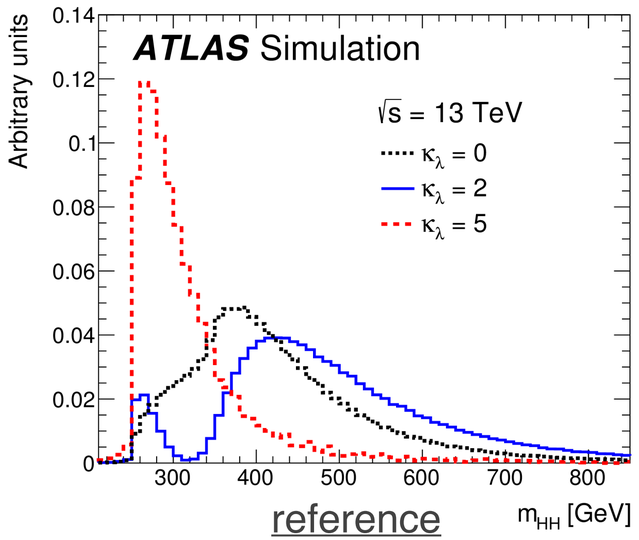
Vector Boson Fusion production (VBF)

$$\sigma^{\mathrm{SM}}_{\mathrm{VBF}}(HH) = 1.73^{+0.03\%}_{-0.04\%}\,(\mathrm{scale}) \pm 2.1\,\%\,(\mathrm{PDF} + \alpha_s)\ \mathrm{fb}$$

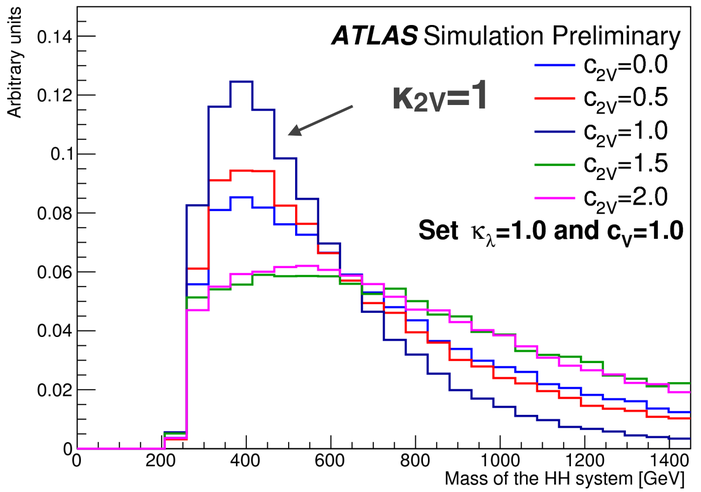
The challenges

- Destructive interference between the triangle and box amplitudes
  - m_{HH} shape strongly depends on κ
- $\kappa_\lambda \sim 2.4$ max. destruction at $m_{HH} \sim$ **350 GeV**
- **Soft** kinematics for large $|\kappa_\lambda|$
  - Decay production difficult to detect
  - **Hard** kinematics for large $|\kappa_{2V}|$





