李政道研究所
Tsung-Dao Lee Institute

上海交通大學
SHANGHAI JIAO TONG UNIVERSITY

Constraining the Higgs boson self-coupling from single- and double-Higgs production with the ATLAS detector using *pp* collision data *at* $\sqrt{s}$=13 TeV

Changqiao Li

SJTU/TDLI

中国物理学会高能物理分会第十一届全国会员代表大会暨学术年会

Aug 11th, 2022

Introduction

- Higgs at 10: interaction with the fermions and vector bosons (μ, τ, **b, W, Z, t**) are precisely studied
- Higgs self-interaction is also crucial
  - Probe of the shape of the Higgs potential

$$V = V_0 + \lambda v^2 h^2 + \lambda v h^3 + \frac{\lambda}{4} h^4$$
$$= V_0 + \frac{1}{2} m_h^2 h^2 + \frac{m_h^2}{2v^2} v h^3 + \frac{1}{4} \frac{m_h^2}{2v^2} h^4$$

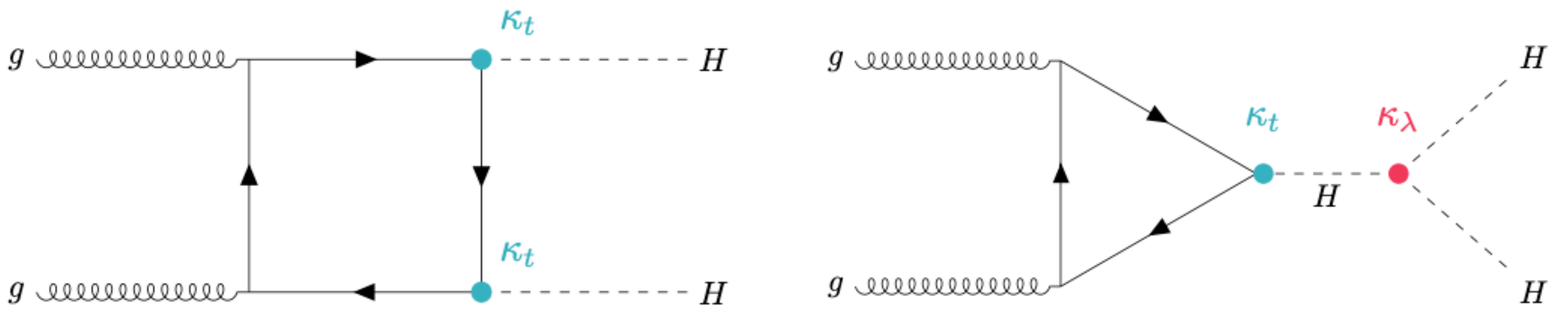
$$\lambda_{hhh} = \frac{m_h^2}{2v^2}$$

  - Higgs boson self coupling λ = ~ 0.13 in SM prediction
  - $\kappa_\lambda = \kappa_3 = \frac{\lambda_{HHH}}{\lambda^{SM}_{HHH}}$ introduced to define the deviation of λ from the SM
  - The measurement of κ_λ is important for both studying the Higgs boson and probing physics Beyond the SM (BSM)

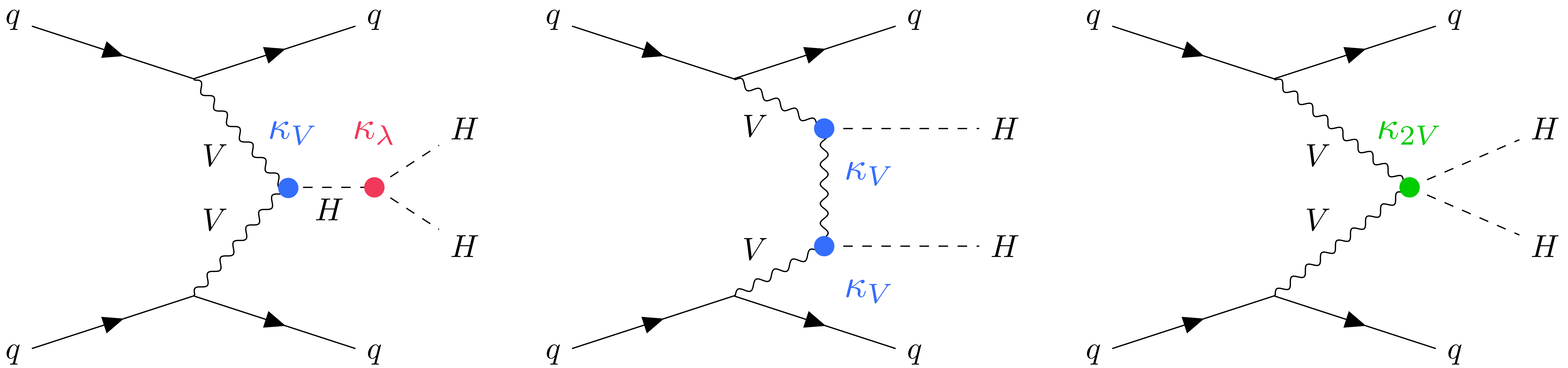
Where to measure κ_λ?

- Di-Higgs production provides a **direct** access to λ

ggF HH
31.05 fb



VBF HH
1.73 fb



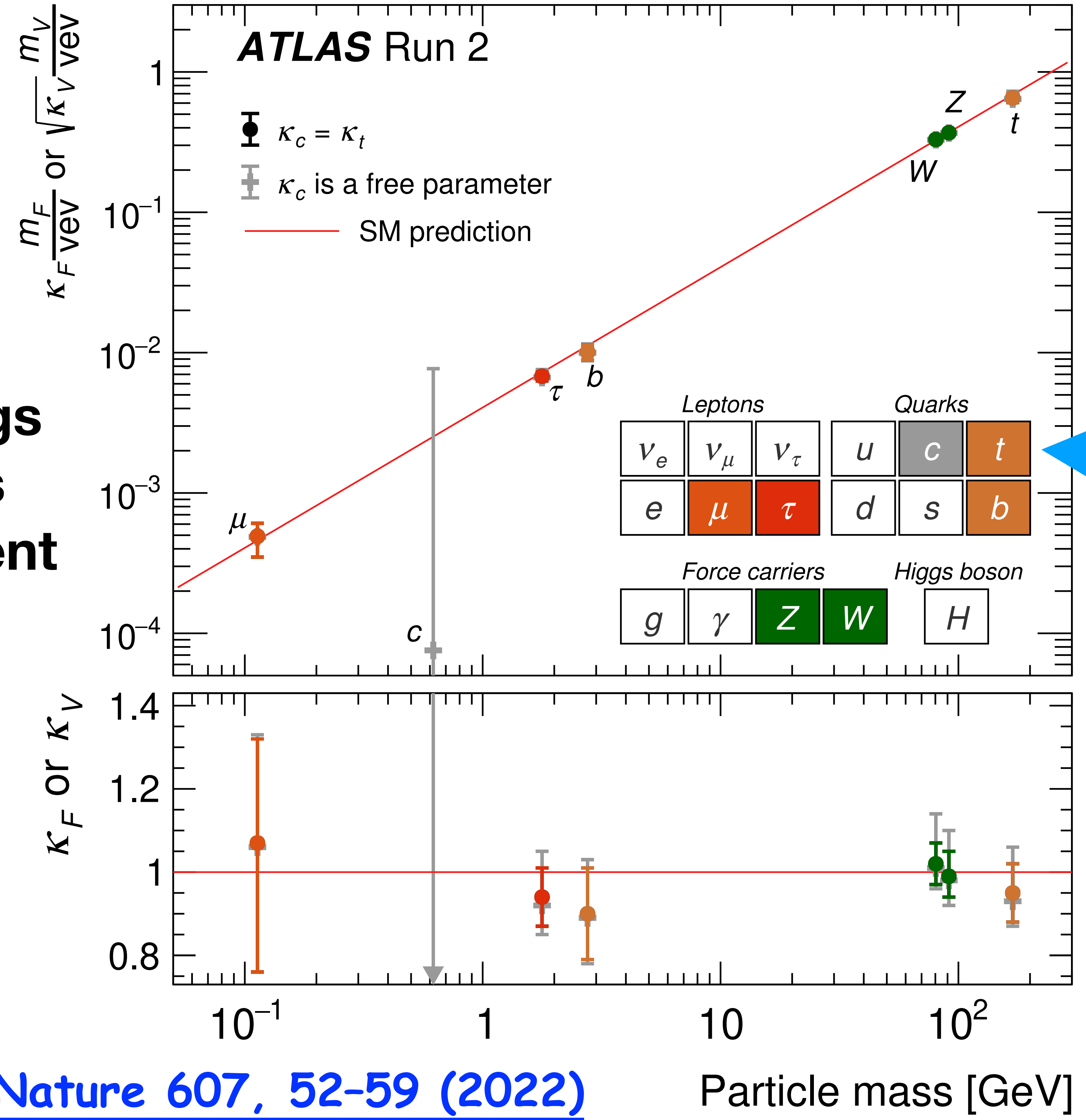
Also **other couplings** will get involved in the Di-Higgs measurement.

Which context of the measurement?

