Higgs and HH combinations at the CMS experiment

14th Aug 2024

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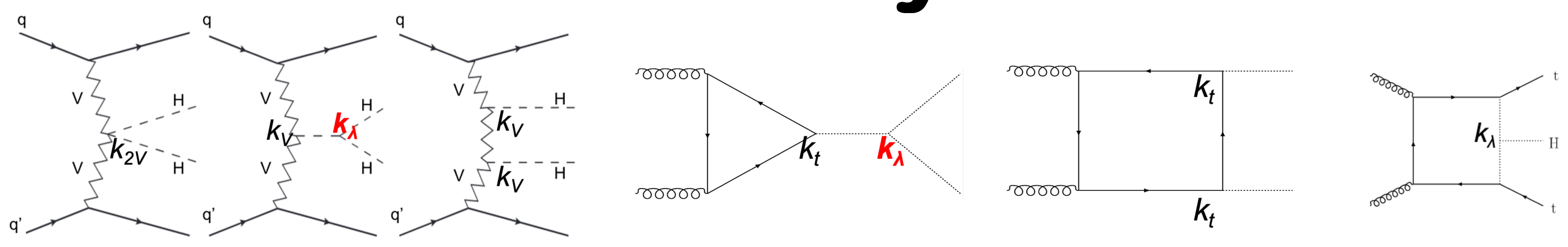
On behalf of the CMS Collaboration

PAPER LINK

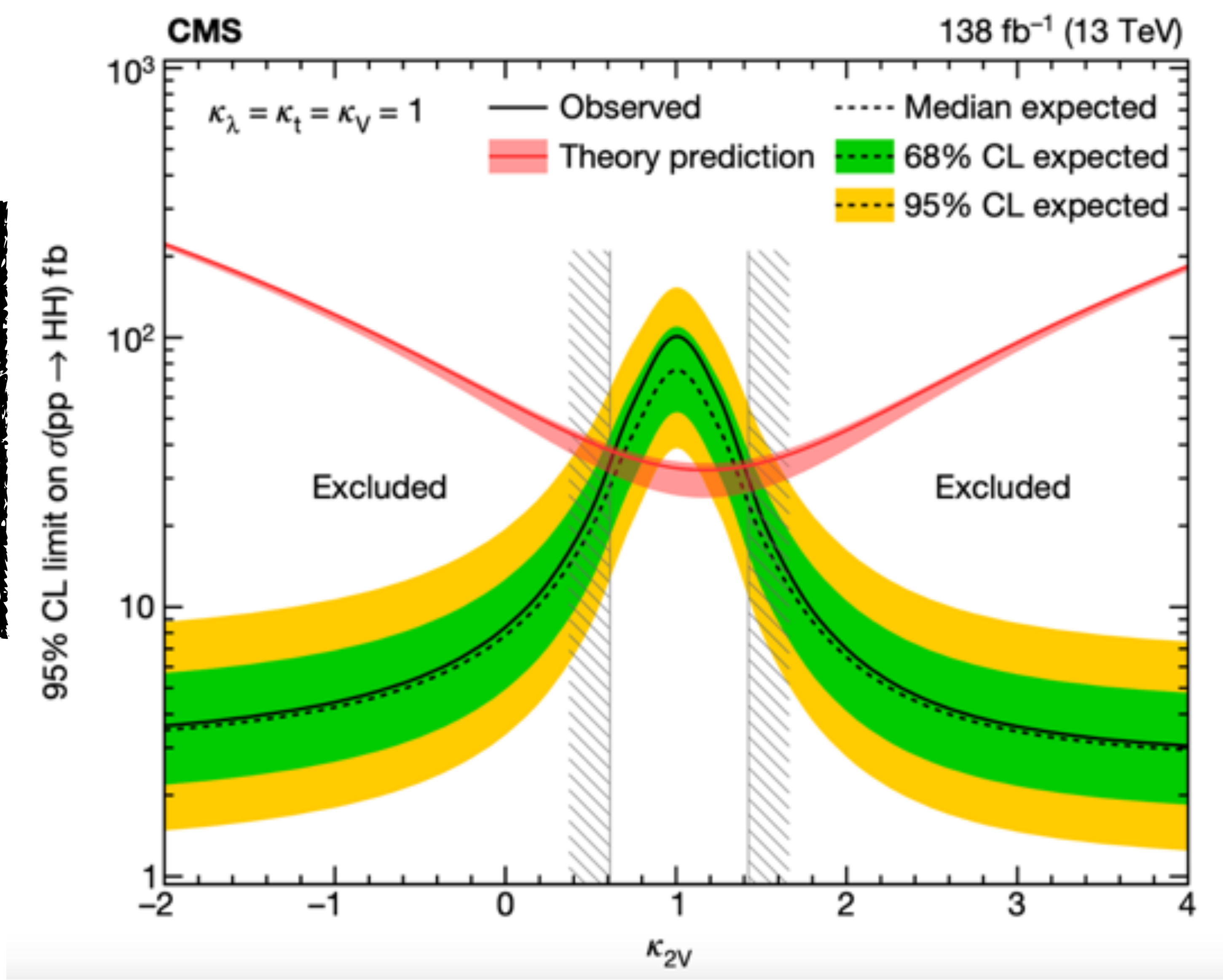
Outline

- Combination of single-H and double-Higgs measurements
  - Test compatibility with SM
    - Signal strength of single-H combination
    - Signal strength of HH combination
  - Measurement of H coupling to fermions and vector bosons
    - HHVV coupling (κ_{2V}) from VBF HH production
  - Constrain on the Higgs boson self-coupling λ

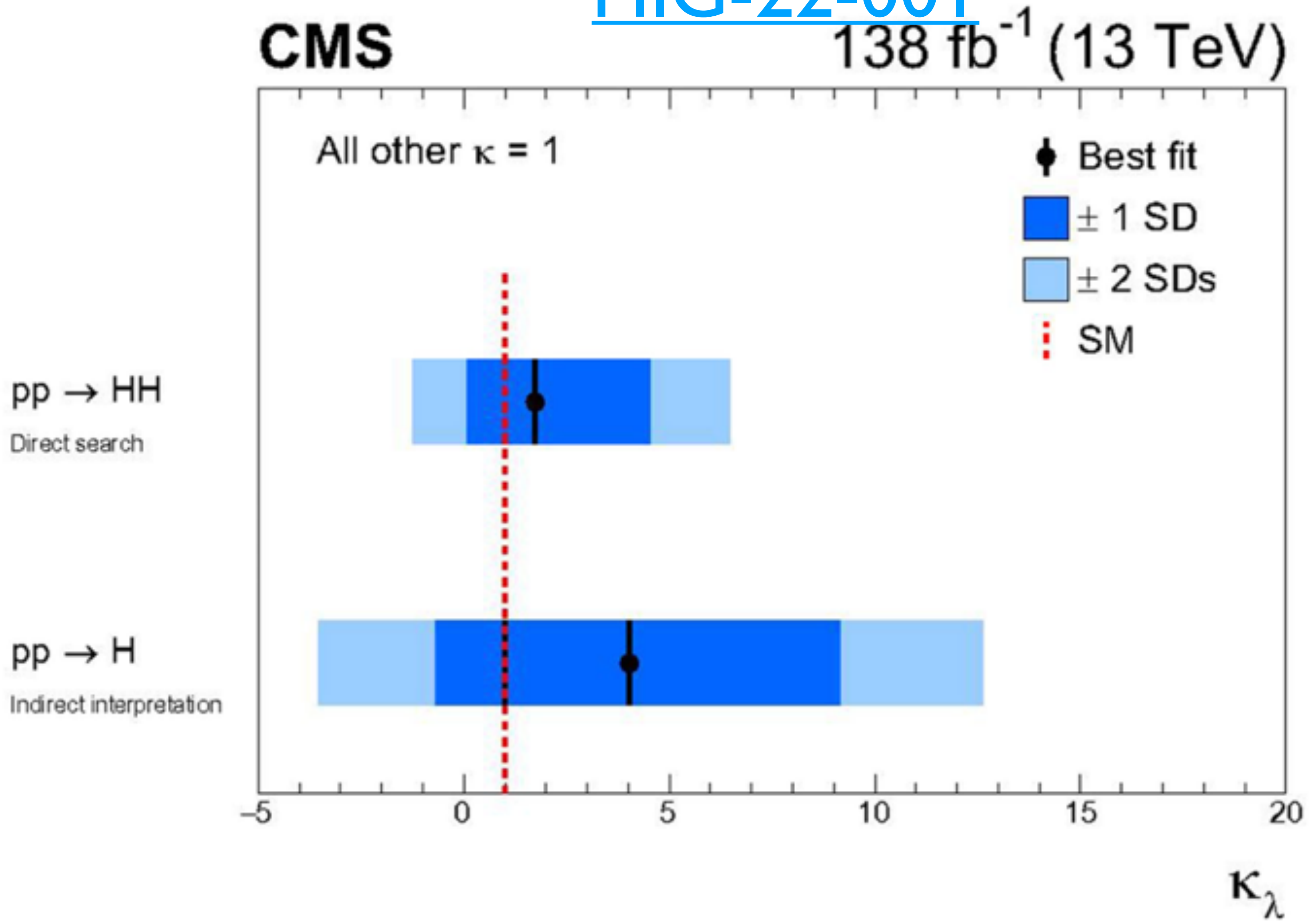
Why a H+HH Combination



- $\kappa_{2V} = 0$ is excluded with other couplings fixed to SM



HIG-22-001



- Measurement of Higgs trilinear self-coupling lambda is a fundamental test of SM($\kappa_\lambda = \kappa/\kappa_{SM}$)
- κ_λ accessible from both HH and single-H XS measurements
- First exclusion of $\kappa_{2V} = 0$ at 6.6σ from HH combination with other single-H coupling fixed to SM
  - With H+HH constraints on κ_{2V} with more general assumptions on single-H coupling
- BSM expected to introduce changes in more than one coupling, HH has better κ_λ sensitivity but single-H provides constrain other Higgs couplings
  - More general statements about κ_λ

Input Analysis

All the main H production and decay modes covered
Analyses for HH production targeting GGF,VBF and V-associated production
Differences with respect to single-H and HH combinations of HIG-22-001

- Do not consider in this combination
  - $H \to invisible$ (does not constrain on κ_λ)
  - $H \to Z\gamma$
    - Sensitivity to κ_λ is negligible because of the large Stat. Uncertainties
  - $HH \to bbZZ(4l)$: low sensitivity and high overlap with HZZ(4l).

