Constraining the Higgs boson self-coupling from single- and double-Higgs production at ATLAS

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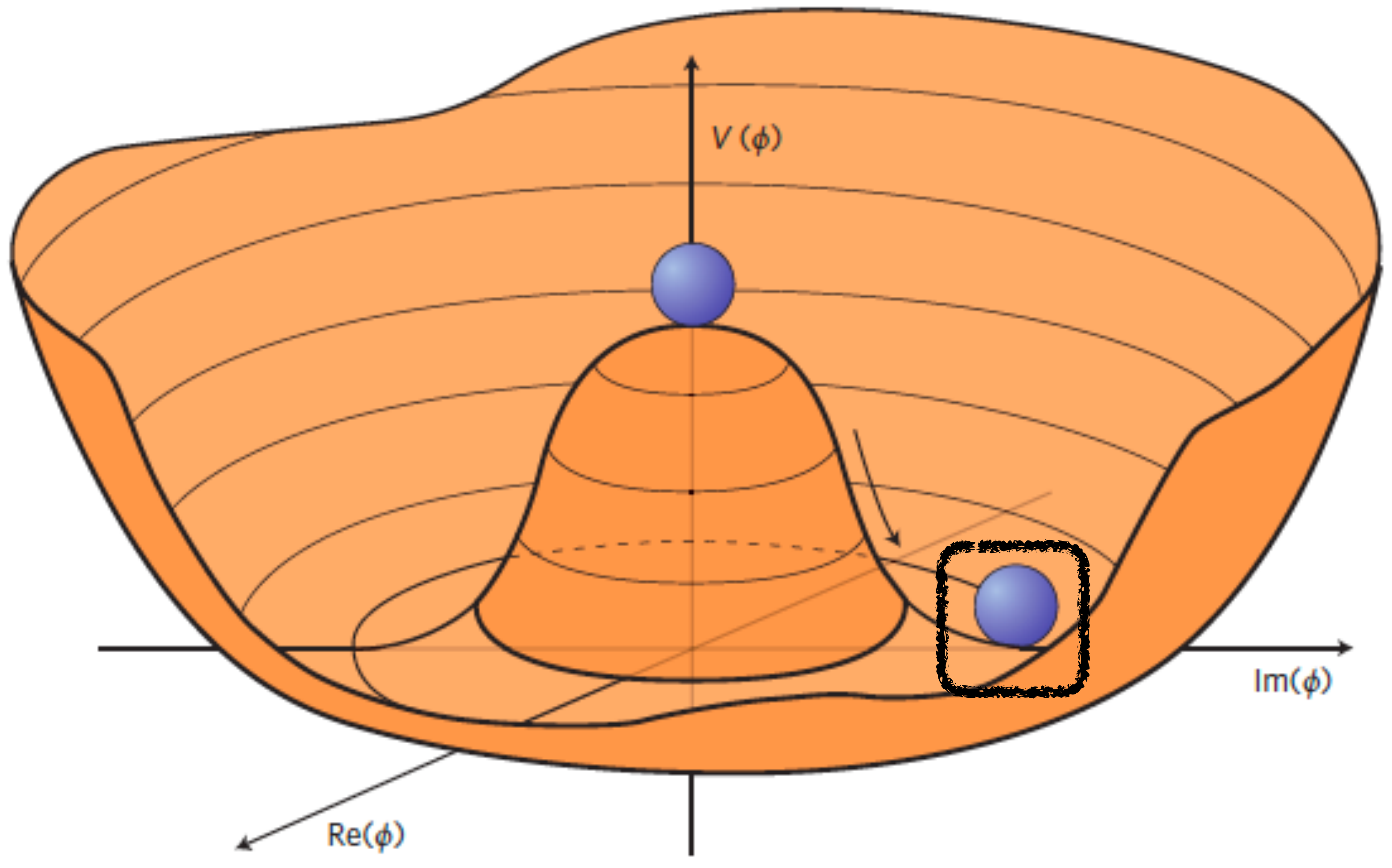
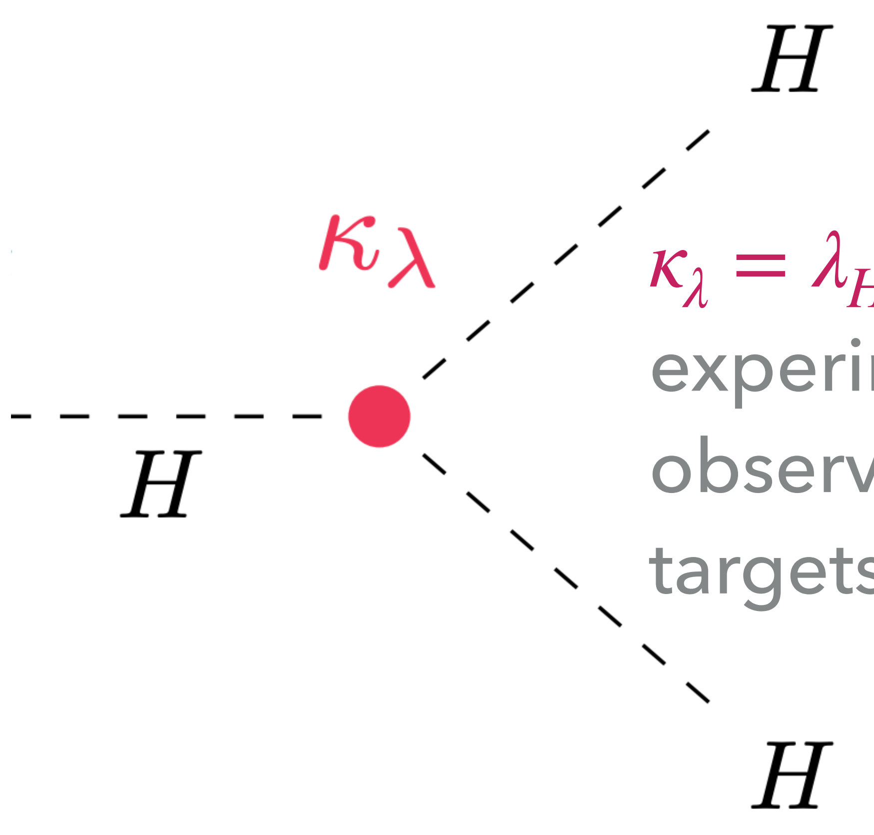
Introduction

- Higgs self-interaction is important to understand the non trivial structure to Higgs potential
- $V(\phi) = \mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2, \mu^2 < 0$
  - Non-zero ground state: $\pm\mu/\sqrt{2\lambda} = \pm v/\sqrt{2}$
  - Gauge EW symmetry is broken spontaneously

➡ $V(H) = \frac{m_H^2}{2}H^2 + \lambda v H^3 + \frac{1}{4}\lambda H^4$

- Higgs mechanism + Yukawa coupling give elementary particles masses
- Plays fundamental role in understanding the stability of the universe



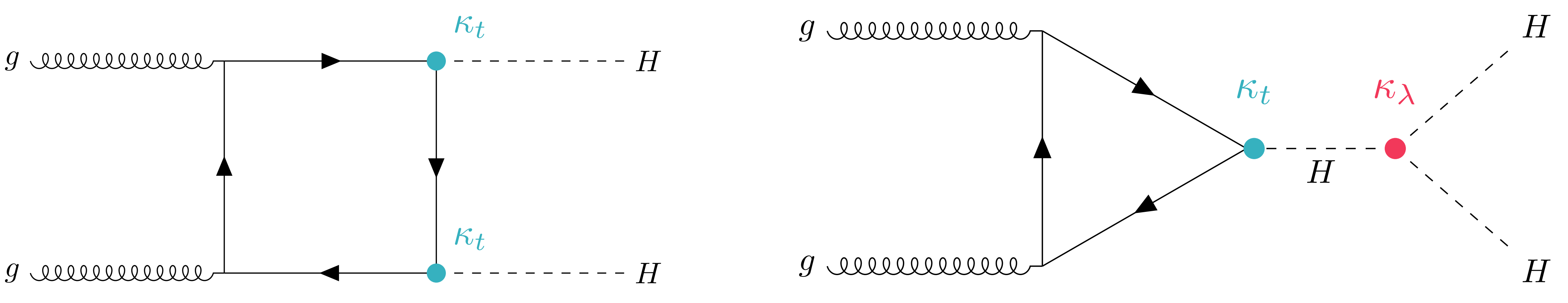


$\kappa_\lambda = \lambda_{HHH}/\lambda_{HHH}^{SM}$, not experimentally observed; One of the targets of HL-LHC

Di-Higgs production

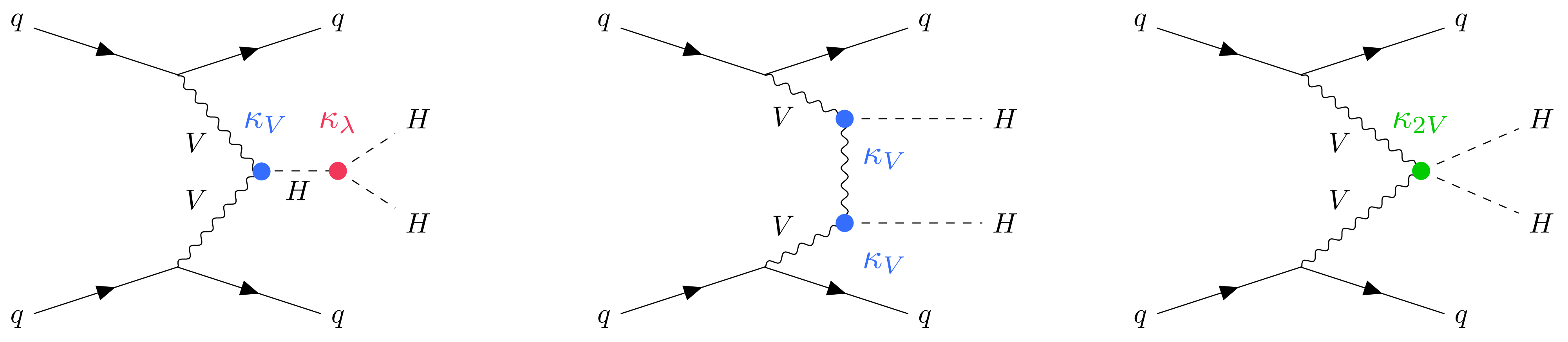
- Directly sensitive to self-coupling at LO

ggF (31 fb, dominant)

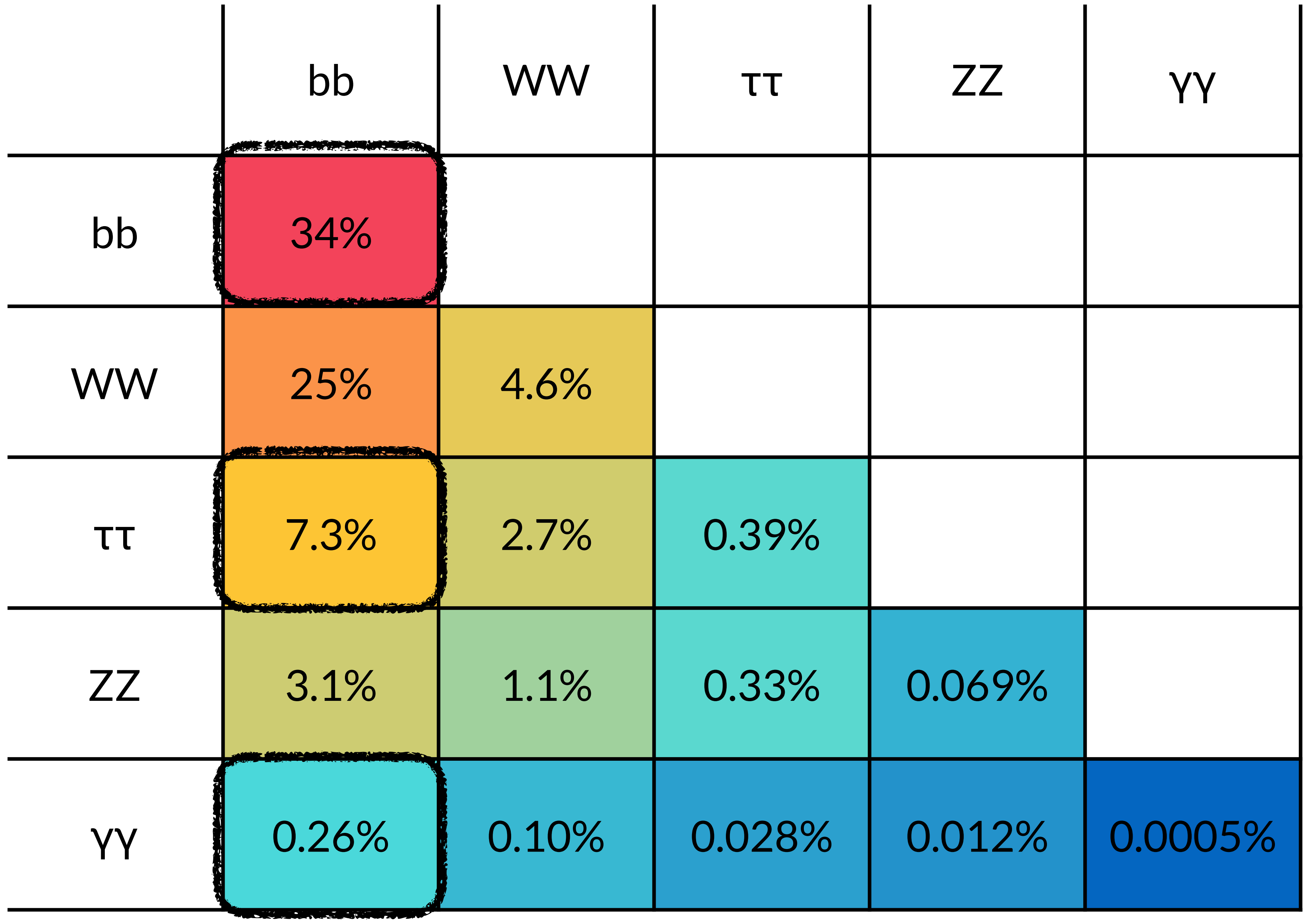


$$\mathscr{A}_{ggF} \sim \kappa_t^2 \mathscr{A}_1 + \kappa_t \kappa_\lambda \mathscr{A}_2$$