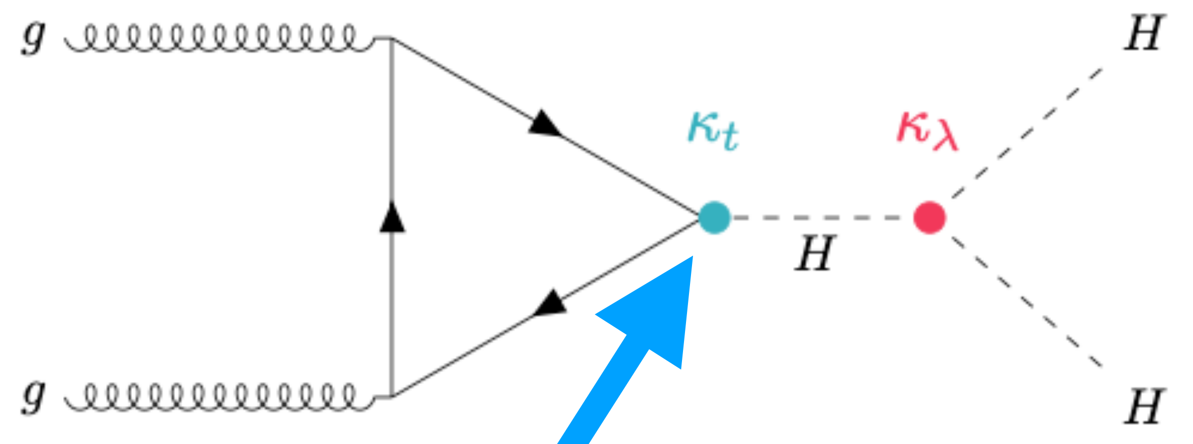
Assumption on BSM impact	Pros.	Cons.
only alter κλ	feasible with Di-Higgs production	other couplings as SM assumption
alter both κλ and other couplings	less model dependent	poor precision on κλ

generic model

single-Higgs couplings measurement



[Nature 607, 52-59 (2022)]



Constrained by introducing single-Higgs measurement

To have a self contained measurement

κλ impact on Single-Higgs should be considered as well

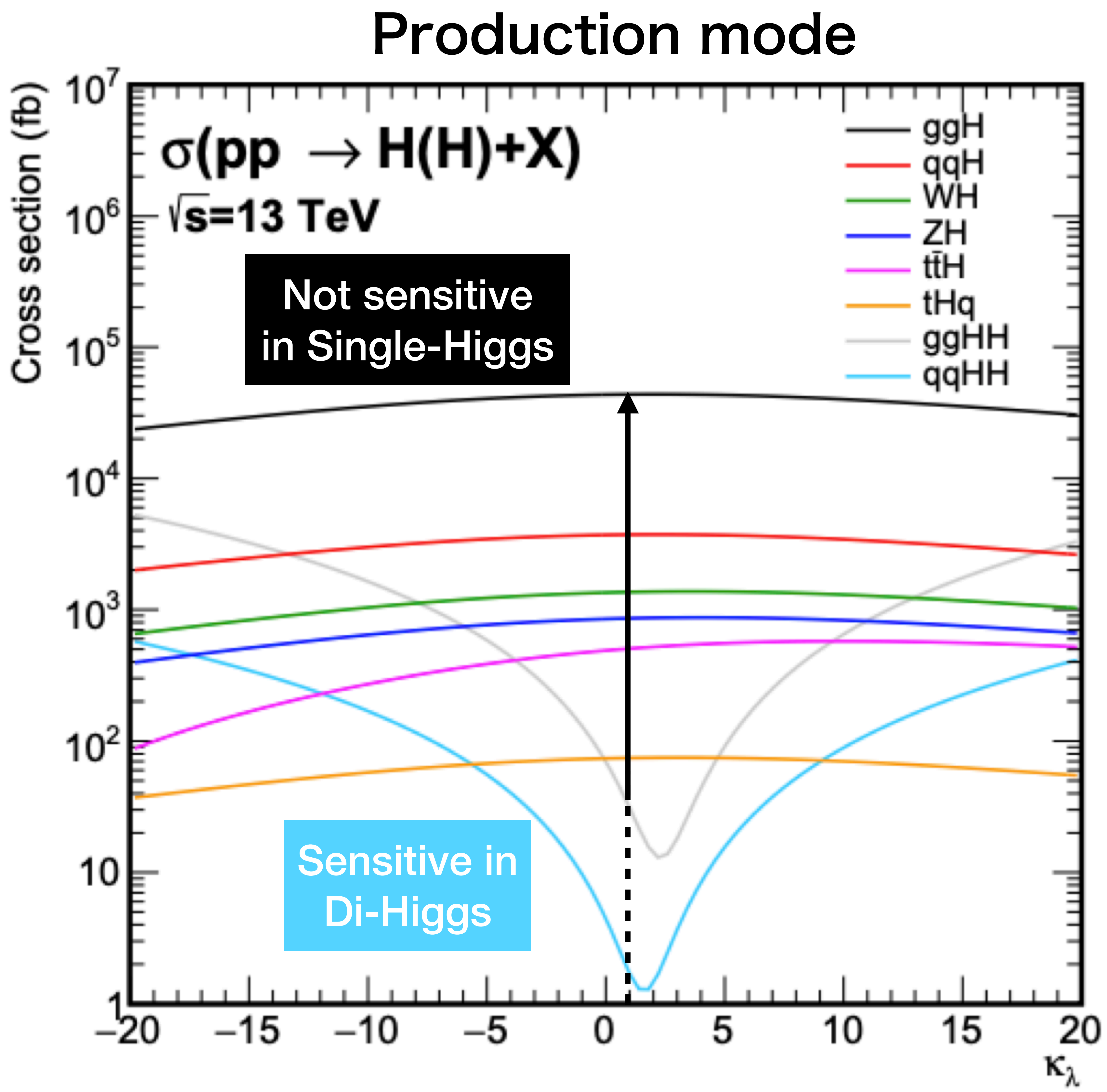
κλ impact on Single-Higgs

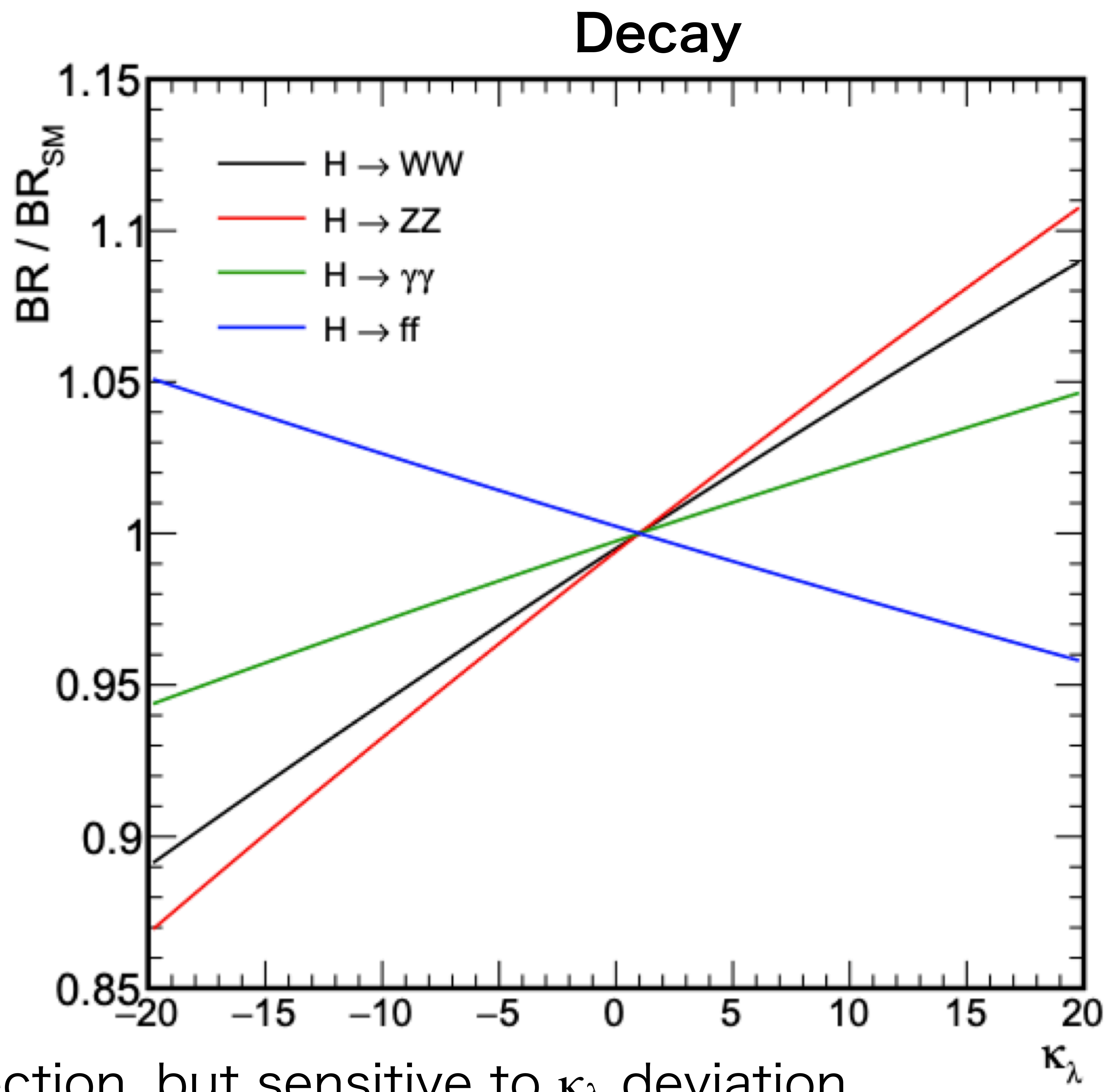
Production mode | **Decay**

- Self-coupling makes impacts as **NLO** EW correction

JHEP 1612, 080 (2016)
Eur. Phys. J. C (2017) 77: 887

Impacts on Production and Decay





- Though HH has much less production cross-section, but sensitive to κ_λ deviation

Fit input and statistical model

- Combining available Full Run 2 di-Higgs and single-Higgs analyses ATLAS-CONF-2022-050
- Build the likelihood by combining the likelihood from each individual channel