Removal of overlapping categories between single-H and HH. Optimized to provide maximum sensitivity to k_λ, k_V, k_F

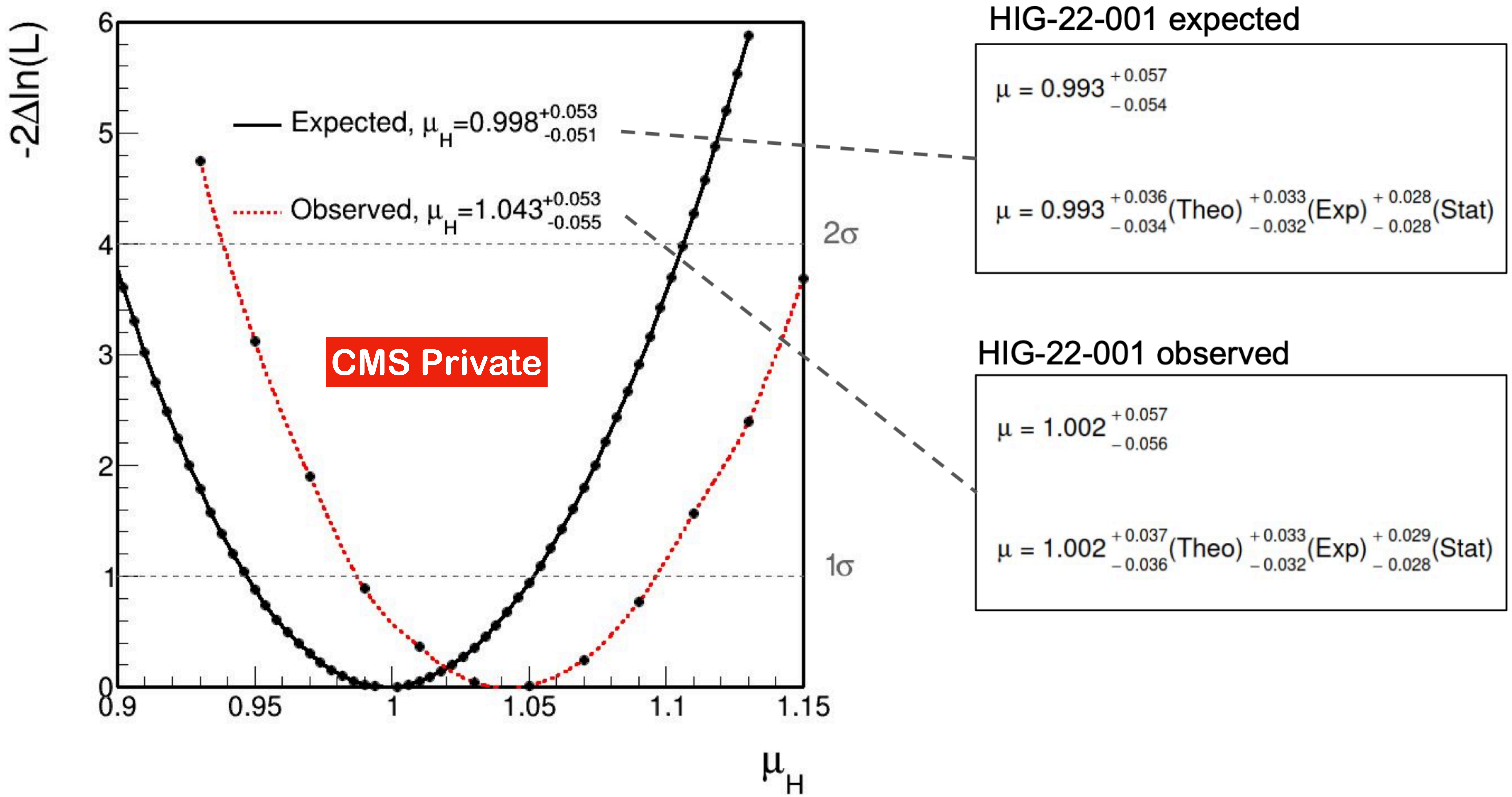
Single-Higgs

Process	$H \to ZZ \to 4l$	$H \to bb$	$VH(H \to bb)$	$ttH(H \to bb)$	$ttH(multilepton)$	$H \to \mu\mu$	$H \to \gamma\gamma$	$H \to \tau\tau$	$H \to WW$
Paper	HIG-19-001	HIG-19-003	HIG-18-016	HIG-17-026	HIG-19-008	HIG-19-006	HIG-19-015/ HIG-19-018	HIG-19-010	HIG-20-013
Lumi	138	138	77	36	138	138	138	138	138
Phase-space	STXS 1.2	Inclusicve	Inclusicve	Inclusicve	Inclusicve	Inclusicve	STXS 1.2/Inclusive	STSX 1.2	STSX 1.2

Double-Higgs

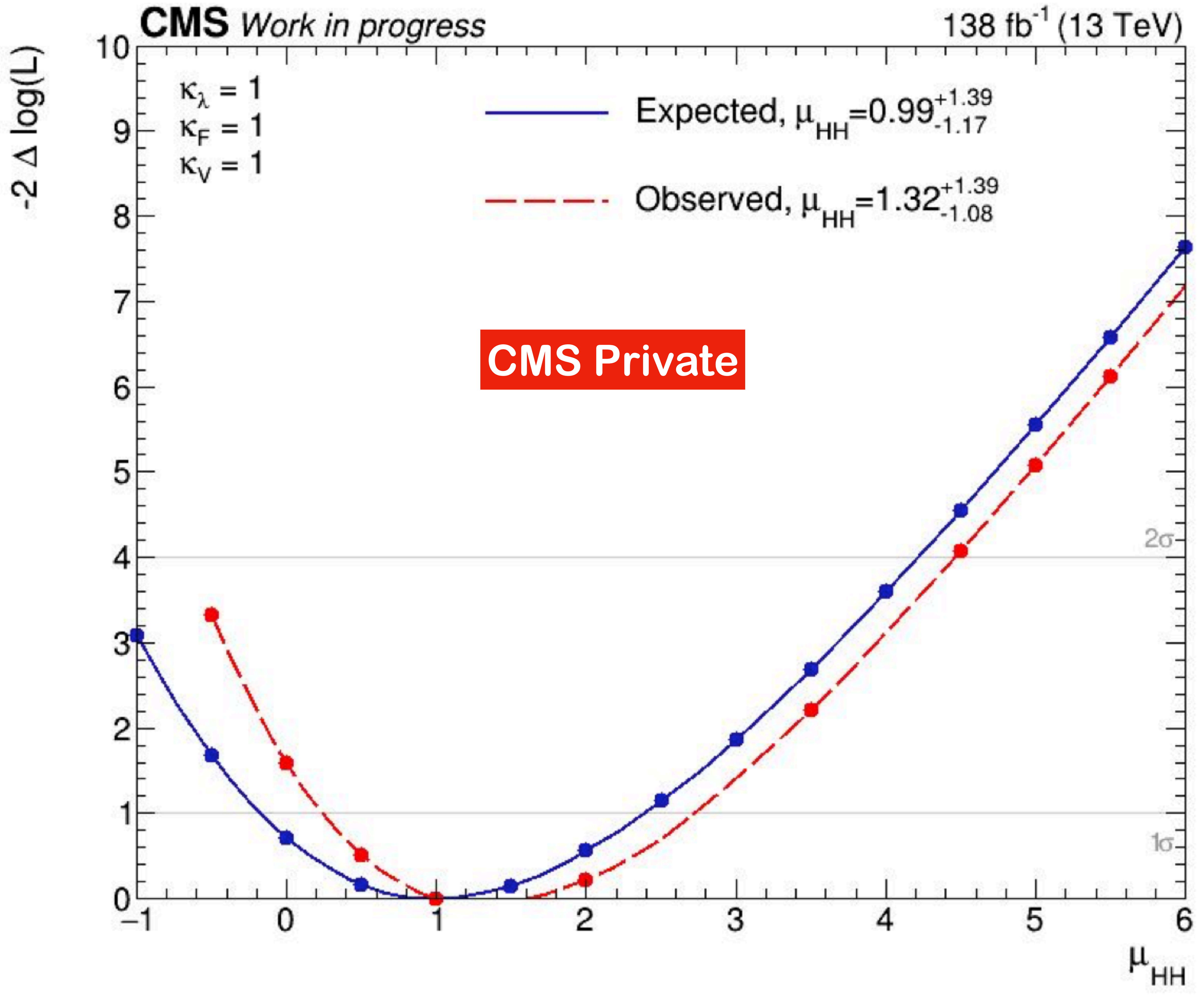
Process	$HH \to bb\gamma\gamma$	$HH \to bb\tau\tau$	$HH \to bbbb(resolved)$	$HH \to bbbb(boosted)$	$VHH \to bbbb$	$HH \to 4V/2V2\tau/4\tau$	$HH \to bbWW$
Paper	HIG-19-018	HIG-20-010	HIG-20-005	B2G-22-003	HIG-22-006	HIG-21-002	HIG-21-005
Production	ggHH/qqHH	ggHH/qqHH	ggHH/qqHH	ggHH/qqHH	VHH	ggHH	ggHH/qqHH

Signal strength(μ_H) from single-H combination



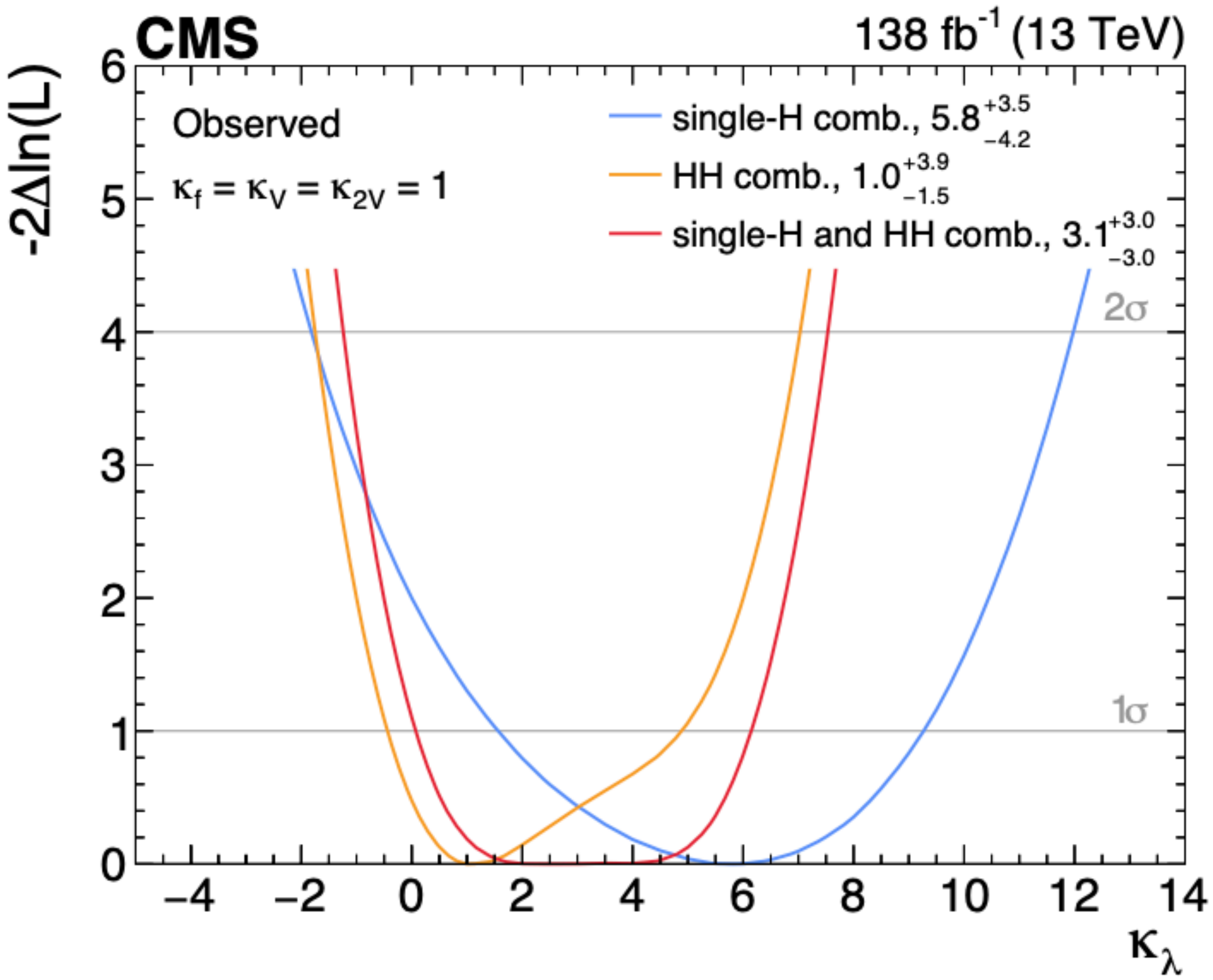
- Best fit shifted of ~4% with respect to HIG-22-001, but still within 1σ uncertainty
  - Probably driven by switch of $H \to \tau\tau$ from inclusive(obs.$\mu_H = 0.81 \pm -0.10$) to STXS(obs.$\mu_H = 0.95 \pm -0.13$)
- Small reduction of uncertainty with respect to HIG-22-001
  - Probably driven by switch of $H \to WW$ from inclusive(obs.$\mu_H = 0.93 + 0.10/-0.09$) to STXS(obs.$\mu_H = 0.95 \pm -0.08$)
- Good compatibility of impact between this combination

