



# DiHiggs searches (HH, HY) at ATLAS and CMS

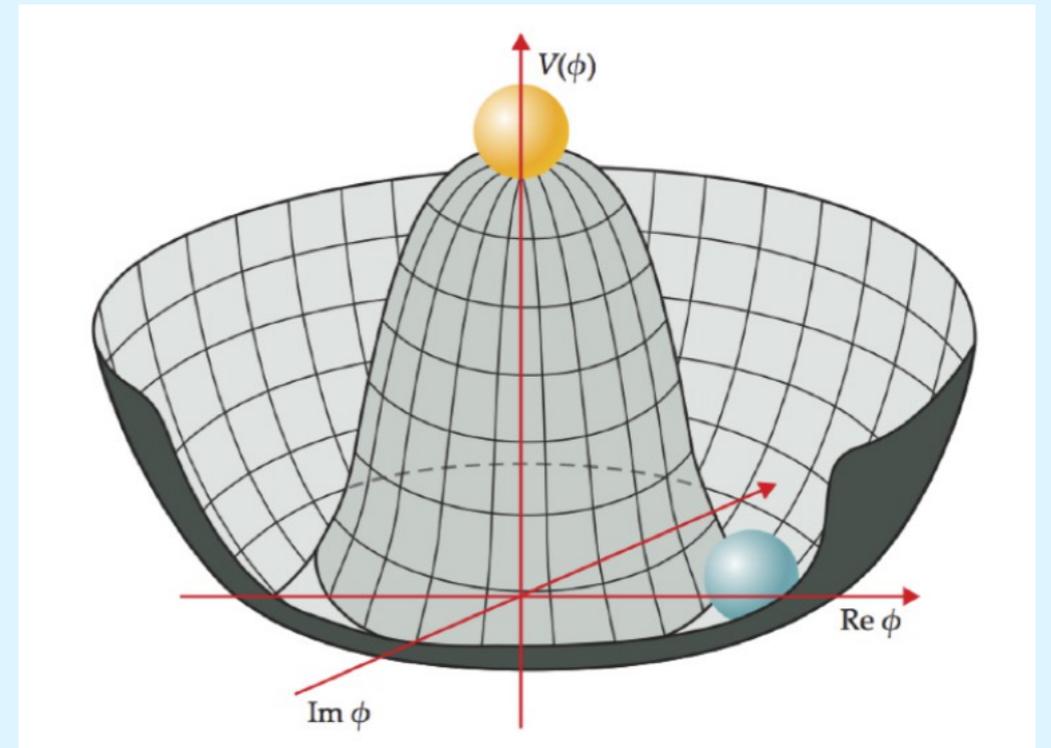
Moriond EW 29/03/2025

Angela Taliencio on behalf of the CMS and ATLAS collaborations

# Introduction: HH production in the SM

In Standard Model destructive interference of triangle and box contributions → tiny cross section → Experimentally very challenging

$$V(\phi^\dagger\phi) = \mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$



The direct measure of  $\lambda$  is a strong test of the Electroweak Symmetry Breaking (EWSB) mechanism

**Deep fundamental questions**

- ❖ What is the order of the EW phase transition?
- ❖ What is the fate of the Universe? Is it stable?

# Introduction: HH production in the SM

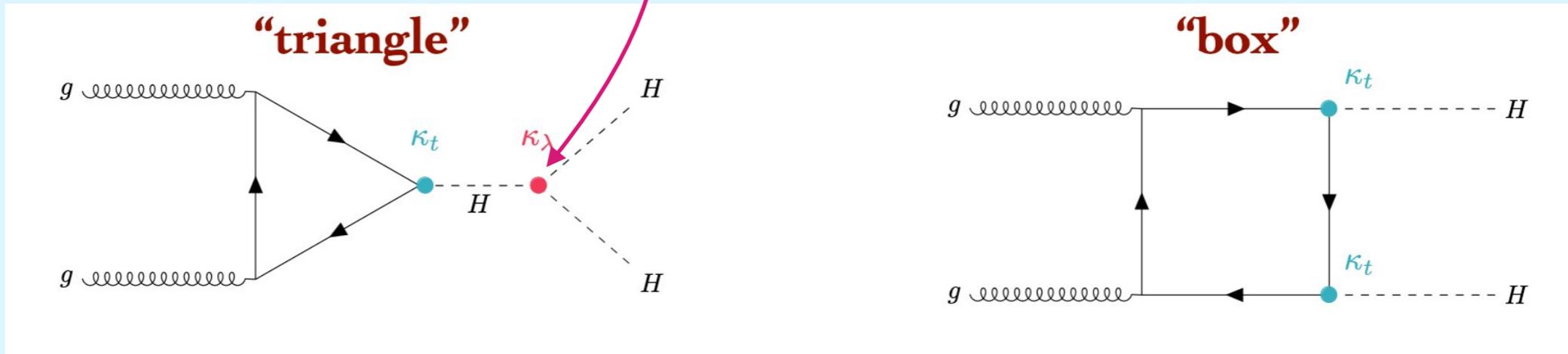
The direct measure of  $\lambda$  is a strong test of the SM prediction ( $\lambda \sim 0.13$  from theoretical SM prediction)

$$V(\phi^\dagger\phi) = \mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$

- HH gluon-gluon fusion production (around 4000 events produced in the full RunII)

$$\sigma_{ggF}^{HH} = 31.05^{+2\%}_{-7\%} \text{ fb (scale } \oplus \text{ PDF } \oplus \alpha_S \oplus m_t)$$

\*remark:  
 $\kappa_X$  is a coupling modifier:  $\kappa_X = c_X/c_{SM}$  Where  $c$  is the coupling



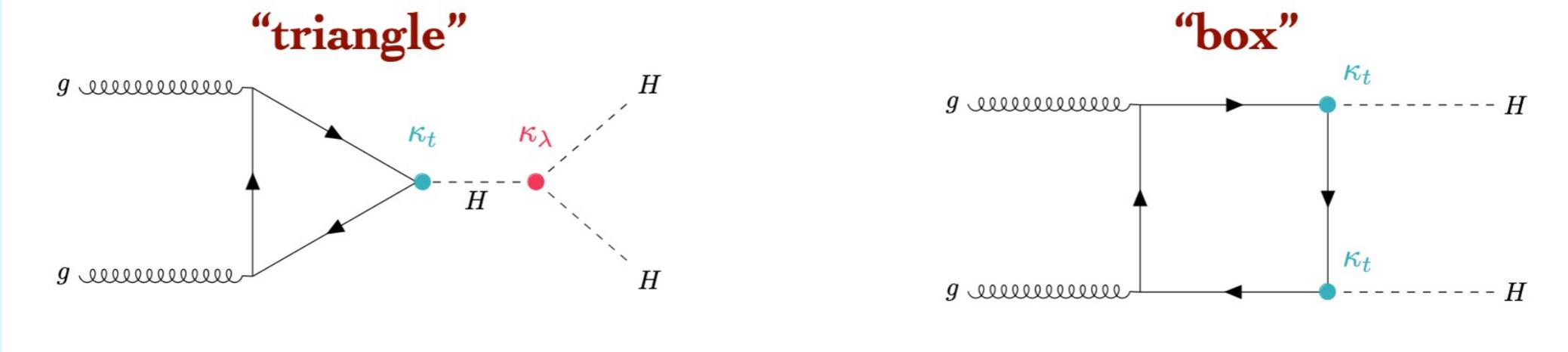
Gives a direct handle on the  $\kappa_\lambda$  parameter +  $\kappa_t$  dependence in the box diagram

# Introduction: HH production in the SM

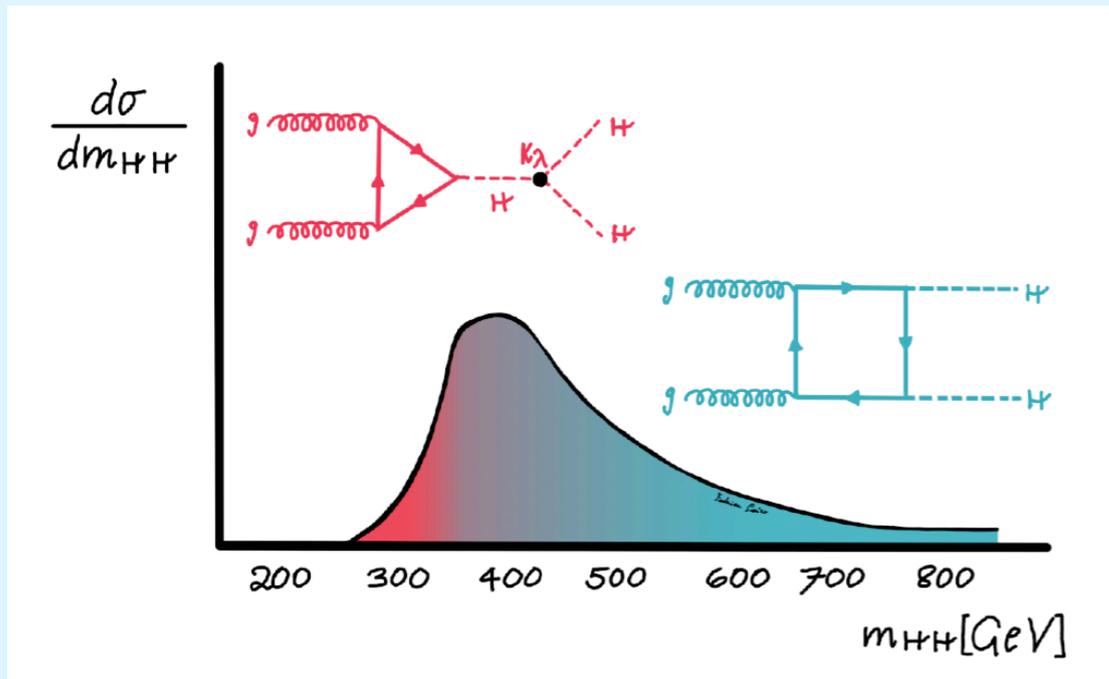
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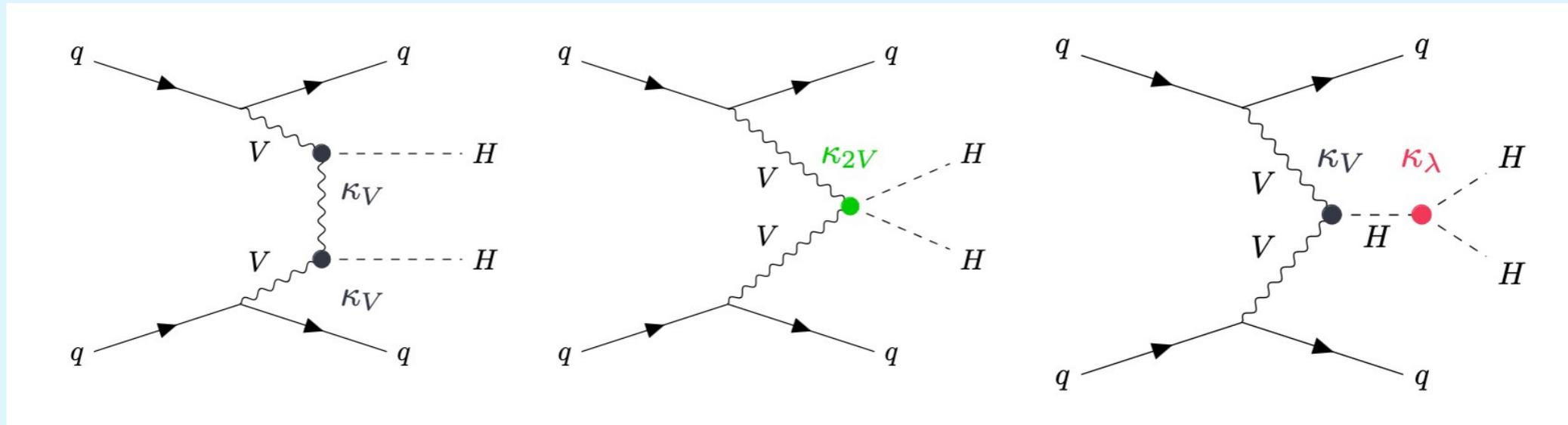


- Di Higgs kinematic strongly dependent on  $\kappa_\lambda$
- Different  $m_{HH}$  ranges can be explored to be sensitive at different physics scenarios

# Introduction: HH production in the SM

- HH VBF fusion production (around 300 events produced in the full RunII)

$$\sigma_{VBF}^{HH} = 1.73 \pm 0.04 \text{ fb (scale } \oplus \text{ PDF } \oplus \alpha_S \oplus m_t)$$



VBF production mode is less dominant but gives a direct handle on the  $\kappa_V$  and  $\kappa_{2V}$  couplings

# EFT Frameworks used in HH

- The **kappa-framework**: Modifies the couplings predicted by the SM

$$\kappa_\lambda = \frac{\lambda}{\lambda_{SM}}$$

- Higgs EFT (HEFT)**: **Natural extension** of the **kappa-framework** with additional BSM couplings
- Standard Model EFT (SMEFT)**: Similar to HEFT but the **Higgs is a SM doublet** adding correlations between H and HH

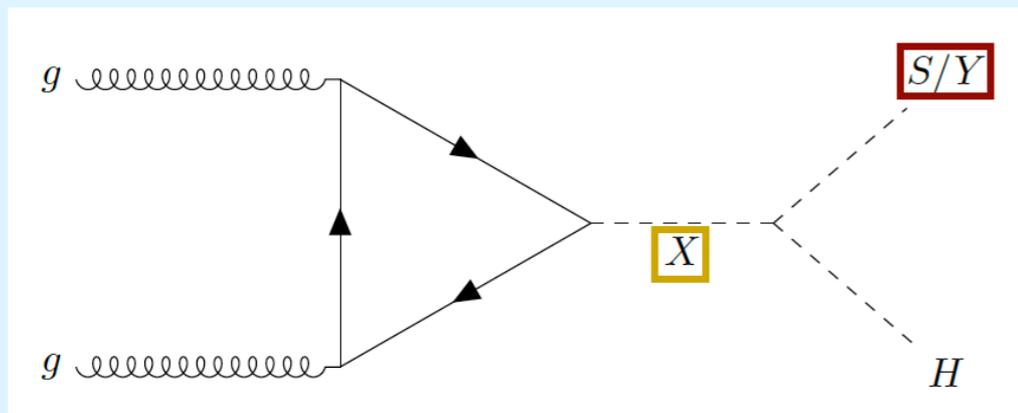
	ATLAS		CMS	
HH production	ggF	VBF	ggF	VBF
kappa-framework	✓	✓	✓	✓
HEFT	✓		✓	
SMEFT	✓	✗	✗	✗