VBF (1.7 fb, sensitive to κ_{2V})



$$\mathscr{A}_{VBF} \sim \kappa_V \kappa_\lambda \mathscr{A}_1 + \kappa_V^2 \mathscr{A}_2 + \kappa_{2V} \mathscr{A}_3$$



	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%

- Combine 3 most sensitive channels
  - *bbbb* (high m_{HH}): largest BR; but large QCD bkg
  - *bbγγ* (low m_{HH}): Excellent $m_{\gamma\gamma}$ resolution, clean sig; but tiny BR
  - *bbττ*: Higher BR than *bbγγ*, lower bkg than *bbbb*

Combined HH results

- Overlaps among 3 analyses are negligible

- Before constrain κ_λ and κ_{2V}, upper limits of HH XS are measured

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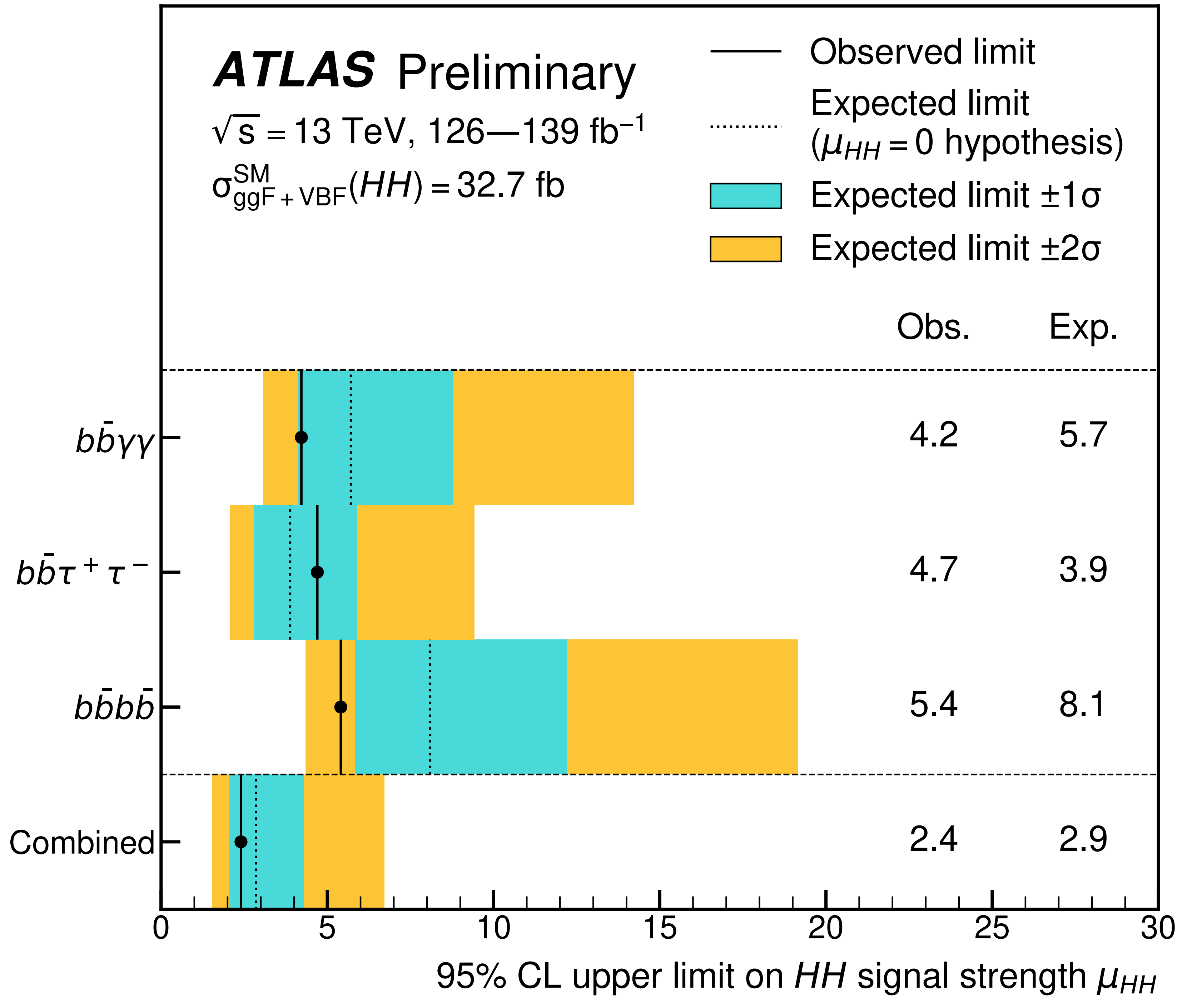

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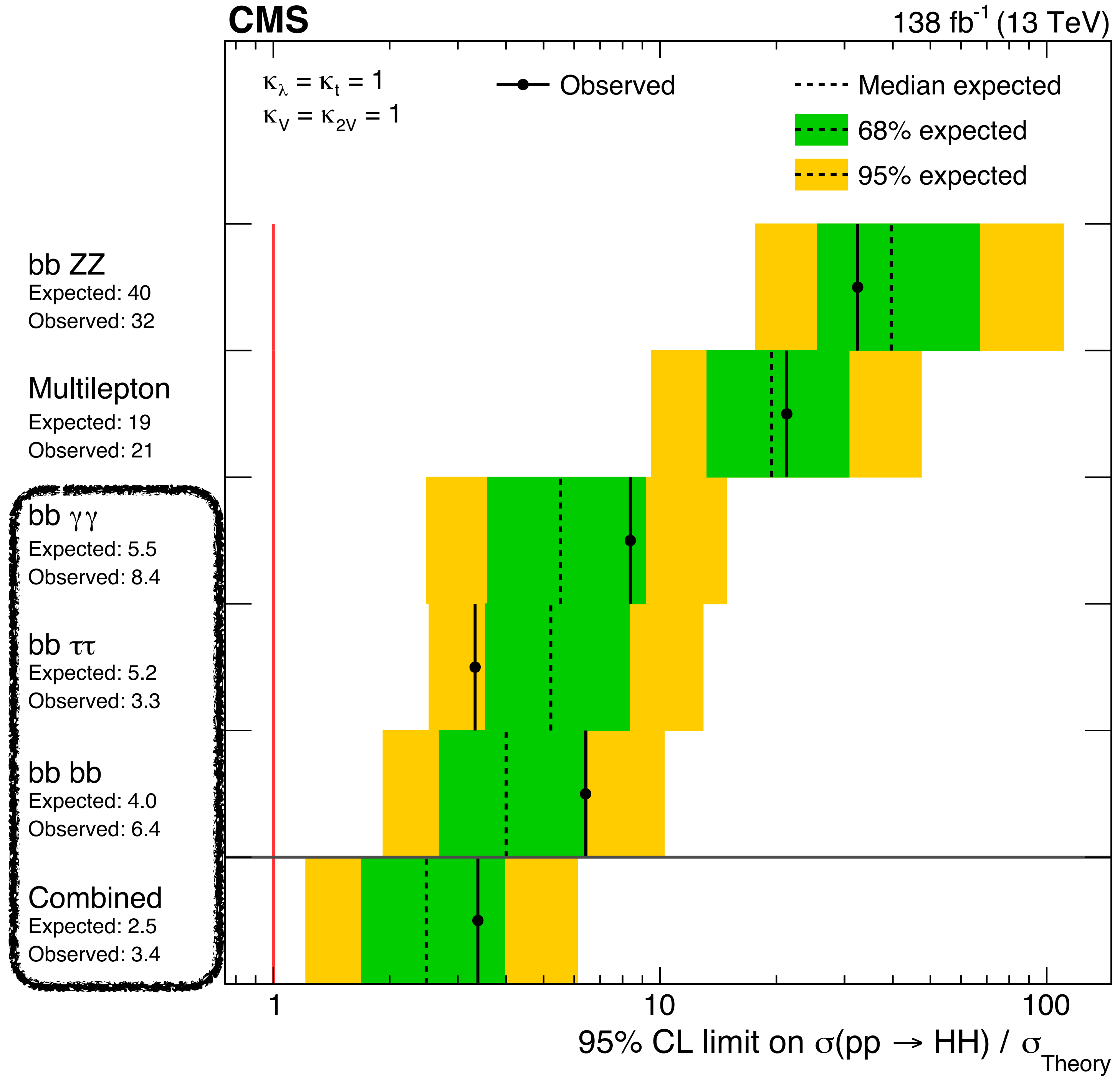
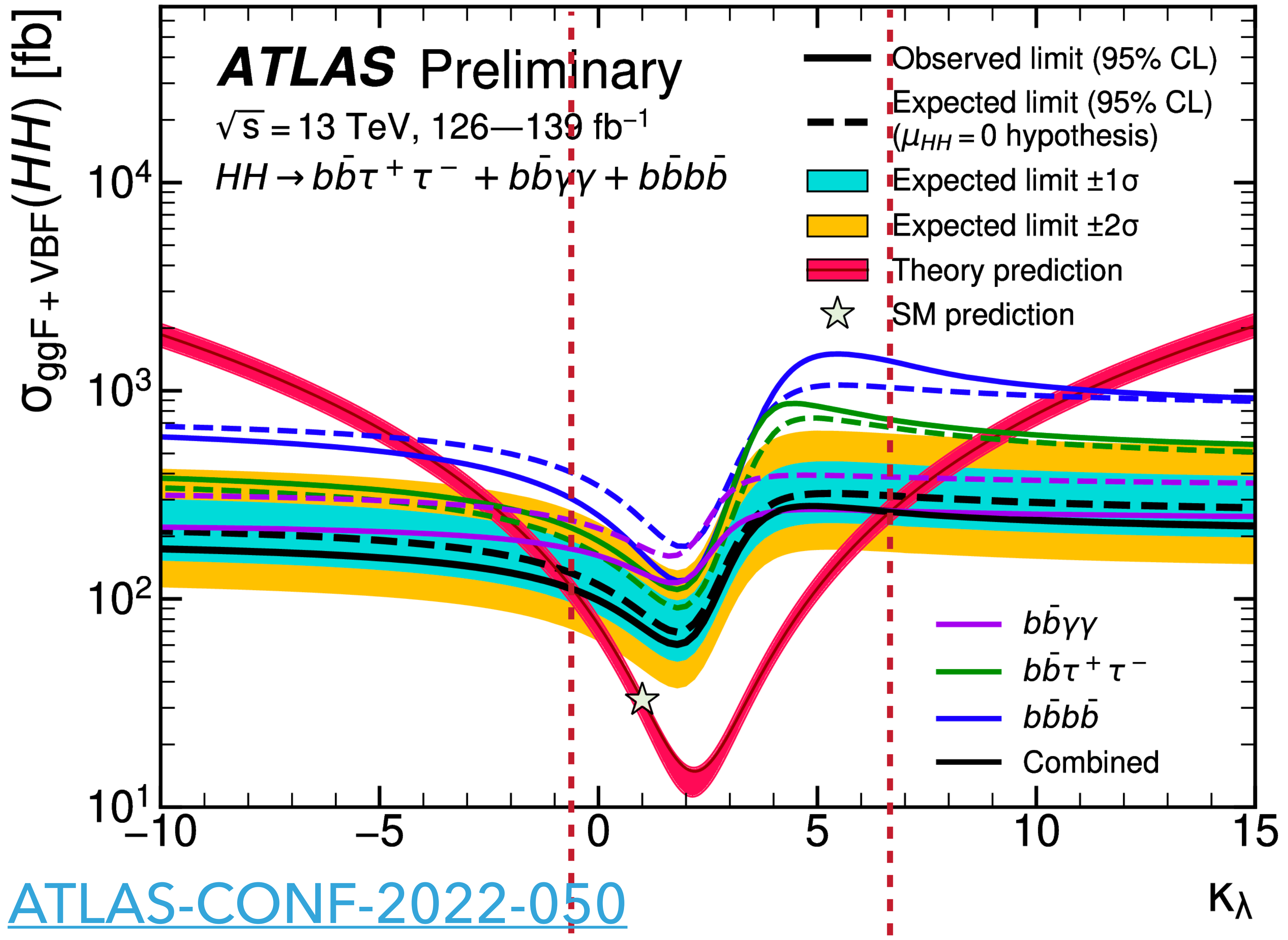


- $\mu_{HH} \equiv \frac{\sigma_{ggF+VBF}}{\sigma^{SM}_{ggF+VBF}} = -0.73 \pm 1.25, p_{SM} = 20\,\%$
- Upper limit of σ_{HH} at 95% CL: 73 fb (85 fb)
- Compare to 36 fb^{-1} ATLAS HH combination [Phys. Lett. B 800 (2020) 135103]
  - 3.4 times better exp. upper limit
- Compare to CMS
  - *bbbb*: ATLAS resolved; CMS resolved + boosted
  - Others are compatible