Signal strength(μ_{HH}) from HH combination



- Good compatibility of μ_{HH} and impact are found between expected and observed

Likelihood Scans of k_λ

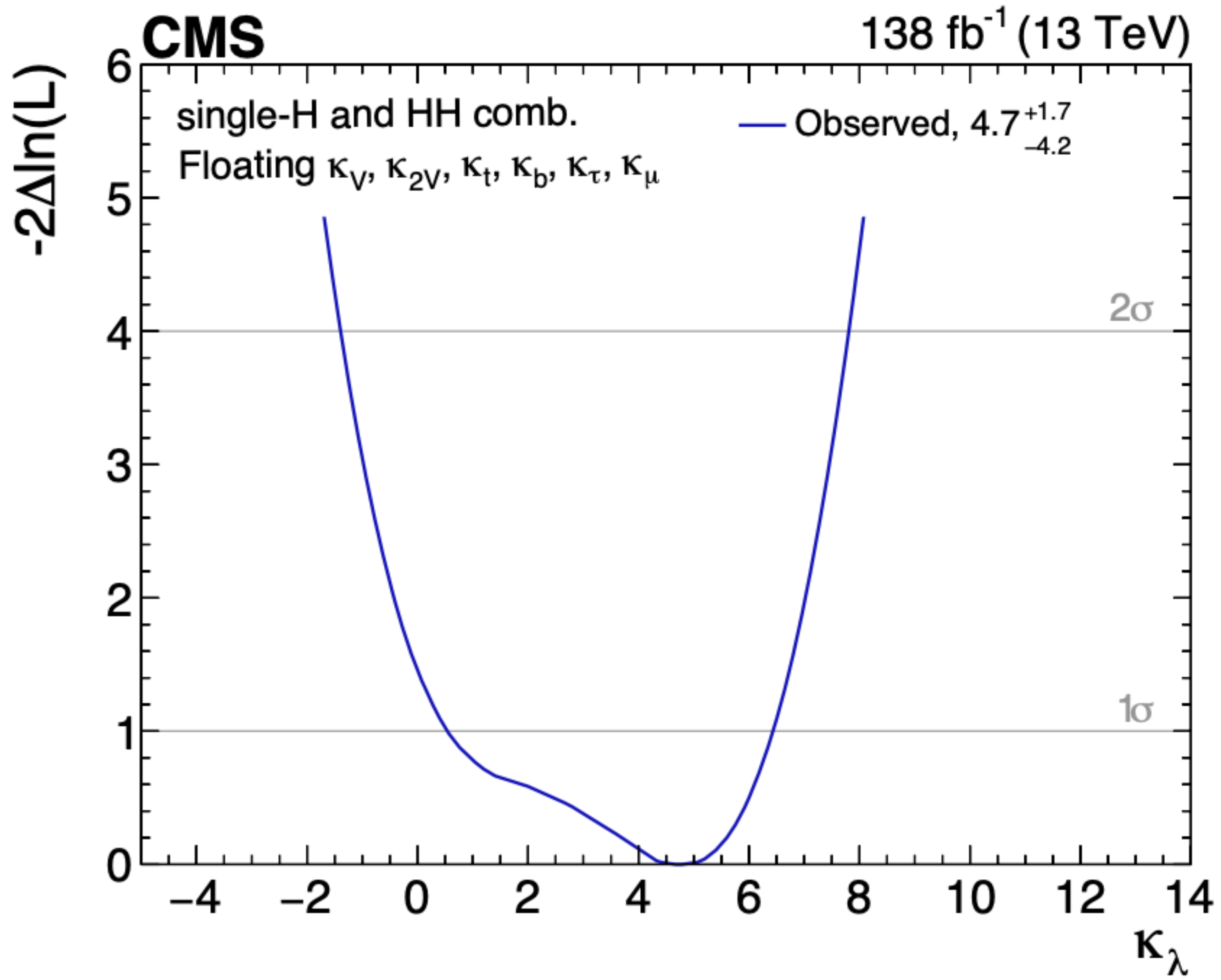


- Results compatible with SM within 2σ in [-1.2 , 7.5]
- Best fit k_λ from single-H combination shifted to higher value

Likelihood Scan of k_λ under more general assumptions

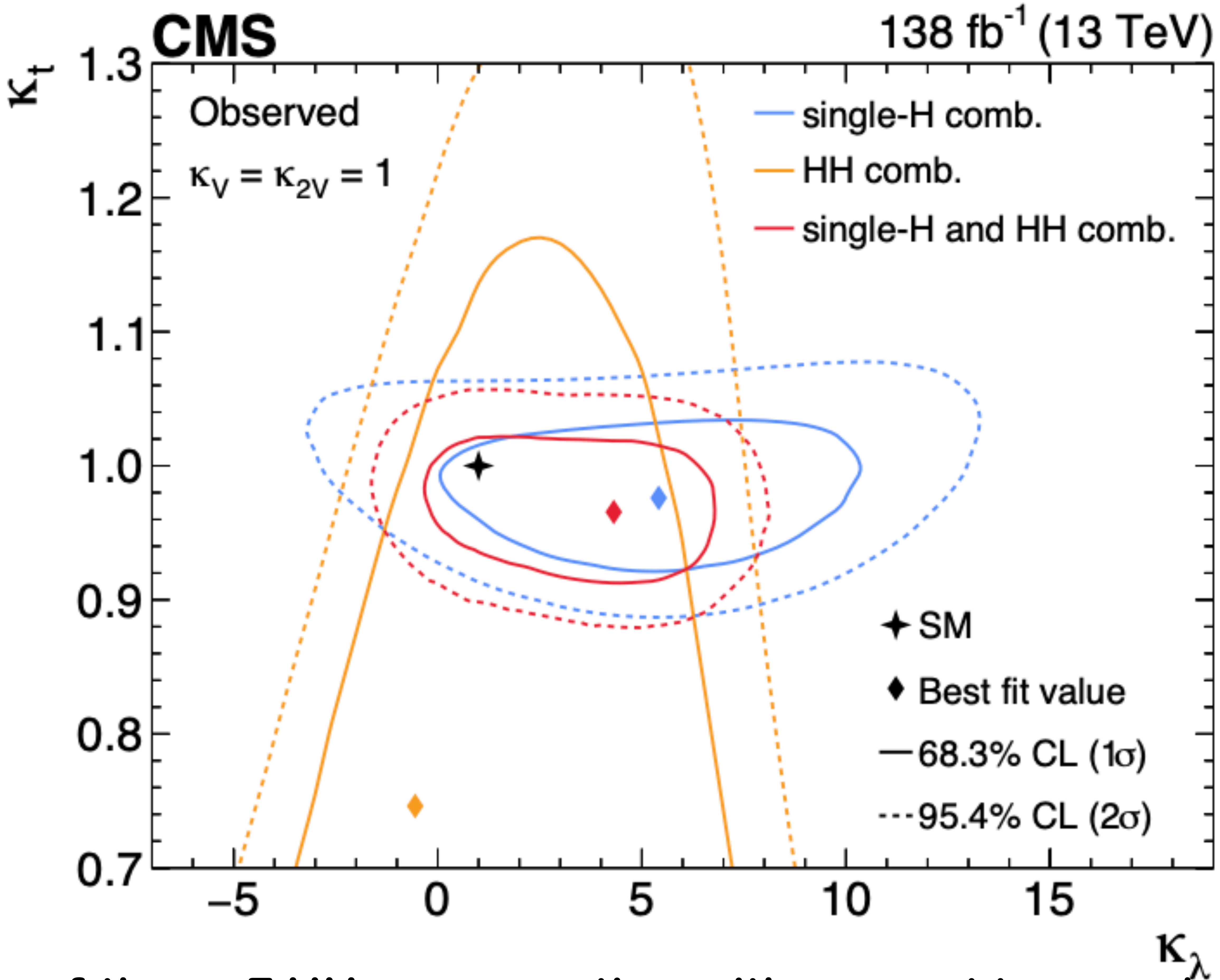
Hypothesis	Best fit $\pm 1\sigma$ Expected	Best fit $\pm 1\sigma$ Observed	2σ interval Expected	2σ interval Observed
Other couplings fixed to SM	$1.0^{+4.6}_{-1.7}$	$3.1^{+3.0}_{-3.0}$	$[-2.0, +7.7]$	$[-1.2, +7.5]$
Floating $(\kappa_V, \kappa_{2V}, \kappa_f)$	$1.0^{+4.7}_{-1.8}$	$4.2^{+2.1}_{-4.4}$	$[-2.2, +7.8]$	$[-1.7, +7.7]$
Floating $(\kappa_V, \kappa_t, \kappa_b, \kappa_\tau)$	$1.0^{+4.8}_{-1.8}$	$4.7^{+1.7}_{-4.1}$	$[-2.3, +7.7]$	$[-1.4, +7.8]$
Floating $(\kappa_V, \kappa_{2V}, \kappa_t, \kappa_b, \kappa_\tau, \kappa_\mu)$	$1.0^{+4.8}_{-1.8}$	$4.7^{+1.7}_{-4.2}$	$[-2.3, +7.8]$	$[-1.4, +7.8]$