# Resonant di-Higgs introduction

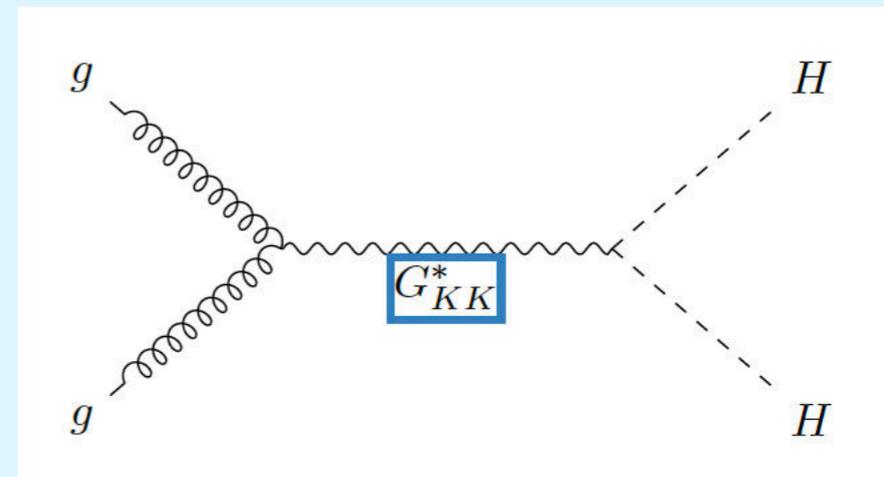
BSM scenarios where the Higgs boson couple to particles beyond the standard model makes are natural probe  $\rightarrow$  HH final state allows also to explore new topologies:

Spin-0: for example predicted by **extended H sector** completed by an **Electroweak Singlet**:

- ATLAS and CMS have different convention to denote the extra scalar (S vs Y)



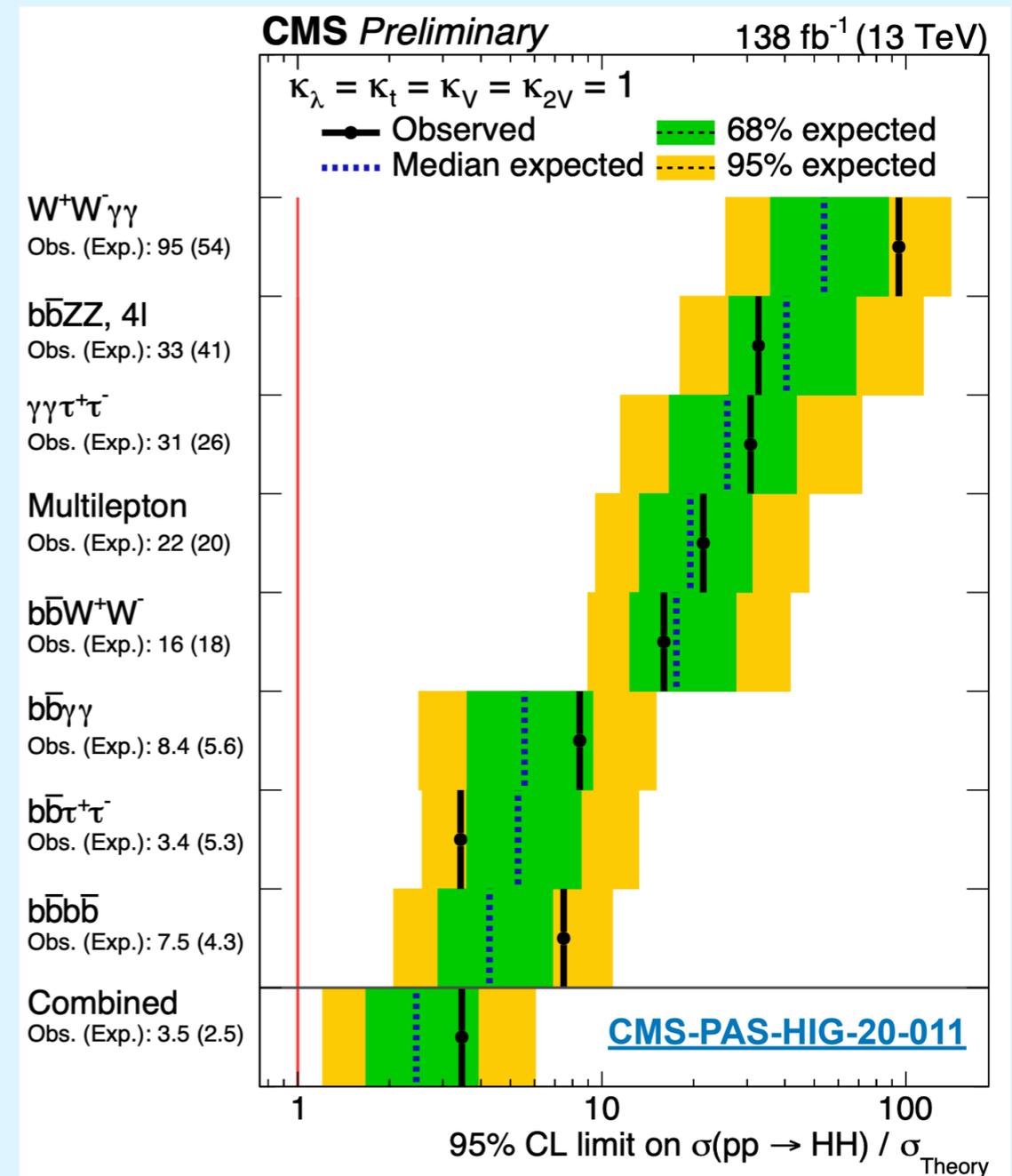
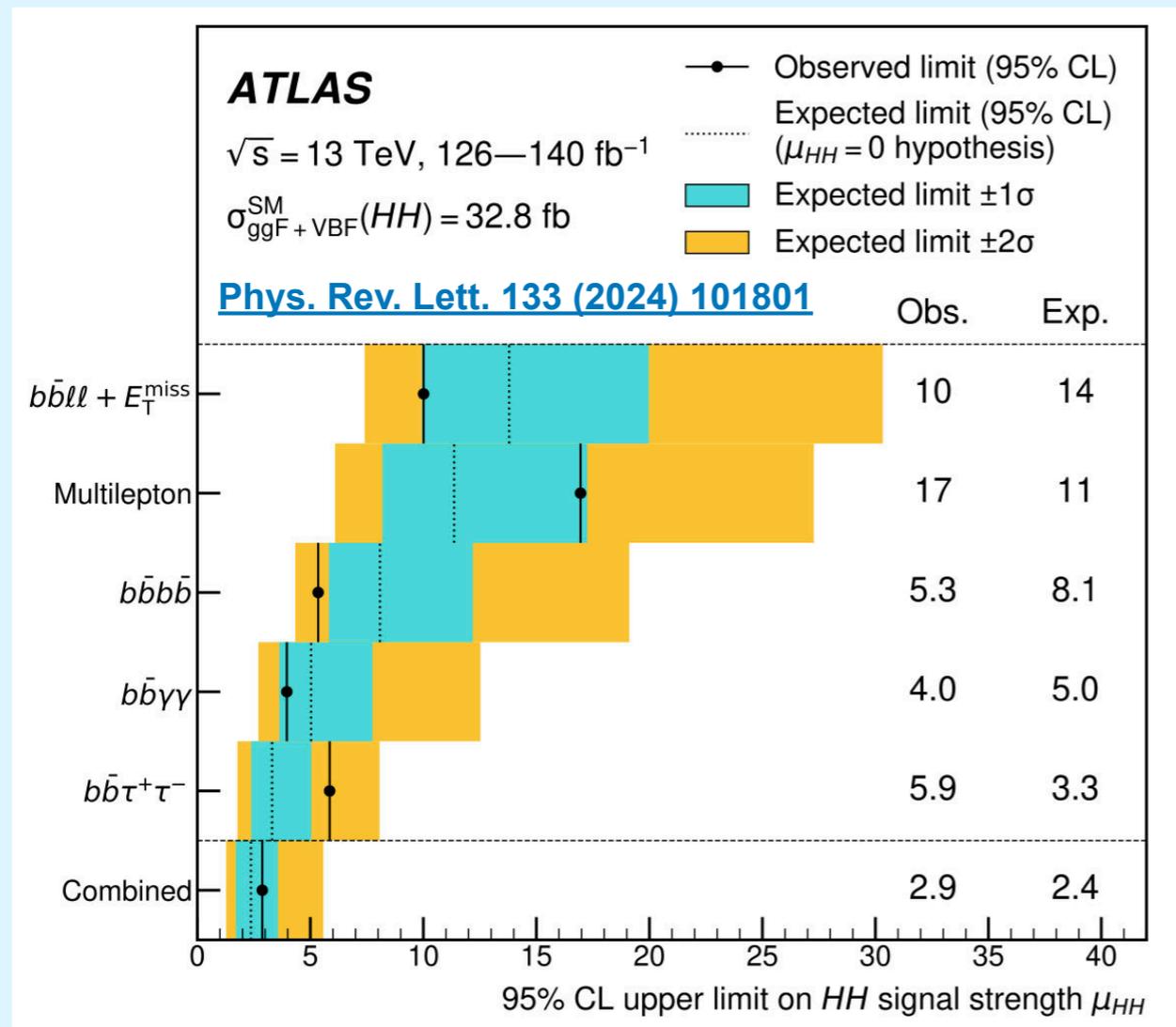
Spin-2: for example predicted by a **Kaluza-Klein graviton** in the context of the bulk Randall Sundrum (RS) model of warped extra dimensions



# HH production cross-section

Limit on the HH cross-section relative to its SM prediction (signal strength  $\mu$ ) is shown in those plots:

- 'Golden channels' are  $4b$ ,  $b\bar{b}\gamma\gamma$ ,  $b\bar{b}\tau\tau$
- ATLAS combination leads to  $2.9 \times SM$  (exp  $2.4 \times SM$ ), CMS combination leads to  $3.5 \times SM$  (exp  $2.5 \times SM$ )

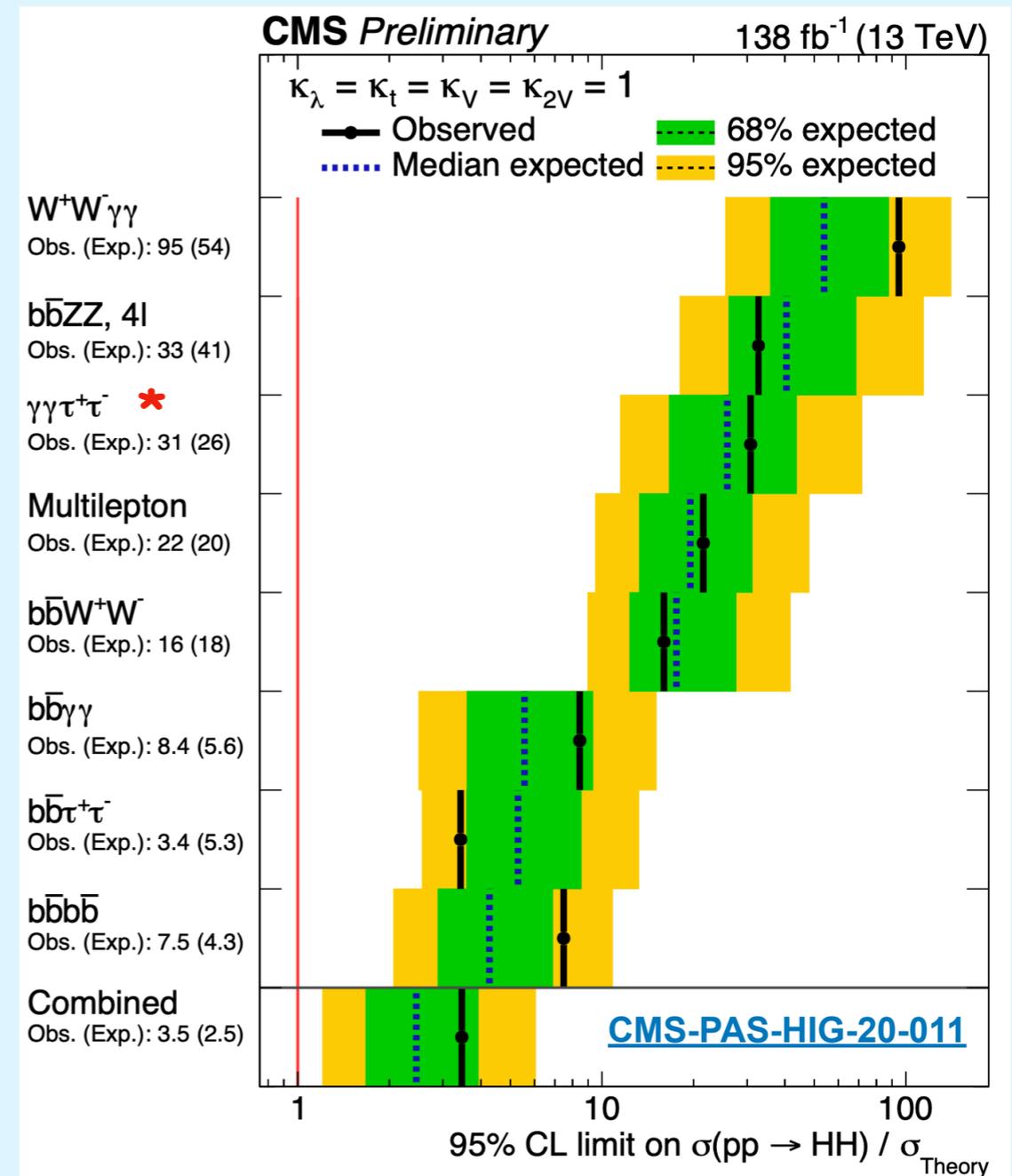
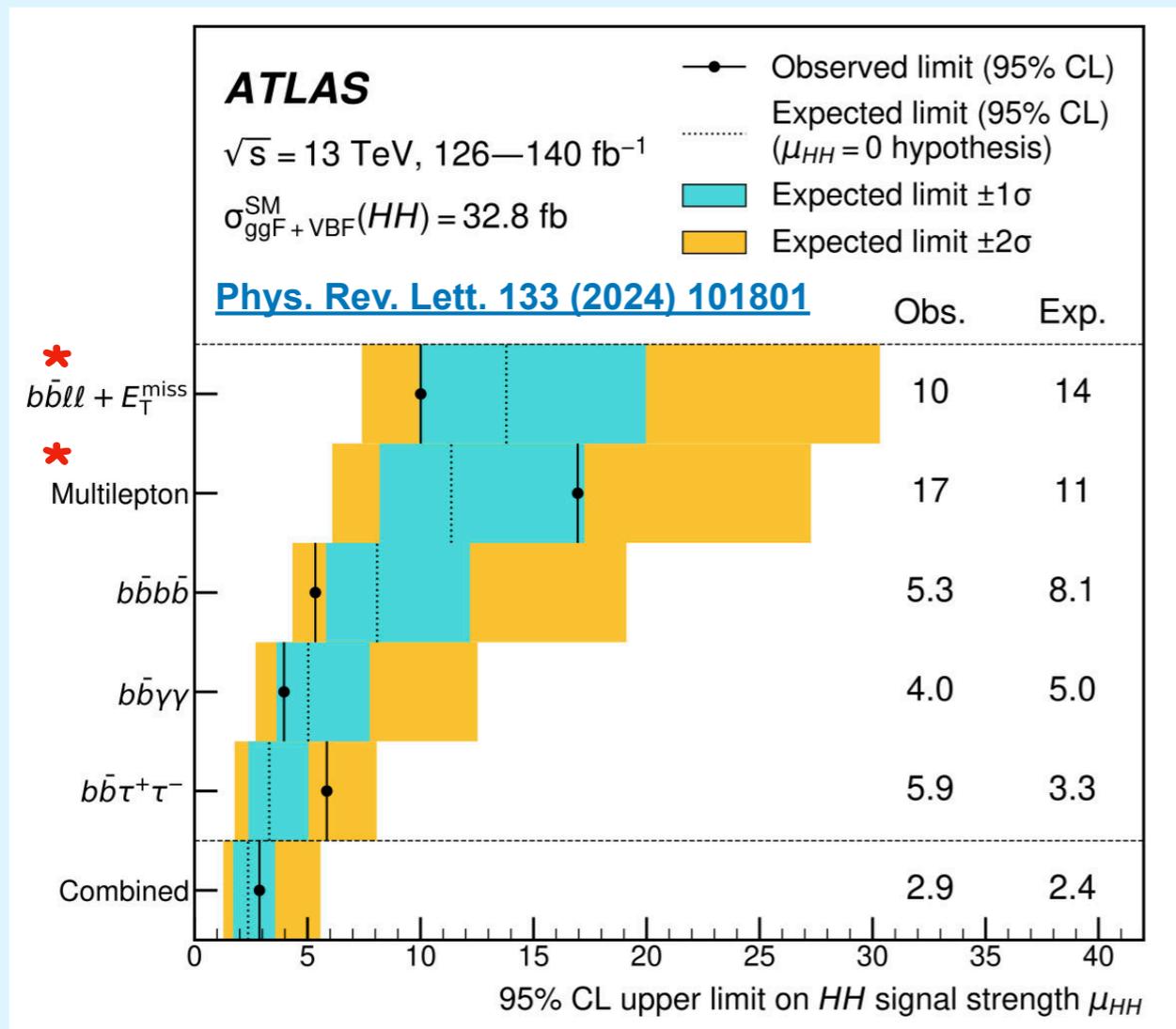