Combined HH results (κ_λ)



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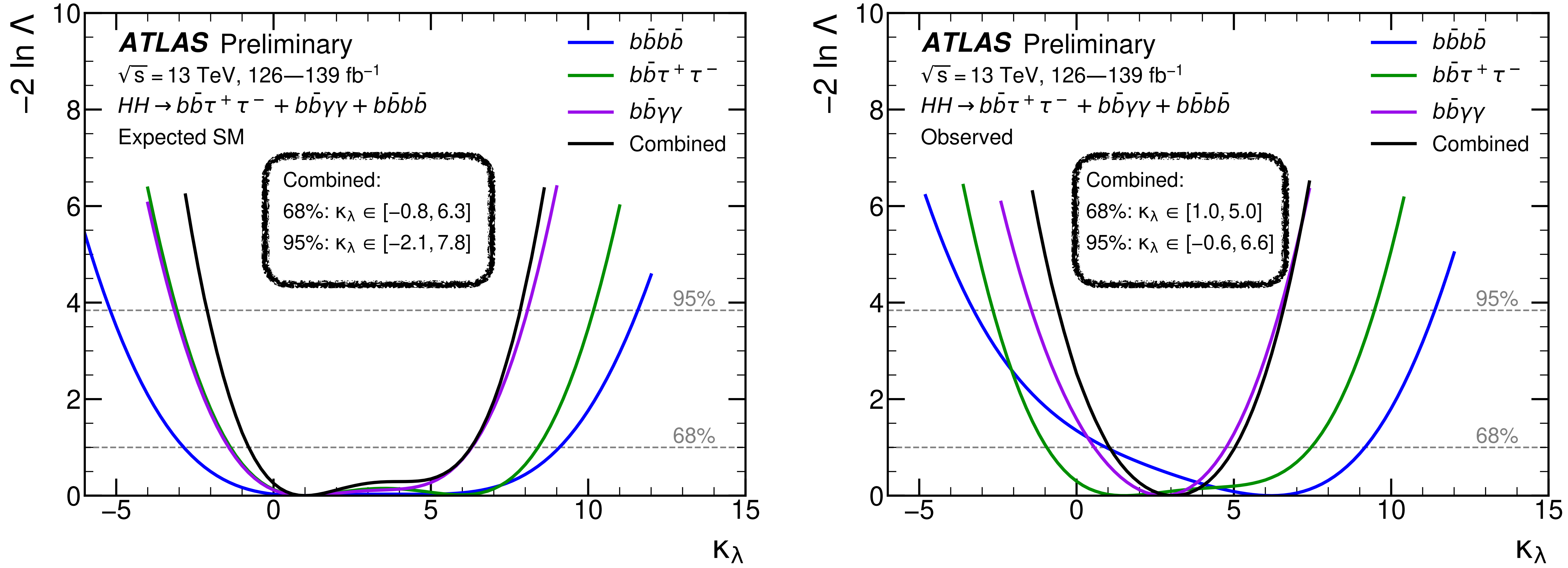

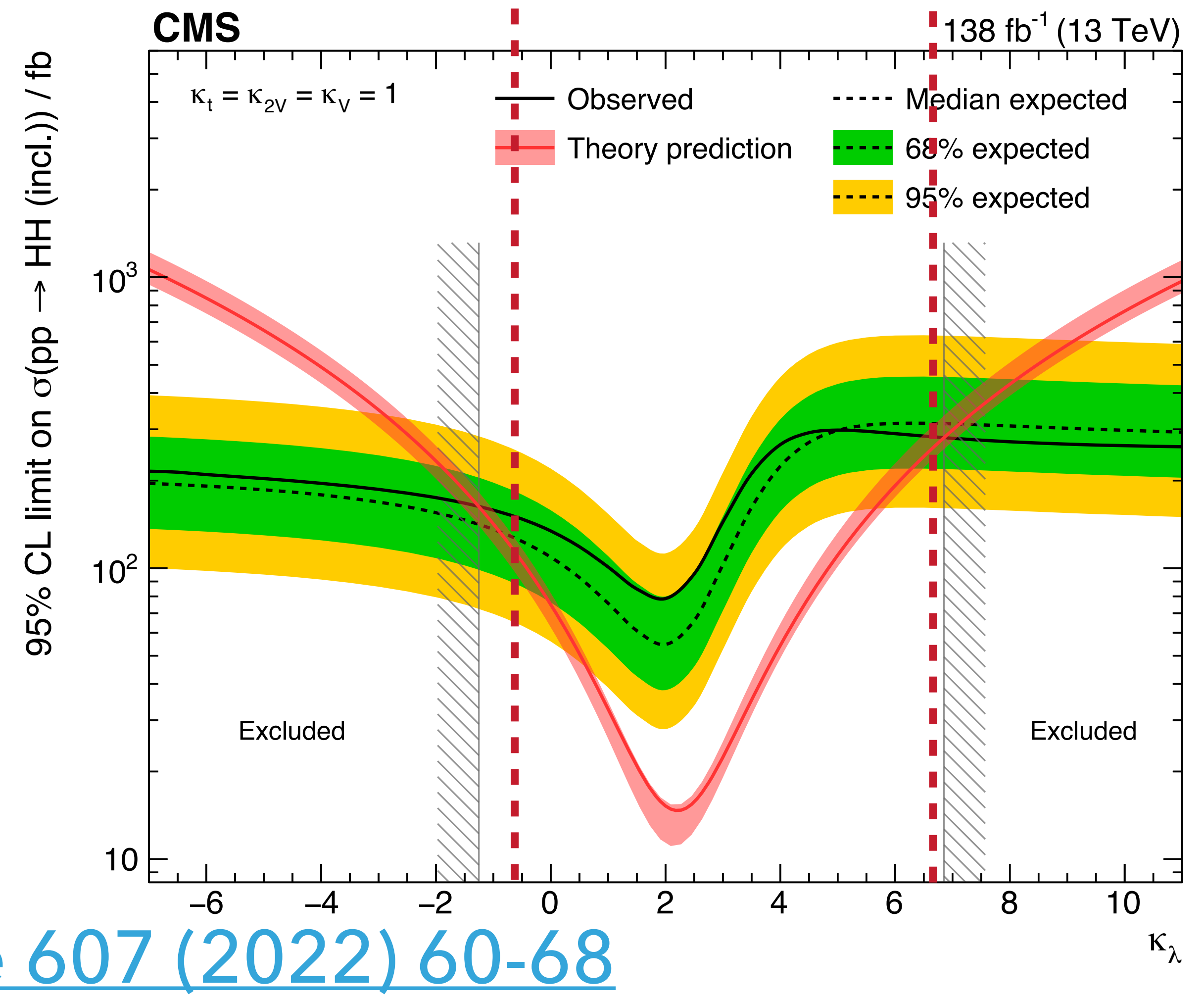

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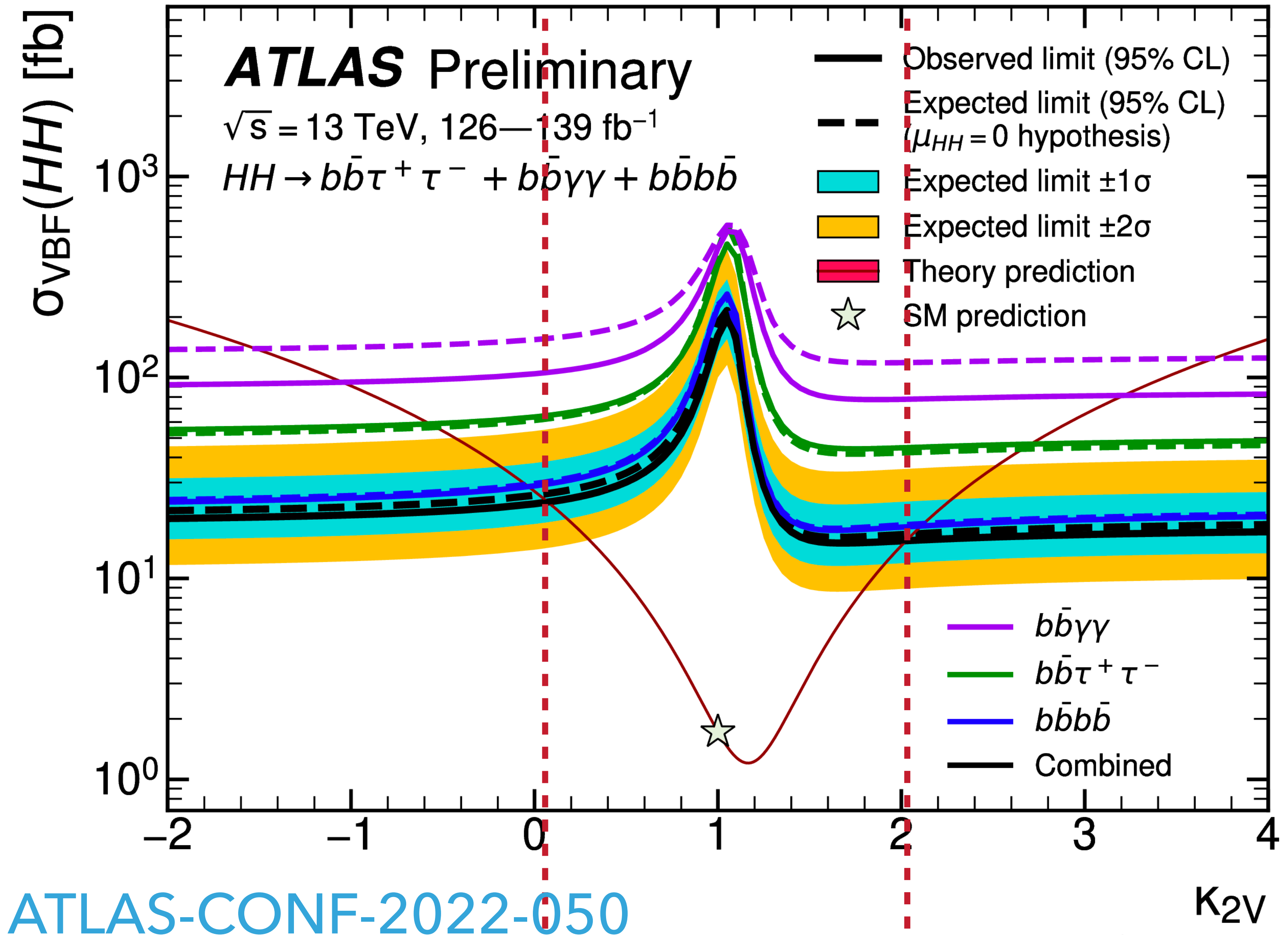
- Shape of $\sigma_{HH}(\kappa_\lambda)$ exclusion limit are determined by $A \times \epsilon$ and kinematic dependence on κ_λ
- Most sensitive: $bb\gamma\gamma$ due to low m_{HH}
- 2.4 times better κ_λ limit than 36 fb^{-1} [ATLAS HH combination](#)
- Compatible with CMS

Combined HH results (κ_{2V})



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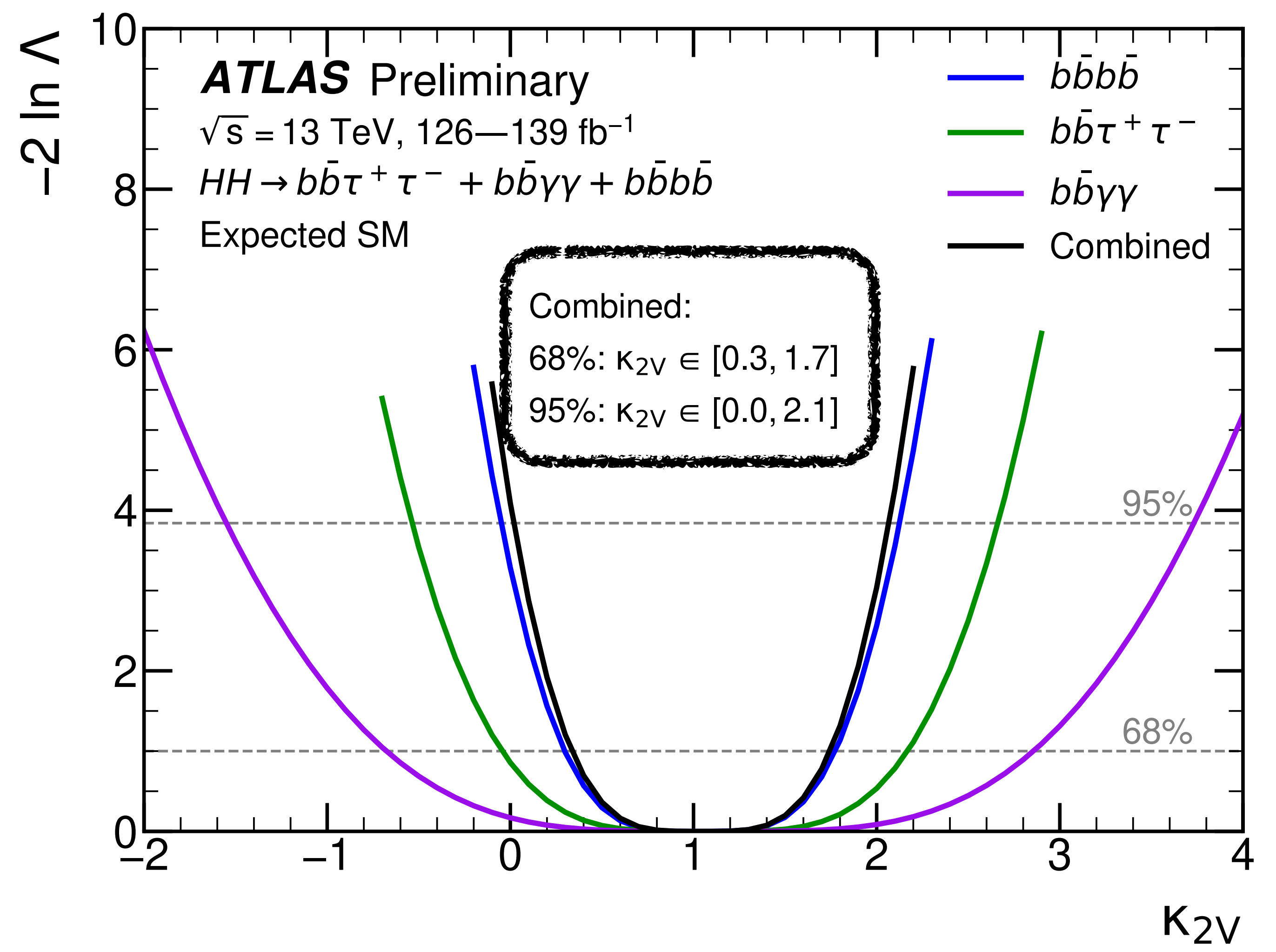