Similar to ATLAS:
PLB 843, 10 August 2023, 137745



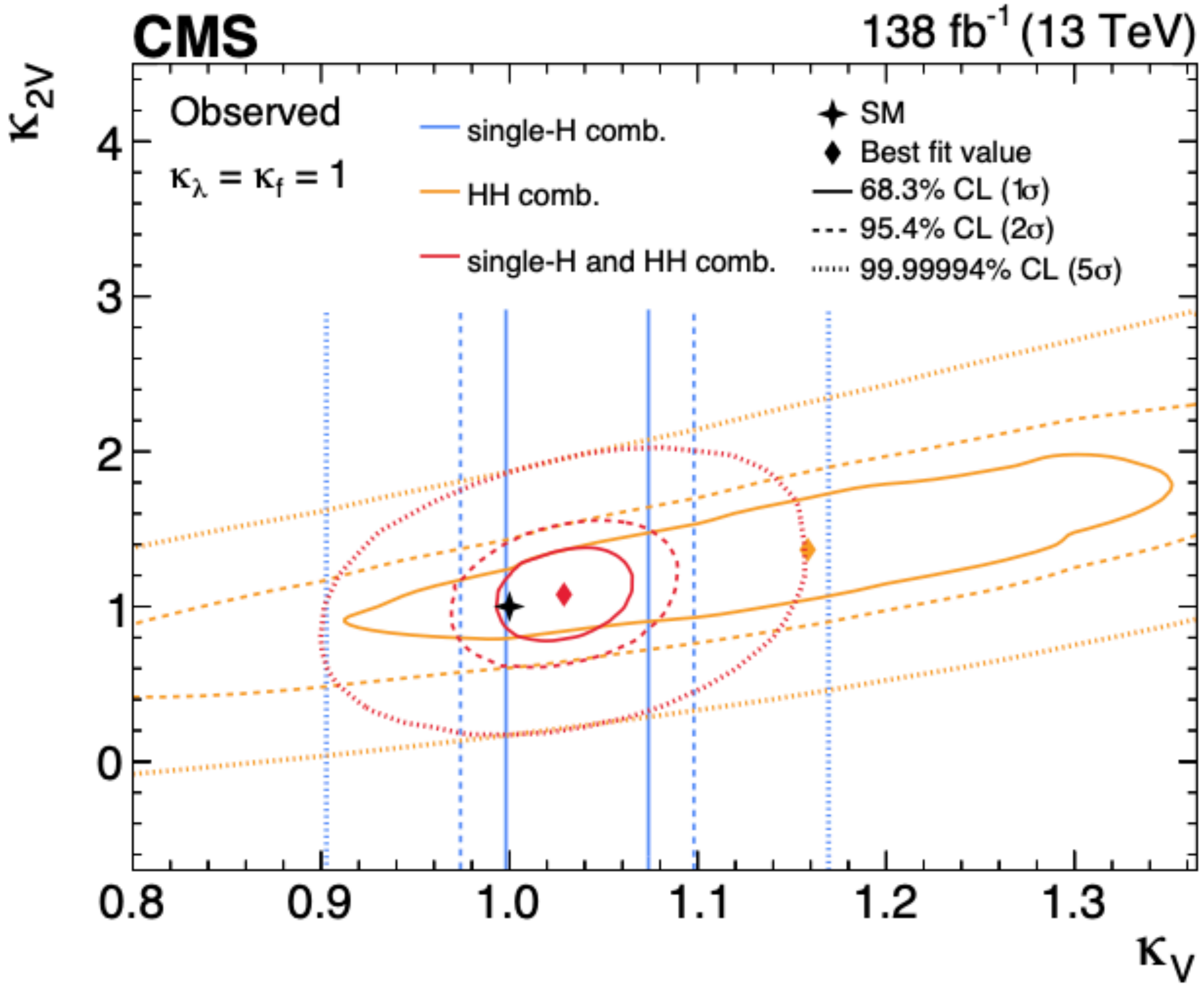
- Fits with additional floating POIs seem to slightly favor K_λ around 4.5

2D likelihood scan of (K_λ, k_t)



- A large degeneracy of the ggF HH cross section with respect to κ_λ and κ_t limits the κ_λ sensitivity of the HH channels
  - κ_t arise mostly from the contamination of single-H events in the HH enrich categories and from κ_t dependence of the H branching fractions
- The single-H combination provides a stringent constraint on κ_t

2D likelihood scan of (K_V, k_{2V})



- The constraint on k_{2V} is driven by the HH categories enriched in VBF HH events
- The single-H channels have no sensitivity on the k_{2V} but provide a stringent constraint on k_V
- Exclusion of $k_{2V} = 0$ for any value of k_V observed at 5σ significance.
  - √Same conclusion as HIG-22-001. But we don't fixed coupling in single-H

Summary

- H and HH combination provide fundamental extensive tests of SM
- All k_λ measurements compatible with SM within 1 or 2σ, depending on the input channels
- Observed result constraints k_λ at $95\ \%\ CL$ with $k_V, k_{2V}, k_t, k_b, k_\tau, k_\mu$ floating in interval $-1.4 < k_\lambda < 7.8$
  - With other POIs fixed: $-1.2 < k_\lambda < 7.5$
- Exclusion of $k_{2V} = 0$ for any value of k_V observed at 5σ significance

Thanks !

Backup

Table 3: Summary of overlaps between the considered single H and HH analyses included in this combination. Non-overlapping analyses are indicated by a ✓, overlaps removable with negligible impacts on the combination are indicated by a ✗.

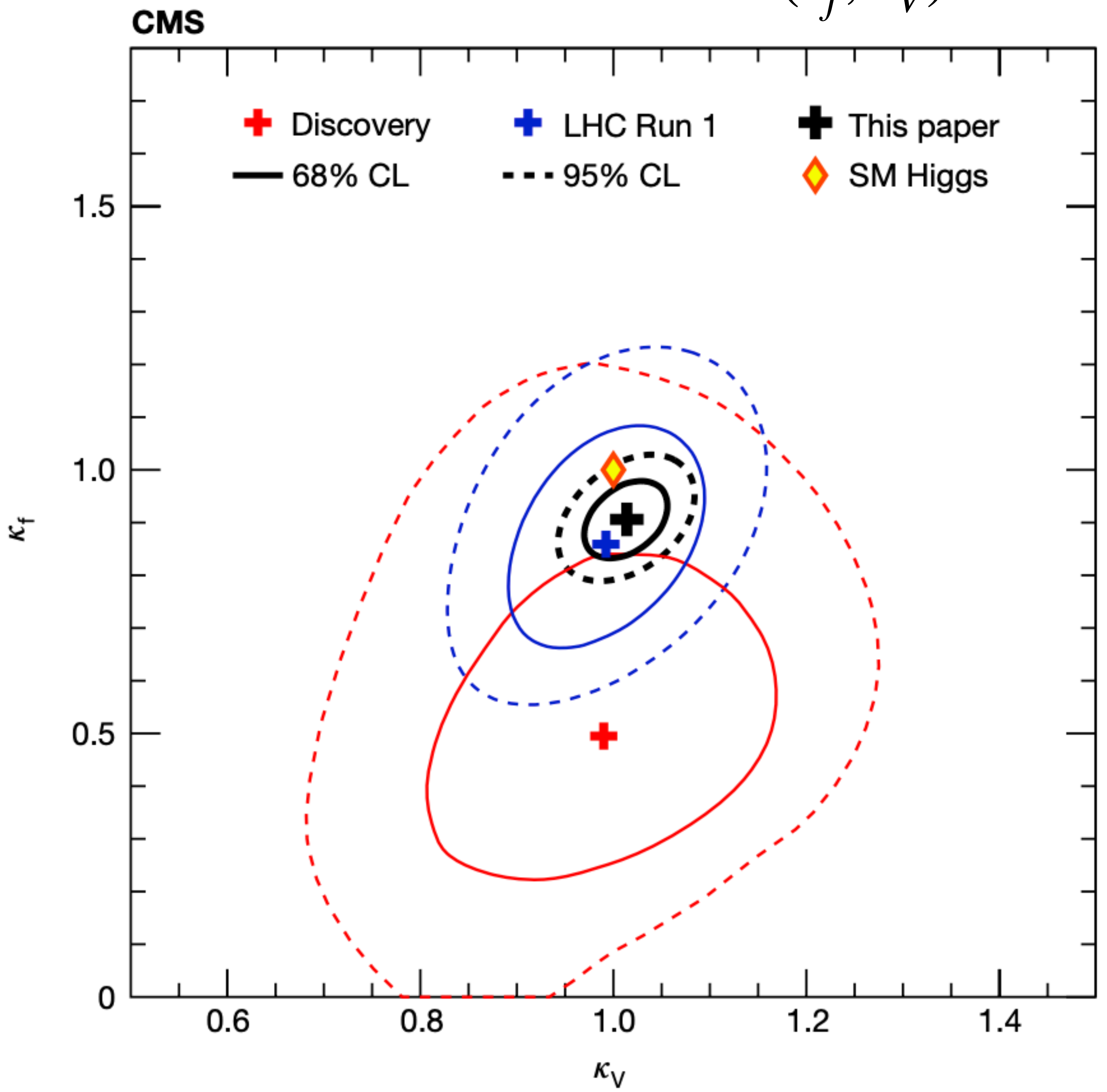
single H / HH analysis	$HH \to \gamma\gamma b\bar{b}$	$HH \to \tau\tau b\bar{b}$	$HH \to 4b$	$VHH \to b\bar{b}b\bar{b}$	HH (leptons)	$HH \to WWb\bar{b}$
$H \to \gamma\gamma$	✗	✓	✓	✓	✓	✓
$H \to WW$	✓	✓	✓	✓	✗	✗
$t\bar{t}H$ (leptons)	✓	✗	✓	✓	✓	✗
$H \to \mu\mu$	✓	✓	✓	✓	✓	✓
$H \to ZZ \to 4l$	✓	✓	✓	✓	✓	✓
$H \to b\bar{b}$ (ggH, VH, $t\bar{t}H$)	✓	✗	✗	✓	✓	✗
$H \to \tau\tau$	✓	✗	✓	✓	✓	✓
$VHH \to b\bar{b}b\bar{b}$	✓	✓	✗	✓	✓	✓

PAS

H couplings to fermions and vector bosons

Coupling modifiers κ to quantify couplings deviations from SM predictions ($\kappa_f = \frac{\kappa}{\kappa_{SM}}$)

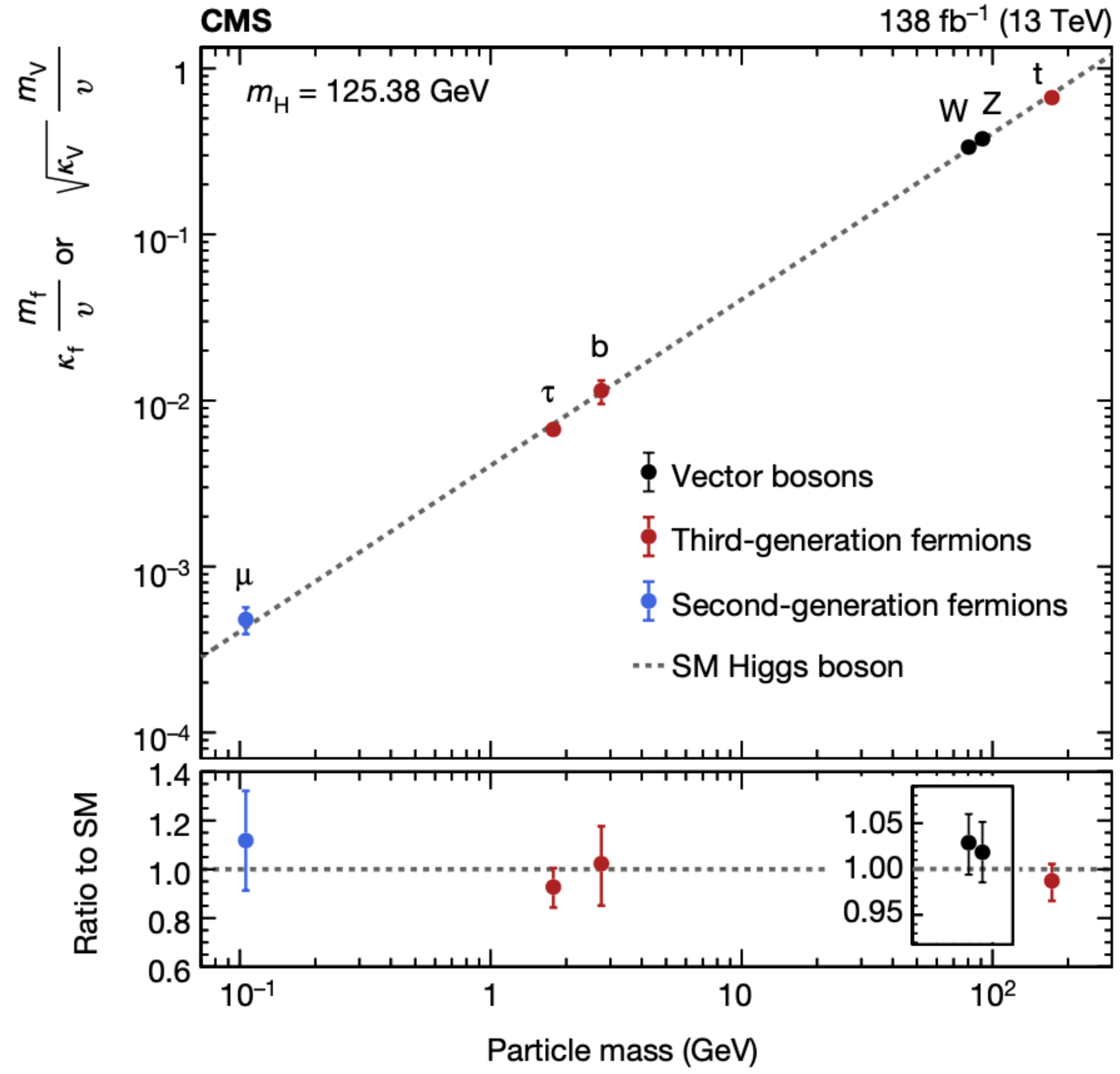
Likelihood scan of (κ_f, κ_V)