reference

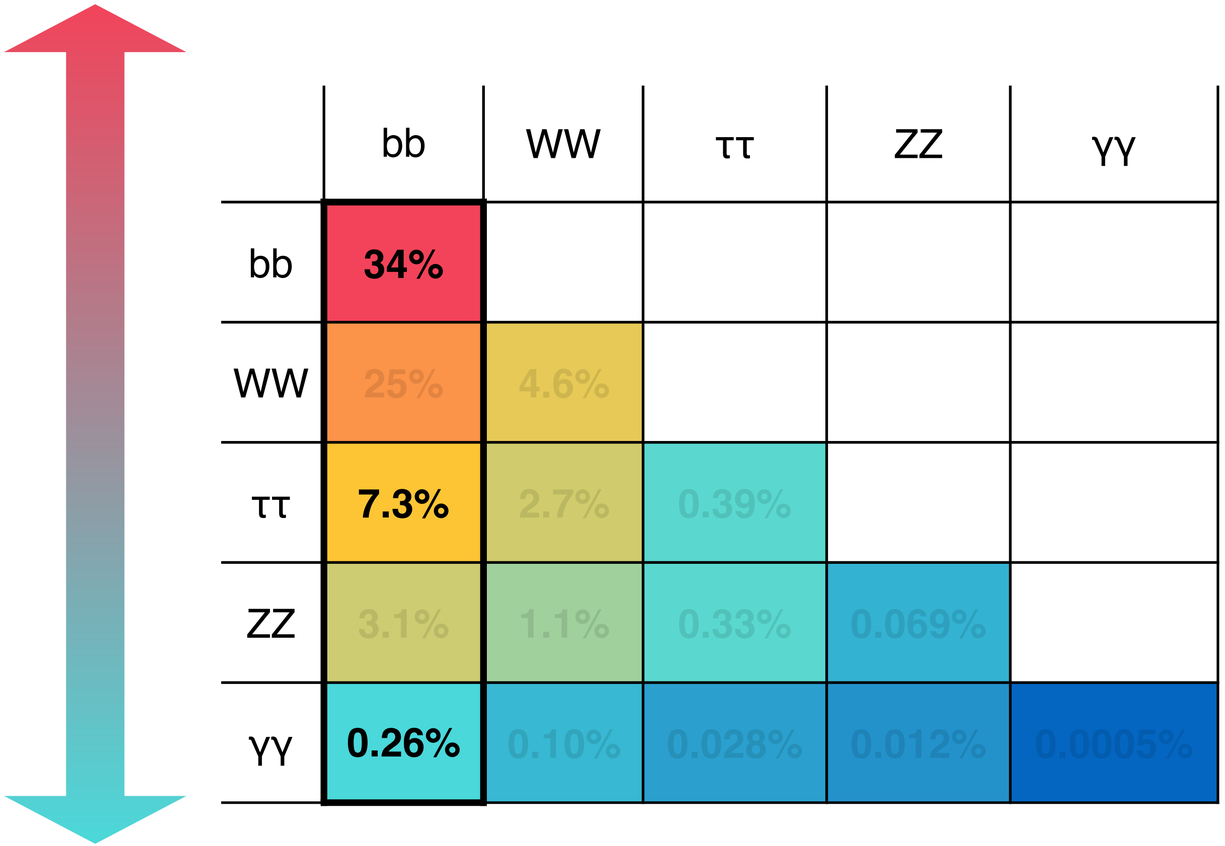


reference

Need excellent experimental performance and analysis techniques

HH decay channels

Large decay fraction



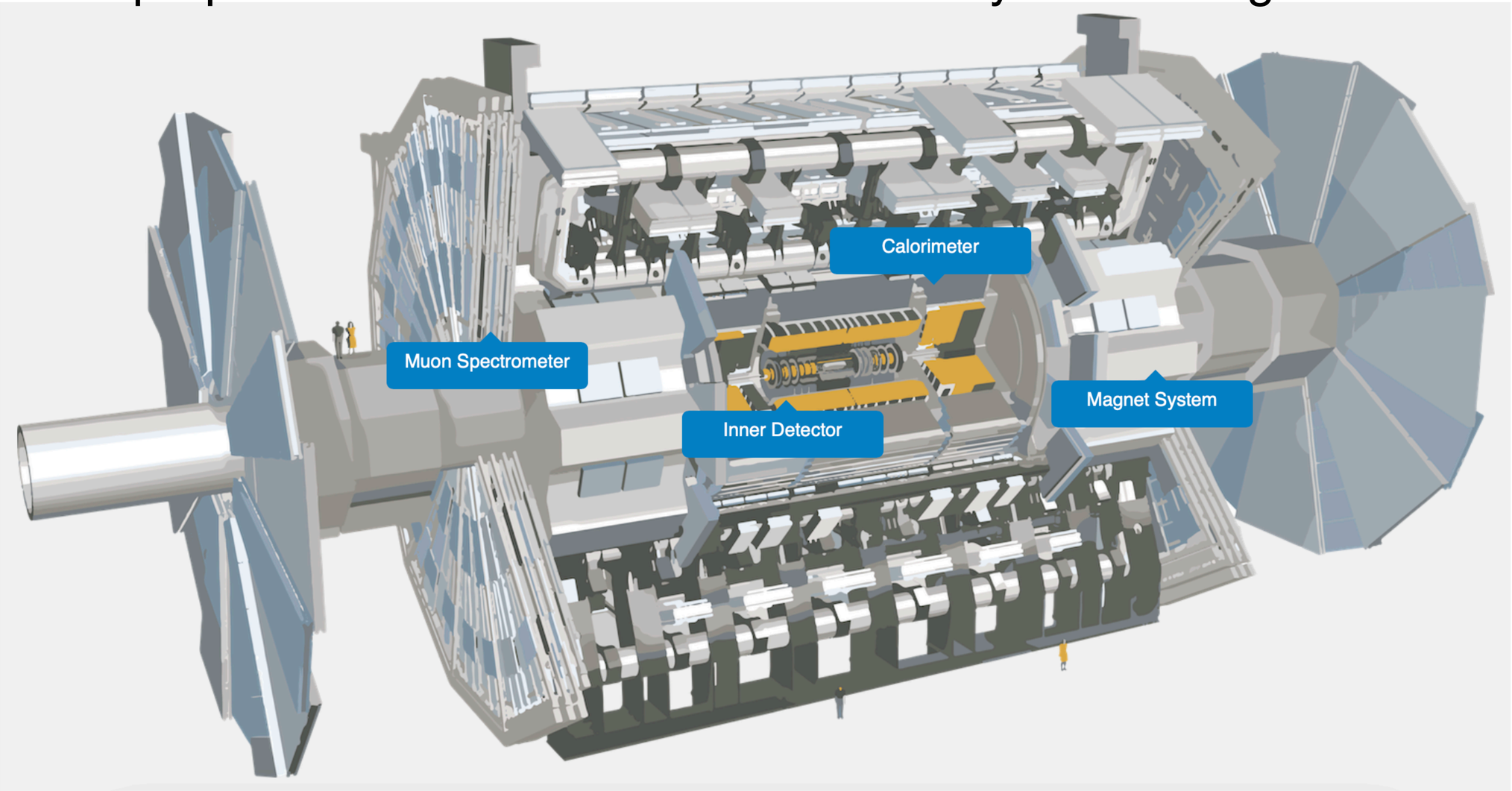
	bb	WW	ττ	ZZ	γγ
bb	**34%**				
WW	25%	4.6%			
ττ	**7.3%**	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	**0.26%**	0.10%	0.028%	0.012%	0.0005%