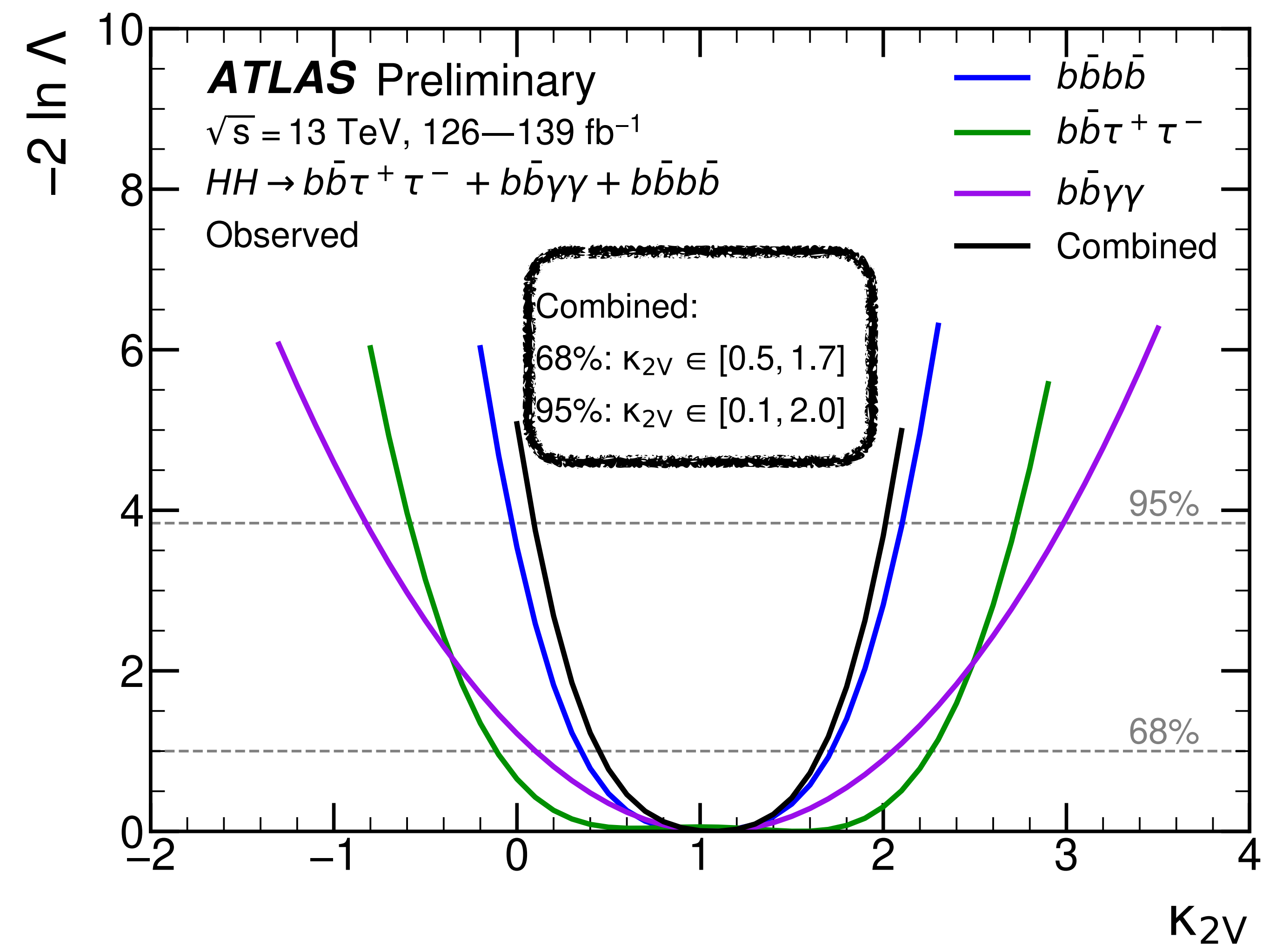

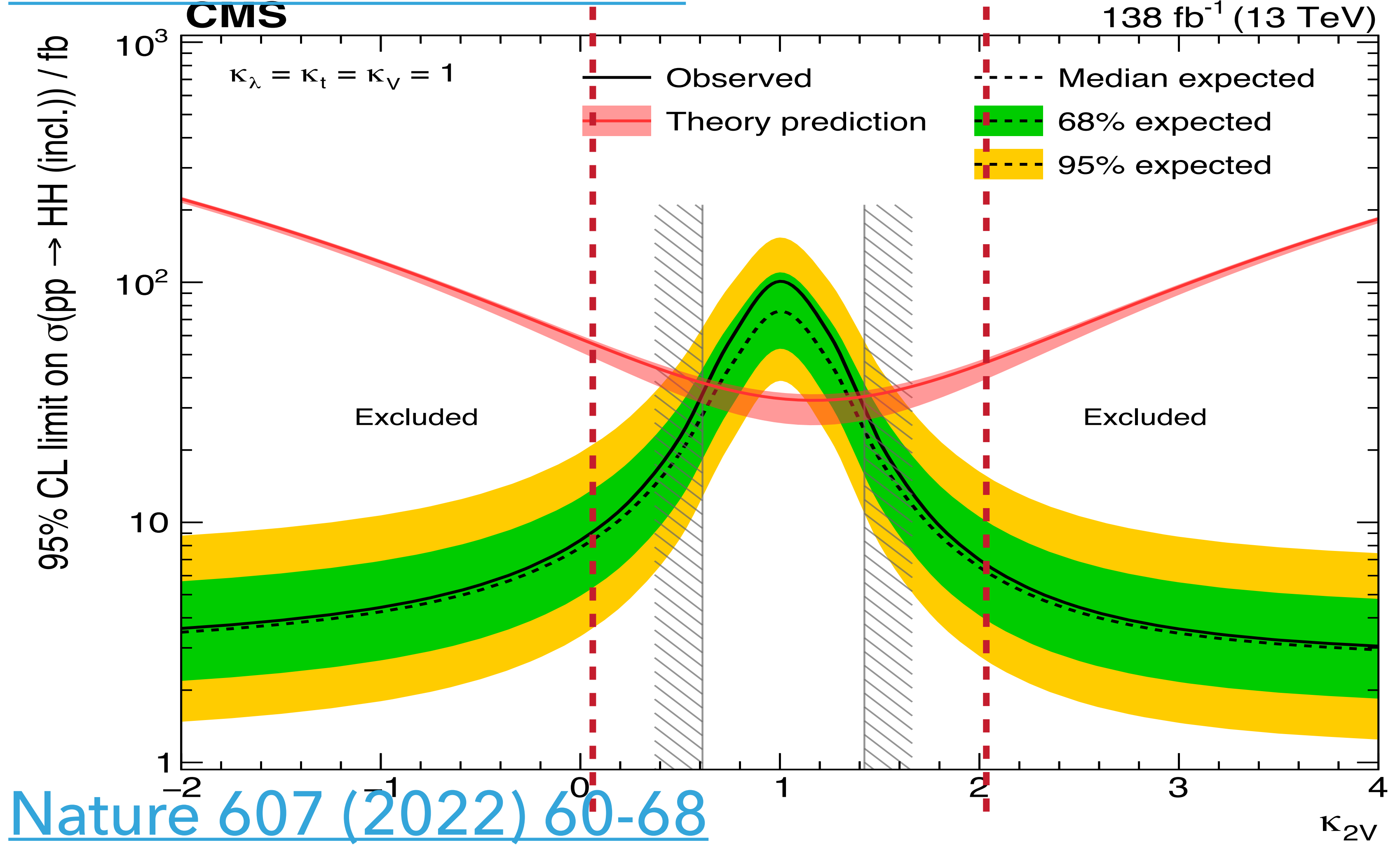

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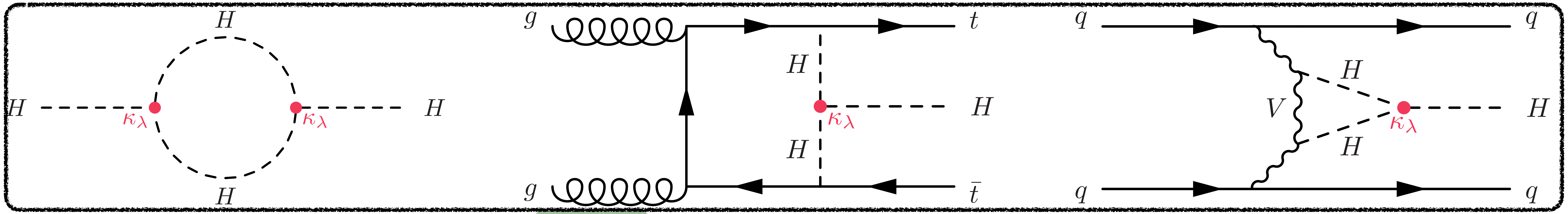
- VBF is sensitive to $HHVV$ interaction, constrain κ_{2V} first time in combination
- Most sensitive: $bbbb$
- CMS ([0.67, 1.38]) is ~2.7 times better and exclude $\kappa_{2V} = 0$ with 6.6σ
  1. Dominantly contributed by boosted 4b
  2. Different assumption: SM ggF in ATLAS VS profile ggF+VBF in CMS → lower VBF sensitivity in ATLAS

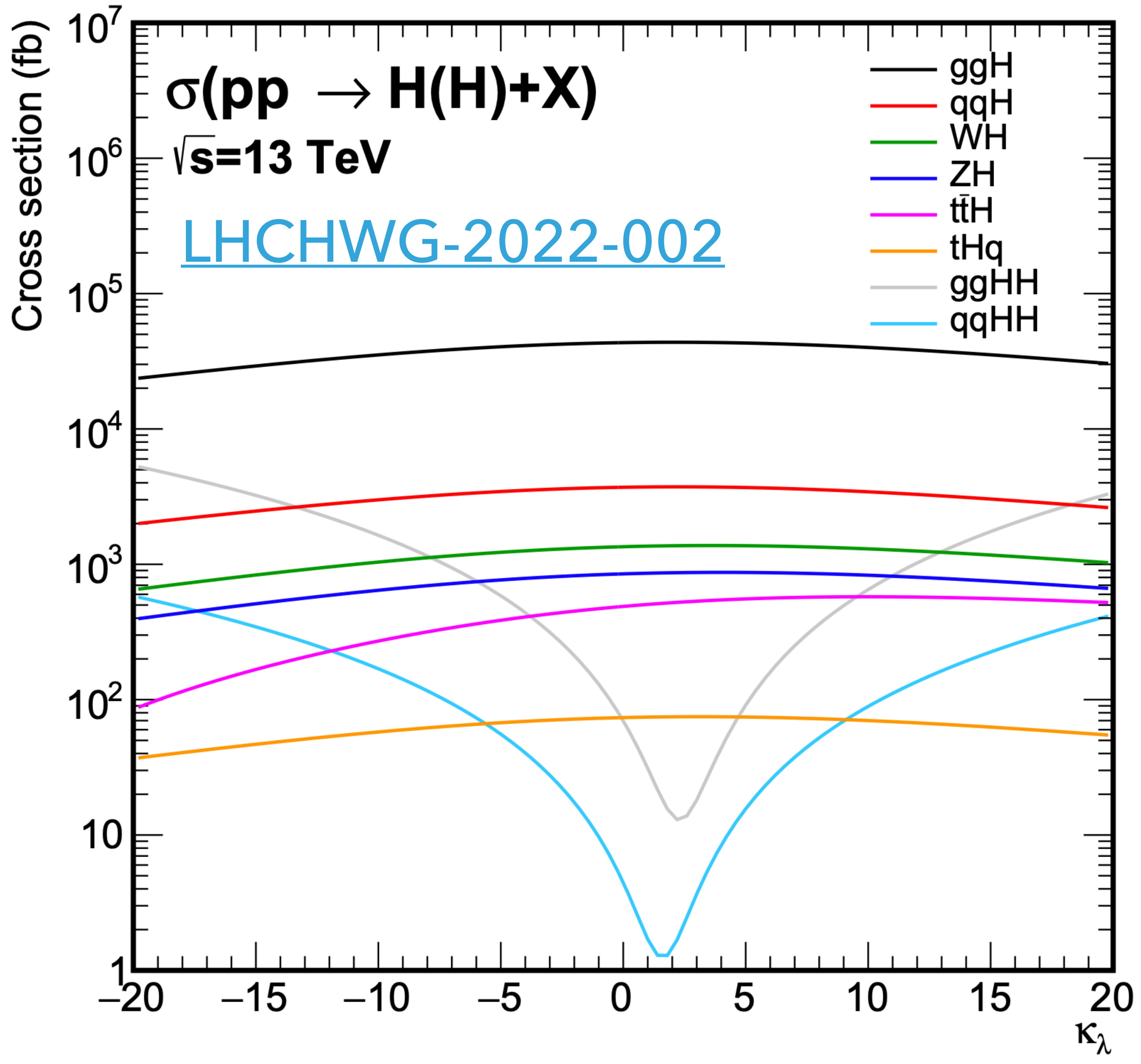
Single-/Double-Higgs combination

κ_λ interpretation on single Higgs productions

- κ_λ also contributes to single Higgs XS and BR via NLO EW corrections (complementary indirect approach)