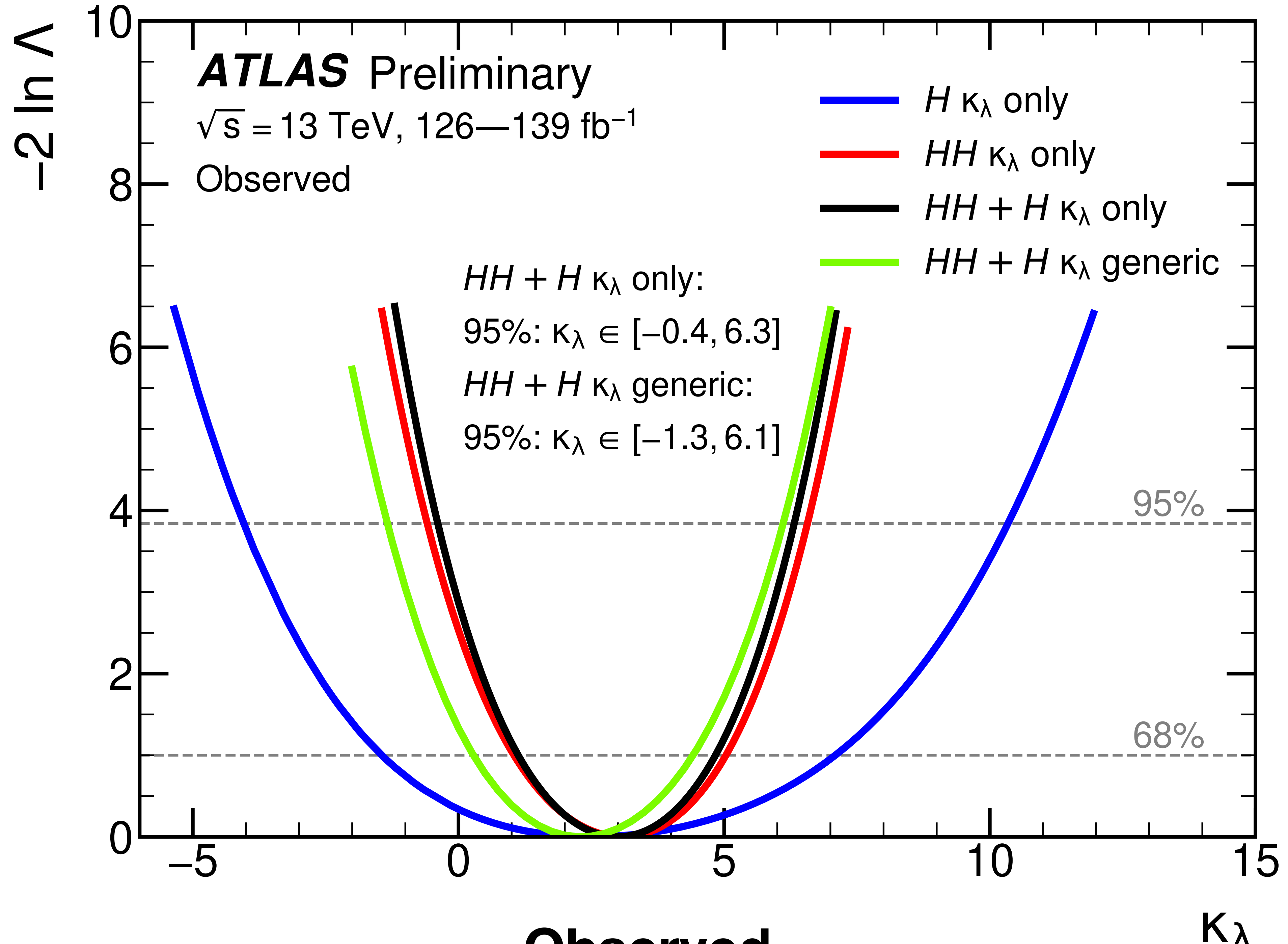
Channel	Integrated luminosity (fb^{-1})
$HH \to b\bar{b}\gamma\gamma$	139
$HH \to b\bar{b}\tau\bar{\tau}$	139
$HH \to b\bar{b}b\bar{b}$	126
$H \to \gamma\gamma$	139
$H \to ZZ^* \to 4\ell$	139
$H \to \tau^+\tau^-$	139
$H \to WW^* \to e\nu\mu\nu$ (ggF,VBF)	139
$H \to b\bar{b}$ (VH)	139
$H \to b\bar{b}$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

Full Run 2

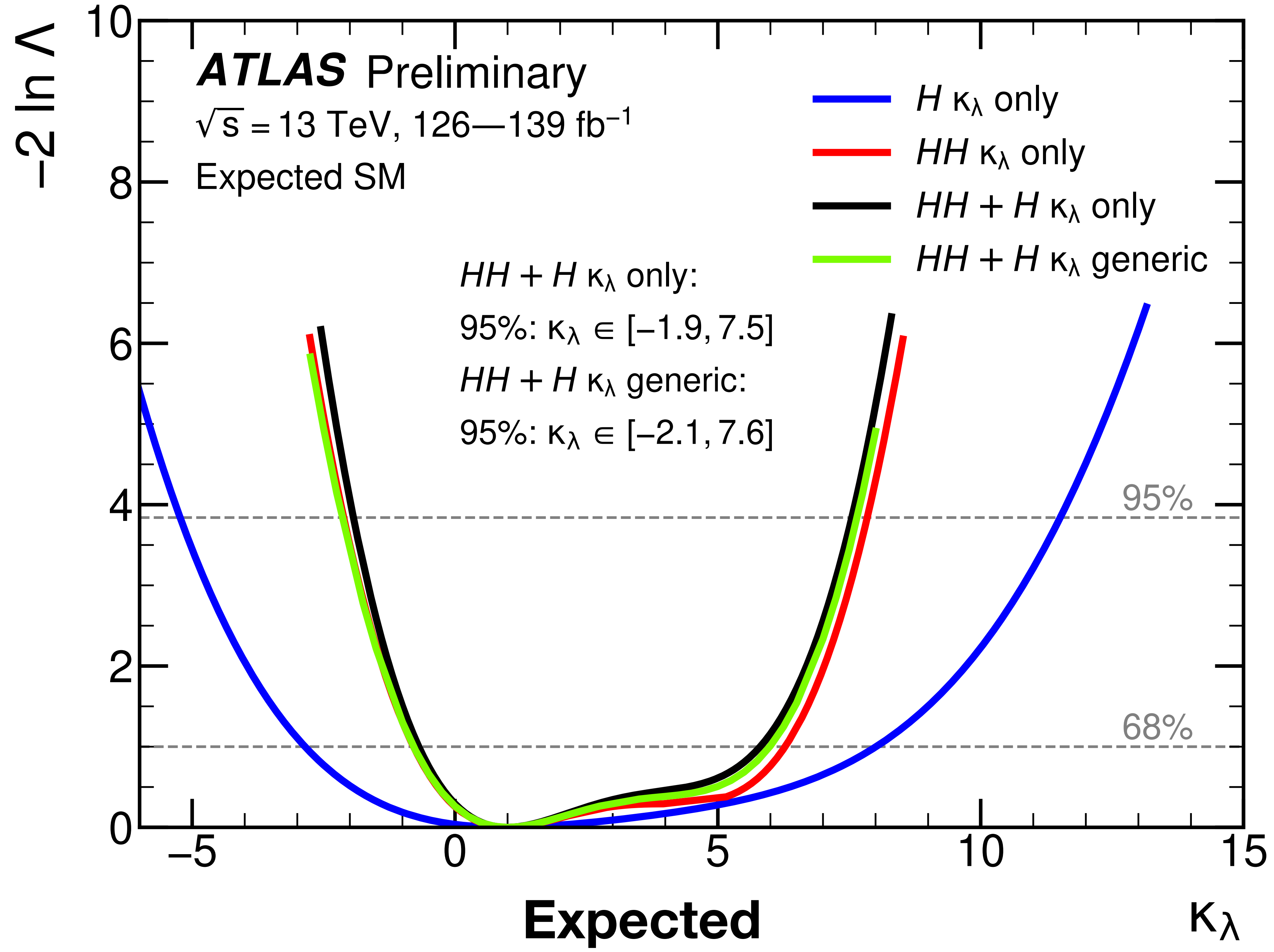
Results from κ_λ likelihood scans

- Likelihood scan as the function of κ_λ

ATLAS-CONF-2022-050



Observed



Expected

- **Di-Higgs** has much stronger constraining power than **Single-Higgs**
- Once single-Higgs and di-Higgs combined, constraining power in κ_λ **only model** is similar to **generic model** as other couplings well constrained by single-Higgs