➡Compatibility with SM within 10%

➡Around 5 times improvement w.r.t discovery

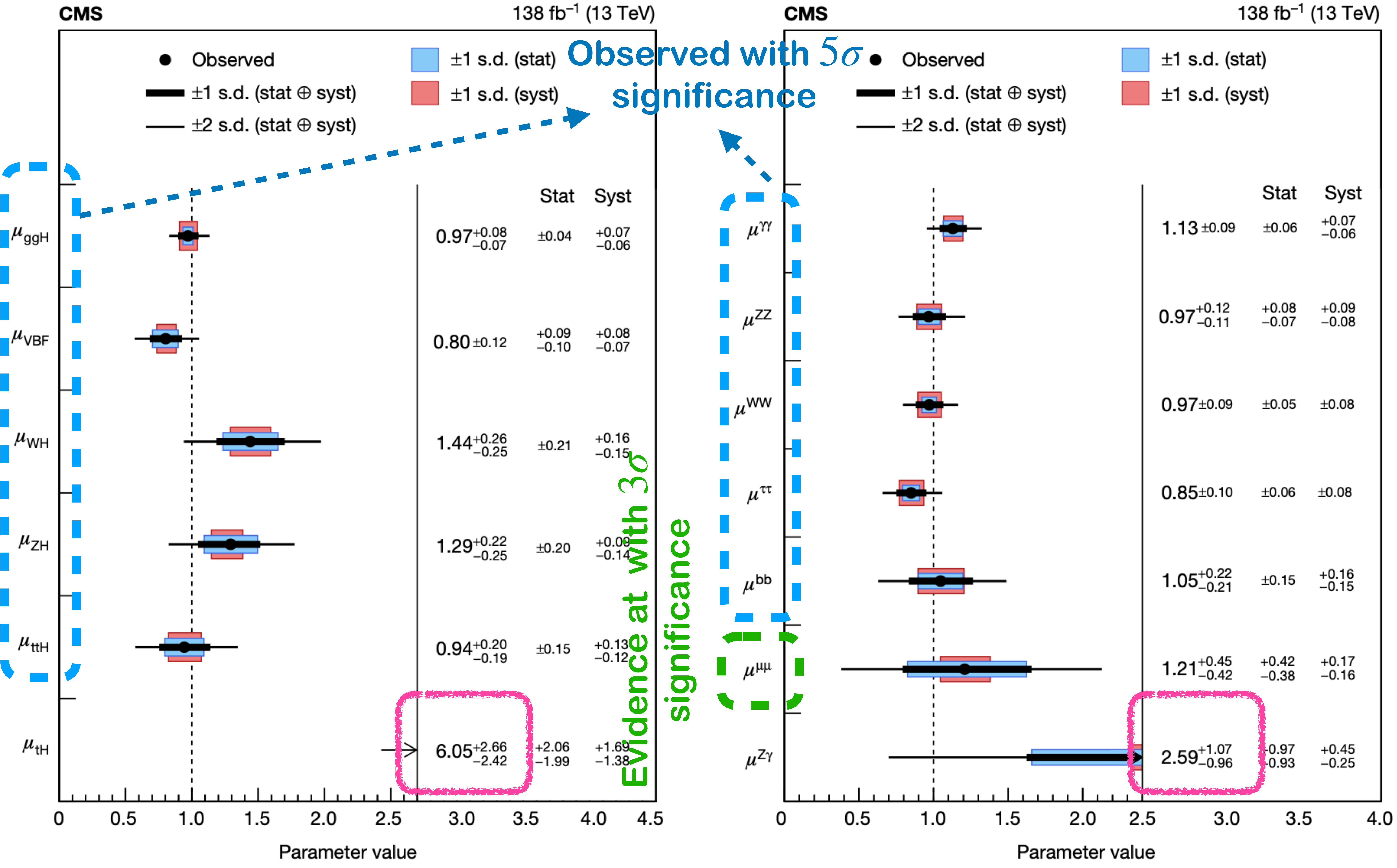
H couplings VS particle mass



➡ Agreement with SM for masses within 0,1- 200GeV

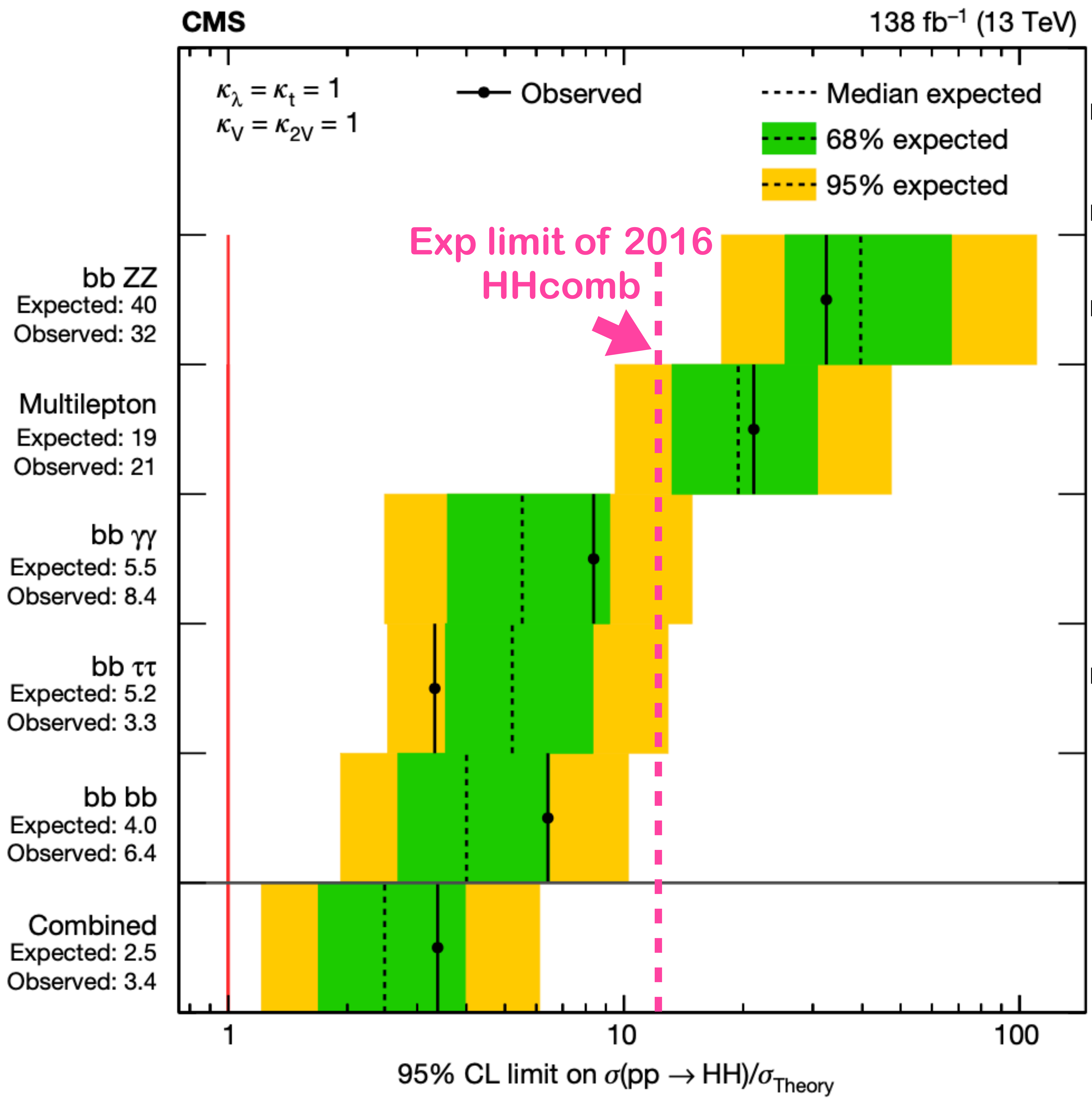
Test XS and BR compatibility with the SM

$$\mu = 1.002 \pm 0.057[\pm 0.036(theory) \pm 0.033(exp.) \pm +0.029(stat.)]$$



- ➡**Overall good compatibility with SM**
- ➡**Small excesses in μ_{tH} and in $\mu_{Z\gamma}$**
- ➡**Systematics uncertainties crucial for H measurements**
  - Reduce exp. Uncertainties with new or improved approaches
  - Need of more precise theory predictions