- Also limits on the VBF production mode available, both experimet are sensitive to  $\sim 90 \times SM$

# HH production cross-section

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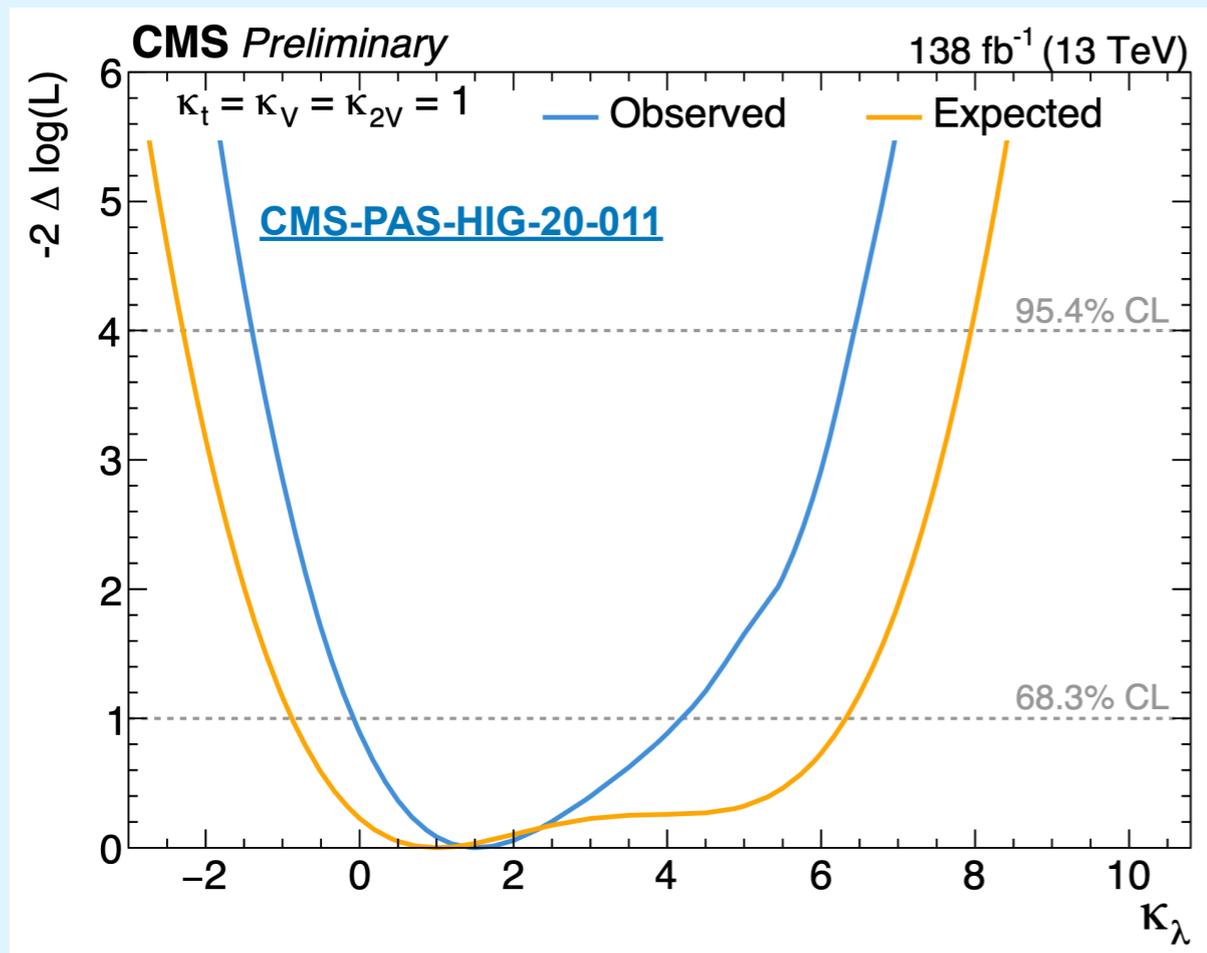
**\*new with respect to Nature combination**



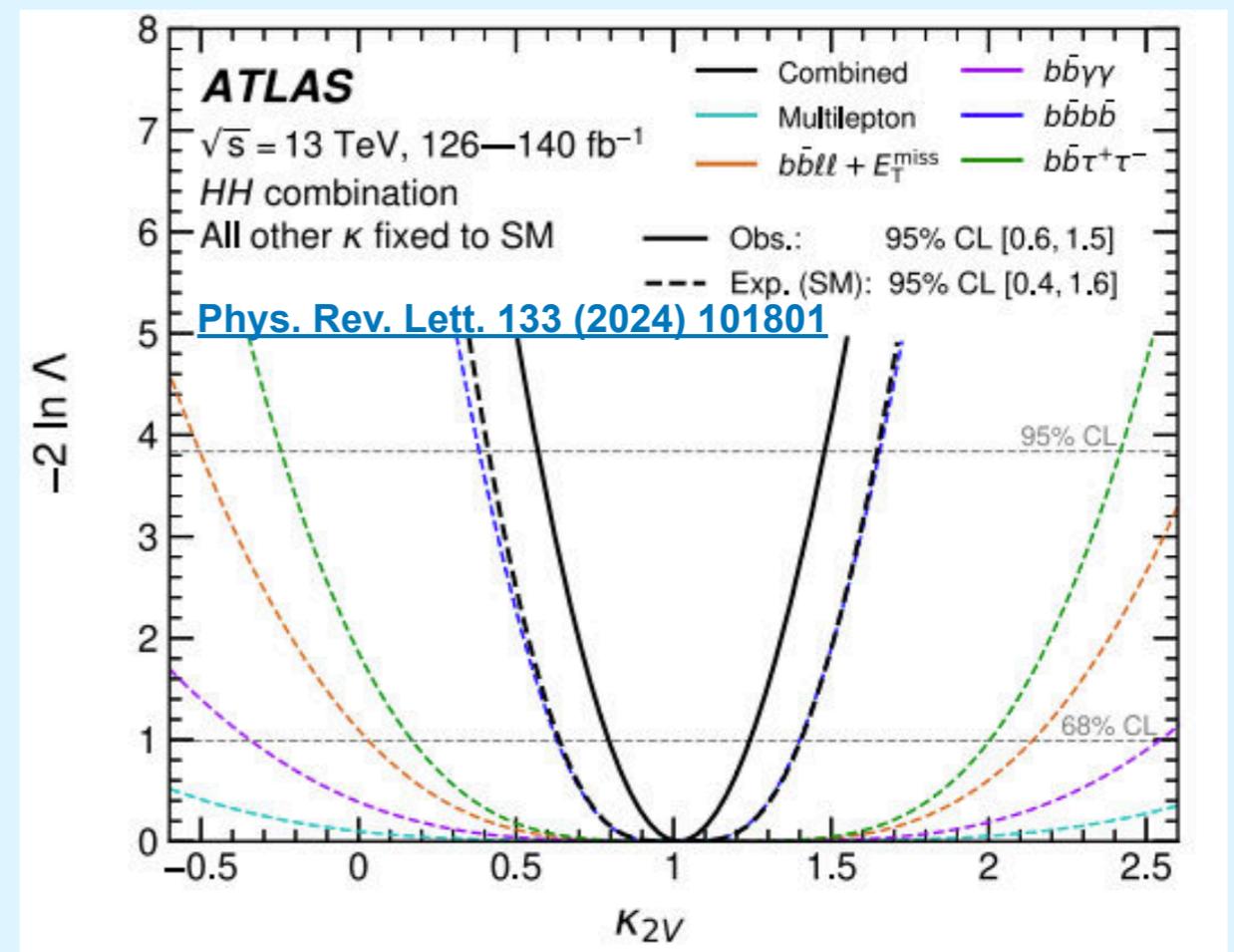
# Higgs self-coupling and quartic HHVV coupling

Both collaborations provided results for  $k_\lambda$ ,  $k_t$  and  $k_{2V}$  relative results

- $k_\lambda$  scan dominated by  $b\bar{b}\gamma\gamma$  and  $b\bar{b}\tau\tau$
- $k_{2V}$  scan dominated by 4b boosted signature

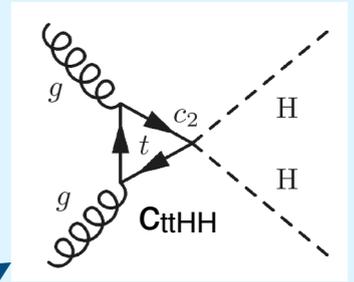


Constrain on the  $k_\lambda$   $[-1.4, 6.4]$  obs - CMS  
 Constrain on the  $k_\lambda$   $[-1.2, 7.2]$  obs - ATLAS



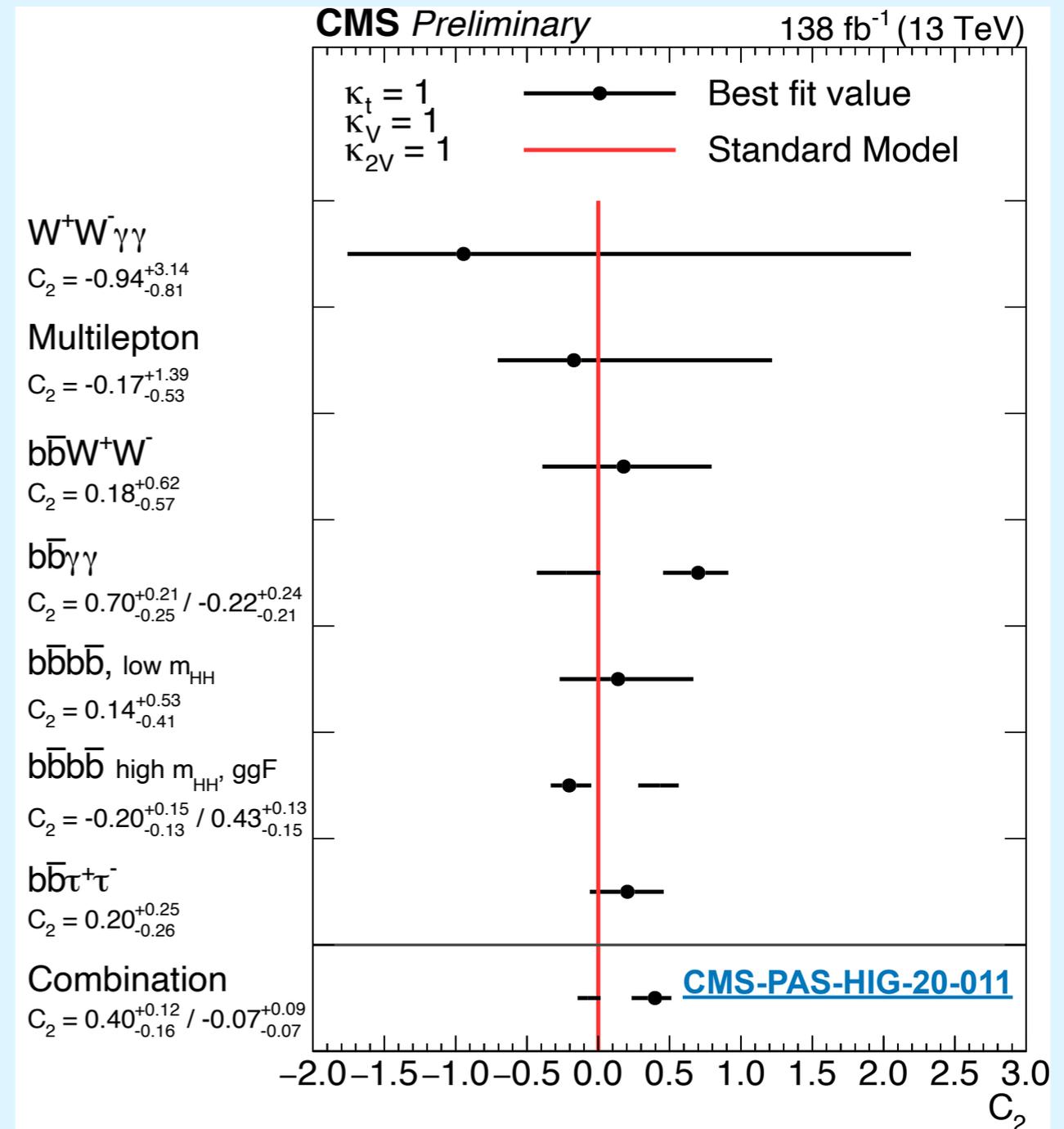
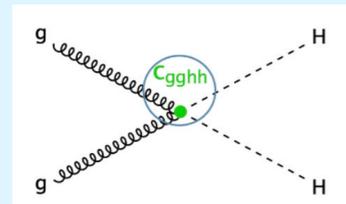
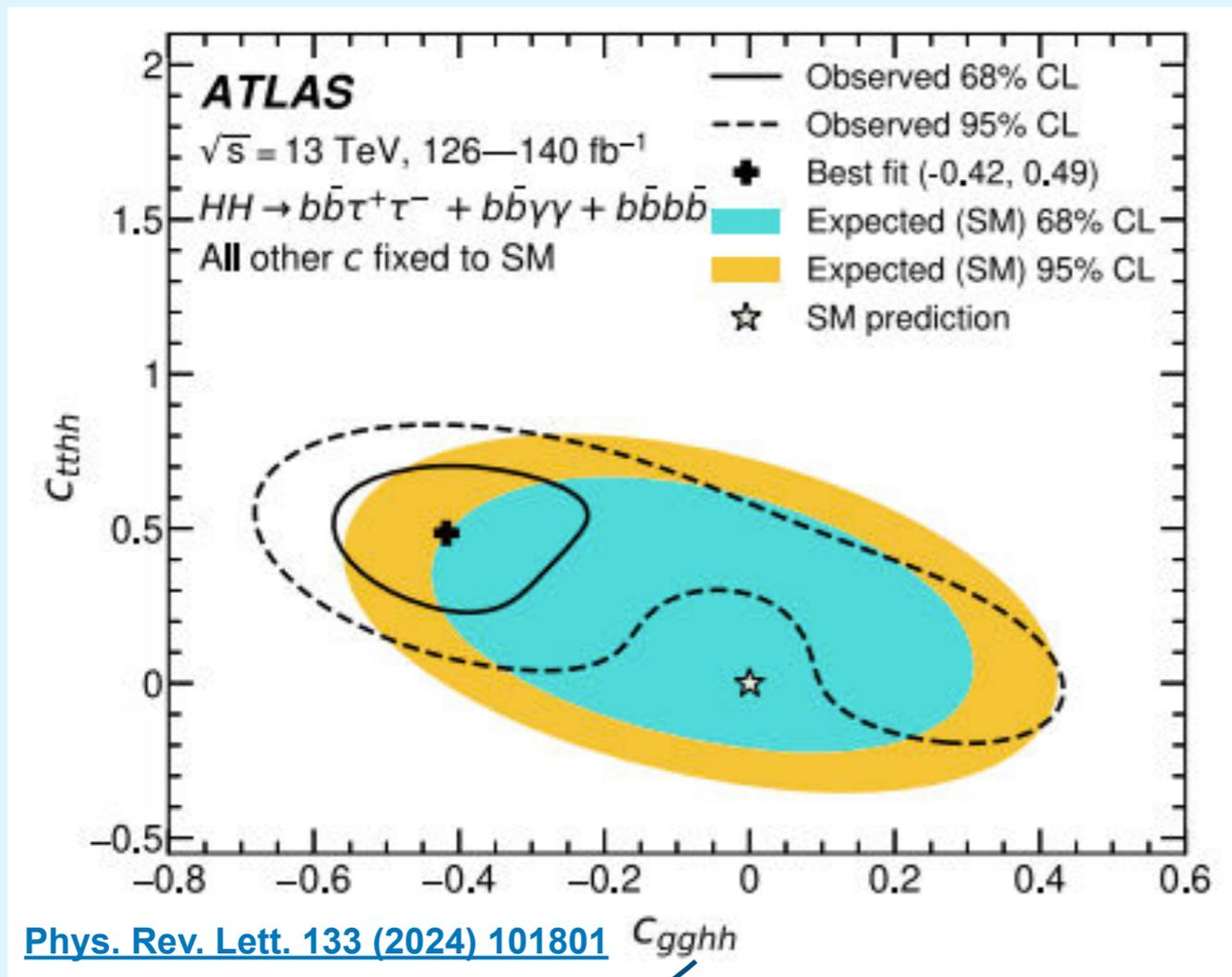
Constrain on the  $k_{2V}$   $[0.6, 1.4]$  obs - CMS  
 Constrain on the  $k_{2V}$   $[0.6, 1.5]$  obs - ATLAS  
 $k_{2V} = 0$  excluded at  $>6\sigma$  from both collaborations