Results from κ_λ likelihood scans

- Likelihood scan as the function of κ_λ

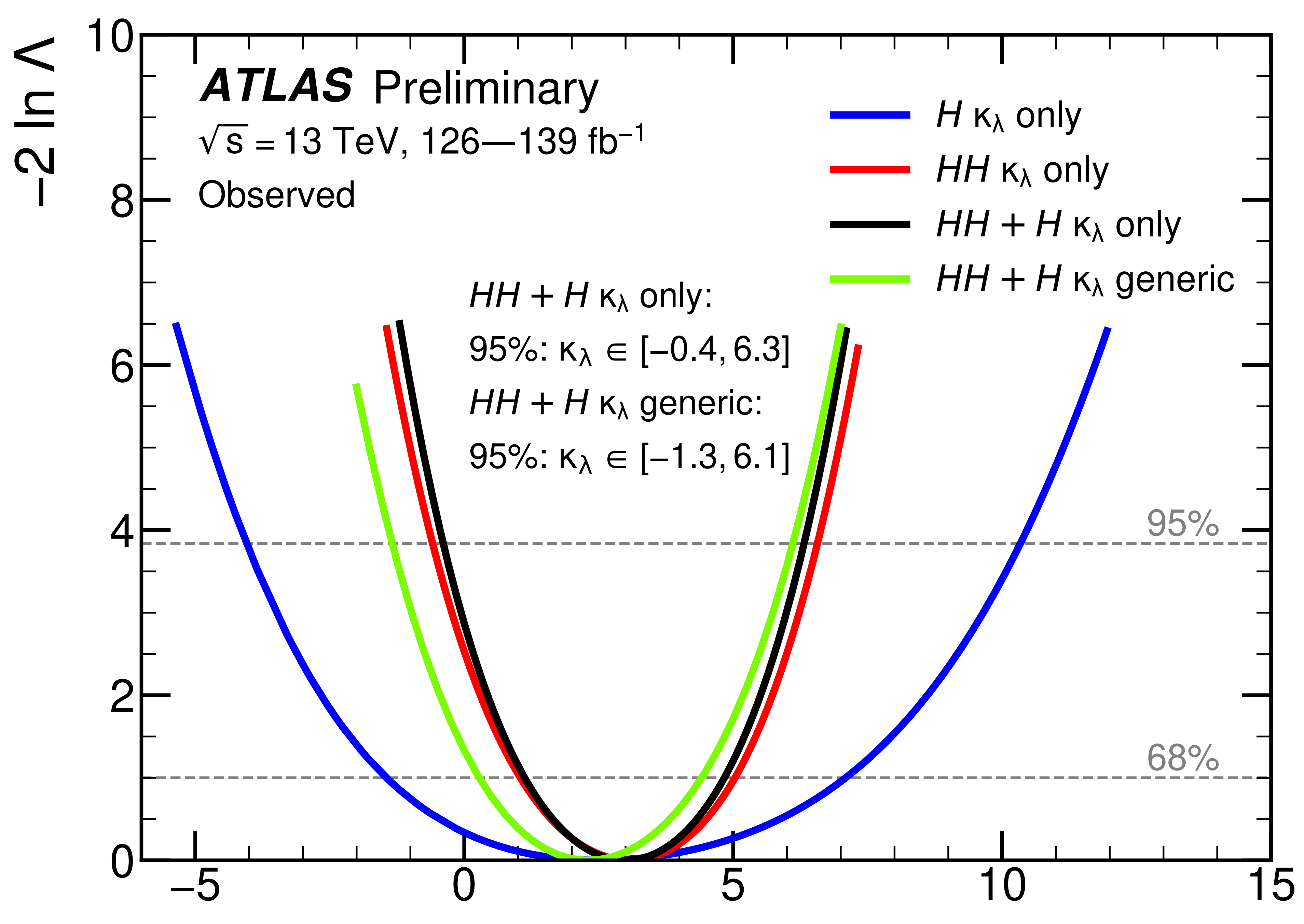
ATLAS-CONF-2022-050

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 floating	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
HH+H combination, κ_t, κ_V, κ_b, κ_τ floating	$-1.3 < \kappa_\lambda < 6.1$	$-2.1 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 2.3^{+2.1}_{-2.0}$

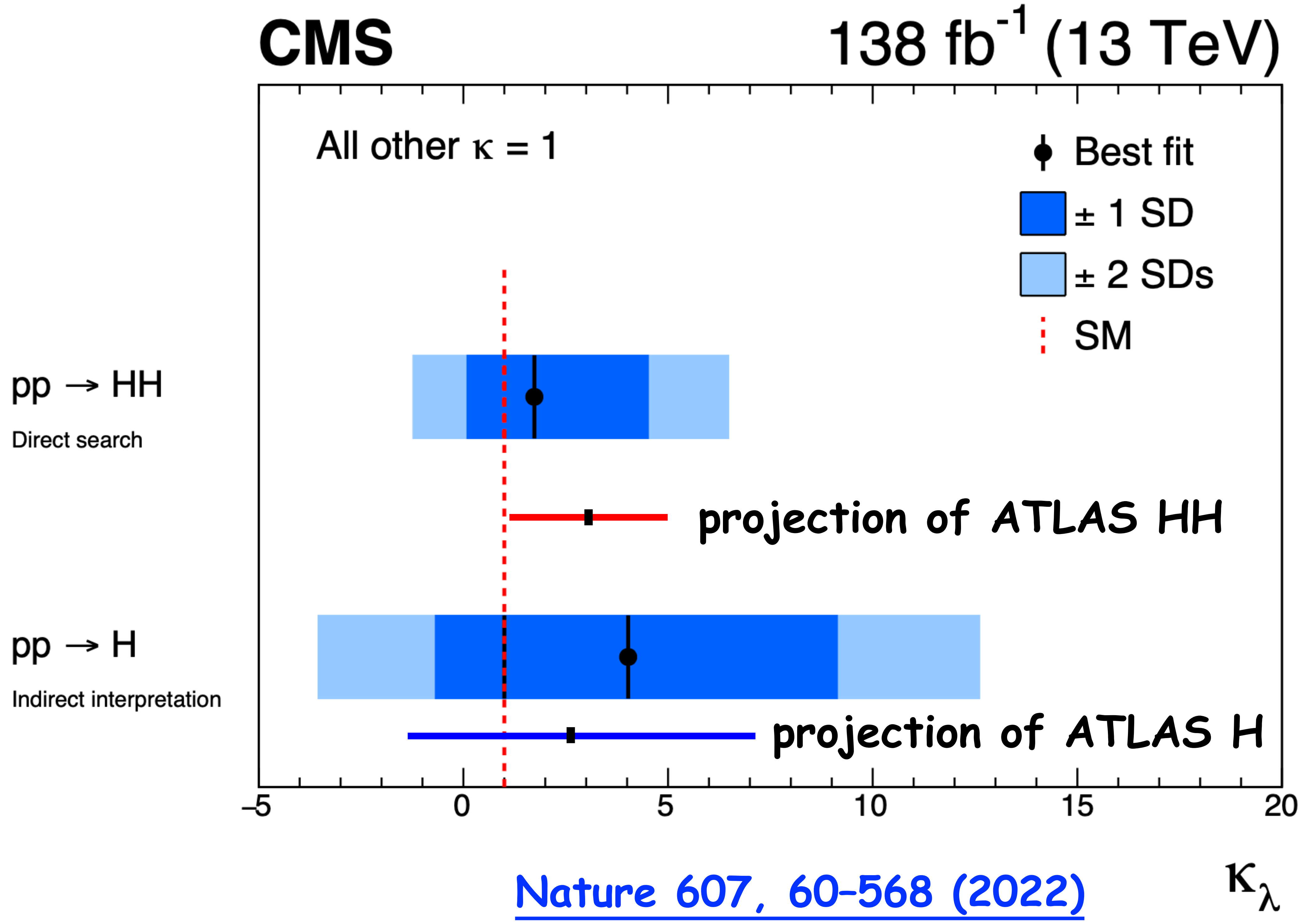
- **Di-Higgs** has much stronger constraining power than **Single-Higgs**
- Once single-Higgs and di-Higgs combined, constraining power in κ_λ **only model** is similar to **generic model** as other couplings well constrained by single-Higgs

Comparison with CMS results

- Self coupling measurement results also published by CMS collaboration



ATLAS-CONF-2022-050



Nature 607, 60-568 (2022)

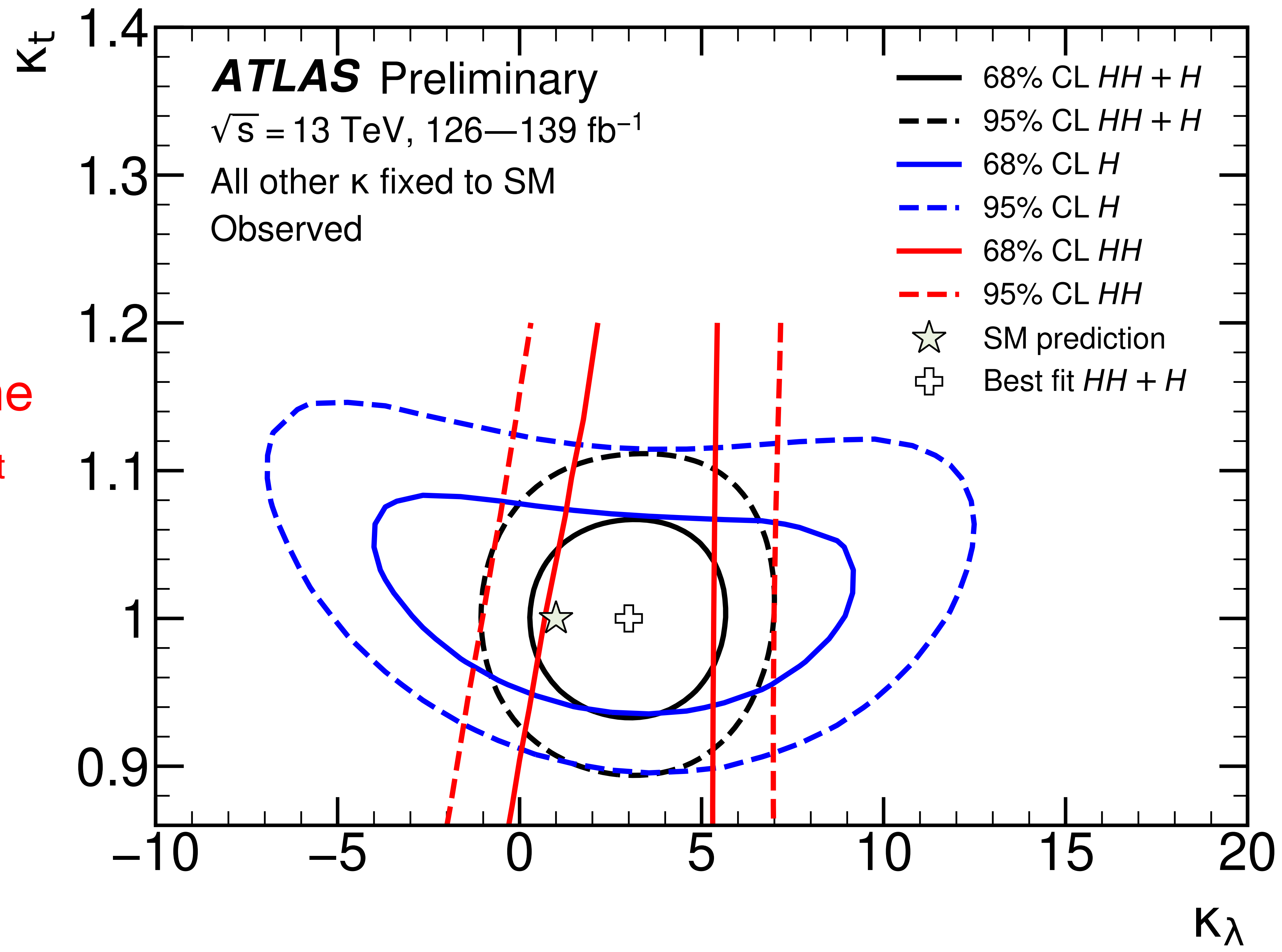
- Compatible with observed κ_λ limit from CMS
  - as shown in the **Single-Higgs** projection and **Di-Higgs** projection