Upper limit on HH signal strength

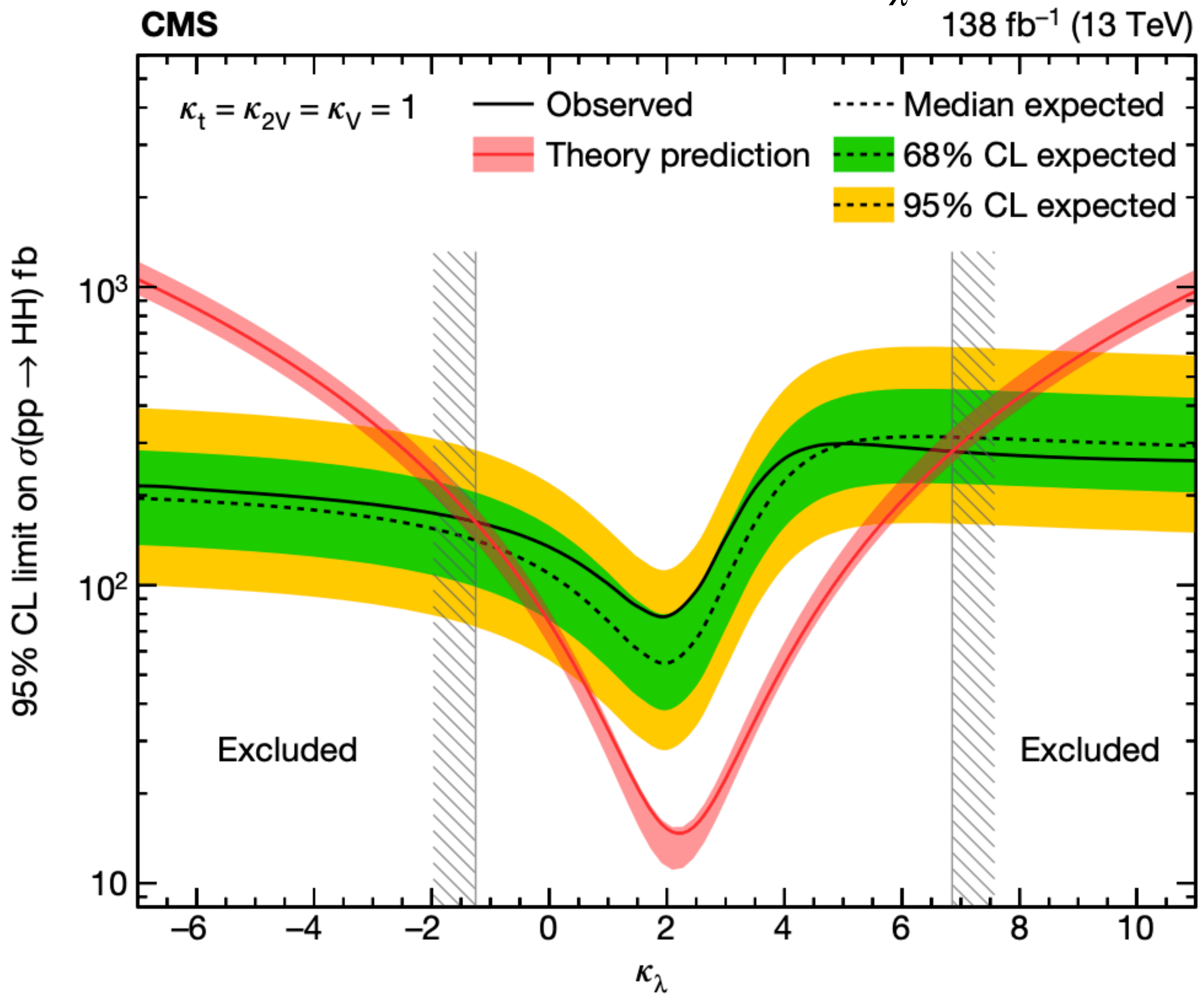


- ➡Obs(exp) upper limit on $\mu_{HH} = 3.4(2.5)$
- ➡No deviations from SM observed
- ➡2.5 time better than 2016 result scaled by Lumi
  - Extensive usage of ML tools + boosted topologies
- ➡HH will be one of the most exciting results of Run3
  - Scaling by end of Run3 and combing with ALTAS vary to 1!

Constraints on κ_λ

- **Observed results compatible to SM predictions**

Limit on HH XS vs κ_λ



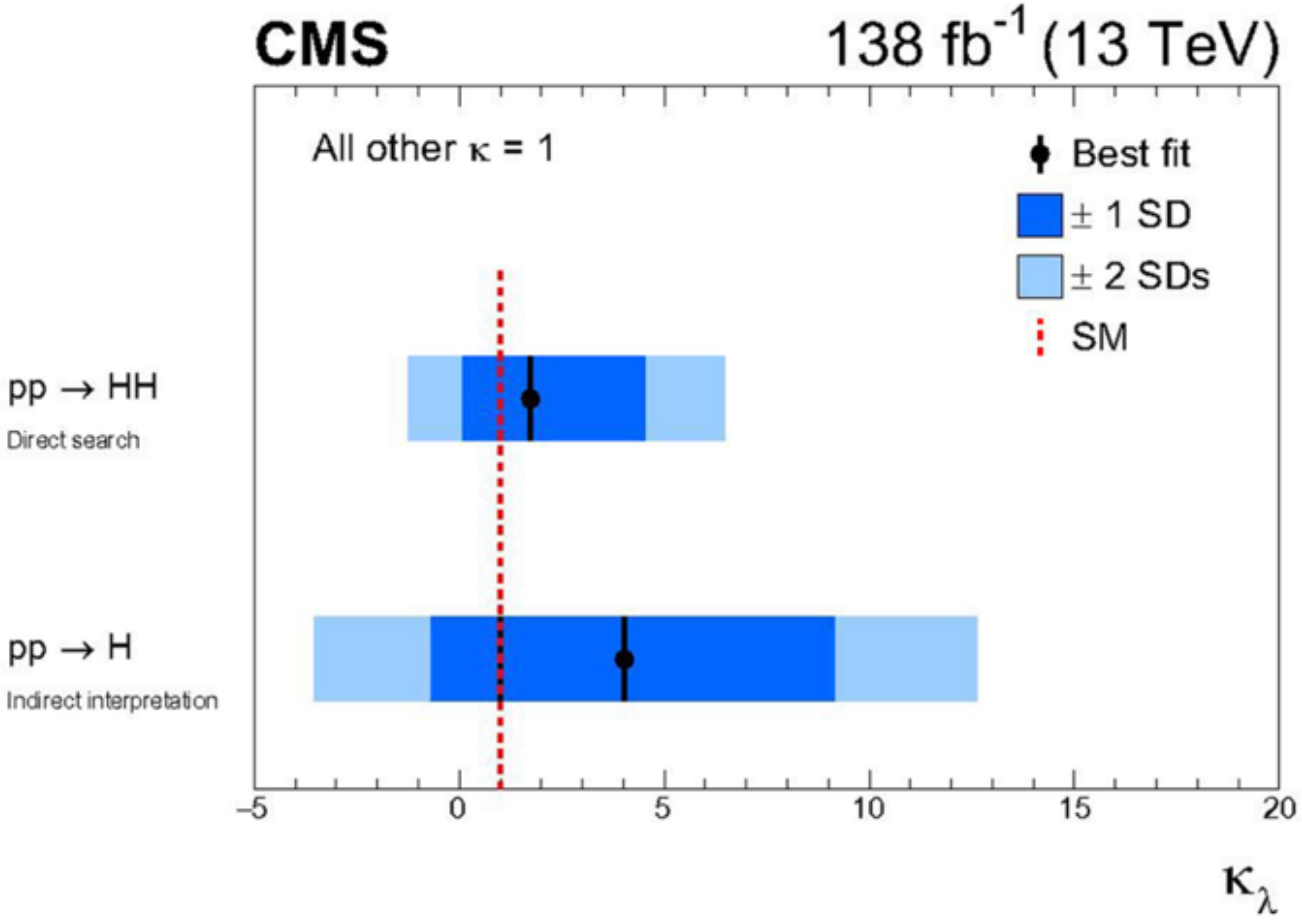
Obs. $\kappa_\lambda \in [-1.3, 6.9]$

Exp. $\kappa_\lambda \in [-0.9, 7.0]$

➡**Close to exclusion of $\kappa_\lambda = 0$**

- Possible with Run3 data or with Run2 HHcomb of CMS+ATLAS

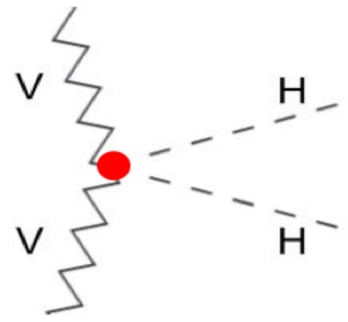
κ_λ measurement from HH vs from single-H



➡**First CMS measurement of κ_λ from signle-H**

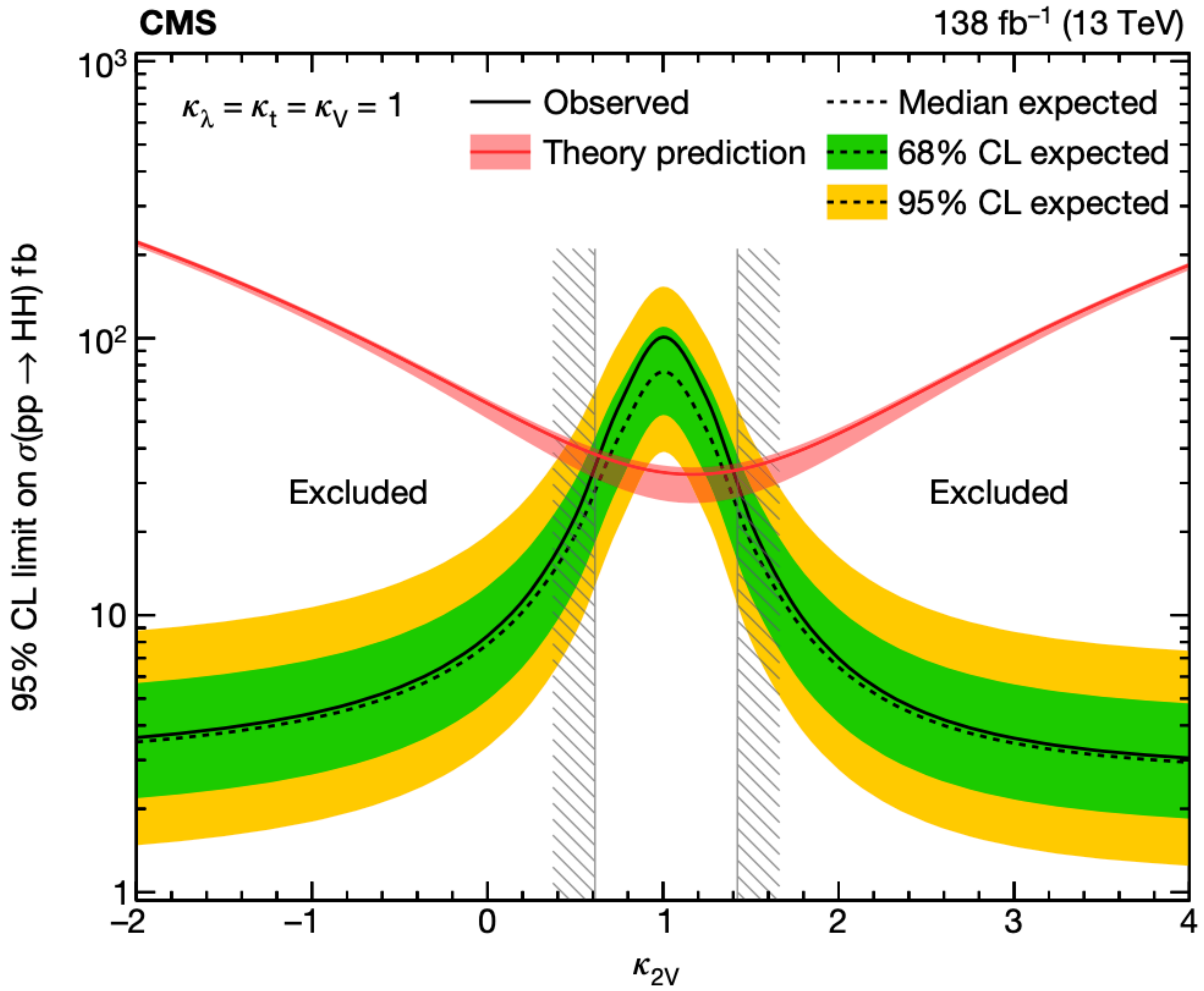
- Ultimate κ_λ results with Run 2 dataset will be updated soon by combining H+HH