# HEFT results



Both collaborations provided results in the HEFT framework:

- **CMS new results:**  $c_2$  scan dominated by the  $b\bar{b}\tau\tau$  channel
- **ATLAS 2D scan:**  $c_2$  VS  $C_{gghh}$

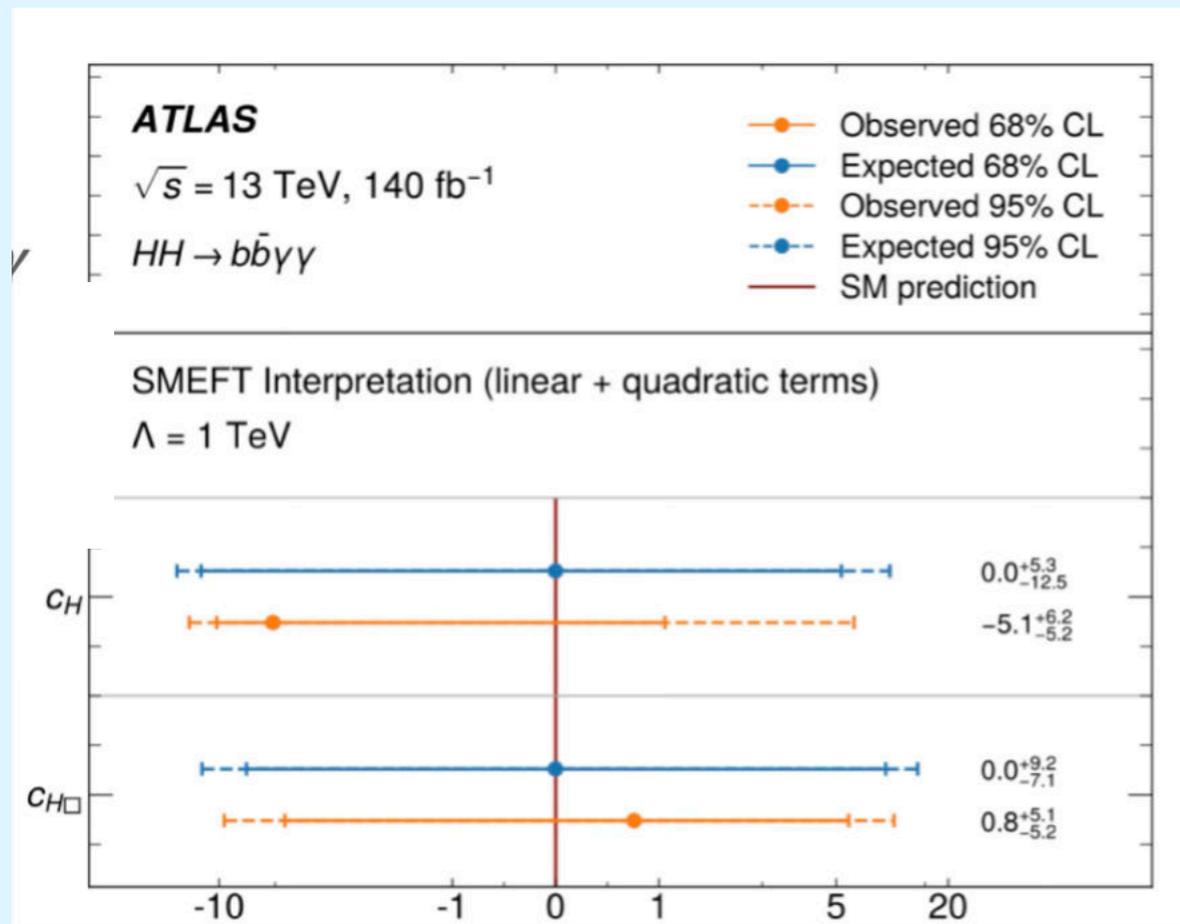


# SMEFT results: ATLAS only

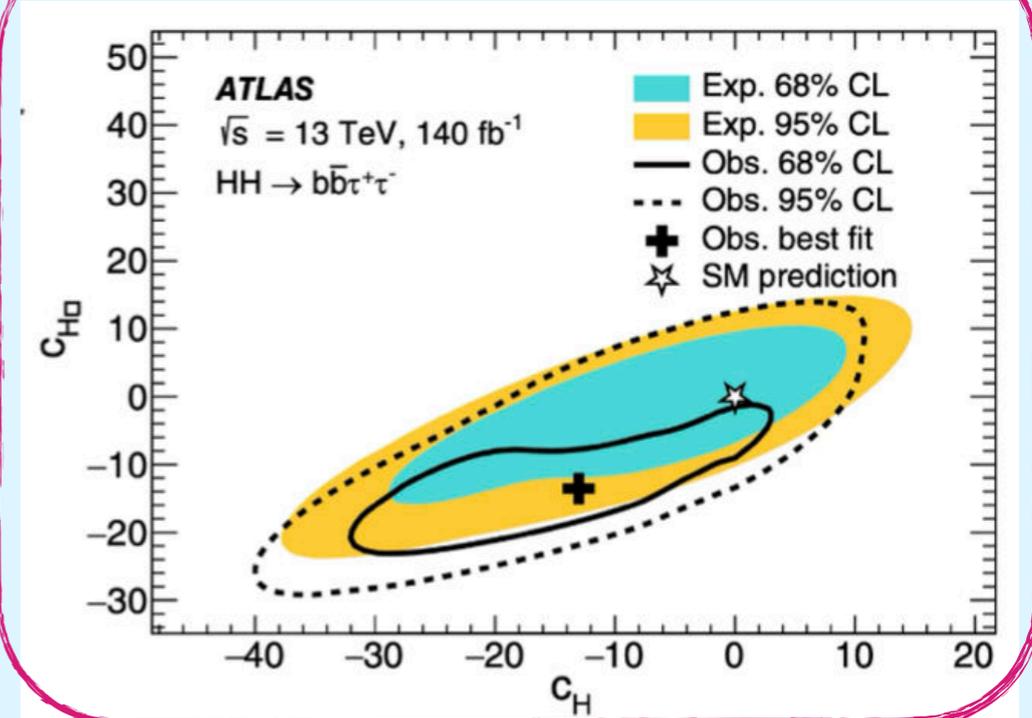
ATLAS is providing SMEFT results for  $b\bar{b}\gamma\gamma$ ,  $b\bar{b}\tau\tau$ ,  $4b$  channels separately

- Effect of SMEFT operators on singleH background are accounted

$b\bar{b}\gamma\gamma$



$b\bar{b}\tau\tau$



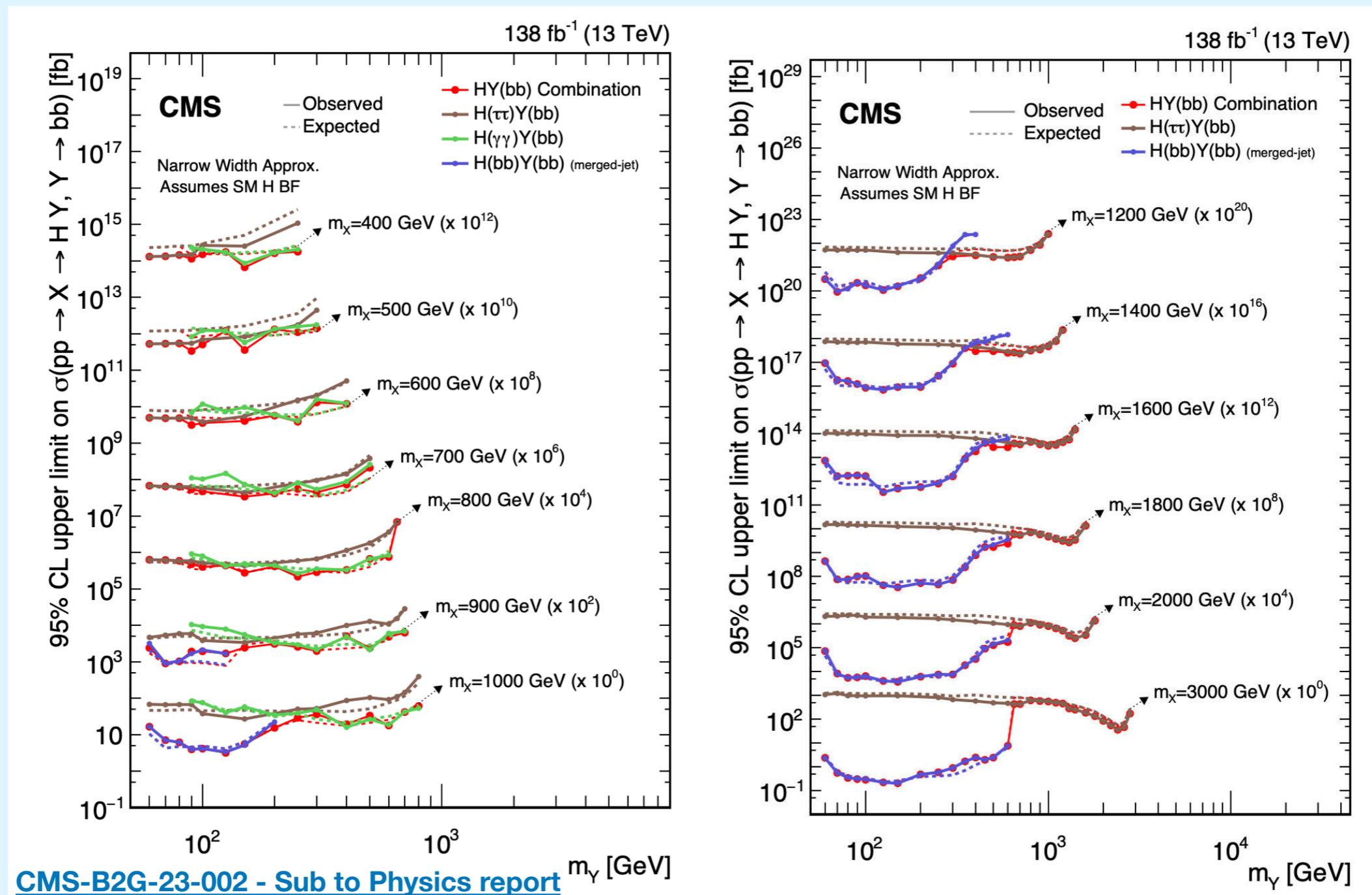
$4b$

Parameter	Expected constraint		Observed constraint	
	Lower	Upper	Lower	Upper
$c_H$	-20	11	-22	11
$c_{HG}$	-0.056	0.049	-0.067	0.060
$c_{H\Box}$	-9.3	13.9	-8.9	14.5
$c_{tH}$	-10.0	6.4	-10.7	6.2
$c_{tG}$	-0.97	0.94	-1.12	1.15

# Summary of BSM results: CMS only

CMS  $X \rightarrow HY$  searches for the main 3 channels, with no significant excess