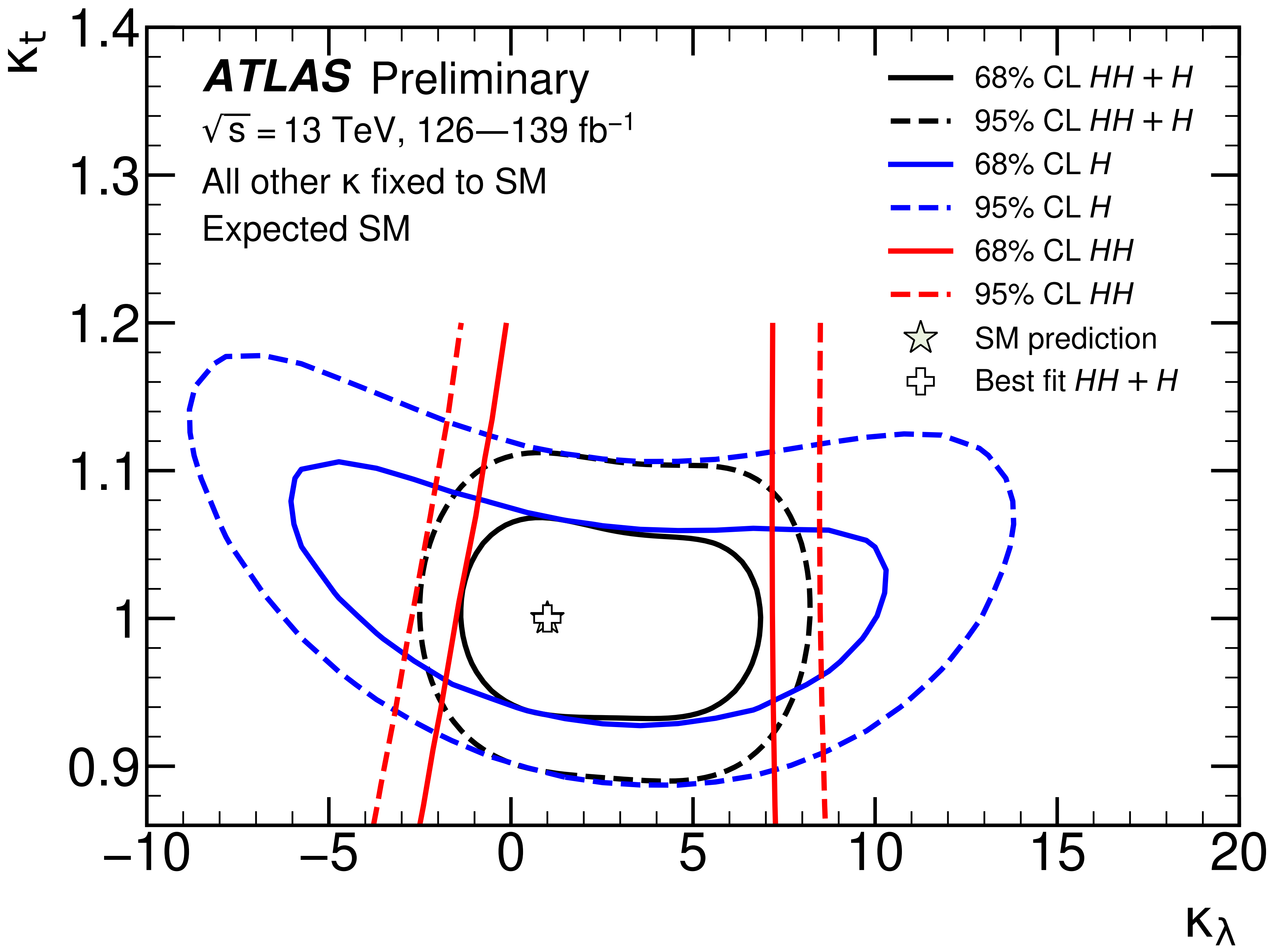
κ_λ - κ_t 2D contours

- To understand the correlation with other couplings

ATLAS-CONF-2022-050

Cannot reach the boundary on κ_t with the given scope in HH





- **Single Higgs** has much stronger containing power on κ_t, while **di-Higgs** stronger on κ_λ
- Can explain why generic model measurement of κ_λ is similar to κ_λ only model