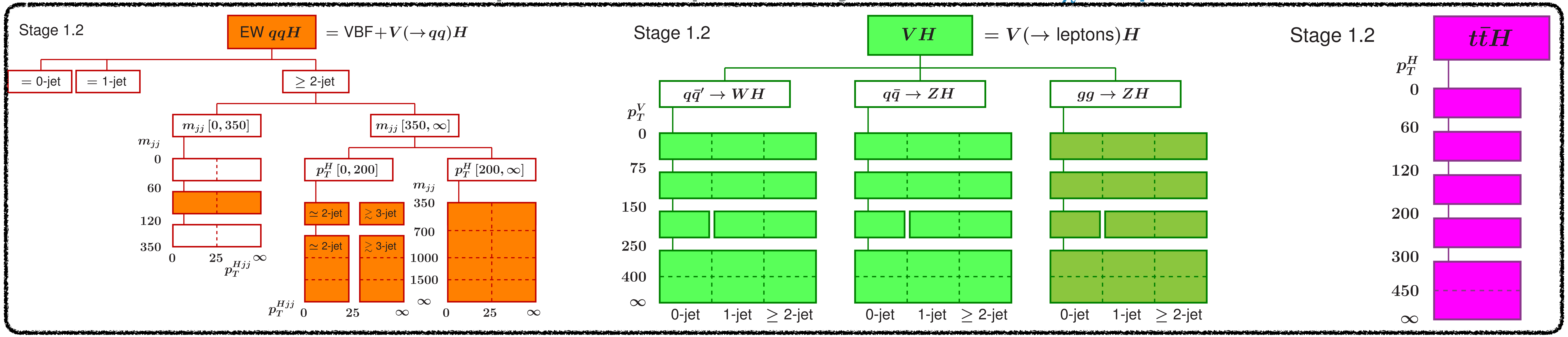


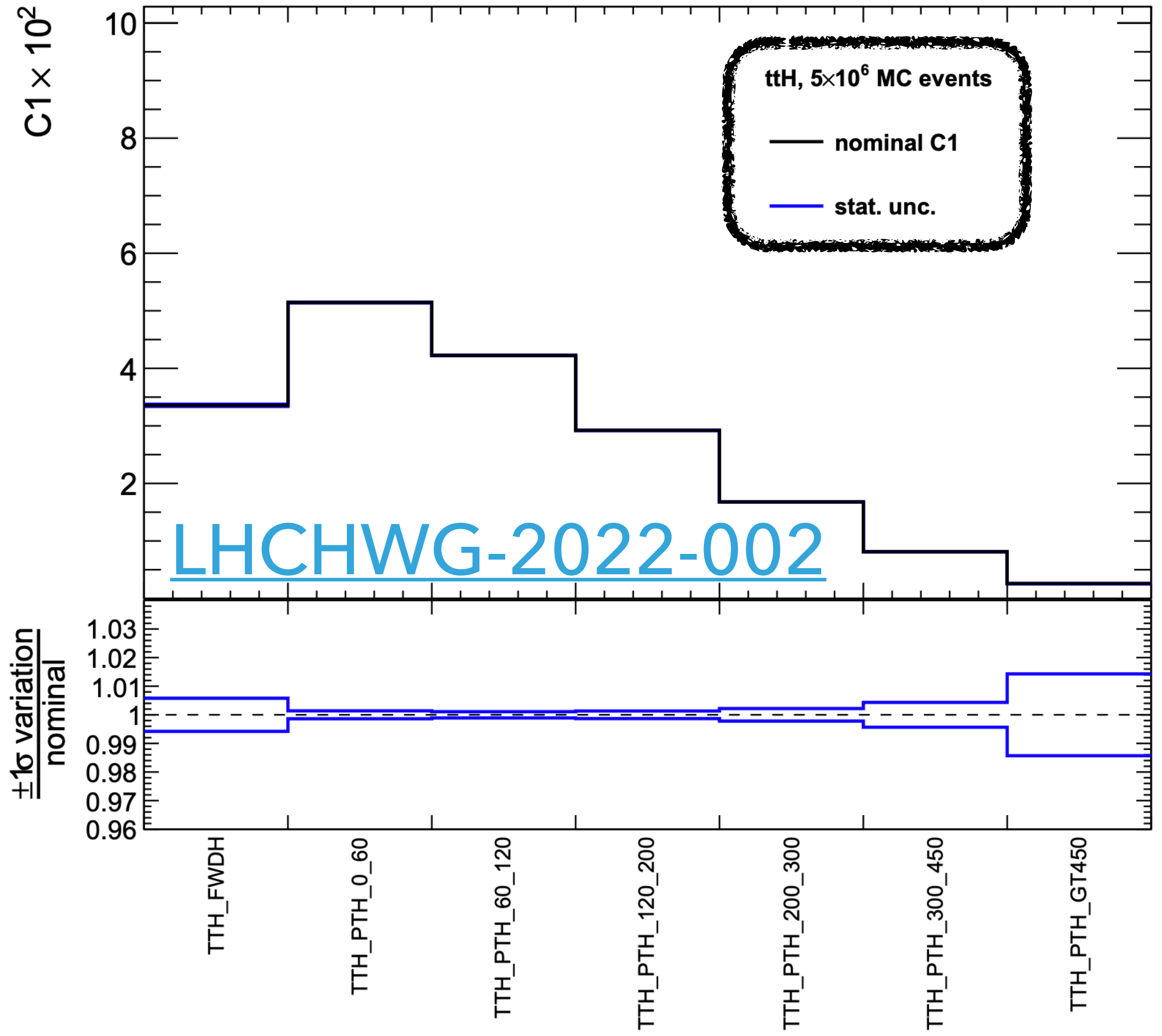
- $\mu_{if}(\kappa_\lambda) = \mu_i(\kappa_\lambda) \times \mu_f(\kappa_\lambda) \equiv \frac{\sigma_i(\kappa_\lambda)}{\sigma_i^{SM}} \times \frac{BR_f(\kappa_\lambda)}{BR_f^{SM}}$
  - $\mu_i(\kappa_\lambda, \kappa_i) = Z_H^{BSM}(\kappa_\lambda)\left[\kappa_i^2 + \frac{(\kappa_\lambda - 1)C_1^i}{K_{EW}^i}\right], Z_H^{BSM}(\kappa_\lambda) = \frac{1}{1-(\kappa_\lambda^2-1)\delta Z_H}$
  - $K_{EW}^i = \frac{\sigma_{NLO}^{SM,i}}{\sigma_{LO}^{SM,i}}$: full NLO EW correction
  - C_i^i: process and kinematic-dependent coefficient



Kinematic dependence of κ_λ on STXS

- Differential STXS are exploited to precisely describe κ_λ dependence





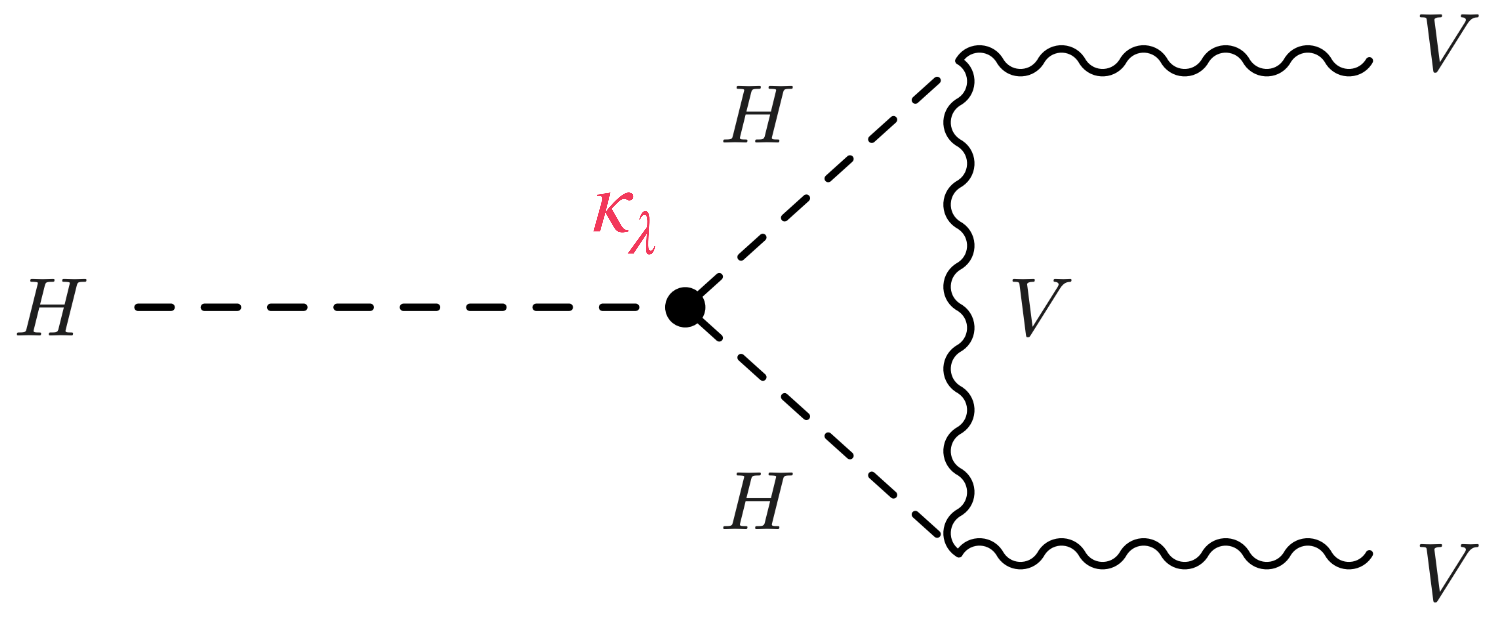
LHCHWG-2022-002

STXS BIN	K_{EW}
TTH_FWDH	1.017
TTH_PTH_0_60	1.041
TTH_PTH_60_120	1.025
TTH_PTH_120_200	1.002
TTH_PTH_200_300	0.978
TTH_PTH_300_450	0.956
TTH_PTH_GT450	0.923

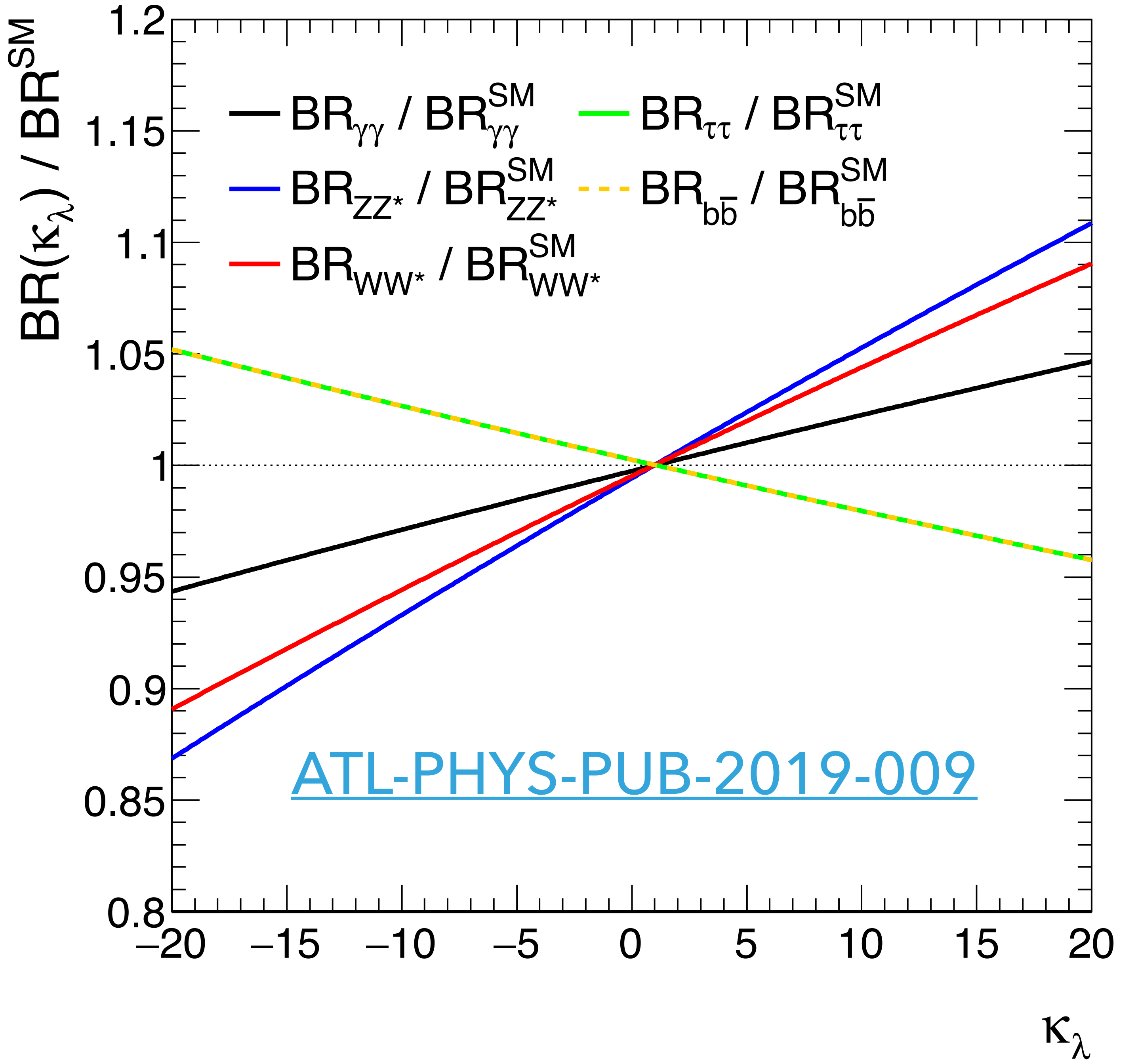
- ggF: only inclusive dependences on κ_λ are available