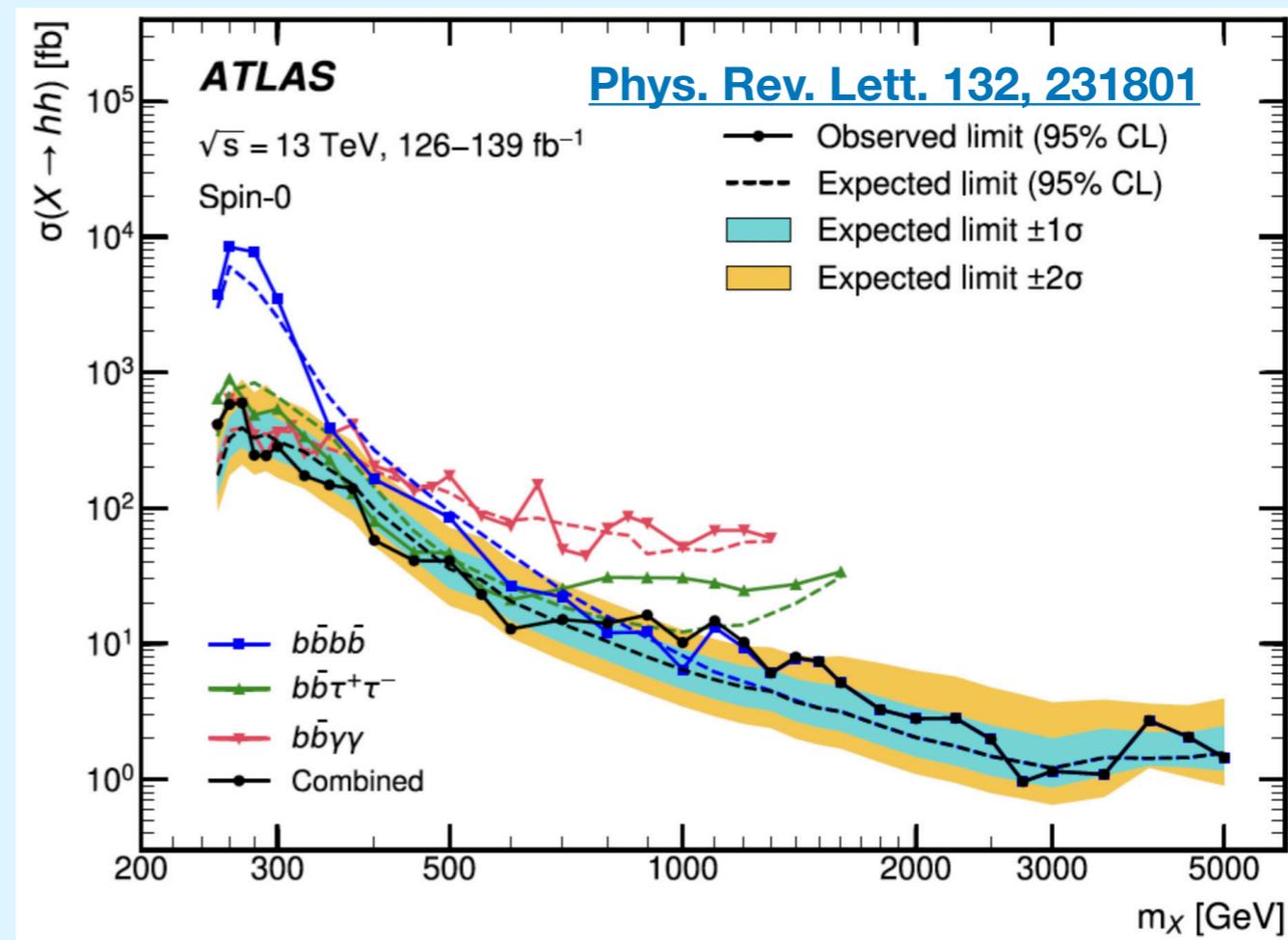
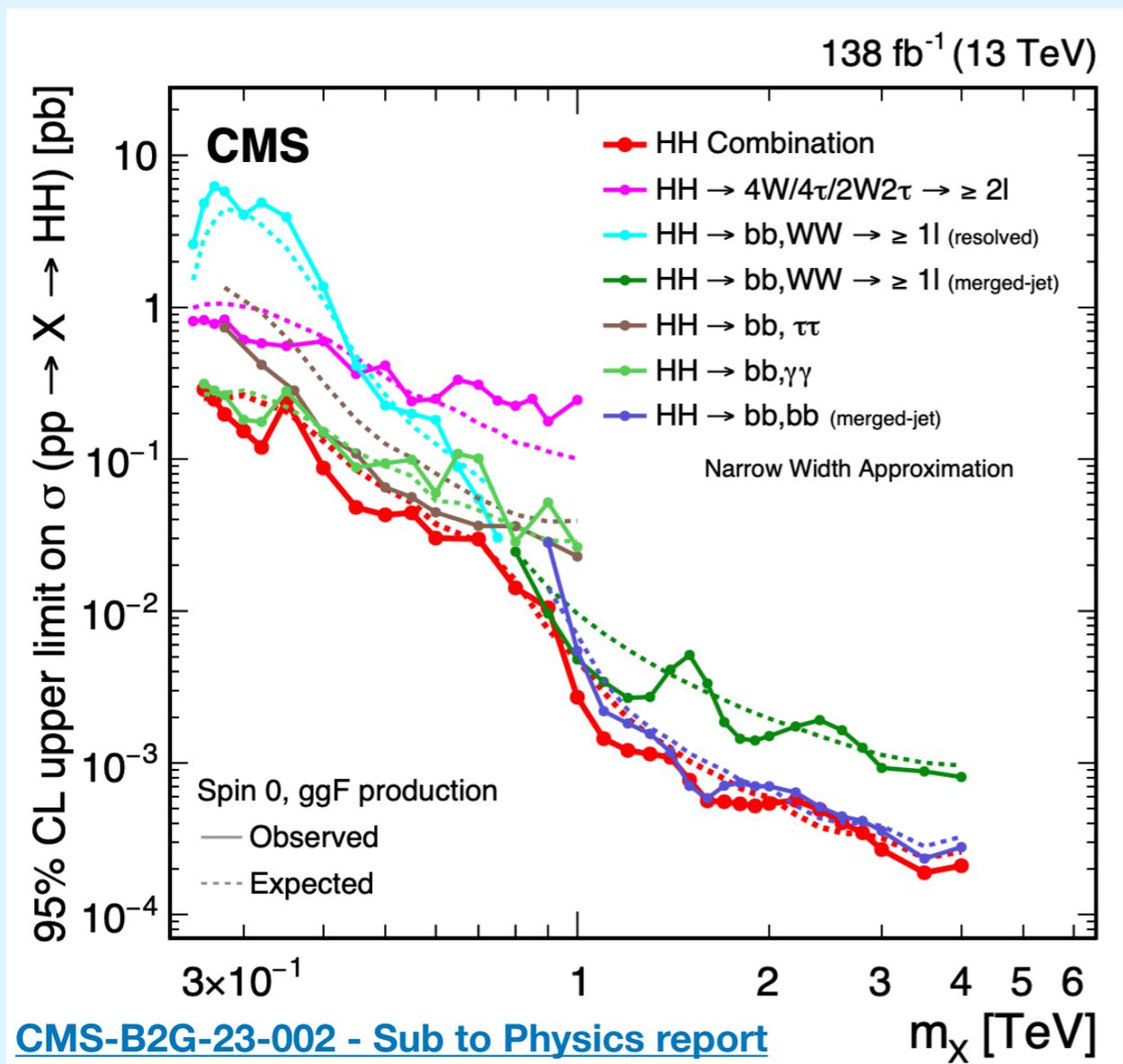
- BR of the  $H \rightarrow \tau\tau, \gamma\gamma, bb$  is assumed the same as the SM



# Summary of BSM results: spin0 results

The different searches are often complementary for different mass ranges. They are presented in a model agnostic way and often reinterpreted in the 2HDM and MSSM models.

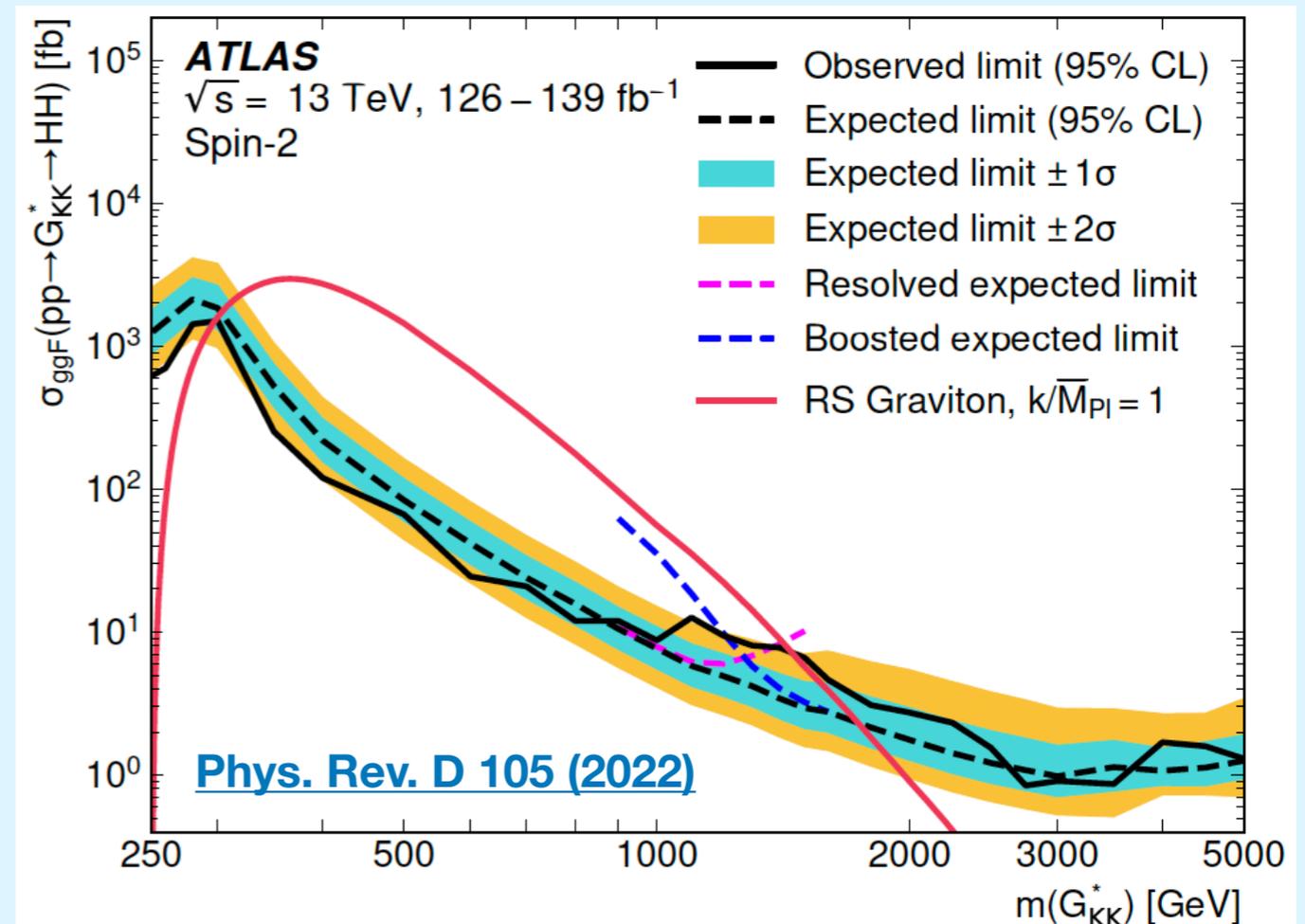
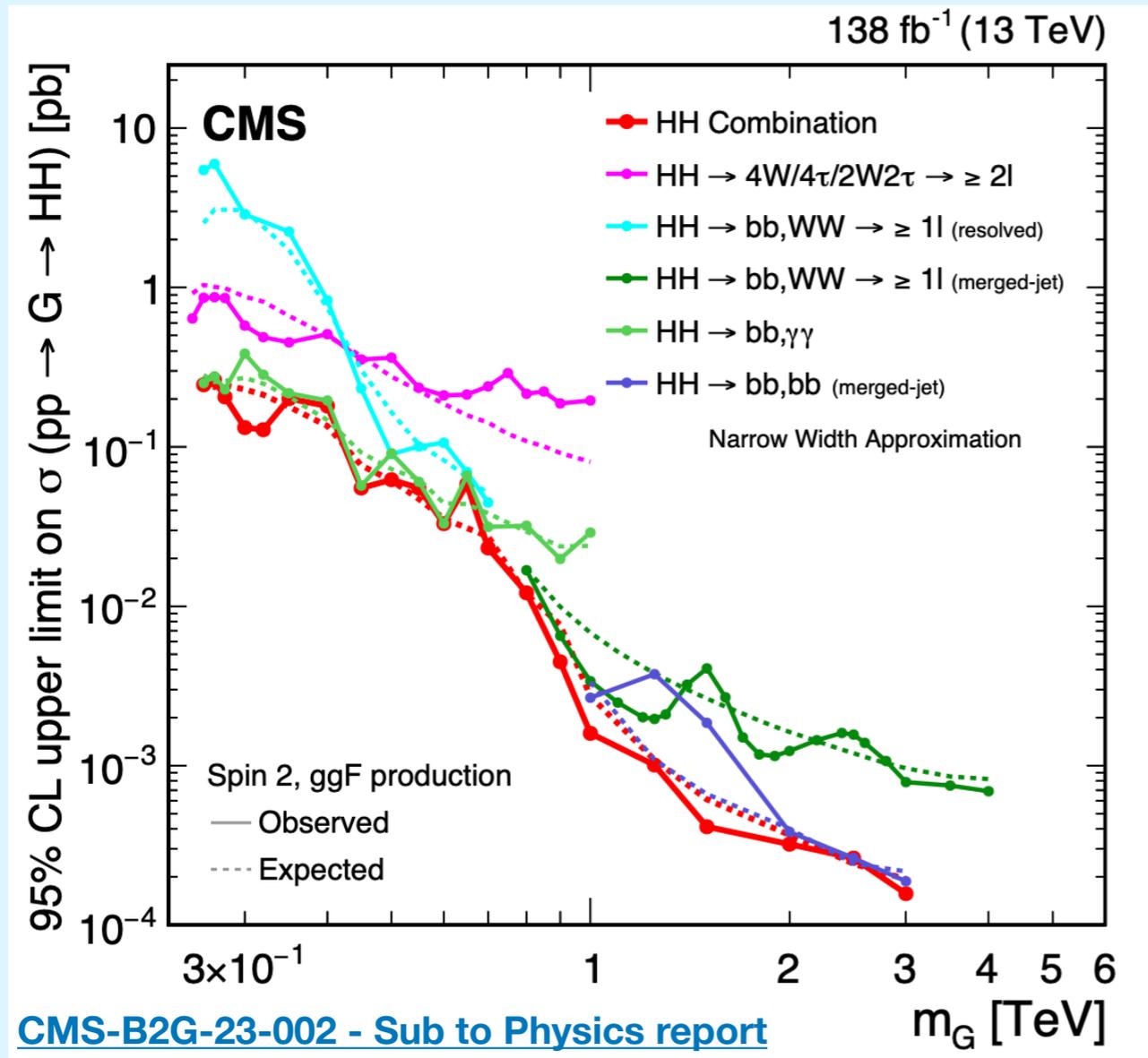
- **ATLAS** also found a small excess with combined local (global) significance of 3.2 (2.1) at 1.1 TeV, not found by CMS



# Summary of BSM results: spin2 results

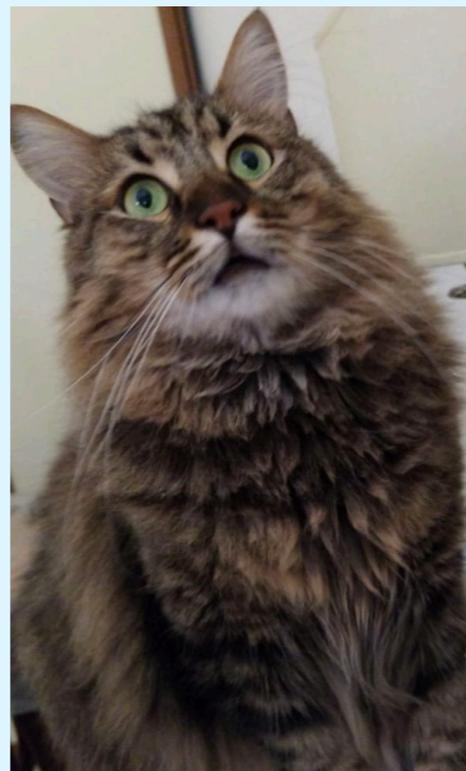
The different searches are often complementary for different mass ranges. They are presented in a model agnostic way and often reinterpreted in the 2HDM and MSSM models.