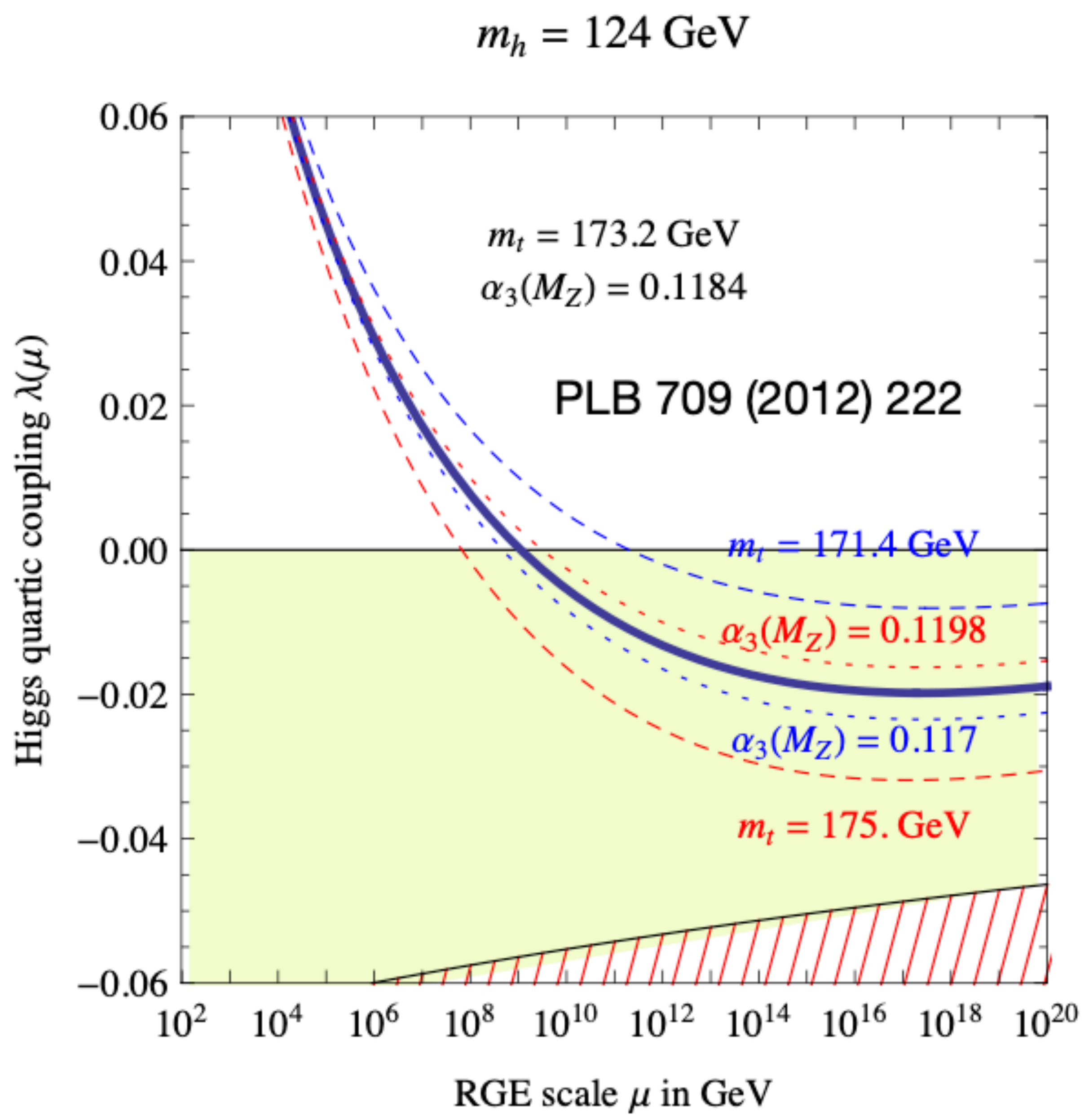
Summary

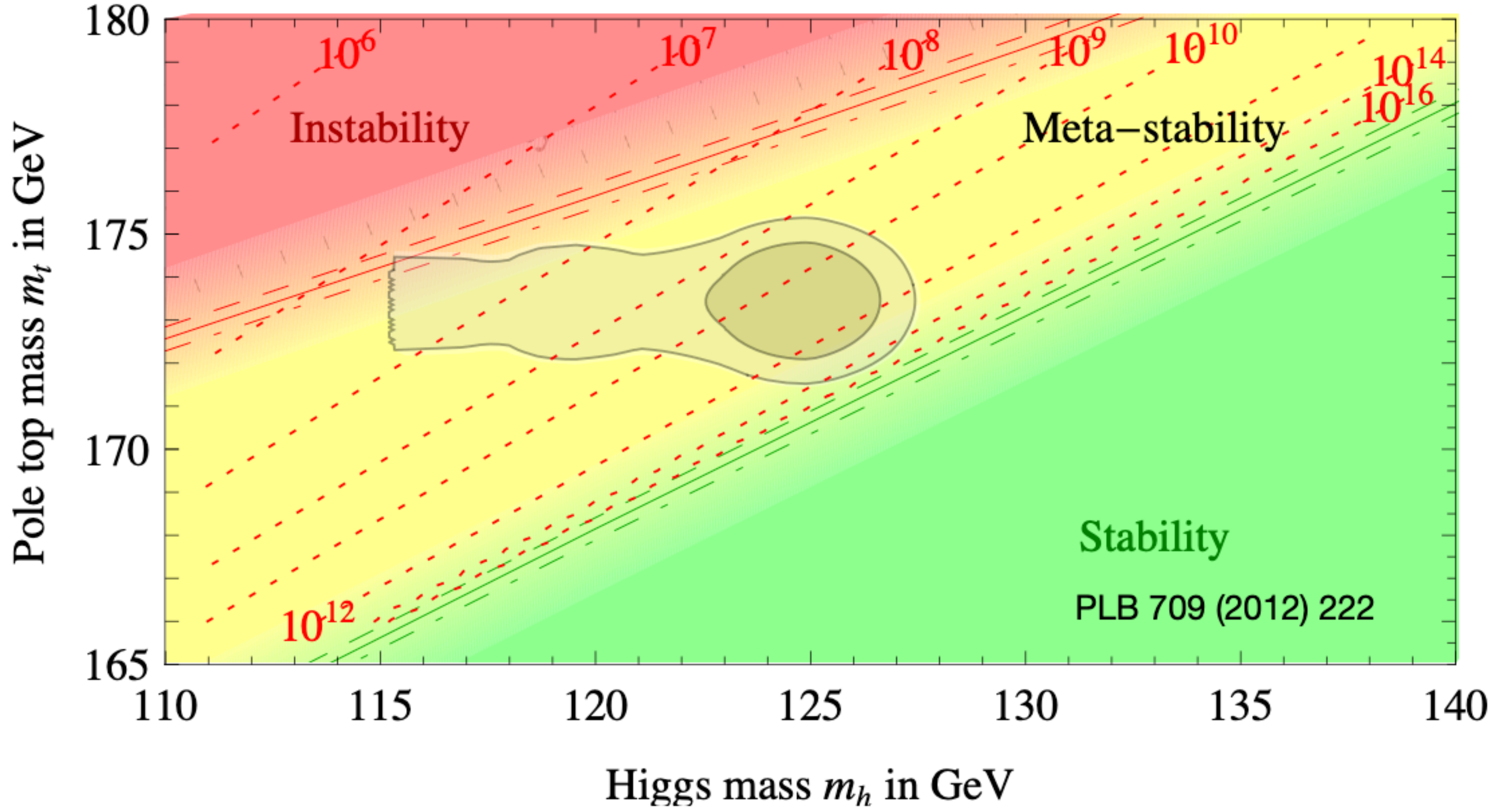
- Higgs self-coupling is important to determine the Higgs potential structure
- Di-Higgs production has the direct access to the self-coupling
- Combination of Di-Higgs and Single-Higgs
  - thanks to single Higgs constraining power on other couplings, we can have the less model dependent measurement,
- The self-coupling is measured by combining 10 individual analyses with Full Run2 dataset at ATLAS ATLAS-CONF-2022-050
  - At 68% C.L., the observed (expected) allowed interval of κ_λ: [-0.4, 6.3] ([-1.9, 7.5])
  - The results are compatible with the one from CMS
- Stay tuned for even better results from LHC Run3 and future experiment results!

Backup and bonus

Scale potential

- Why shape of the scalar potential is important?
  - The shape of the scalar potential is linked to many open questions of particle physics and cosmology





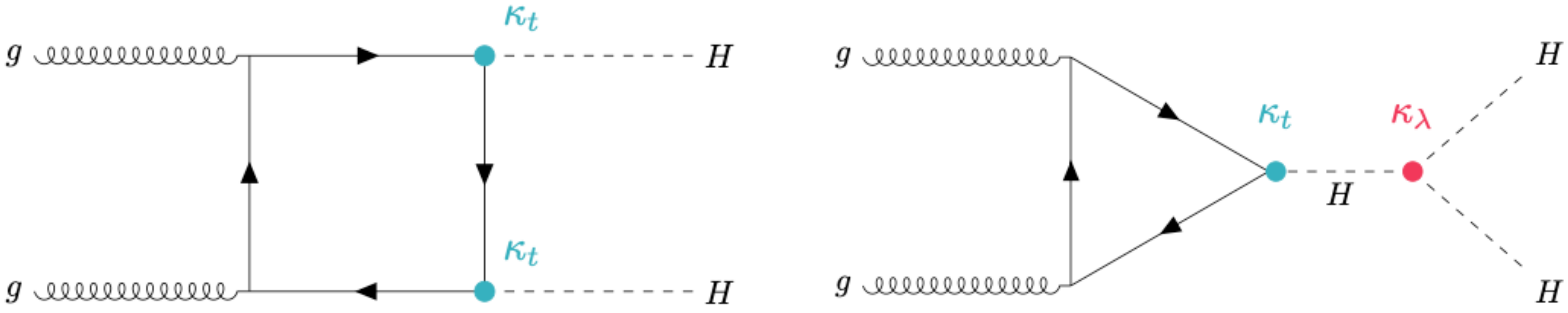
- The modification of the shape of the scale potential at high scales make the EW vacuum metastable
- The stability of the potential at high has an impact of the possible role of the Higgs boson as the inflation in the primordial Universe

Decay BR of the di-Higgs

	bb	WW	ττ	ZZ	γγ
bb	33%				
WW	25%	4.6%			
ττ	7.4%	2.5%	0.39%		
ZZ	3.1%	1.2%	0.34%	0.076%	
γγ	0.26%	0.10%	0.029%	0.013%	0.0005%

Parameterization in Di-Higgs: ggF mode

- Parametrize (κ_λ , κ_t) impacts on ggF



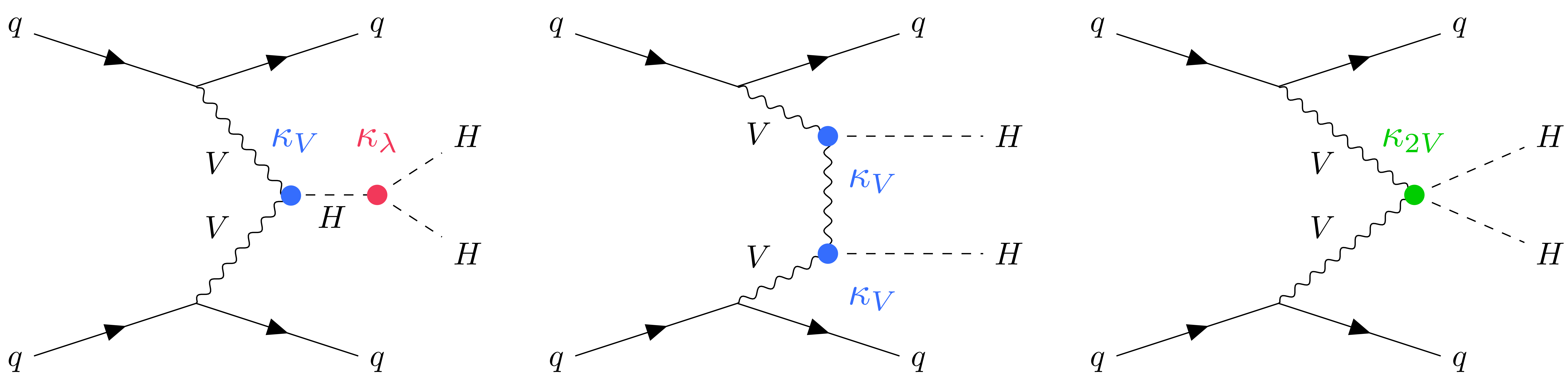
$$\sigma_{\rm ggF}(pp \to HH) \sim \kappa_t^4 \left[\mathcal{A}_1^2 + 2\frac{\kappa_\lambda}{\kappa_t}\mathcal{R}(\mathcal{A}_1^* \mathcal{A}_2) + \left(\frac{\kappa_\lambda}{\kappa_t}\right)^2 |\mathcal{A}_2|^2 \right]$$

$$\sigma = \kappa_t^4 a_1 + \kappa_\lambda \kappa_t^3 a_2 + \kappa_\lambda^4 a_3$$

- For ggF, resolve the 3 coefficients by varying the κ_λ while fixing κ_t =1

Parameterization in Di-Higgs: VBF mode

- Parametrize (κ_λ , κ_V , κ_{2V}) impacts on VBF



$$\sigma(\kappa_{2V}, \kappa_\lambda, \kappa_V) = |A|^2 = |\kappa_V \kappa_\lambda M_s + \kappa_V^2 M_t + \kappa_{2V} M_x|^2$$

$$\sigma = \kappa_V^2 \kappa_\lambda^2 a_1 + \kappa_V^4 a_2 + \kappa_{2V}^2 a_3 + \kappa_V^3 \kappa_\lambda a_4 + \kappa_V \kappa_\lambda \kappa_{2V} a_5 + \kappa_V^2 \kappa_{2V} a_6$$

- For VBF, resolve the 6 coefficients by varying the (κ_λ , κ_{2V}) while fixing κ_V