Clean final state

- bbbb (34%):
  - The most abundant final state
  - Challenging multi-jet backgrounds
- bbγγ (0.26%):
  - Low decay fraction
  - Excellent $m_{\gamma\gamma}$ resolution
- bbττ (7.3%):
  - Happy medium
- bb$\ell\ell$ + neutrinos (2.9%):
  - Targeting where one H ↛ bb
- Multilepton (6.5%):
  - Targeting where both H ↛ bb

ATLAS detector

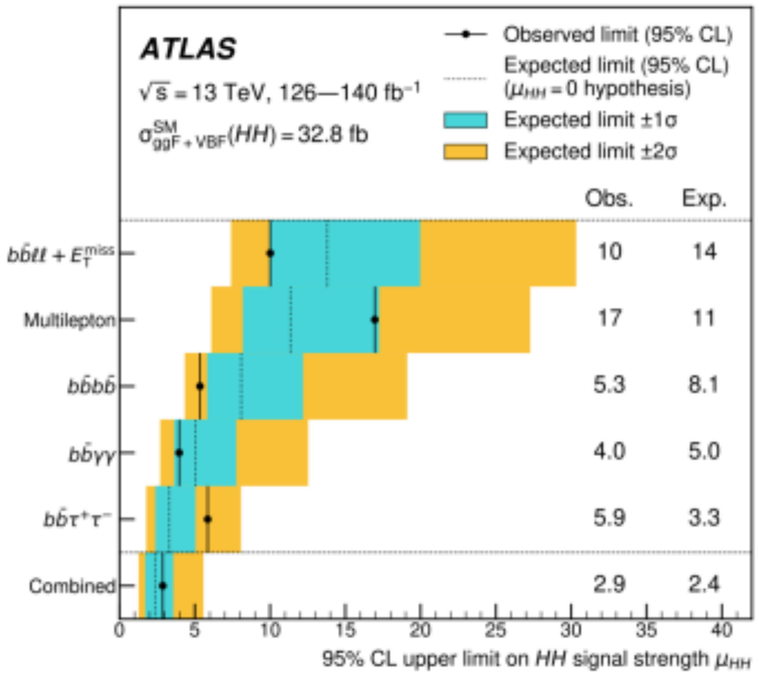
A general-purpose detector at the LHC with nearly 4π coverage in solid angle.

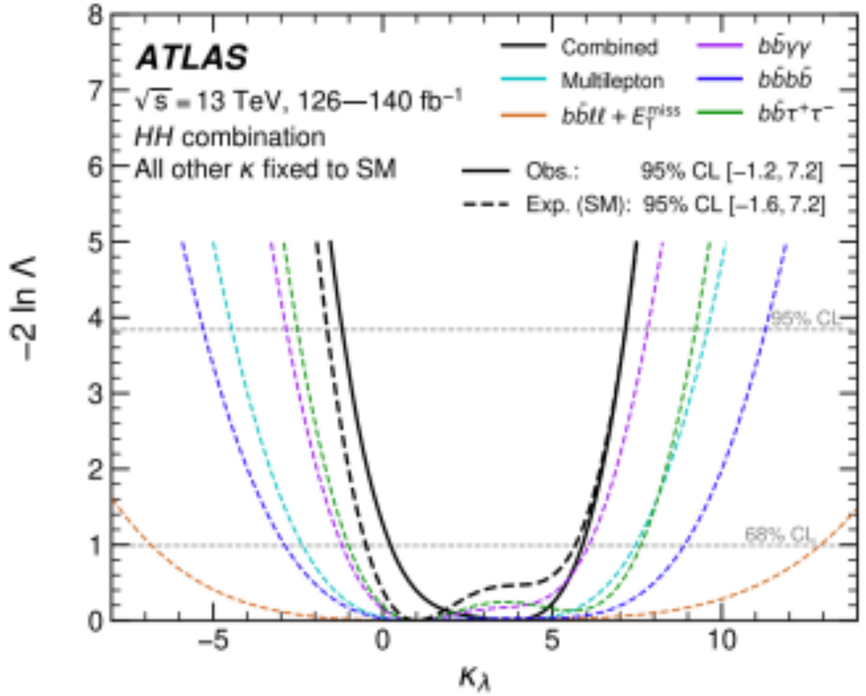


Combination of HH searches in ATLAS

- Combining searches together can maximise 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