- **ATLAS** published only the  $HH \rightarrow 4b$  result
- **CMS** channels that dominates at low mass is  $bby\gamma$ , while at high mass search is dominated by  $4b$  boosted



What comes next????

? ? ? ?



# HL ESU projections: S1, S2, S3

Ultimate sensitivity to HH production will be achieved during HL-LHC

- The two collaborations are actively working to provide inputs for the EU strategy update
- Channels projected:  $4b$ ,  $b\bar{b}\gamma\gamma$ ,  $b\bar{b}\tau\tau$ ,  $b\bar{b}WW$ , multilepton + their combination
- Luminosity scenarios studied:  $2000 \text{ fb}^{-1}$ ,  $3000 \text{ fb}^{-1}$
- Projections provided in **3 systematic uncertainties scenarios**:
  - **S1**: same as Run 2
  - **S2**: unc. with stat. origin reduced by  $1/\sqrt{k_L}$ , theory unc. are halved, MCstat removed
  - **S3**: same systematic assumption as S2 + b tagging and tau ID object run3 improvement

# HH projections: $k_\lambda$ precision and significance

**CMS** and **ATLAS** provided projections for HL:

- evidence of HH production at the end of HL for both experiments
- $k_\lambda$  precision <30%

- 3000 fb<sup>-1</sup> S3 assumption

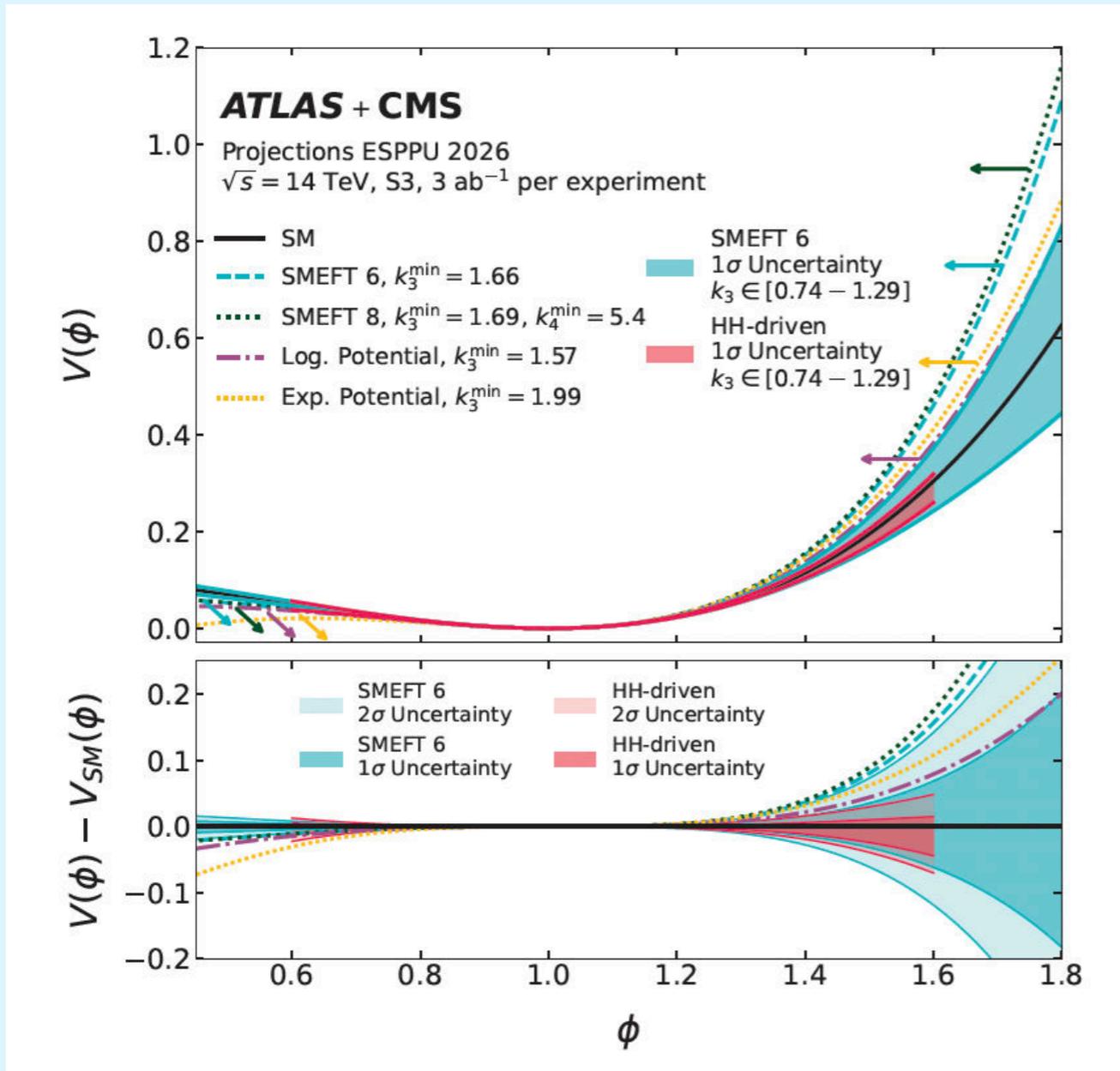
	HH significance		$k_3$ 68% CI	
	CMS	ATLAS	CMS	ATLAS
bb $\tau\tau$	2.7	3.8	[0.3, 2.0]	[0.5, 1.6]
bb $\gamma\gamma$	2.6	2.6	[0.4, 1.9]	[0.5, 1.7]
bbbb resolved	1.3	1.0	[-0.3, 7.2]	[-0.5, 6.1]
bbbb boosted	2.2	\	[-0.4, 8.2]	\
Multilepton	\	1.0	\	[-0.1, 4.7]
bbll	\	0.5	\	[-2.1, 9.1]
Combination	4.5	4.5	[0.6, 1.5]	[0.6, 1.4]
<b>CMS+ATLAS</b>	<b>7.6</b>		<b>-26% / +29%</b>	

What does this mean???

# HH projections: $k_\lambda$ precision and significance

CMS and ATLAS provided projections for HL:

- $k_\lambda$  precision  $< 30\%$



\*reminder

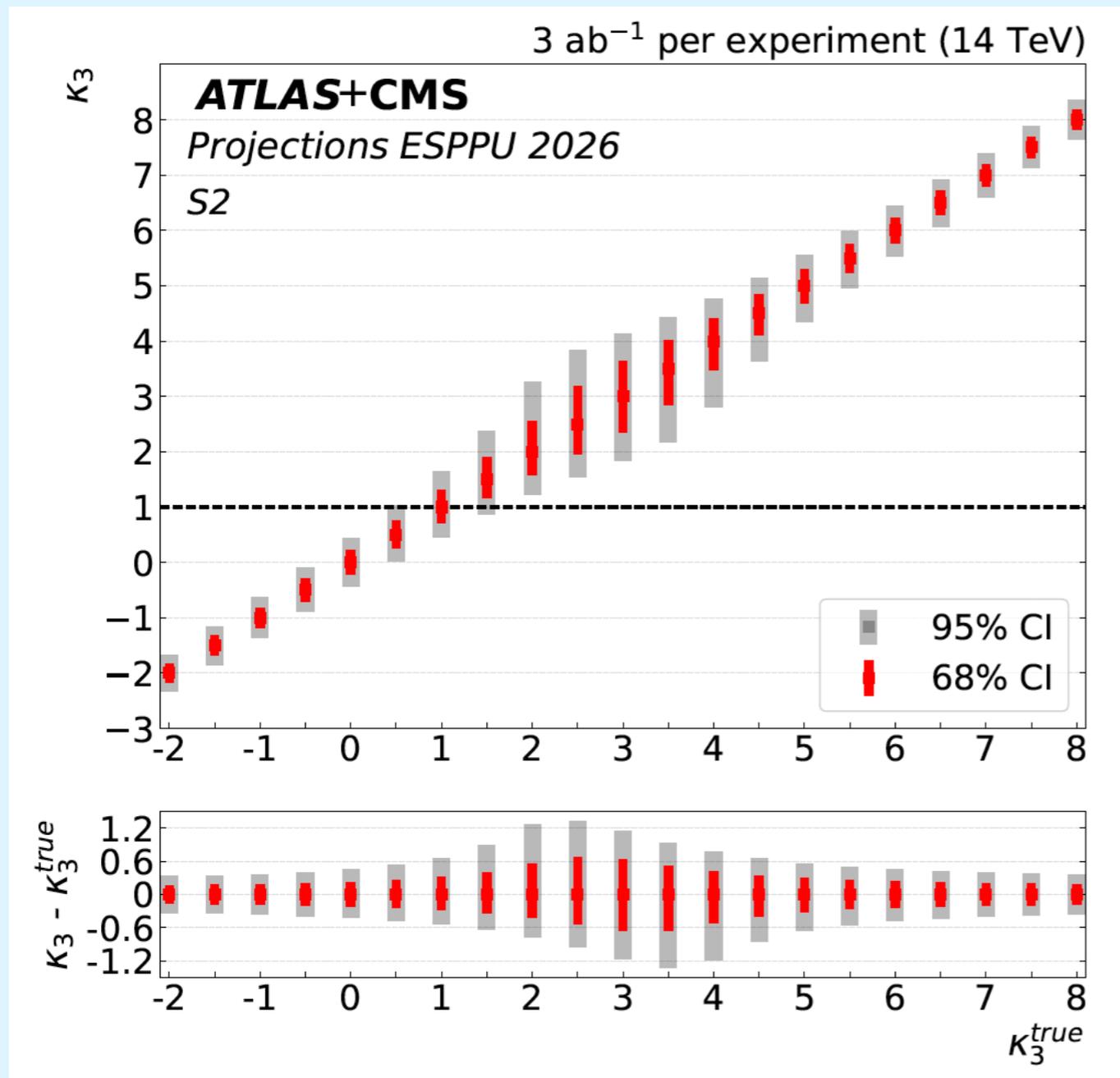
With the sensitivity that we have now we cannot fully determine the shape of the Higgs potential

- Different assumption on the shape are made

CMS+ATLAS projection exclude at  $> 2\sigma$  FOPT SMEFT dim6 potential

# HH projections: $k_\lambda$ precision and significance

What if  $k_\lambda$  is not equal 1??? Is HL sensitive to new physics?



- Maximum interference between box and triangle diagram at 2.45  $\rightarrow$  largest precision
- Still possible to measure  $k_l > 2.0$  and exclude the SM at  $> 2\sigma$

# Conclusions

Many results produced by the CMS and ATLAS collaborations:

- di Higgs SM:
  - Upper limit on the signal strength for ggF and VBF production modes
  - 1D/2D likelihood scans for kappa framework
  - 1D/2D likelihood scans for HEFT
  - SMEFT result by ATLAS
- HH BSM searches:
  - Spin0 results
  - Spin2 results