κ_λ interpretation on Higgs decays

- κ_λ corrections on Higgs decays



- $$\mu_f(\kappa_\lambda, \kappa_f) = \frac{BR_f(\kappa_\lambda)}{BR_f^{SM}} = \frac{\kappa_f^2 + (\kappa_\lambda - 1)C_1^f}{\sum_j BR_j^{SM}[\kappa_j^2 + (\kappa_\lambda - 1)C_1^j]}$$



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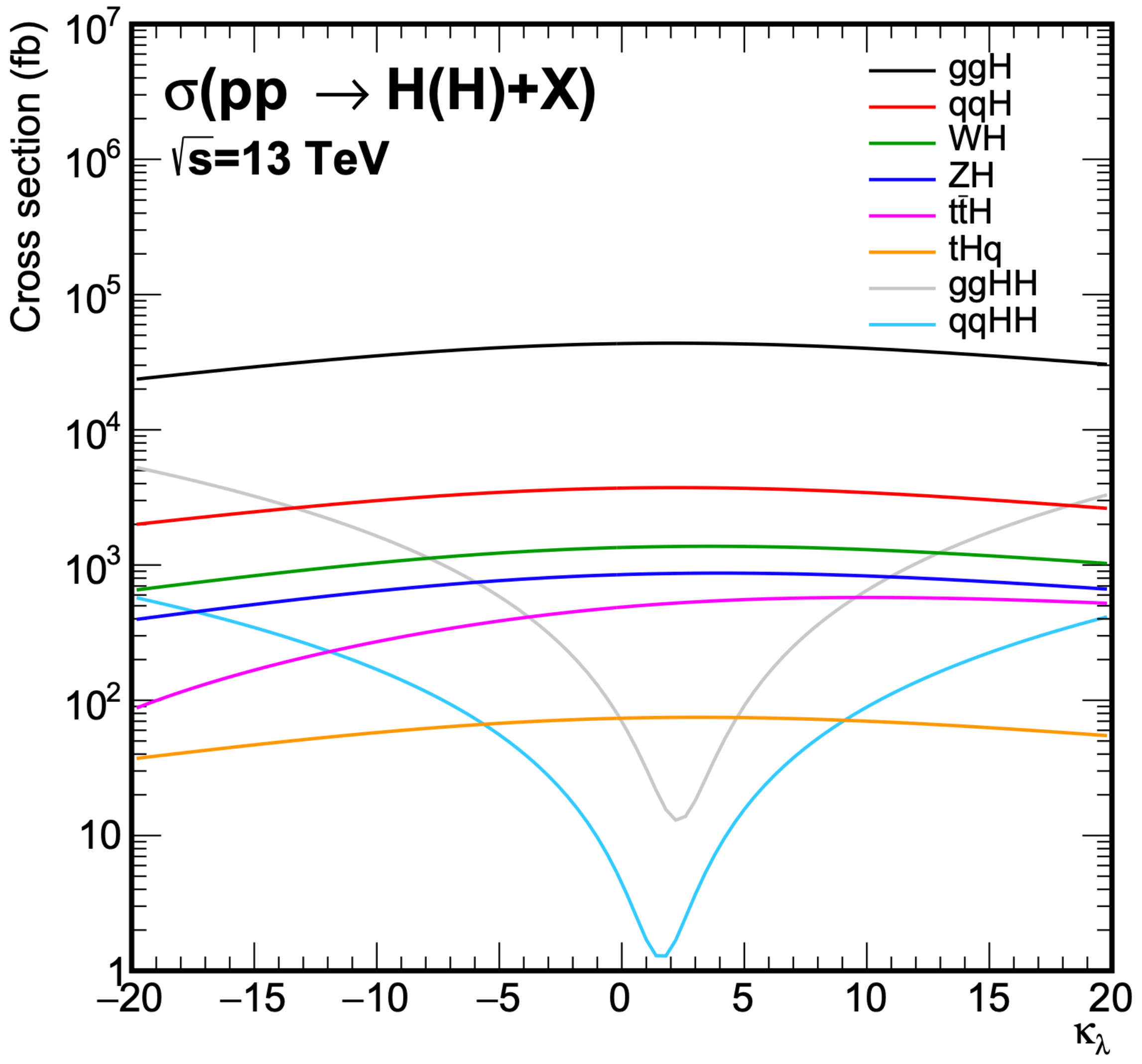
decay mode	$H \to \gamma\gamma$	$H \to WW^*$	$H \to ZZ^*$	$H \to b\bar{b}$	$H \to \tau\tau$
$C_1^f \times 100$	0.49	0.73	0.82	0	0
κ_f^2	$1.59\kappa_V^2 + 0.07\kappa_F^2 - 0.67\kappa_V\kappa_F$	κ_V^2	κ_V^2	κ_F^2	κ_F^2

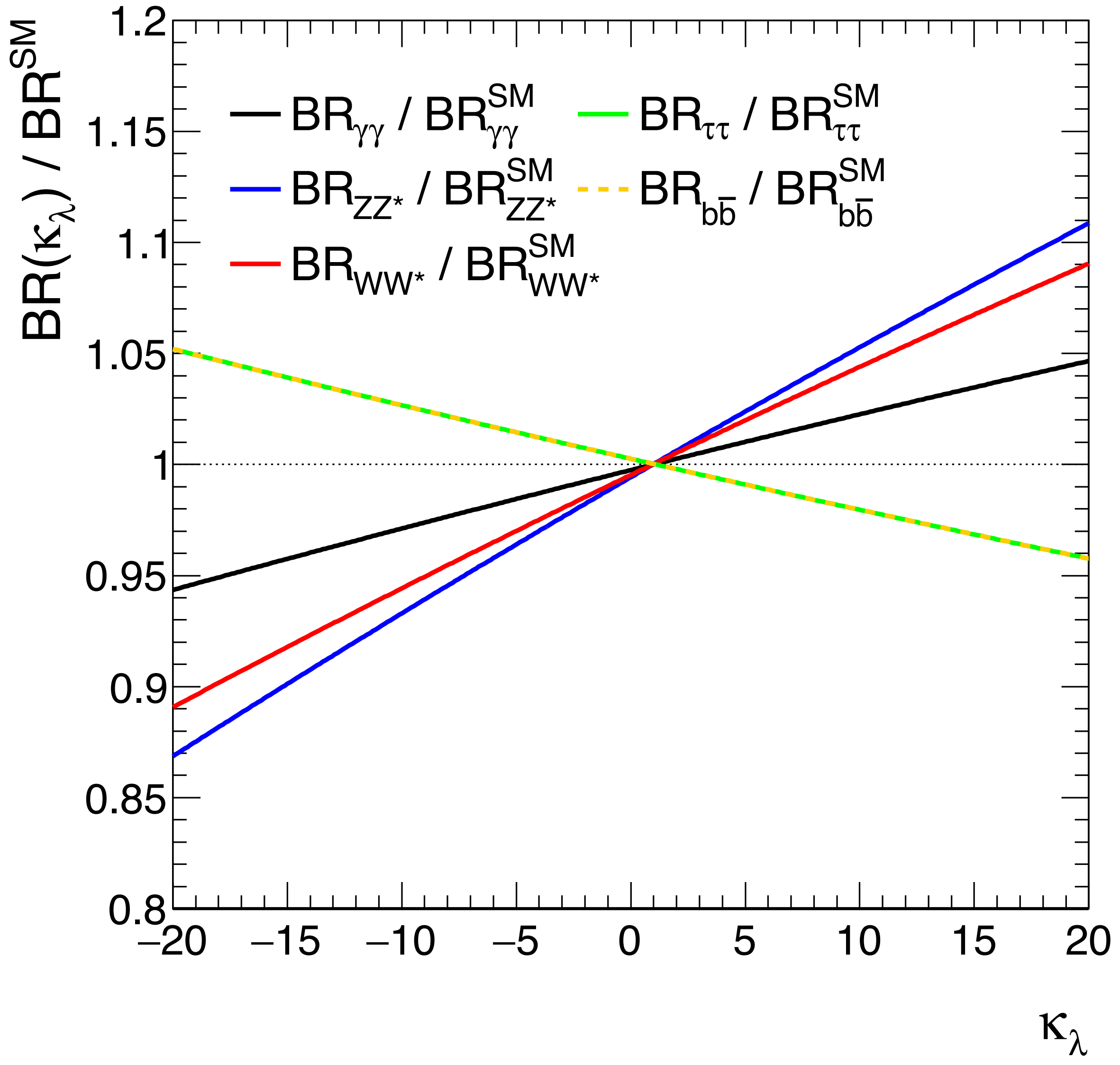
- The κ_λ dependence of $A \times \epsilon$ was evaluated to be negligible in single Higgs
  - Only single Higgs XS/BR are parameterized

Combine with single Higgs

- Combine single- and double-Higgs to have more stringent constraints on κ_λ
- Comprehensive combination to relax assumptions on other Higgs couplings (κ_t, κ_V, etc.)

Channel	Integrated luminosity (fb^{-1})
$HH \to b\bar{b}\gamma\gamma$	139
$HH \to b\bar{b}\tau\bar{\tau}$	139
$HH \to b\bar{b}b\bar{b}$	126
$H \to \gamma\gamma$	139
$H \to ZZ^* \to 4\ell$	139
$H \to \tau^+\tau^-$ remove $ttH, H \to \tau\tau$ in combination	139
$H \to WW^* \to e\nu\mu\nu$ (ggF,VBF)	139
$H \to b\bar{b}$ (VH)	139
$H \to b\bar{b}$ (VBF)	126
$H \to b\bar{b}$ ($t\bar{t}H$)	139

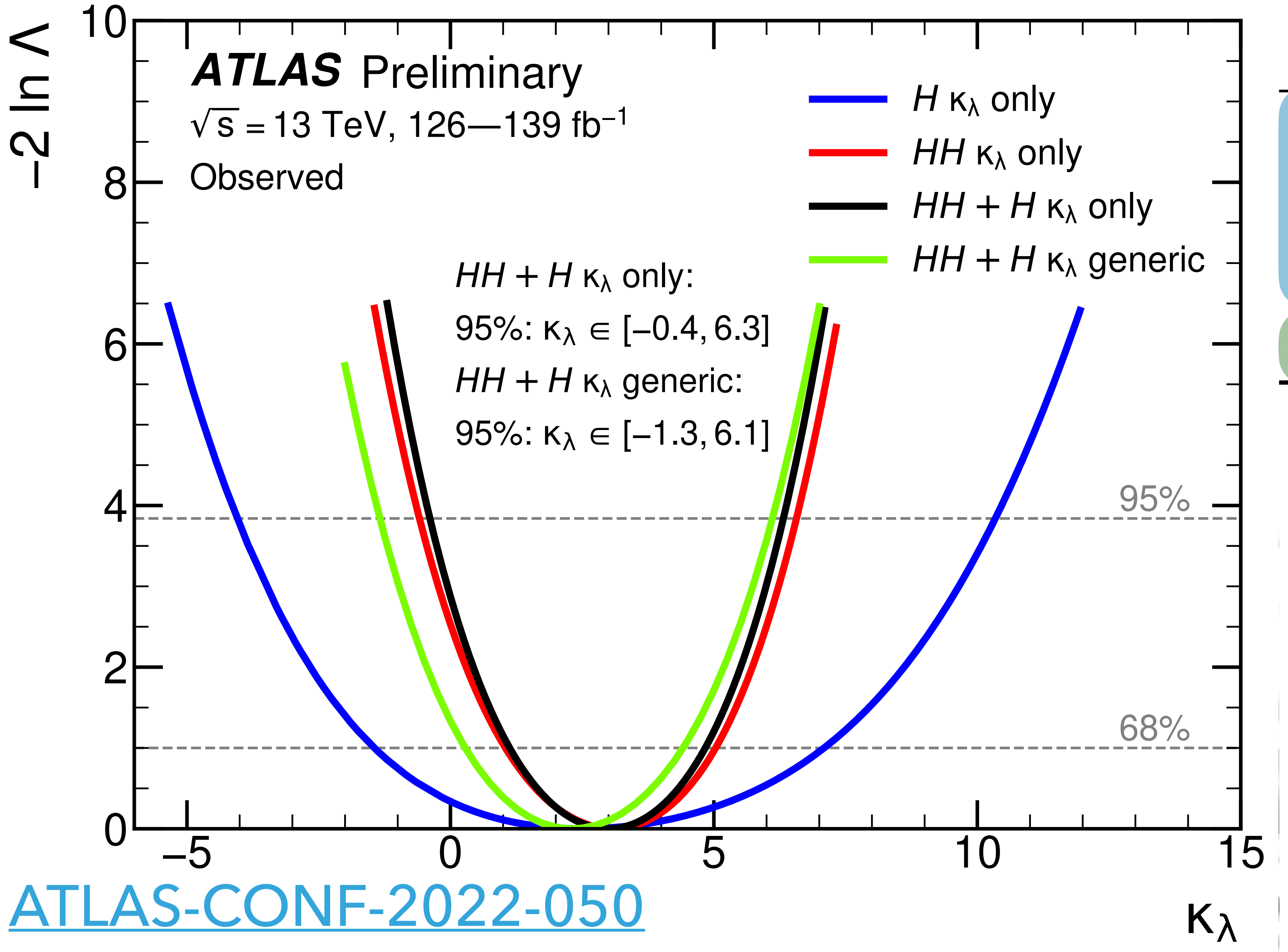




- Overlaps are mostly negligible between single-Higgs and double-Higgs
- Except 4% $HH \to bb\tau\tau$ SR events overlapping with $ttH, H \to \tau\tau$