Phys. Rev.Lett. 133 (2024) 101801



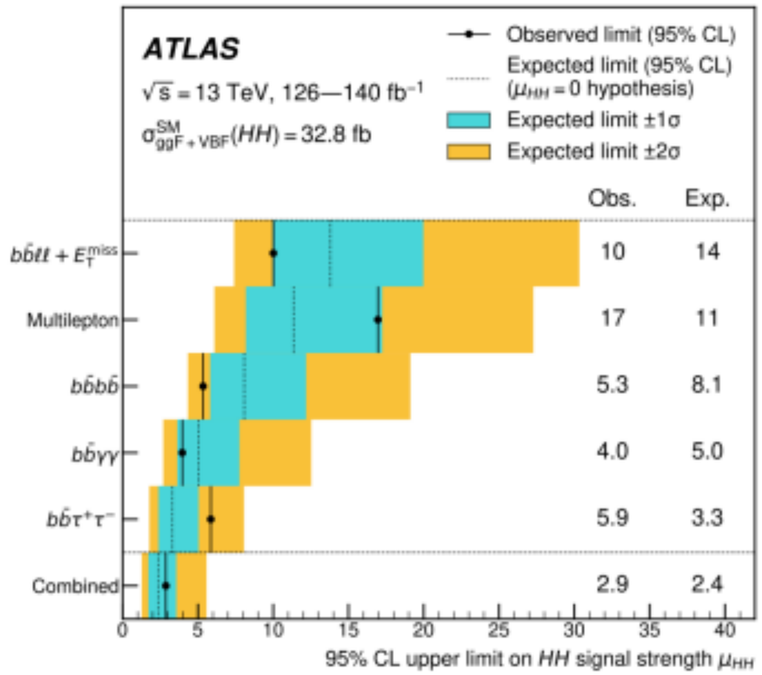


Combination of HH searches with CMS

- ATLAS and CMS has independent datasets
  - Combination benefit from larger statistics

2510.07527, submitted to Reports on Progress in Physics

Phys. Rev.Lett. 133 (2024) 101801



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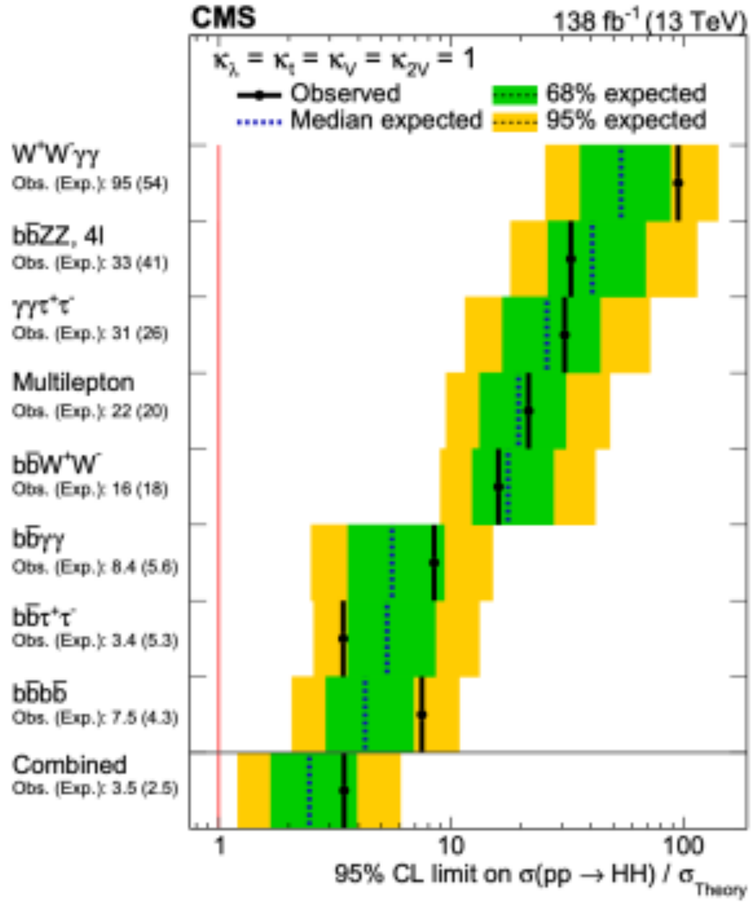
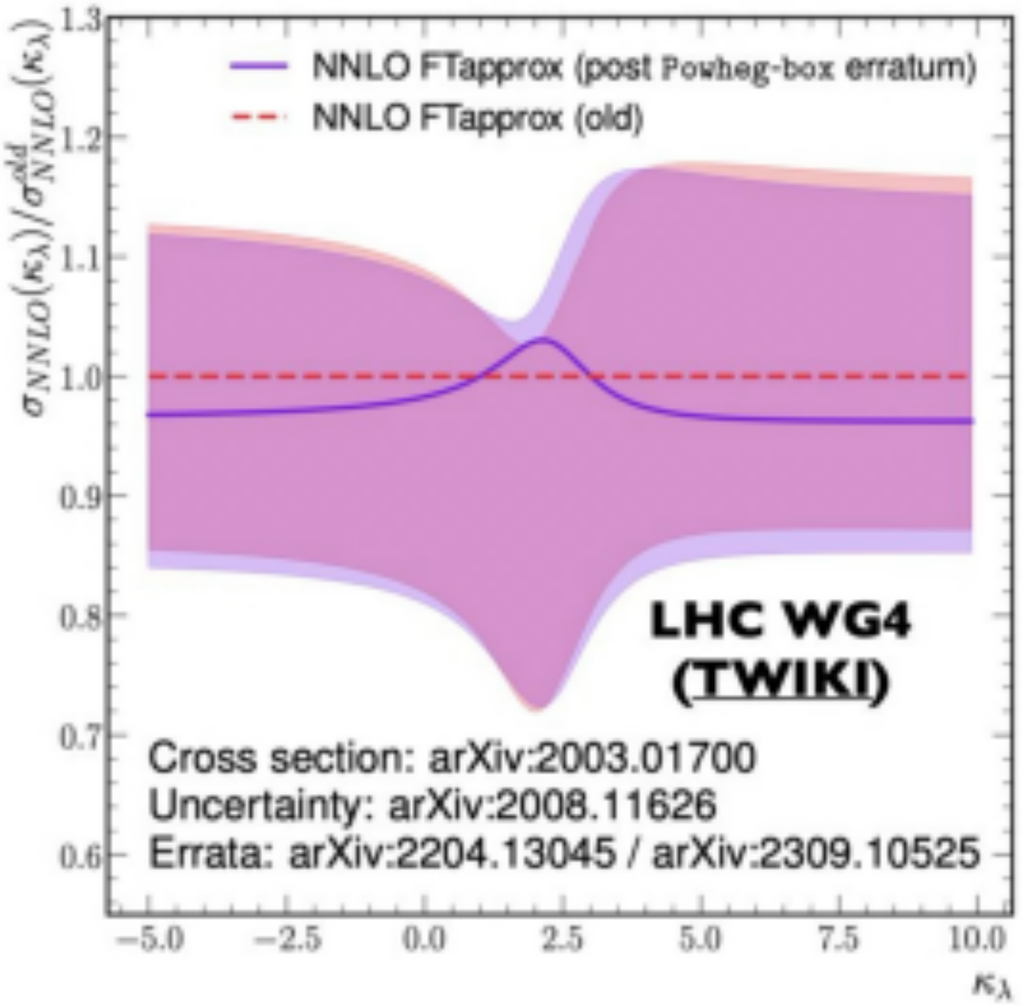