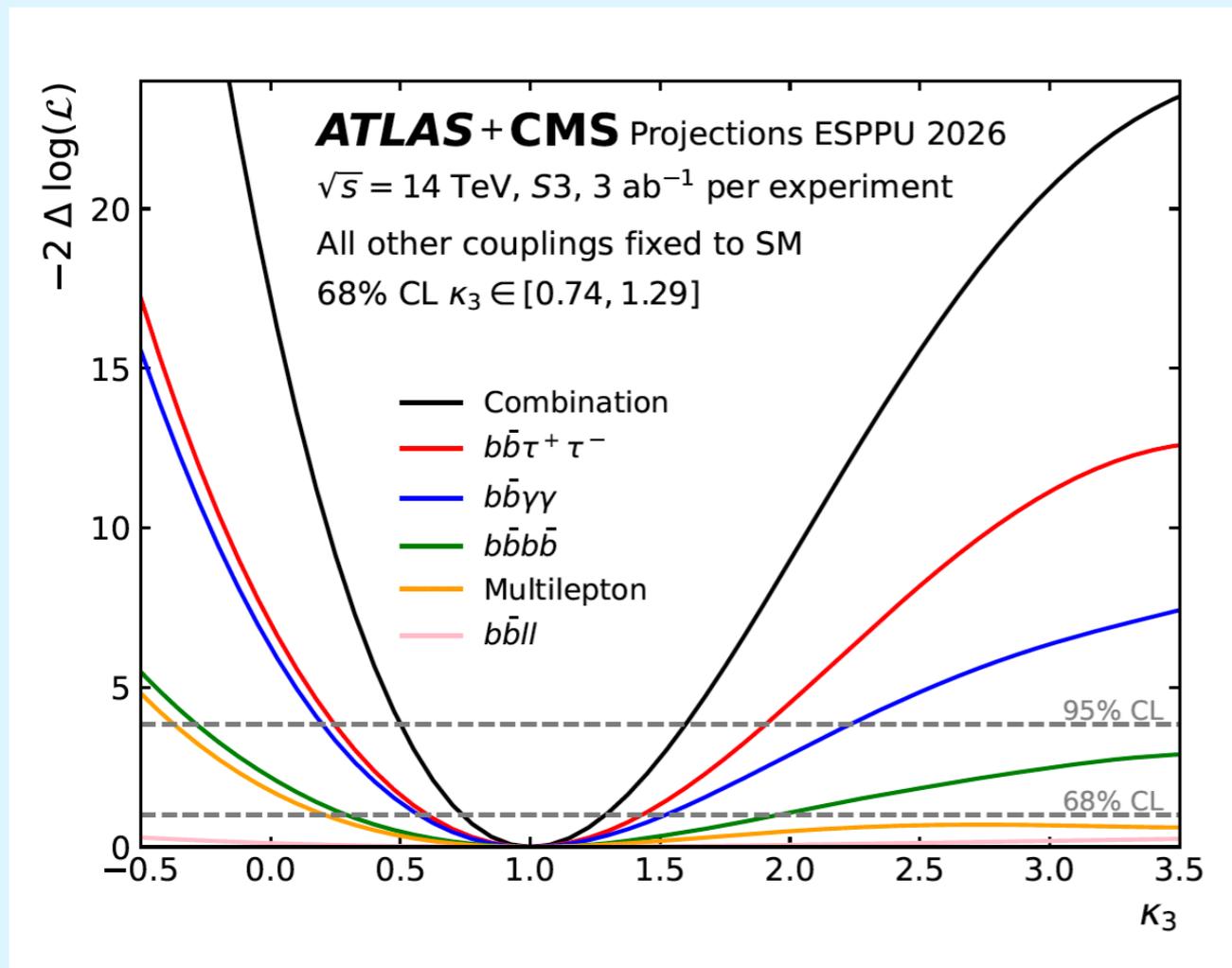
**Many more to come in the Run3!!!**

Backup

# HH projections: $k_\lambda$ precision and significance

**CMS** and **ATLAS** provided projections for HL:

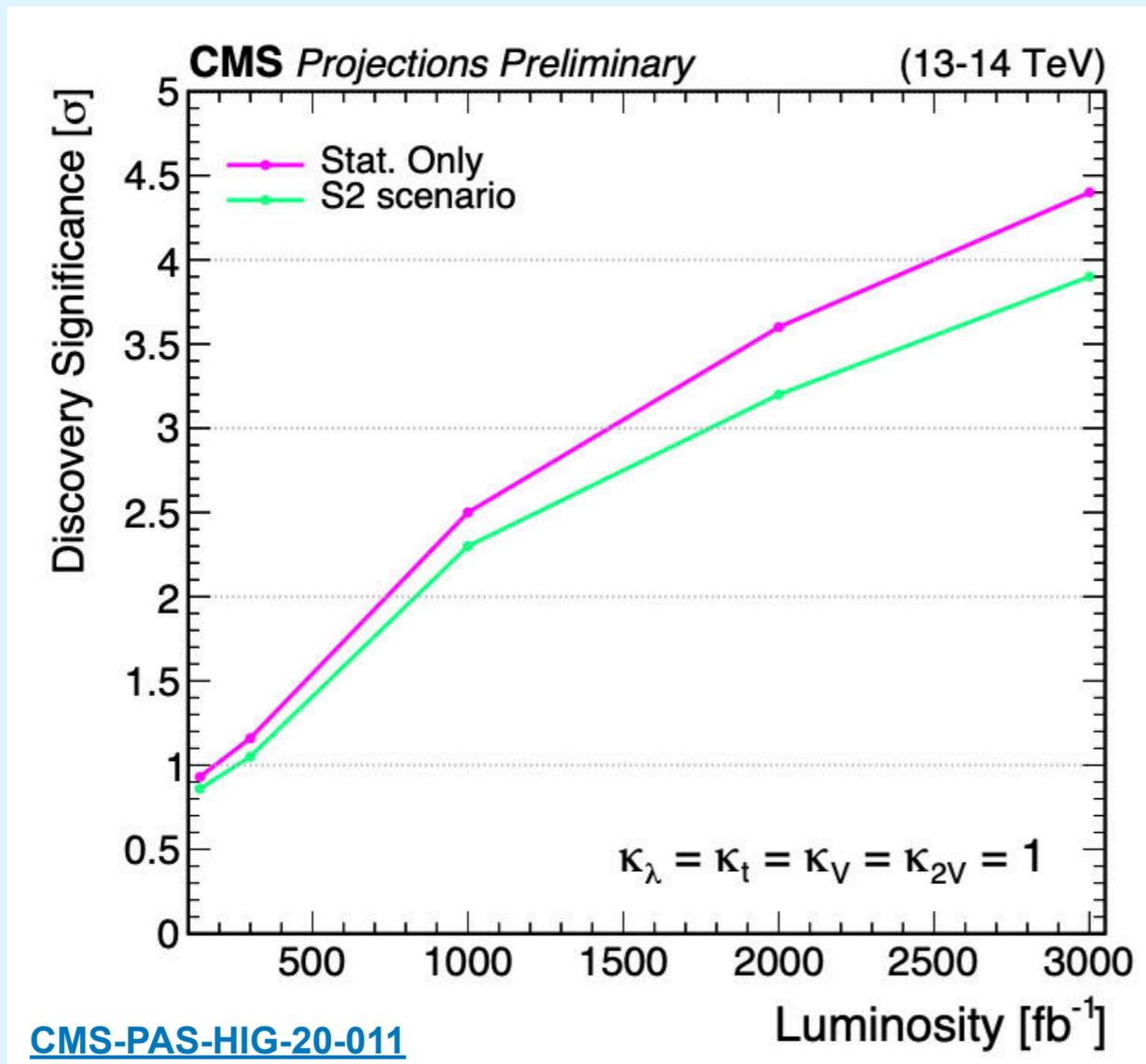
- evidence of HH production at the end of HL for both experiments
- $\sim 27\%$  precision on  $k_\lambda$



# HH projections: $k_\lambda$ precision and significance

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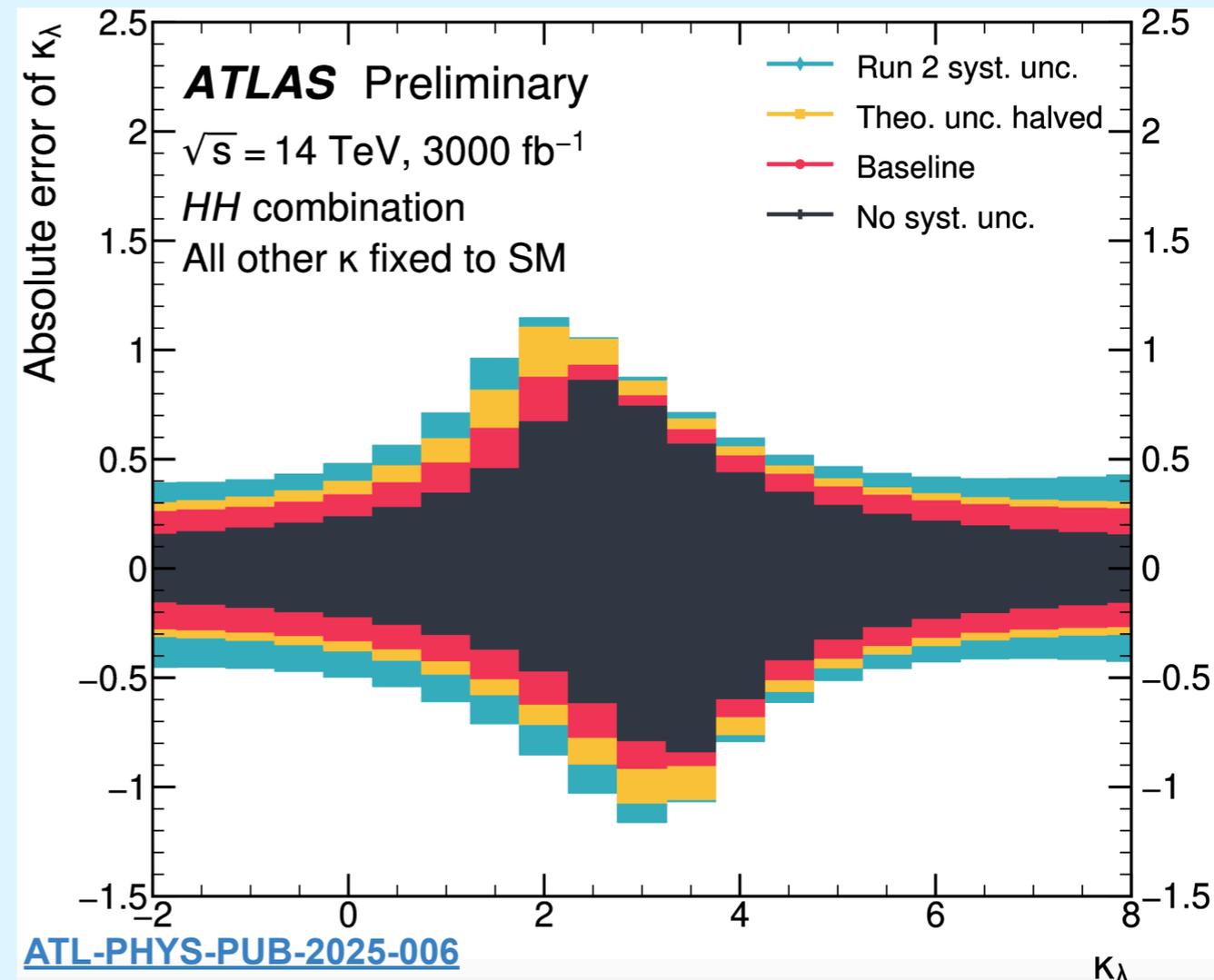
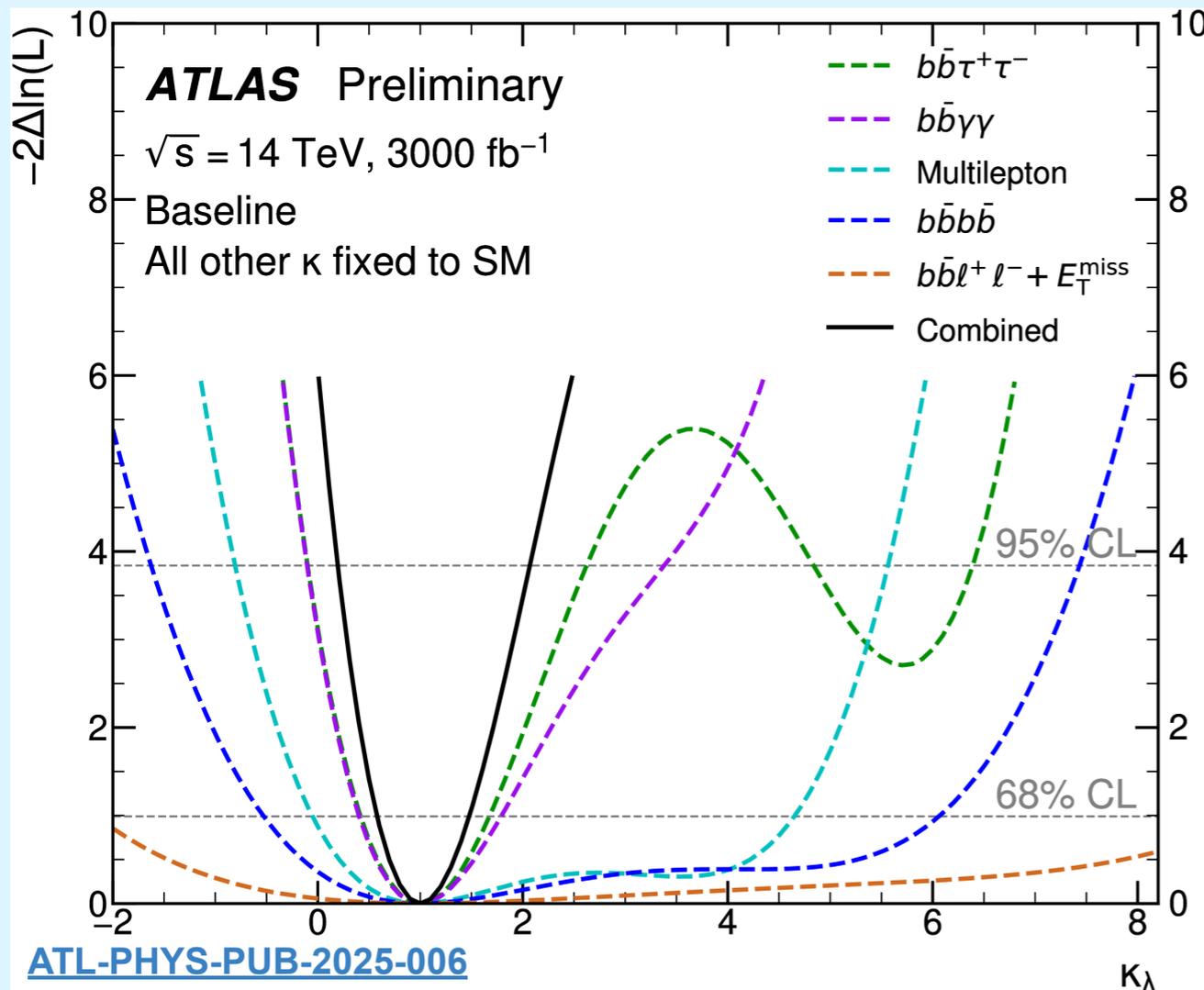
- evidence of HH production at the end of HL for both experiments



# HH projections: $\kappa_\lambda$ precision and significance

**CMS** and **ATLAS** provided projections for HL:

- evidence of HH production at the end of HL for both experiments
- ~40% precision on  $\kappa_\lambda$  determination per single experiment



# HH SMEFT interpretation

SMEFT:

$$L = L_{SM} + \sum_i \frac{C_i^{(6)} O_i^{(6)}}{\Lambda^2} + (O(\Lambda^{-4}))$$

- No light new physics ( $E < \Lambda$ )
- Expansion in  $1/\Lambda^2$ : dimension-6 effects are expected to be dominant over dimension-8 effects etc
- SMEFT is assumed that the physical Higgs boson is part of a doublet transforming linearly under  $SU(2)_L \times U(1)$  - ideal for new physics evidence [1]

# HH SMEFT interpretation

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For the HH case we have 5 different operators:

Wilson Coefficient	Operator
$c_H$	$(H^\dagger H)^3$
$c_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
$c_{tH}$	$(H^\dagger H)(\bar{Q}\tilde{H}t)$
$c_{HG}$	$H^\dagger H G_{\mu\nu}^A G_A^{\mu\nu}$
$c_{tG}$	$(\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{H}G_{\mu\nu}^A$

We want to have the following scans:

- $(c_H, c_{H\Box})$
- $(c_H, c_{tH})$
- $(c_H, c_{HG})$
- $(c_H, c_{tG})$

# HH SMEFT interpretation

Let's take a closer look to our SMEFT operators

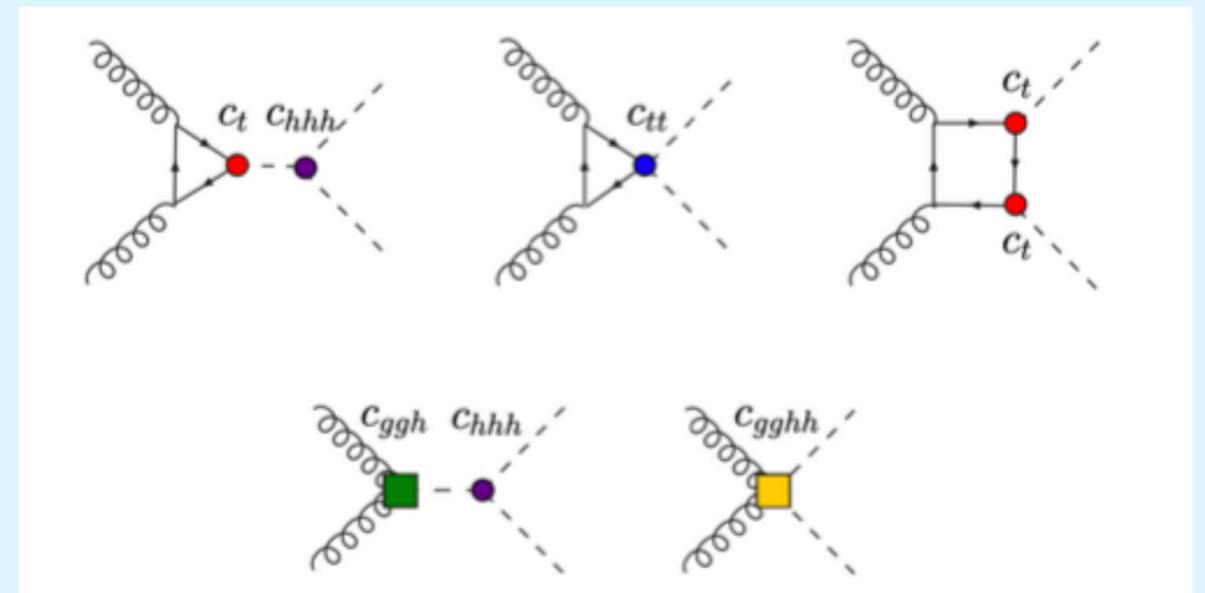
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HEFT	Warsaw
$C_{hhh}^{kl}$	$1 - 2\frac{v^2}{\Lambda^2}\frac{v^2}{m_h^2} C_H + 3\frac{v^2}{\Lambda^2} C_{H\text{box}}$
$C_t^{kt}$	$1 + \frac{v^2}{\Lambda^2} C_{H\text{box}} - \frac{v^2}{\Lambda^2}\frac{v}{\sqrt{2}m_t} C_{tH}$
$C_{tt}^{c2}$	$-\frac{v^2}{\Lambda^2}\frac{3v}{2\sqrt{2}m_t} C_{tH} + \frac{v^2}{\Lambda^2} C_{H\text{box}}$
$C_{ggh}$	$\frac{v^2}{\Lambda^2}\frac{8\pi}{\alpha_s(\mu)} C_{HG}$
$C_{gghh}$	$\frac{v^2}{\Lambda^2}\frac{4\pi}{\alpha_s(\mu)} C_{HG}$