Constrains on κ_{2V}



- **Observed results compatible to SM predictions**

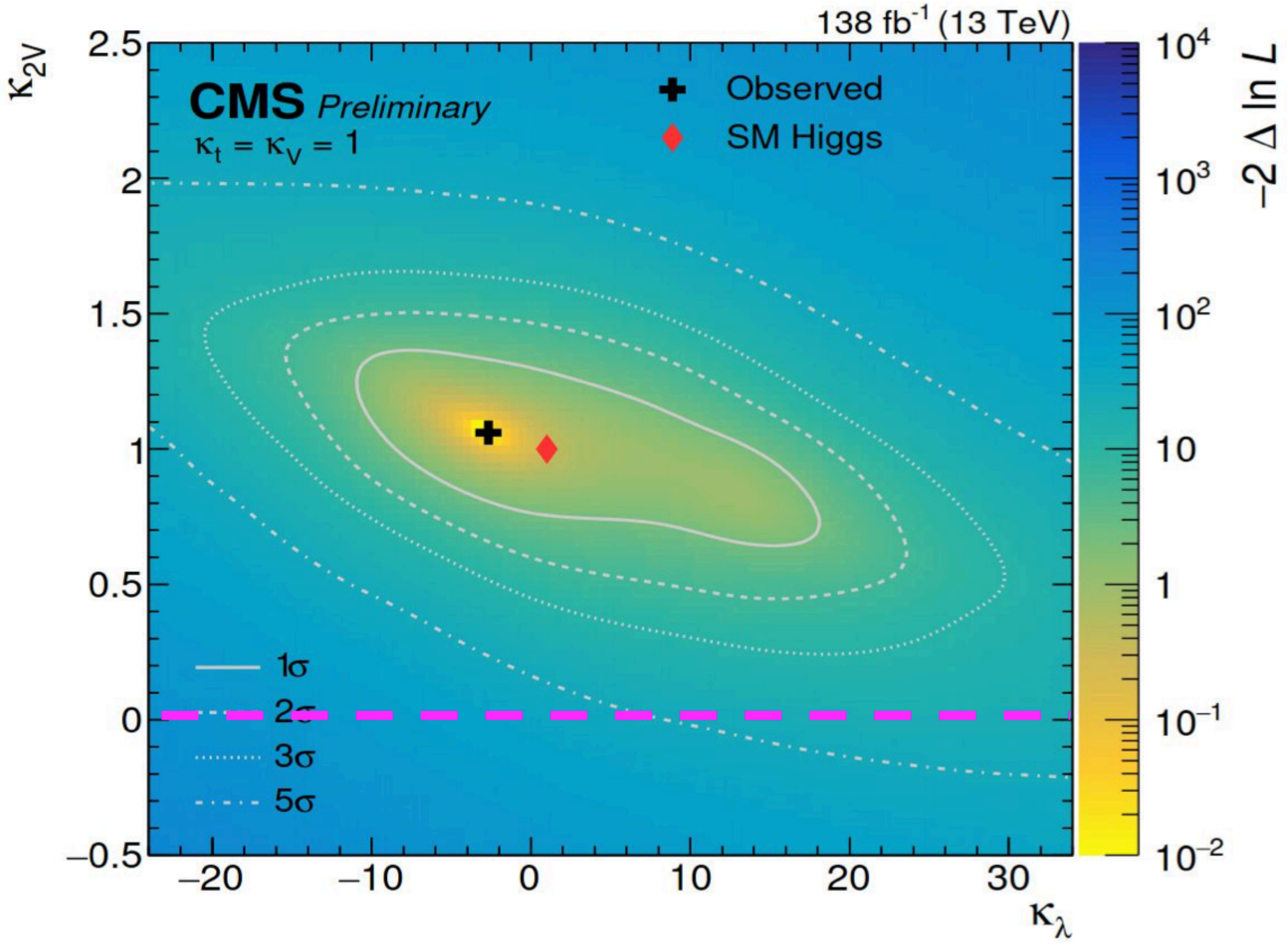
Limit on VBF HH XS vs κ_{2V}



Obs. $\kappa_{2V} \in [0.61, 1.42]$

Exp. $\kappa_{2V} \in [0.6, 1.37]$

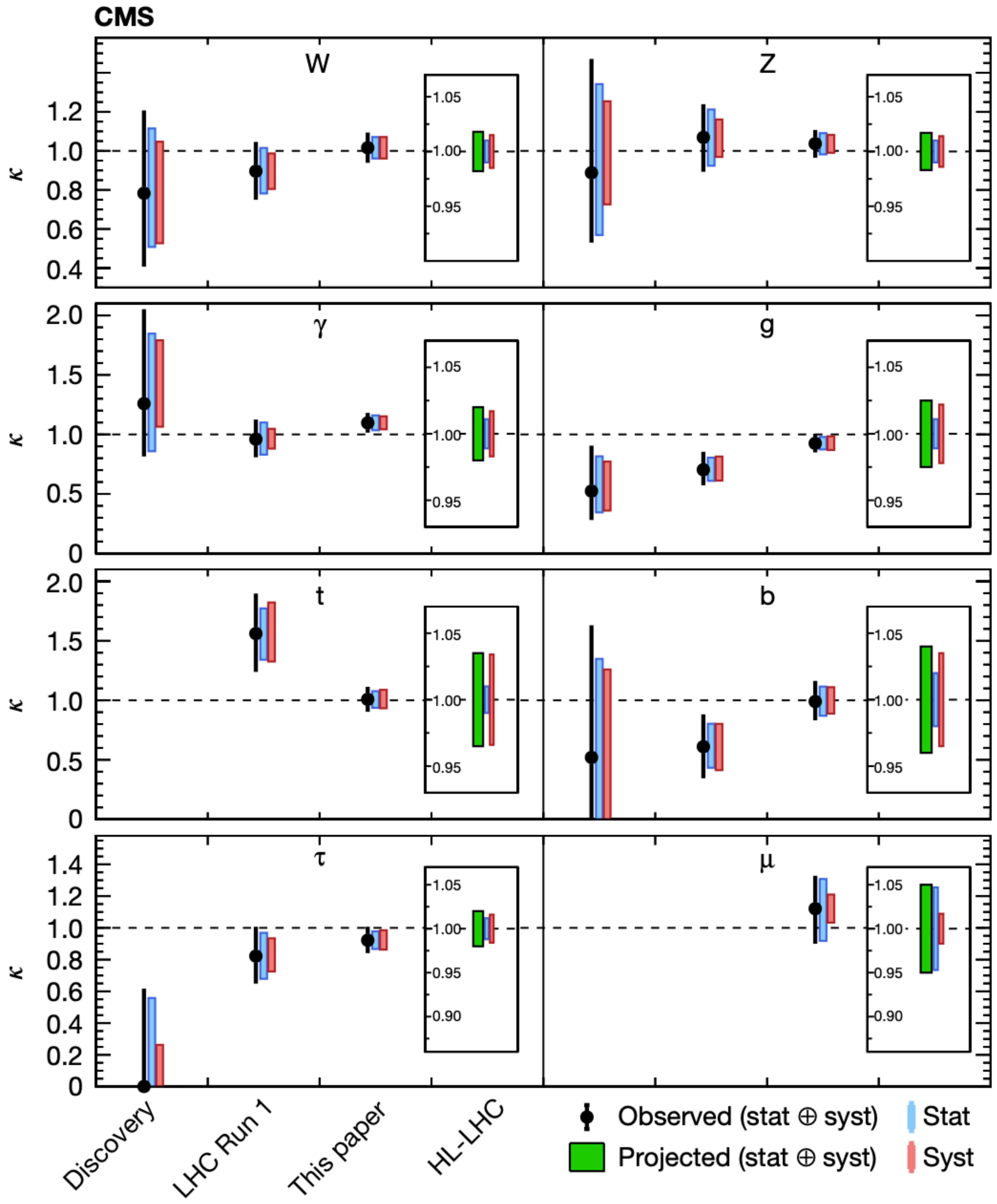
Likelihood scan of $(\kappa_\lambda, \kappa_{2V})$ with considering only boosted HH(4b)



➡$\kappa_{2V} = 0$ **excluded at** $> 5\sigma$ **assuming** $\kappa_\lambda = \kappa_t = \kappa_V = 1$

➡$\kappa_{2V} = 0$ **excluded at** $> 3\sigma$ **for any value of** κ_λ

Evolution from the H discovery towards HL-LHC



➡**At HL-LHC high precision tests of the SM**

- Precision below 5% for all the considered couplings

➡**Projection to $3000fb^{-1}$ on $\mu_{HH} < 1$**

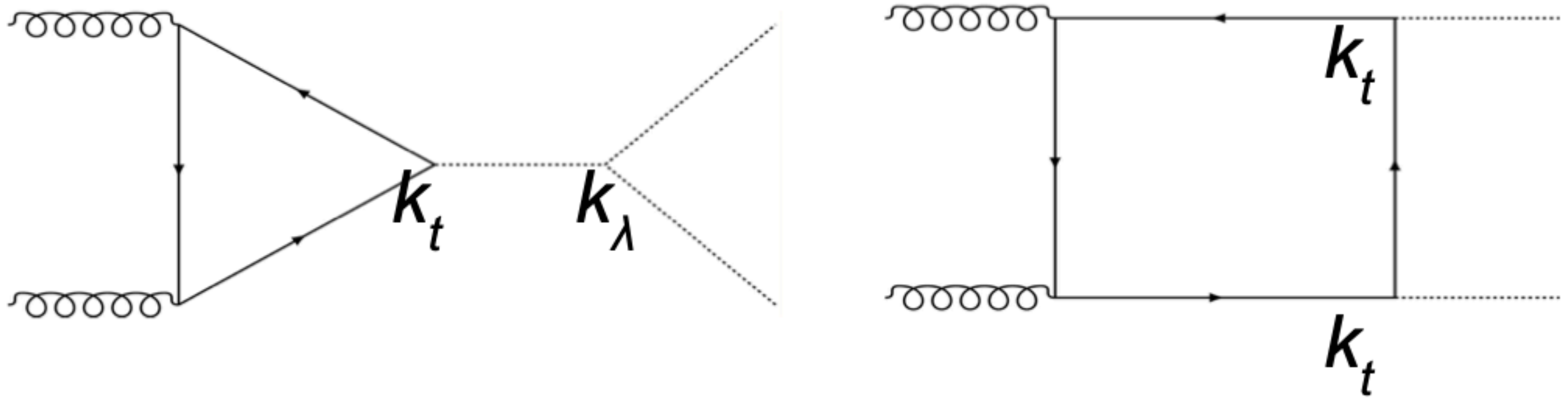
- Evidence of SM HH expected with 4σ for [CERN YR]
- Further improvement possible through new techniques and ideas (observation?)