= ?

Harmonisation between ATLAS and CMS

Run 2 HH analyses are affected by a missing term in Powheg box when calculating two-loop amplitude. Affected cross section and shape for $\kappa_\lambda \neq 1$

κ_λ-dependent correction applied to cross section and uncertainty to $\kappa\lambda \neq 1$. No shape correction is applied.



Harmonisation between ATLAS and CMS

κ_λ impact on Higgs decay branching ratio and single-H production cross-section is included in CMS and ATLAS bbττ

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

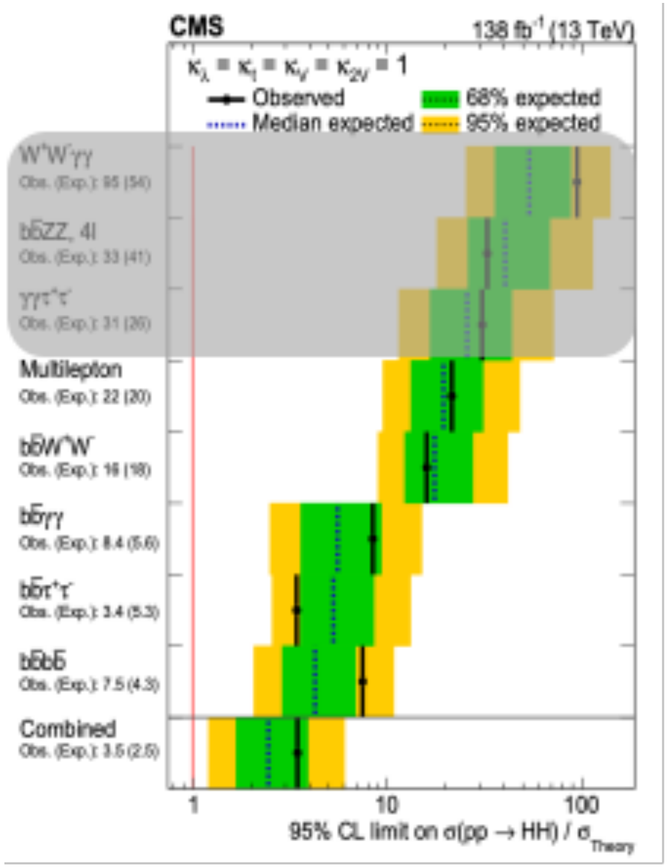
$$\mu_f(\kappa_\lambda, \kappa_f) = \frac{\mathrm{BR}_f^{\mathrm{BSM}}}{\mathrm{BR}_f^{\mathrm{SM}}} = \frac{\kappa_f^2 + (\kappa_\lambda - 1)C_1^f}{\sum_j \mathrm{BR}_j^{\mathrm{SM}}\left[\kappa_j^2 + (\kappa_\lambda - 1)C_1^j\right]}$$

Implemented in ATLAS bbbb, bbγγ

Two experiments developed different fitting tools with dedicated RooFit classes, and many features are incompatible with each other.
We improved ATLAS tools to reliably process CMS fit. It will benefit future ATLAS+CMS combination.

Correlation

- Correlate HH and H theory cross-section and Br systematics
- Experimental systematic remain uncorrelated
- Only five channels from CMS are included
  - The missing channels have impact of < 1%
- Using ATLAS fitting tools get excellent agreement of CMS results



Results: HH

- Fit results

$$\hat{\mu}_{\mathrm{HH}}^{\mathrm{exp}} = 1.0^{+0.9}_{-0.8} = 1.0^{+0.7}_{-0.6}(\mathrm{stat})^{+0.5}_{-0.3}(\mathrm{theory})^{+0.3}_{-0.3}(\mathrm{exp.})$$