  ➡ Remove $ttH, H \to \tau\tau$ categories (low sensitivity to κ_λ) in combination

H+HH combined results



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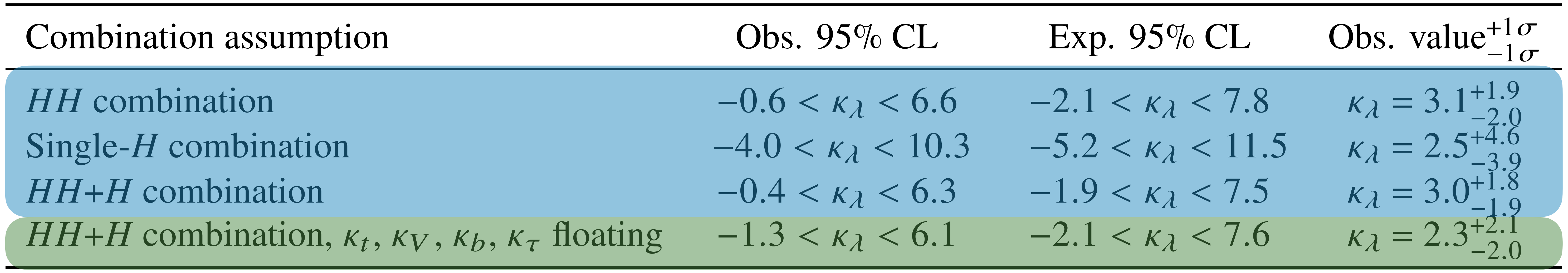
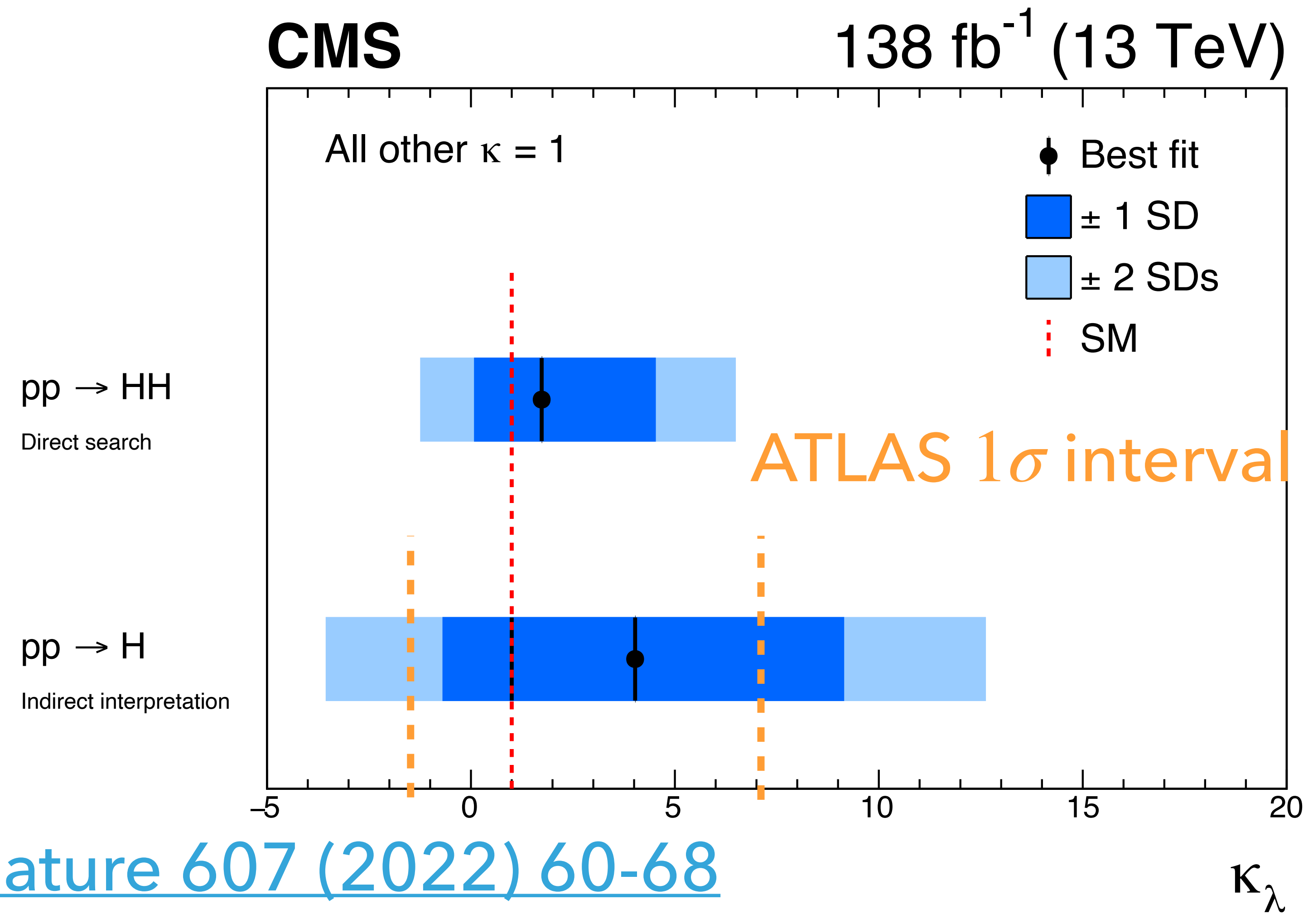


Combination assumption	Obs. 95% CL	Exp. 95% CL	Obs. value$^{+1\sigma}_{-1\sigma}$
HH combination	$-0.6 < \kappa_\lambda < 6.6$	$-2.1 < \kappa_\lambda < 7.8$	$\kappa_\lambda = 3.1^{+1.9}_{-2.0}$
Single-*H* combination	$-4.0 < \kappa_\lambda < 10.3$	$-5.2 < \kappa_\lambda < 11.5$	$\kappa_\lambda = 2.5^{+4.6}_{-3.9}$
HH+*H* combination	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.5$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
HH+*H* combination, κ_t, κ_V, κ_b, κ_τ floating	$-1.3 < \kappa_\lambda < 6.1$	$-2.1 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 2.3^{+2.1}_{-2.0}$

- Compatible single-Higgs κ_λ limit with CMS
- H+HH combination provides the most stringent constraints
  - Exp. κ_λ only limit is 5% better than HH (most sensitive), 78% better than H
- Most generic model (κ_λ, κ_V, κ_t, κ_b, κ_τ) with less model dependences can only be investigated in H+HH and still gives strong constraints on κ_λ



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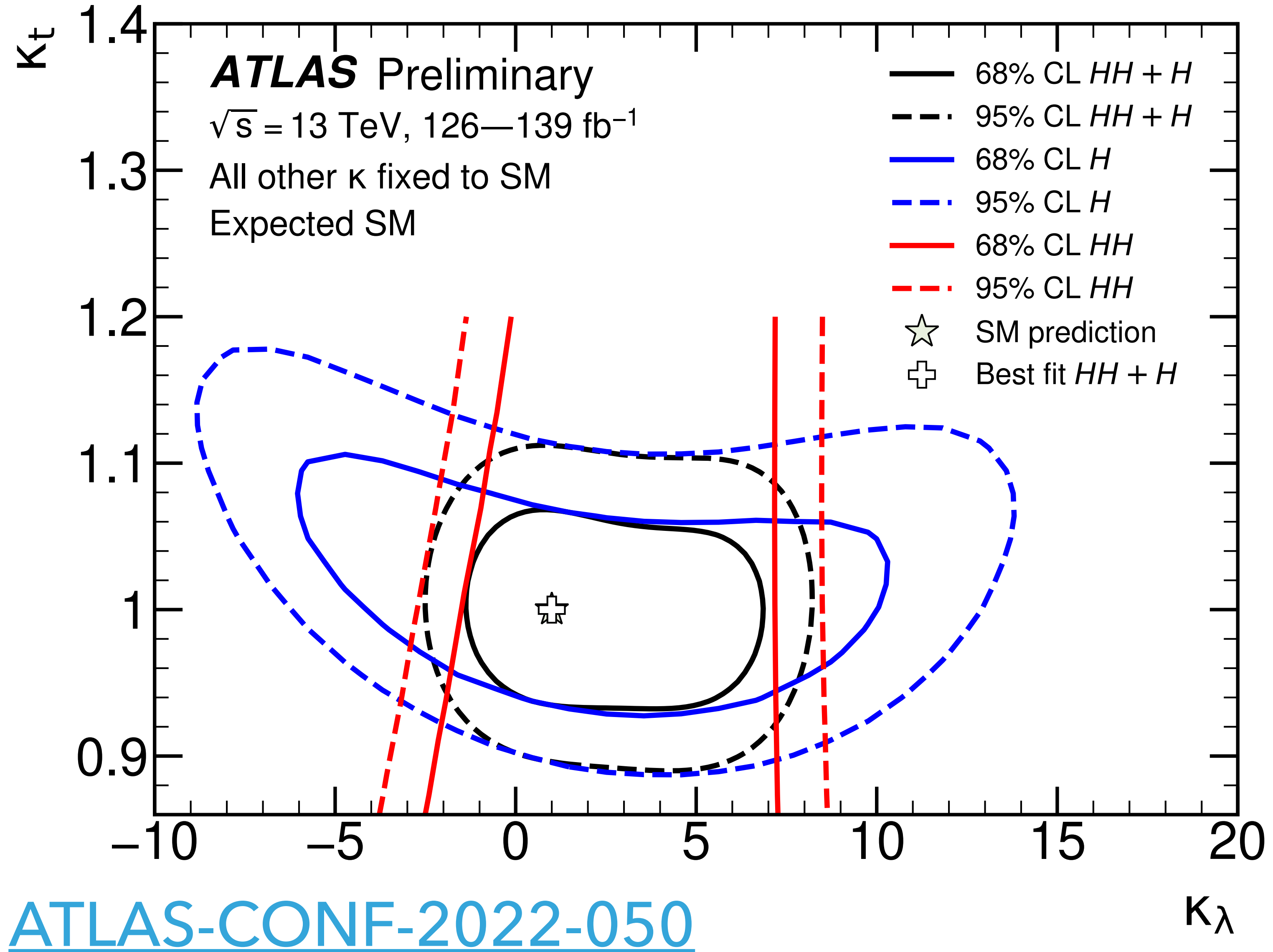
H+HH combined results ($\kappa_\lambda - \kappa_t$)