Parameterization in Single-Higgs

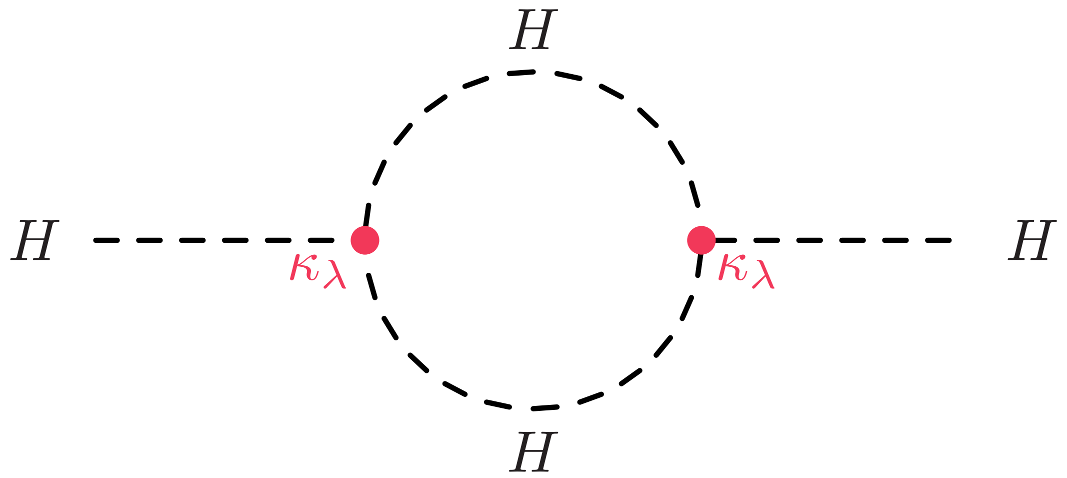
$$\mu_{if}(\kappa_\lambda) = \mu_i(\kappa_\lambda) \times \mu_f(\kappa_\lambda)$$

- Impacts on the production modes (i) and the decay channels (f) expressed as:

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

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

- $Z^{\rm BSM}_H$: wave function renormalization, accounts for the **universal correction**



$$Z_H^{\rm BSM}(\kappa_\lambda) = \frac{1}{1 - (\kappa_\lambda^2 - 1)\delta Z_H}, \text{ with } \delta Z_H = -1.536 \times 10^{-3}$$

- C_1: **process and kinematic-dependent coefficients**, it encodes the magnitude of the κ_λ-dependent linear correction

- $K_{\rm EW}$: represents the full set of NLO EW corrections

JHEP 1612, 080 (2016)

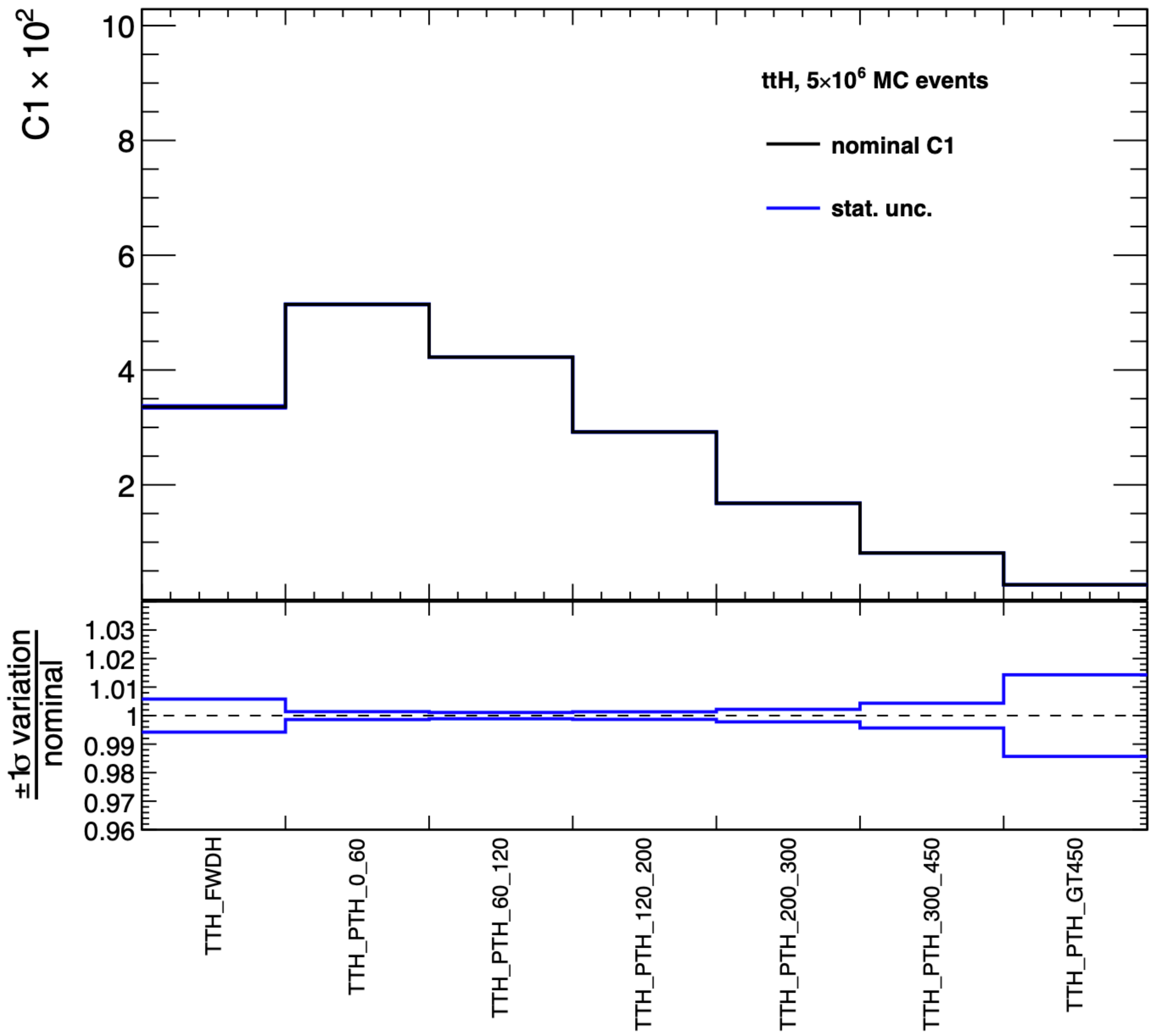
Eur. Phys. J. C (2017) 77: 887

- κ_f and κ_i consist of: κ_λ , κ_V (= κ_W = κ_Z), κ_t, κ_b, κ_τ, κ_c (= κ_t), κ_s (= κ_b), κ_μ (= κ_τ)

κ_λ parameterization in Single-Higgs

- Thanks to recent effort by LHCHWG, C_1 and K_{EW} derived in STXS 1.2 granularity

LHCHWG-2022-002

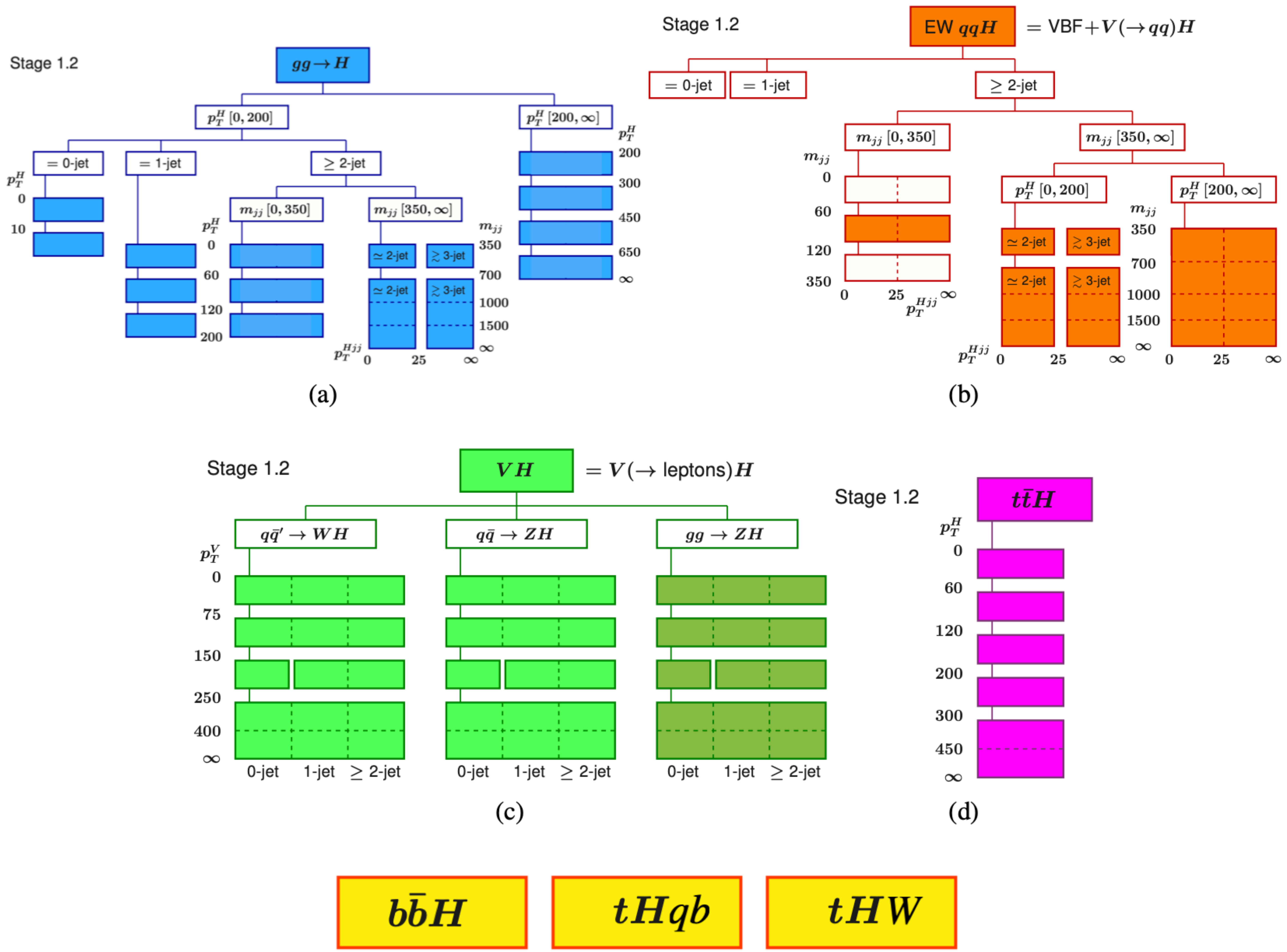


STXS BIN	K_{EW}
TTH_FWDH	1.017
TTH_PTH_0_60	1.041
TTH_PTH_60_120	1.025
TTH_PTH_120_200	1.002
TTH_PTH_200_300	0.978
TTH_PTH_300_450	0.956
TTH_PTH_GT450	0.923