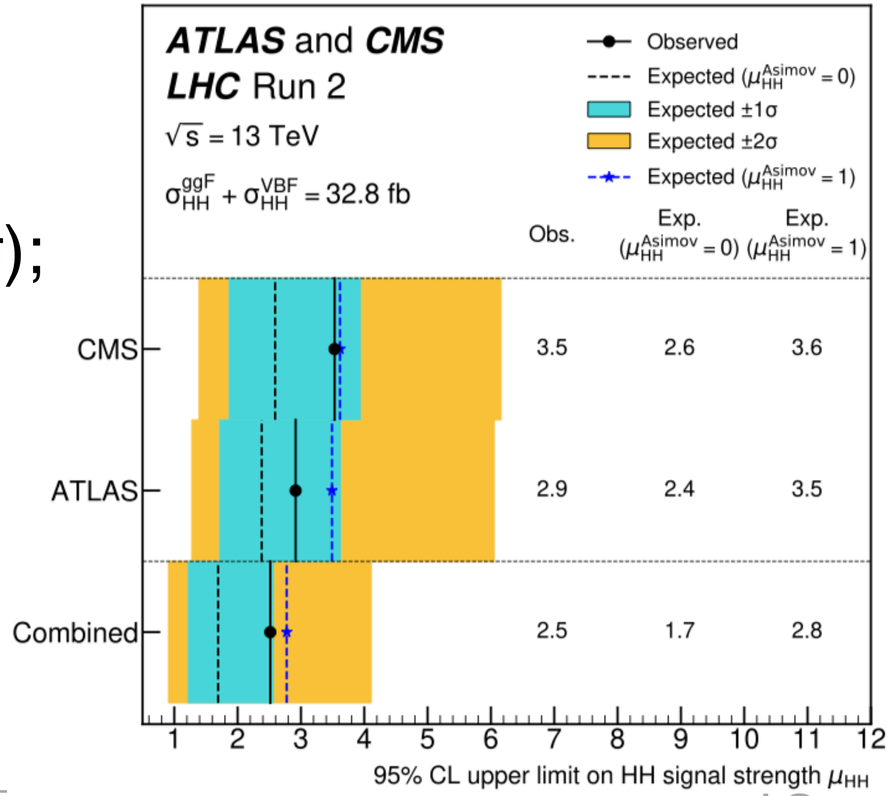
$$\hat{\mu}_{\mathrm{HH}} = 0.8^{+0.9}_{-0.9} = 0.8^{+0.7}_{-0.6}(\mathrm{stat})^{+0.4}_{-0.2}(\mathrm{theory})^{+0.3}_{-0.3}(\mathrm{exp.})$$

The observed (expected) local significance: 1.1σ (1.3σ);

Expected 95% CL upper limit reach 1.7;

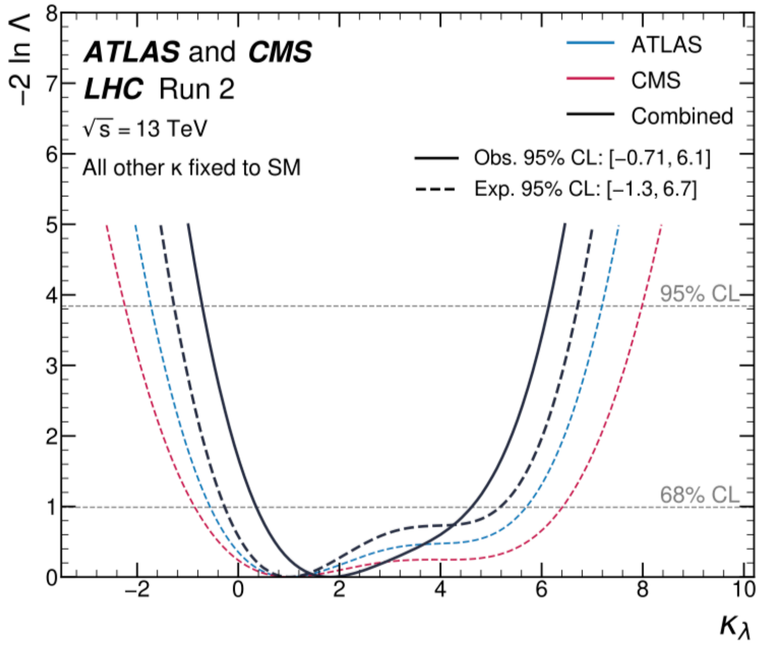
~30% improvement w.r.t. single experiment;

Limit assuming SM HH production (2.8) is close to observed limit (2.5).