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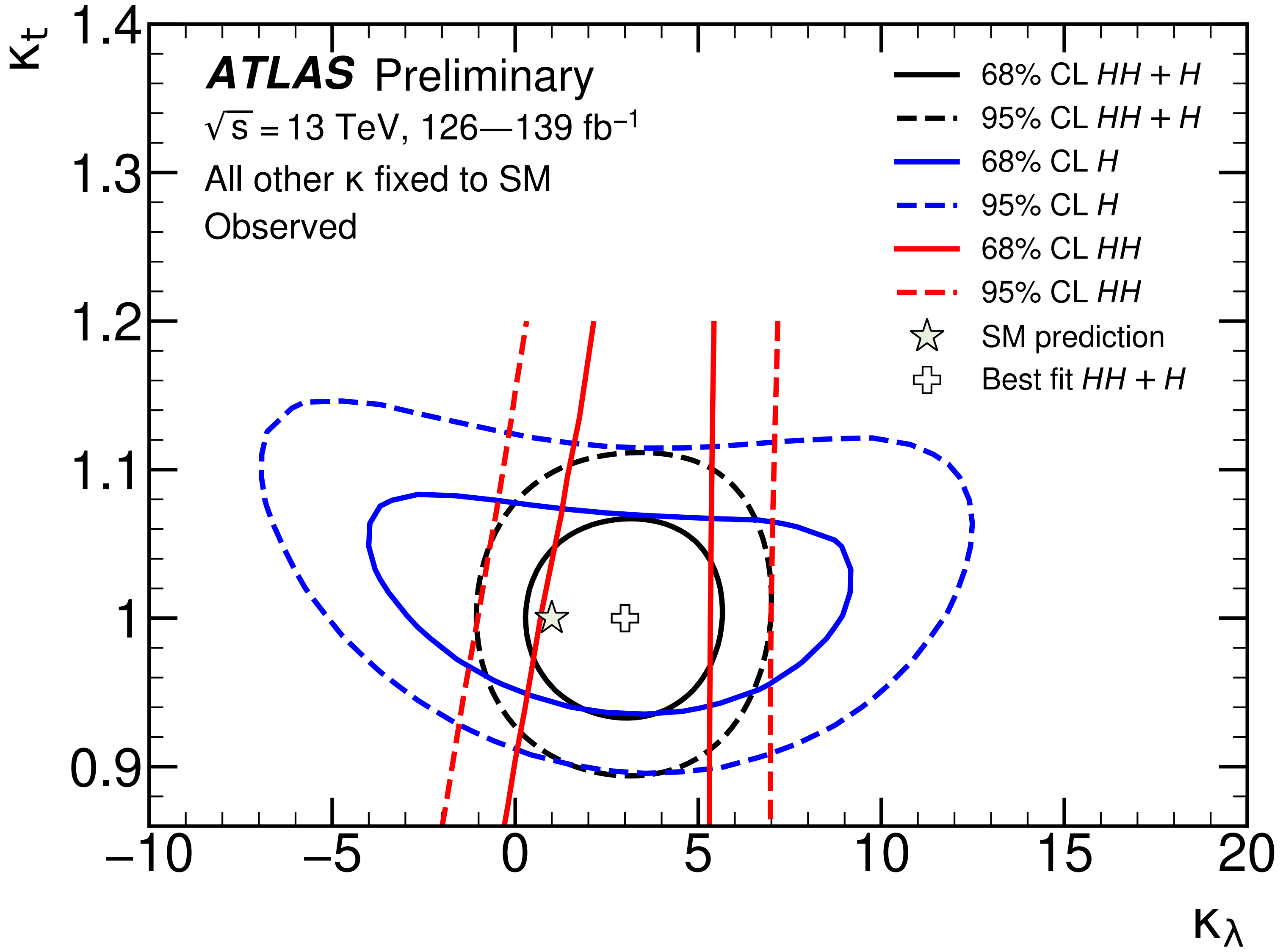


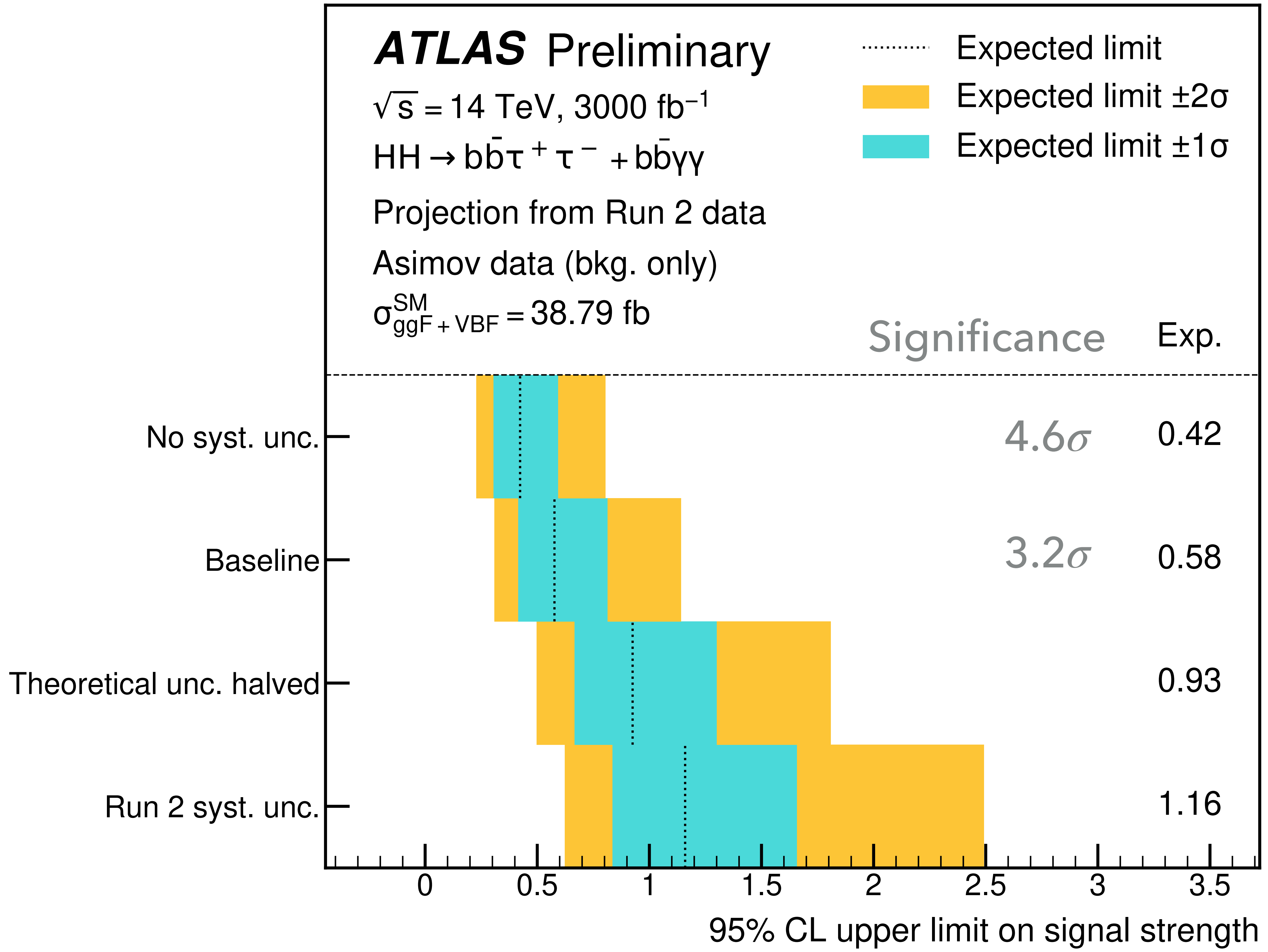
POIs	$\kappa_V{}^{+1\sigma}_{-1\sigma}$	$\kappa_t{}^{+1\sigma}_{-1\sigma}$	$\kappa_b{}^{+1\sigma}_{-1\sigma}$	$\kappa_\tau{}^{+1\sigma}_{-1\sigma}$	$\kappa_\lambda{}^{+1\sigma}_{-1\sigma}$	κ_λ [95% CL]	
κ_λ	1	1	1	1	$3.0^{+1.8}_{-1.9}$ $1.0^{+4.8}_{-1.7}$	$[-0.4, 6.3]$ $[-1.9, 7.5]$	Obs. Exp.
κ_λ-κ_t fit	1	$1.00^{+0.05}_{-0.04}$ $1.00^{+0.05}_{-0.04}$	1	1	$3.0^{+1.8}_{-1.9}$ $1.0^{+4.8}_{-1.7}$	$[-0.4, 6.3]$ $[-1.9, 7.6]$	Obs. Exp.
Generic fit	$1.00^{+0.05}_{-0.05}$ $1.00^{+0.05}_{-0.05}$	$0.93^{+0.07}_{-0.06}$ $1.00^{+0.07}_{-0.07}$	$0.90^{+0.12}_{-0.11}$ $1.00^{+0.12}_{-0.12}$	$0.93^{+0.08}_{-0.07}$ $1.00^{+0.08}_{-0.08}$	$2.3^{+2.1}_{-2.0}$ $1.0^{+5.0}_{-1.8}$	$[-1.3, 6.1]$ $[-2.1, 7.6]$	Obs. Exp.

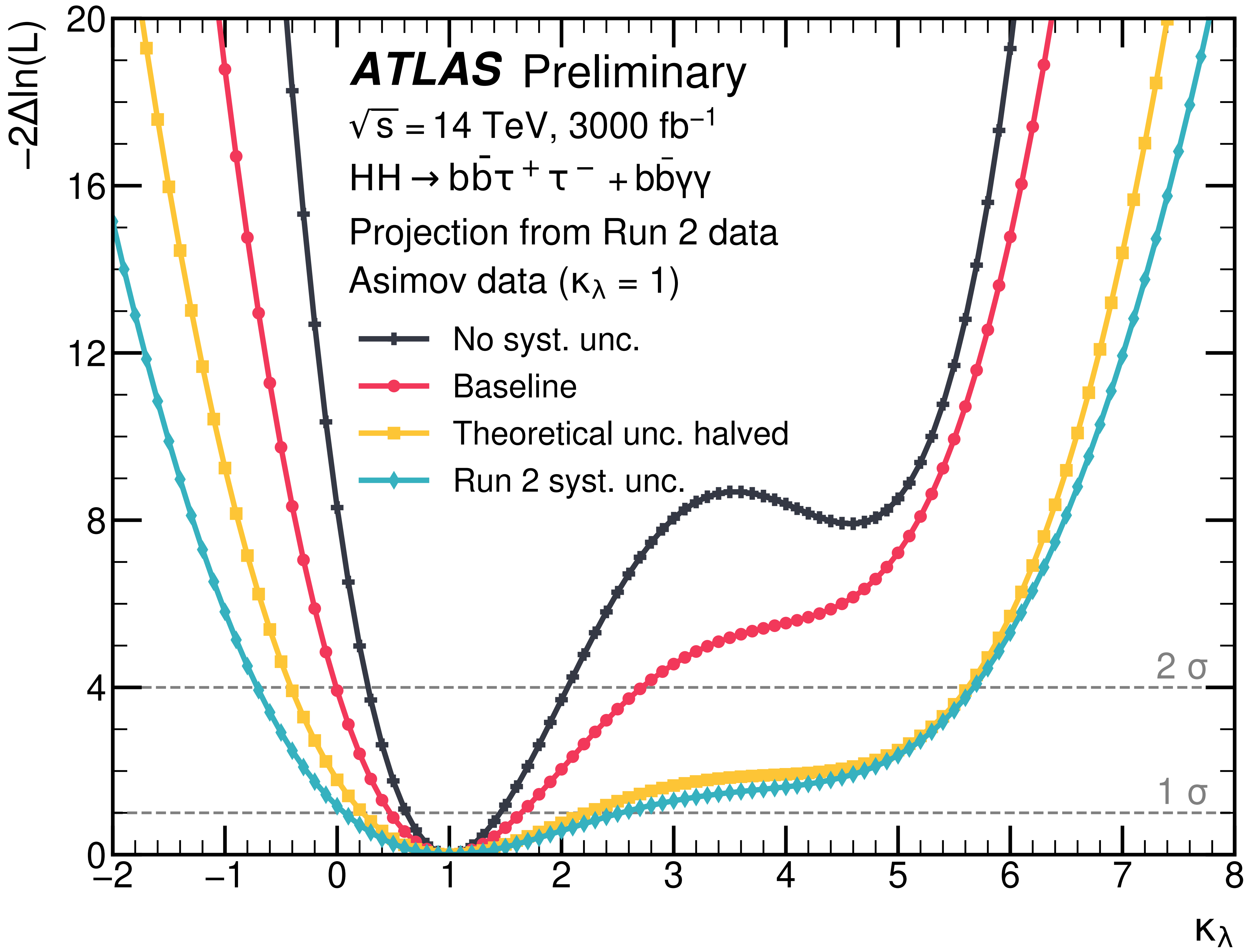
- HH only can't constrain κ_t, κ_λ simultaneously
- With single-Higgs, assumption on κ_t can be relaxed w/o losing κ_λ sensitivity

Summary

- Higgs self-interaction is important to understand the non trivial structure to Higgs potential, which originates EW symmetry breaking
  - Together with Yukawa coupling give elementary particles masses
- Di-Higgs is directly sensitive to self-coupling at LO, 3 most sensitive channels ($bbbb$, $bb\tau\tau$, $bb\gamma\gamma$) are combined to constrain κ_λ [ATLAS-CONF-2022-050]
  - 95% CL upper limit of μ_{HH} is 2.4 (2.9) x SM, 3.4 times better than 36 fb^{-1} HH combination
  - 95% CL interval of κ_λ is [-0.6, 6.6] ([-2.1, 7.8]), 2.4 times better than before
  - κ_{2V} is firstly constrained in HH combination: [0.1, 2.0] ([0.0, 2.1])
- κ_λ also contributes to single Higgs via NLO EW corrections, combine with HH to have more stringent constraints on κ_λ and to relax assumptions on other Higgs couplings
  - κ_λ limit [-0.4, 6.3] ([-1.9, 7.5]) is 5% better than HH alone (most sensitive)
  - HH only can't constrain κ_t, κ_λ simultaneously, with single Higgs both can be measured w/o losing κ_λ sensitivity
  - Most generic model (κ_λ, κ_V, κ_t, κ_b, κ_τ) with can only be investigated in H+HH and still gives strong constraints on κ_λ
- Looking forward to improving measurement precision of Higgs self-interaction in Run3 and HL-LHC!

HL-LHC projection combing $bb\tau\tau + bb\gamma\gamma$ [ATL-PHYS-PUB-2022-005]





Uncertainty scenario	Likelihood scan $1\,\sigma$ CI	Likelihood scan $2\,\sigma$ CI
No syst. unc.	$[0.6, 1.5]$	$[0.3, 2.1]$
Baseline	$[0.5, 1.6]$	$[0.0, 2.7]$

Backup

Thanks a lot!

Kinematic dependence

- κ_λ and κ_{2V} dependences on HH XS, $A \times \epsilon$ and kinematics are considered