Chromomagnetic operator, sometimes ignored as being higher order operator, connected with processes like  $tt$ ,  $ttH$ ,  $ttV$  [1]

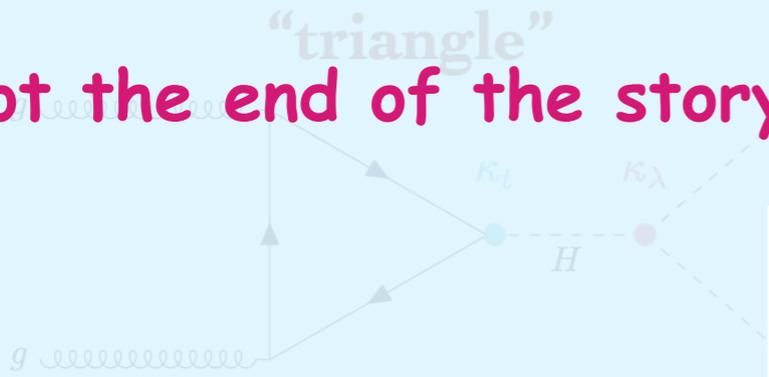
- safe to ignore in a first CMS SMEFT HH study



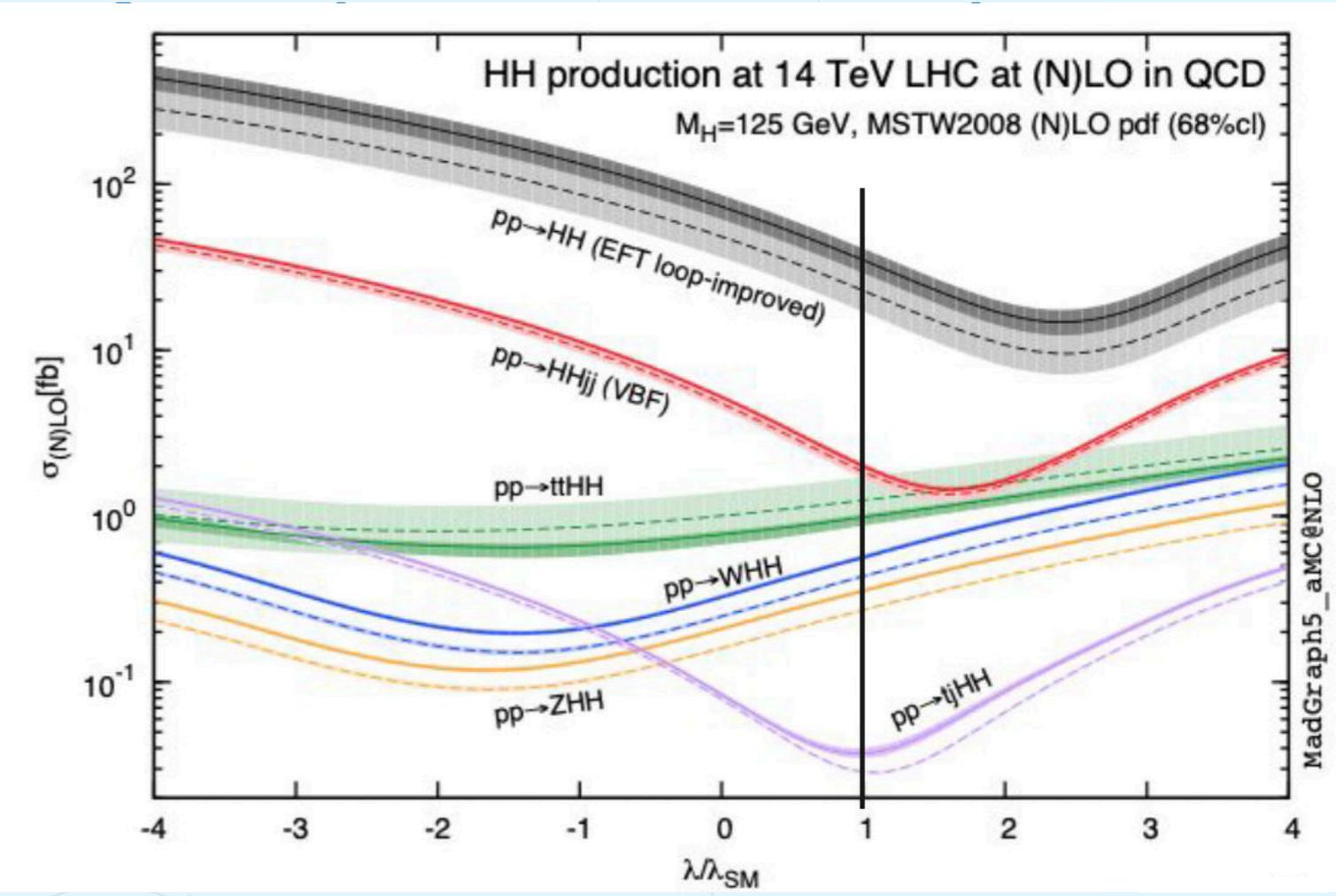
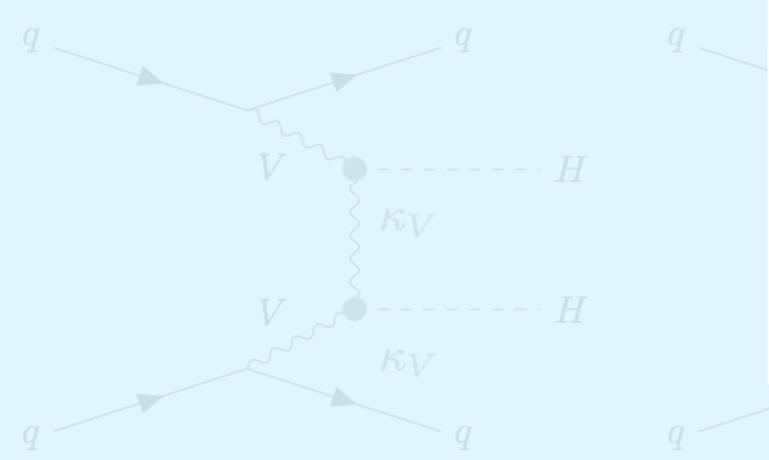
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$$\sigma_{SM}^{HH} = 31.05^{+5\%}_{-7\%} \text{ fb (scale } \oplus \text{ PDF } \oplus \alpha_S \oplus m_t)$$

This is not the end of the story... many other couplings to be studied

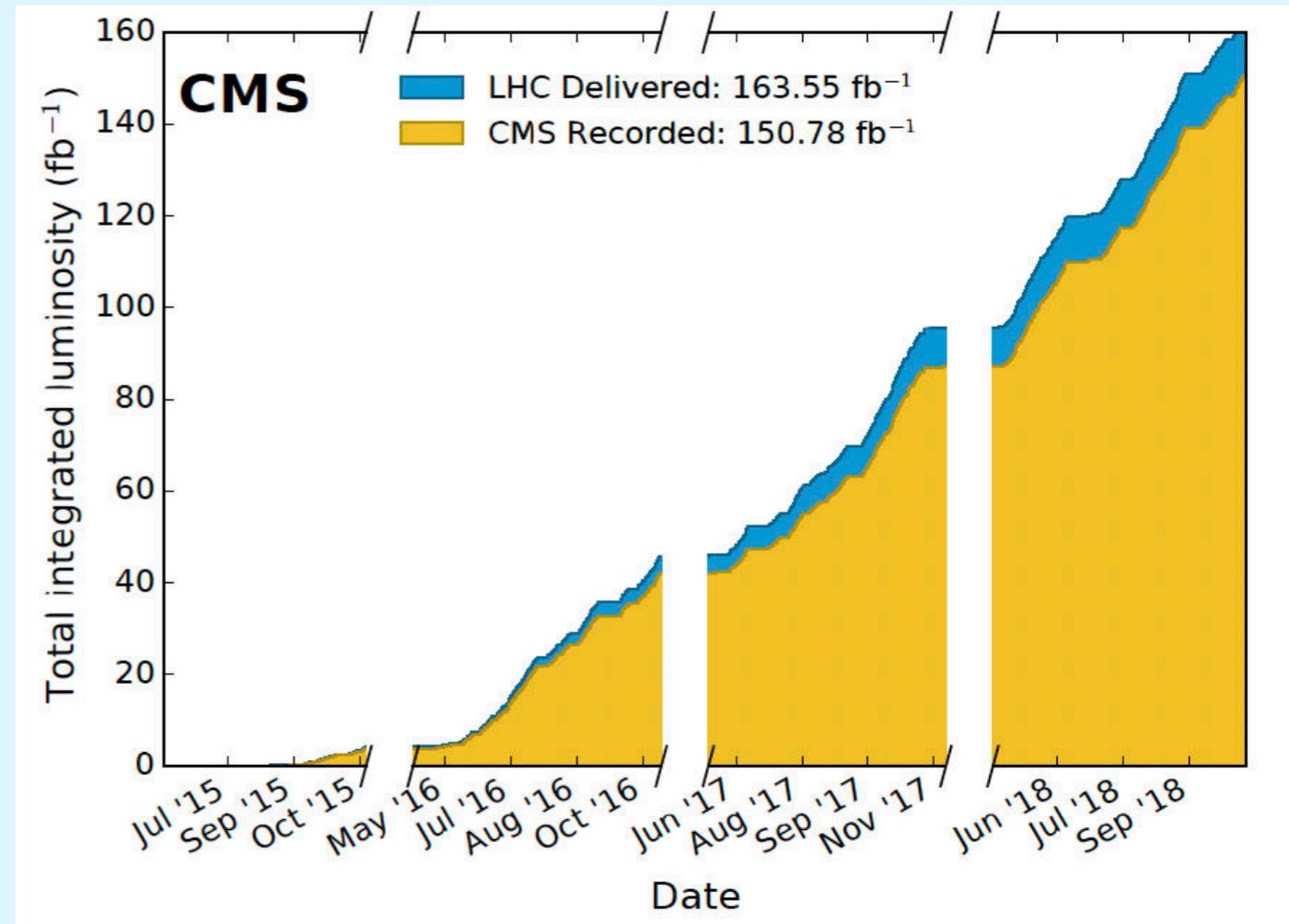
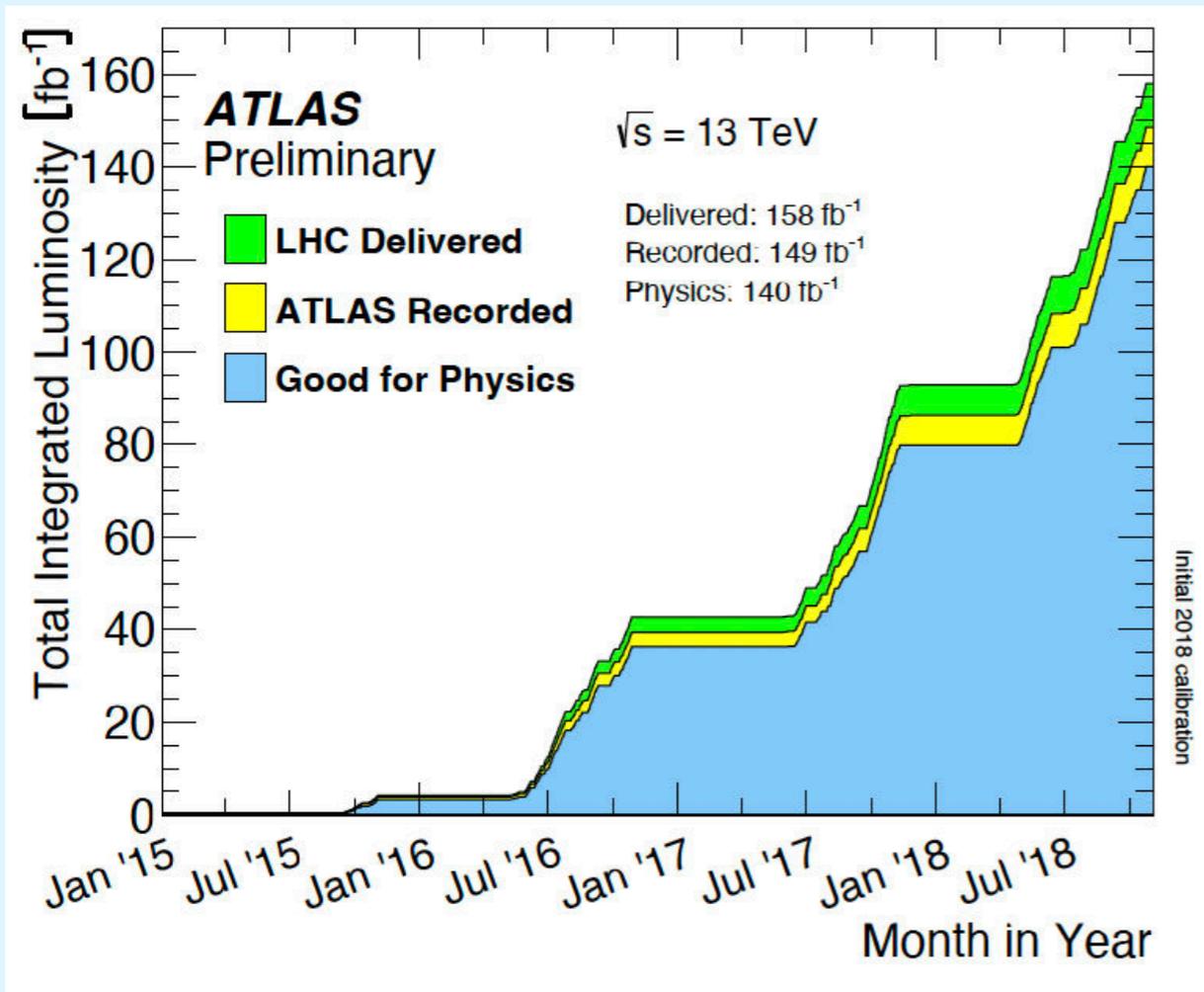


$$\sigma_{SM}^{HH} = 31.05^{+5\%}_{-7\%}$$



# LHC: luminosity collected by CMS ATLAS in Run2

CMS and ATLAS collaborations were able to record  $\sim 140\text{fb}^{-1}$  of (physics) data during the **Run2** phase of the LHC (at 13 TeV)



Run3 is ongoing (center of mass energy 13.6 TeV), it will end in 2026 we expect to double the luminosity collected in Run2