- Calculation at STXS 1.2 is available for ttH, V(lep)H, and Hjj (VBF and V(had)H) processes
  - Only inclusive level available for ggH and tHj due to the missing differential calculations
  - Not available for tHW, bbH and ggZH, thus no NLO EW implemented for consistency

Single Higgs parametrization with STXS

ggF: only inclusive impact
As the differential impact
is not yet available



Best fitted values of κ

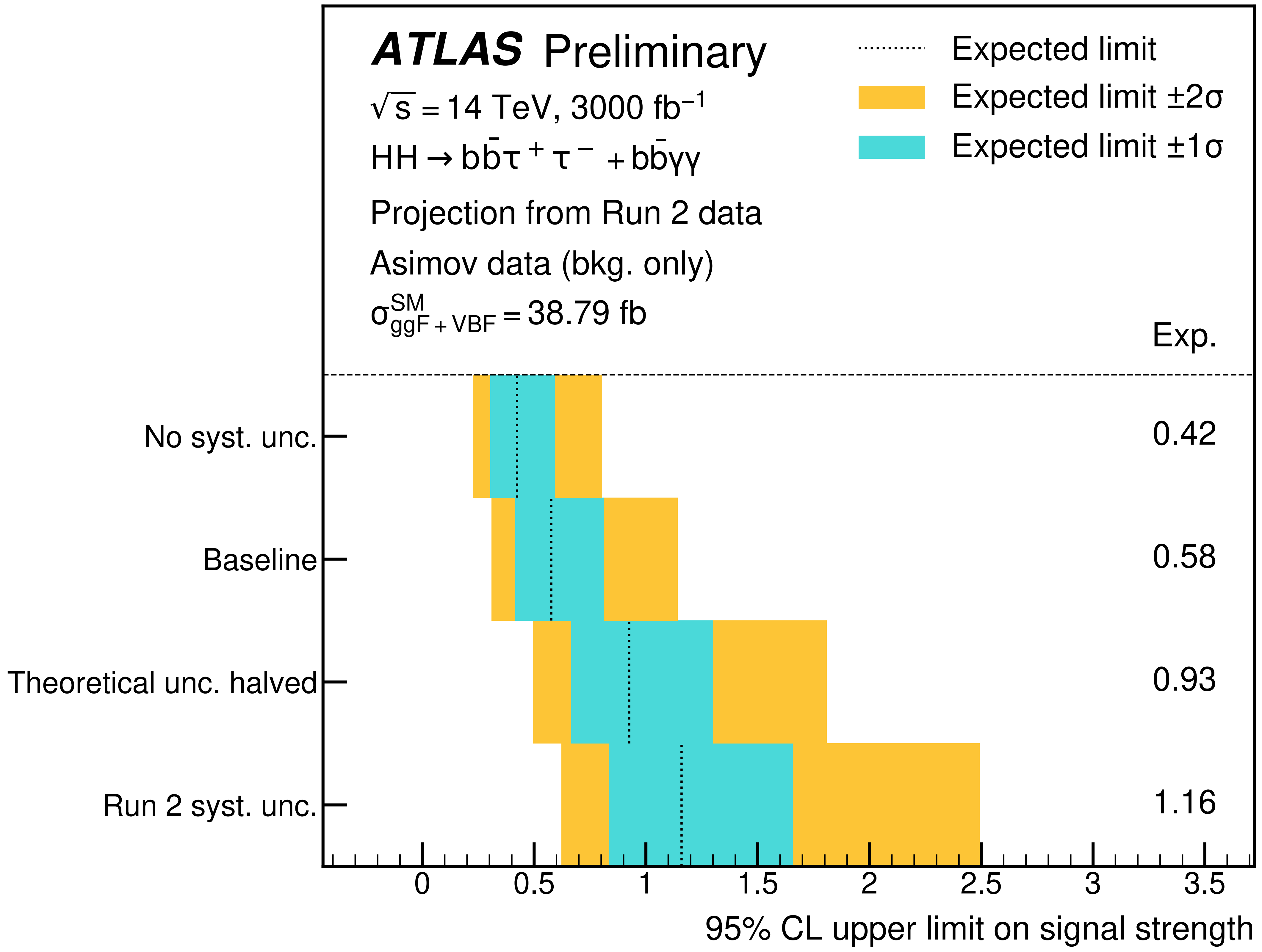
- Fit results in different kappa scenario

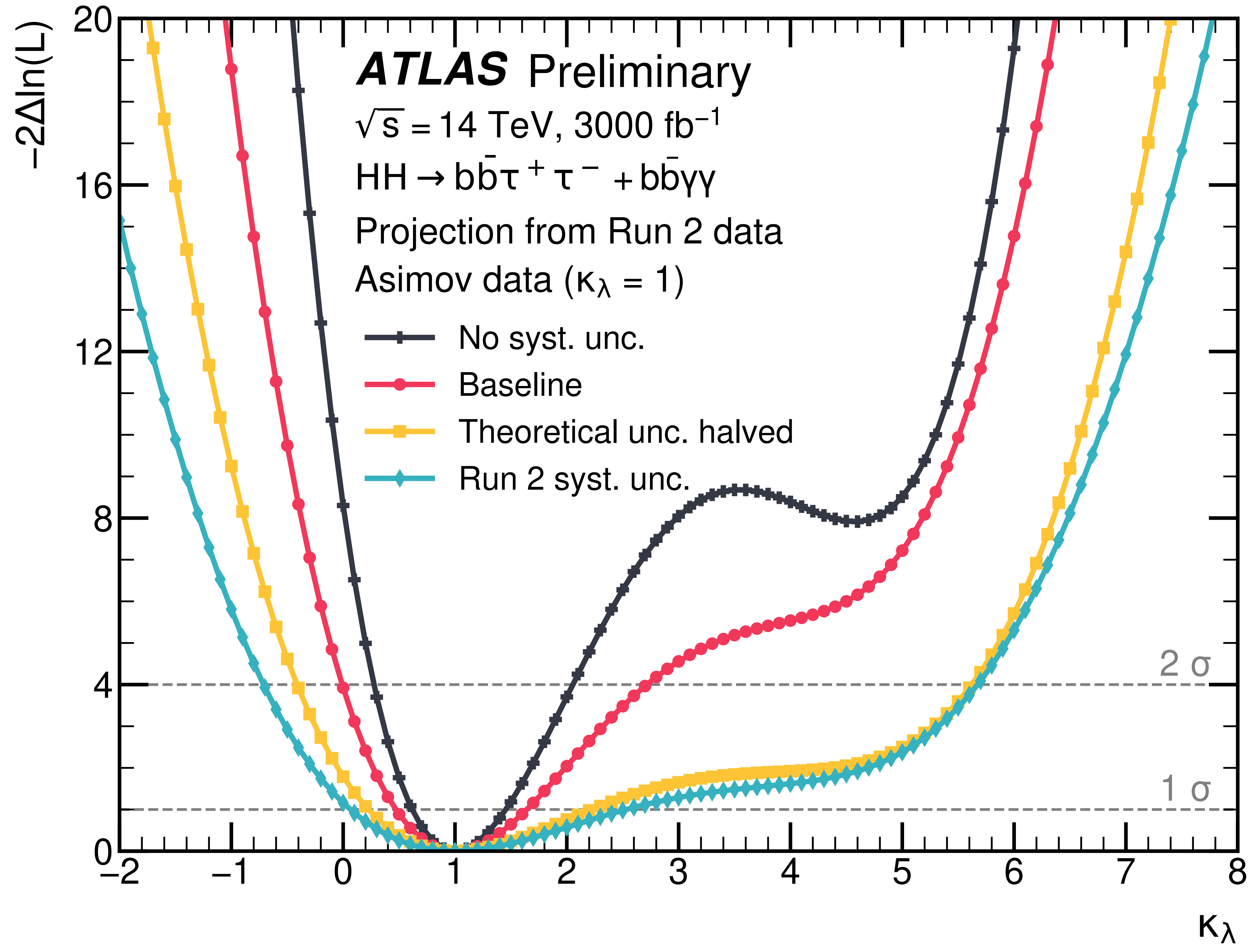
POIs	$\kappa_V{}^{+1\sigma}_{-1\sigma}$	$\kappa_t{}^{+1\sigma}_{-1\sigma}$	$\kappa_b{}^{+1\sigma}_{-1\sigma}$	$\kappa_\tau{}^{+1\sigma}_{-1\sigma}$	$\kappa_\lambda{}^{+1\sigma}_{-1\sigma}$	κ_λ [95% CL]	
κ_λ	1	1	1	1	$3.0^{+1.8}_{-1.9}$	$[-0.4, 6.3]$	Obs.
					$1.0^{+4.8}_{-1.7}$	$[-1.9, 7.5]$	Exp.
κ_λ-κ_t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

HL-LHC projection

$HH \rightarrow b\bar{b}\tau^+\tau^- + b\bar{b}\gamma\gamma$

ATL-PHYS-PUB-2022-005





Uncertainty scenario	Significance [σ] $b\bar{b}\gamma\gamma$	$b\bar{b}\tau^+\tau^-$	Combination	Combined signal strength precision [%]
No syst. unc.	2.3	4.0	4.6	$-23/+23$
Baseline	2.2	2.8	3.2	$-31/+34$
Theoretical unc. halved	1.1	1.7	2.0	$-49/+51$
Run 2 syst. unc.	1.1	1.5	1.7	$-57/+68$

Uncertainty scenario	Likelihood scan 1 σ CI	Likelihood scan 2 σ CI
No syst. unc.	[0.6, 1.5]	[0.3, 2.1]
Baseline	[0.5, 1.6]	[0.0, 2.7]
Theoretical unc. halved	[0.2, 2.2]	[−0.4, 5.6]
Run 2 syst. unc.	[0.1, 2.5]	[−0.7, 5.7]