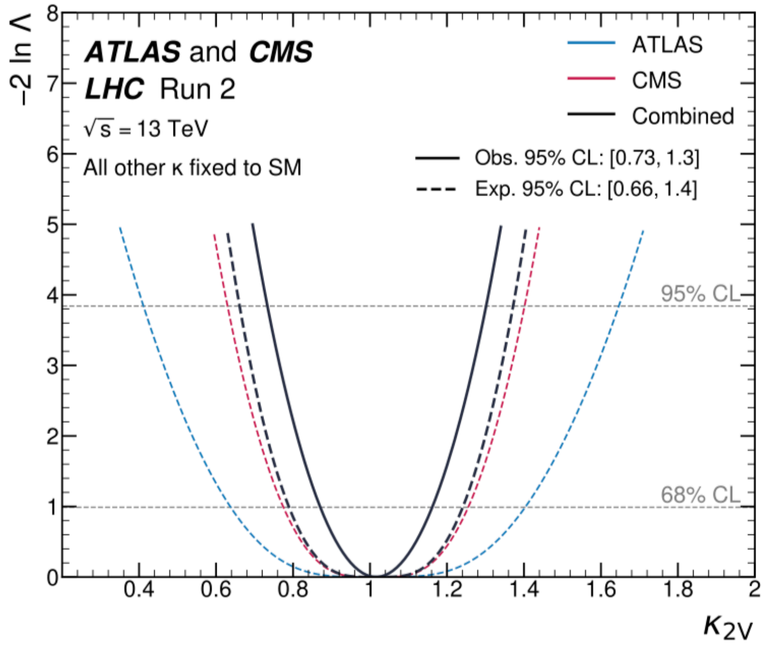


Results: kappa

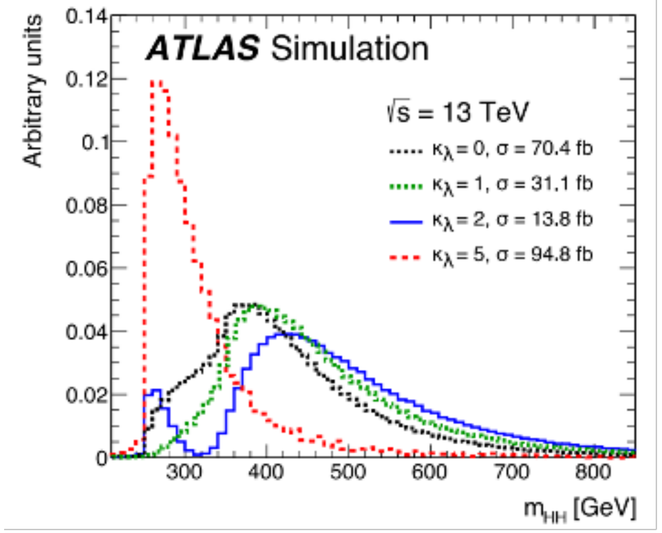
κ_λ is driven by bbγγ and bbττ

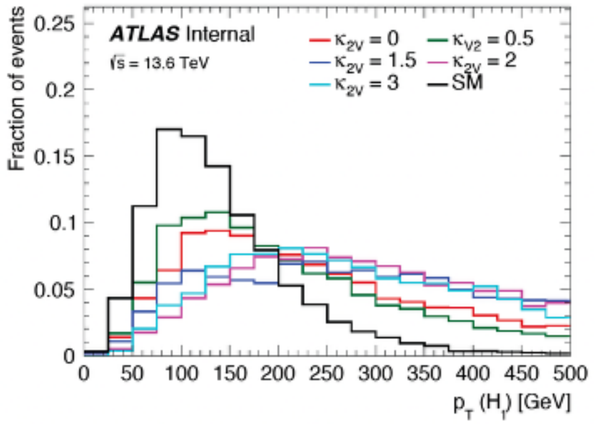


κ_{2V} is driven by bbbb



Recall kinematic dependence on coupling

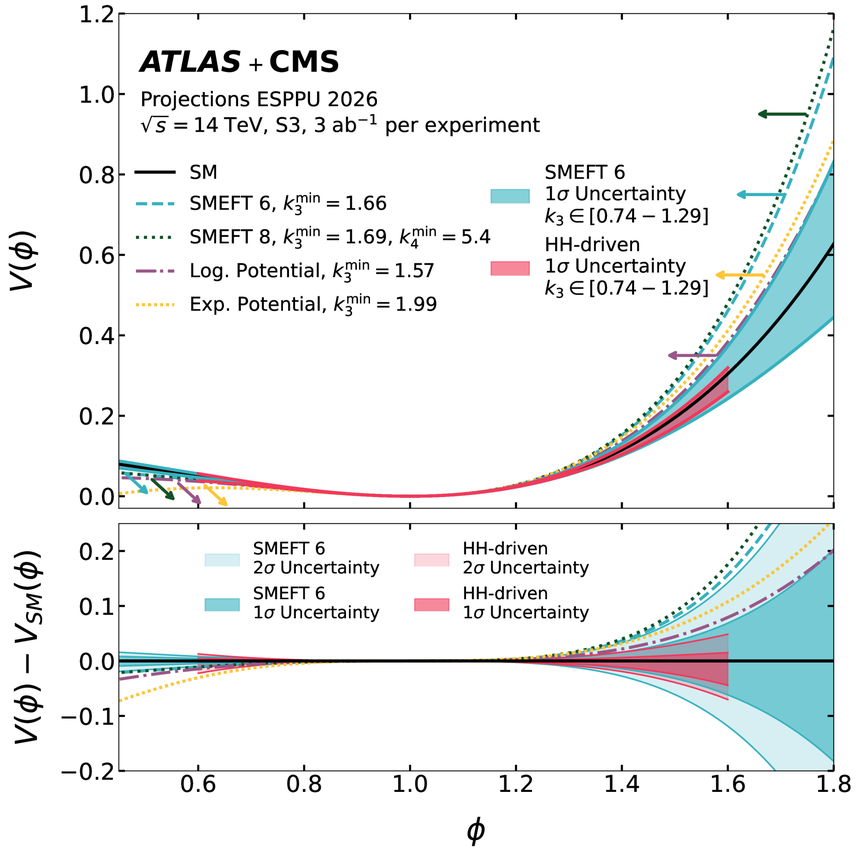


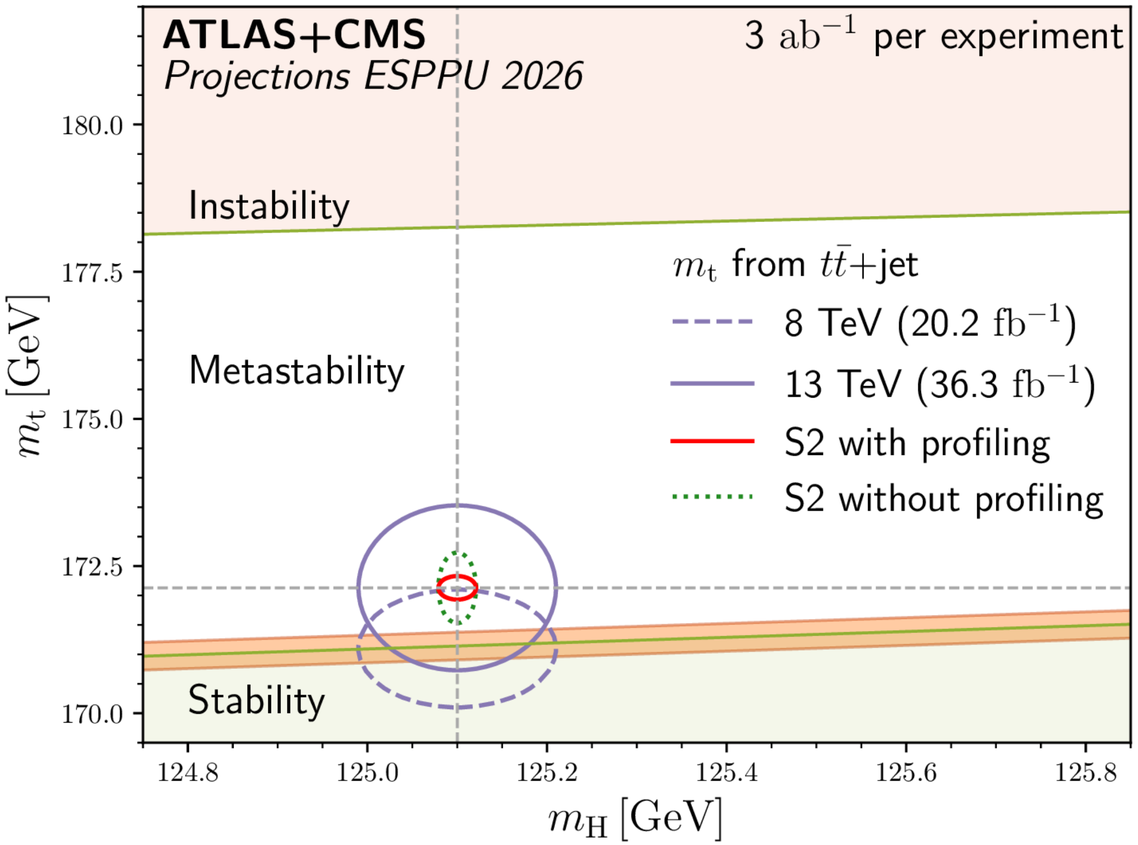


Improve the constraints by 10% on κ_λ and 8% on κ_{2V} w.r.t. the best constraints to date

HL-LHC Projection: ATLAS+CMS

ATL-PHYS-PUB-2025-018

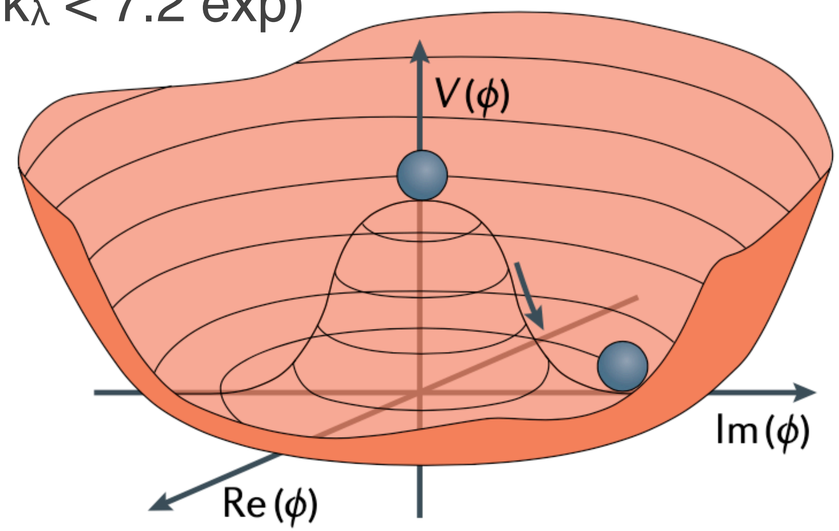




S2: reduced experimental uncertainties, halved theoretical uncertainties, and neglected Monte Carlo statistical uncertainties
Profiling: whether uncertainties are allowed to be constrained or not

Summary

- HH is a unique process to probe the Higgs potential
- HH events are rare (33 fb ➔ ~ 4600 SM events in Run 2 dataset)
  - Call for highly efficient analyses
- ATLAS conducted searches in final states covering 50% of decays
  - Reached best expected sensitivity to date on HH cross section, $\mu_{HH} < 2.9$ (2.4 exp)
  - ... and on the Higgs self-coupling, $-1.2 < \kappa_\lambda < 7.2$ ($-1.6 < \kappa_\lambda < 7.2$ exp)
- Promising prospect for Run 3 and HL-LHC



More details about ATLAS+CMS HH combination in 2602.23991, accepted by PRL