➡**Potential for more extensive test SM, e.g. EFT**

Search for non-resonant HH production

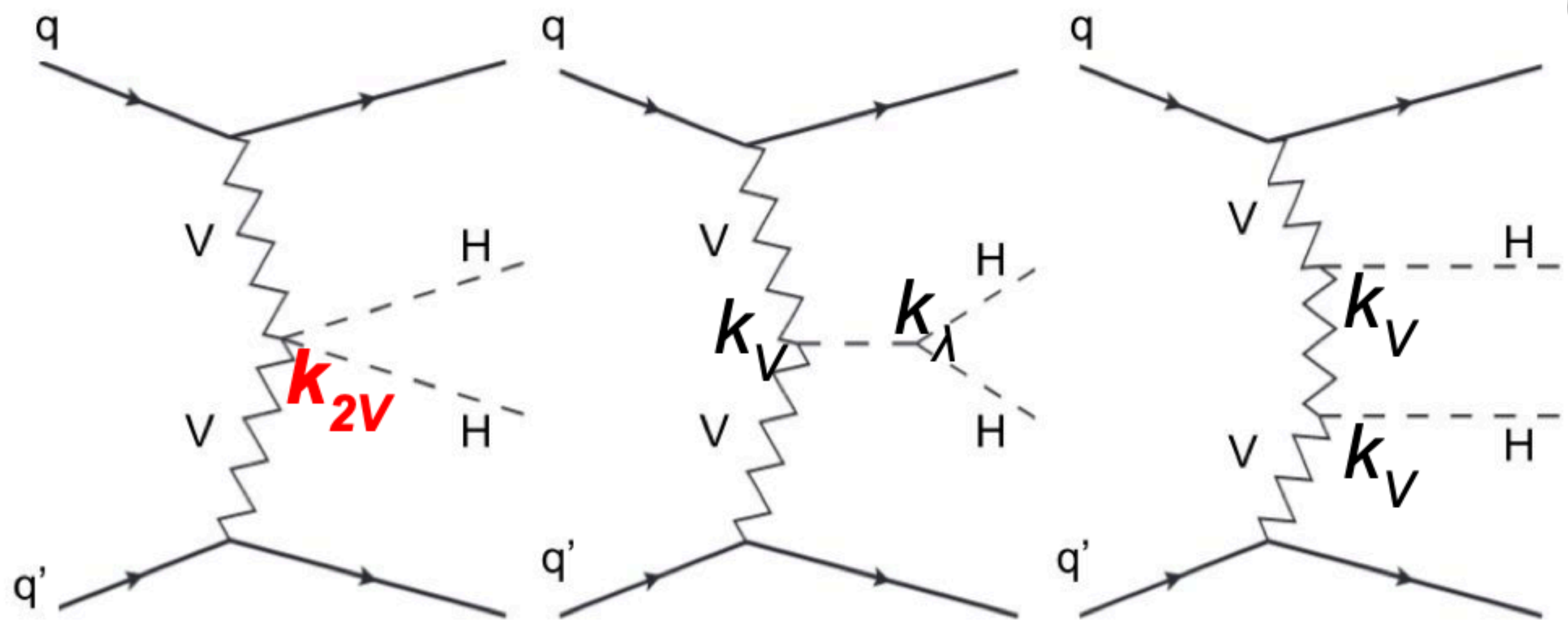
- HH production is sensitive to the Higgs trilinear coupling λ
- VBF HH is sensitive to c_{2V} coupling → $k_{2V} = c_{2V} / c_{2V(SM)}$

ggF production (ggHH) diagrams at LO

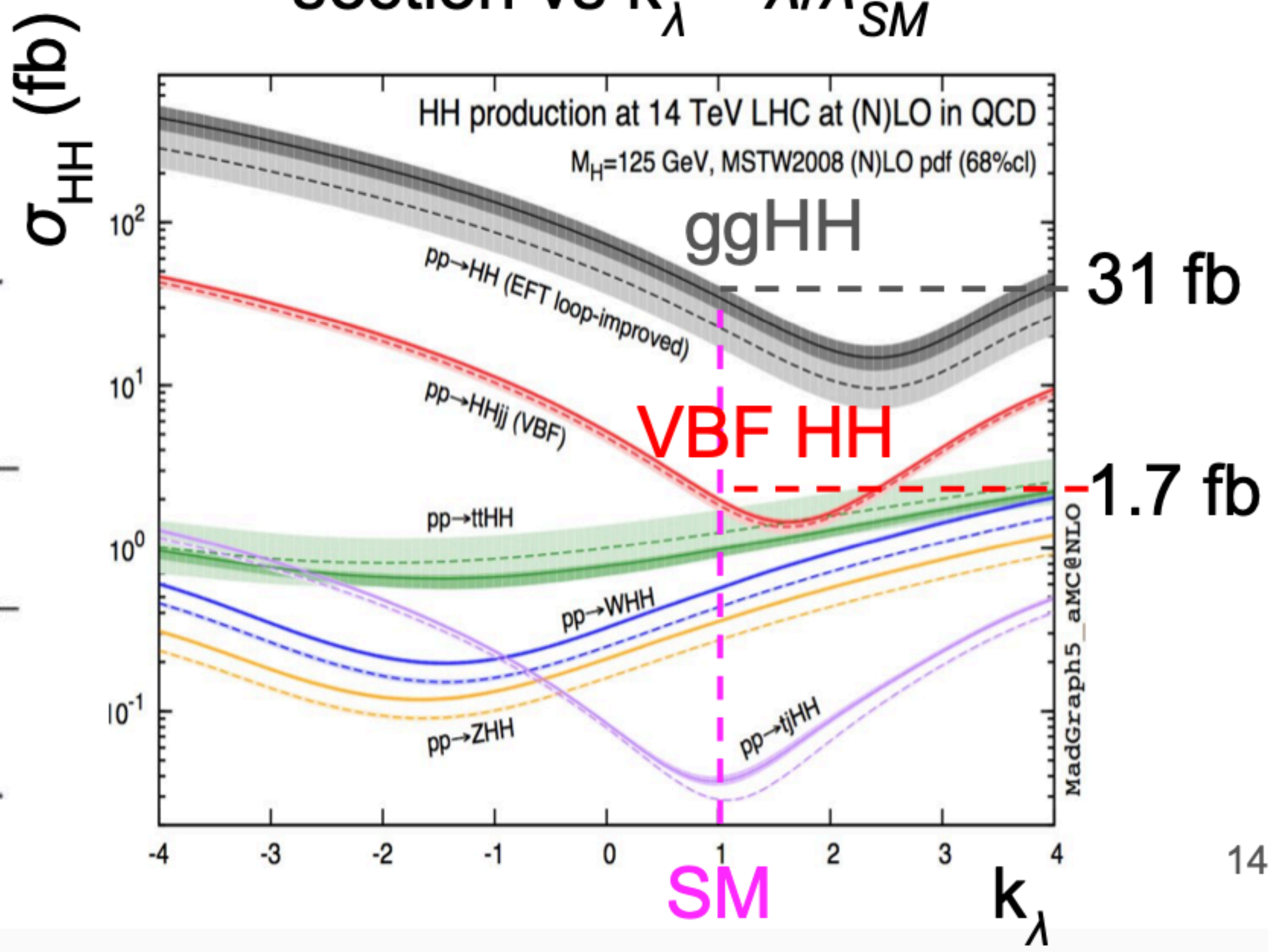


Fundamental tests of SM

VBF HH production diagrams at LO



HH production cross section vs $k_\lambda = \lambda/\lambda_{SM}$



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Evolution since discovery

H Discovery (up to 10.4 fb^{-1} at 7-8 TeV)

μ = 0.87 ± 0.23 [dominated by stat.]

Run 1 comb (up to 24.8 fb^{-1} at 7-8 TeV)

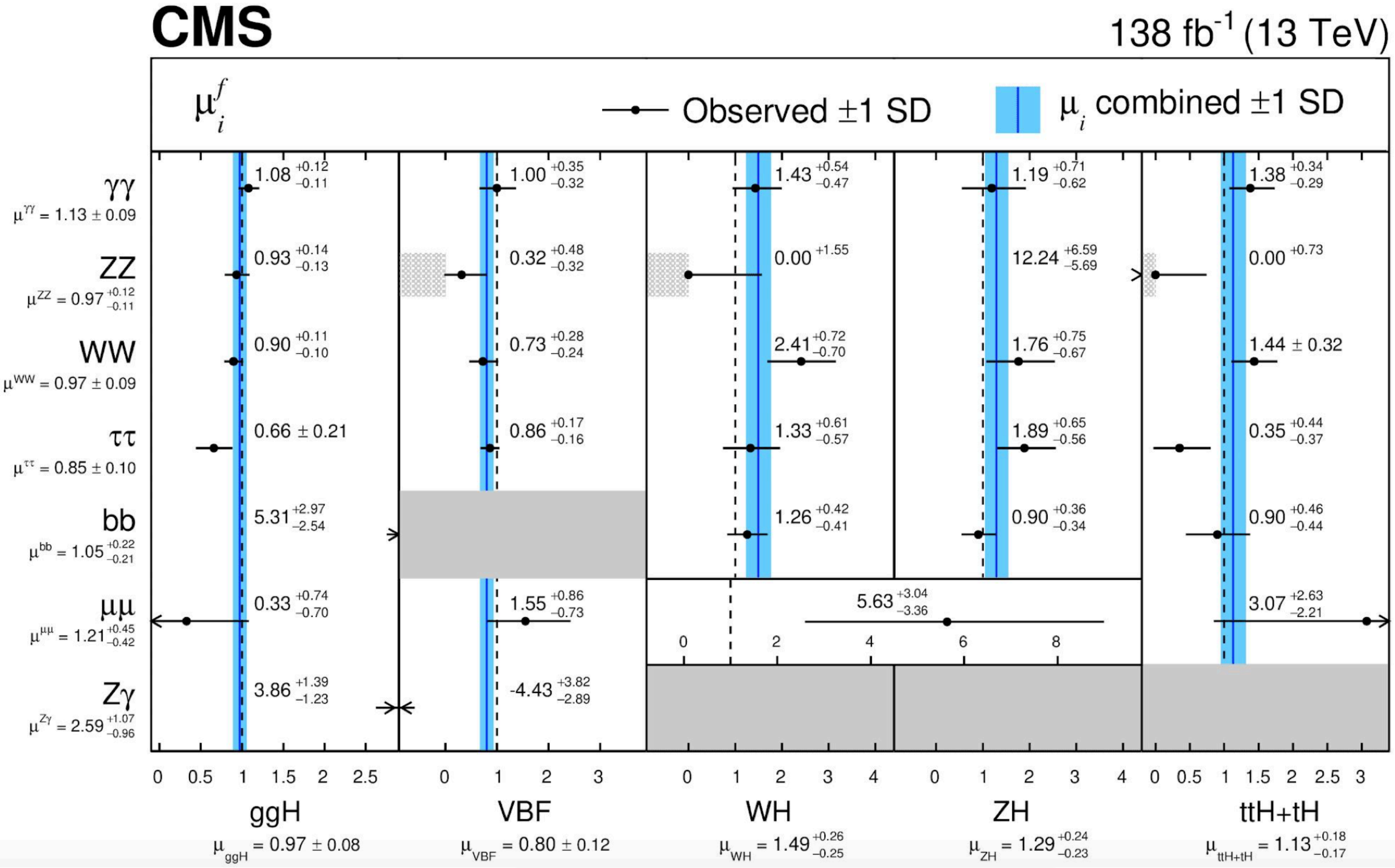
μ = 1.00 ± 0.13 [+0.08/-0.07 (theory) ± 0.07 (exp.) ± 0.09 (stat.)]

This combination (up to 138 fb^{-1} at 13 TeV)

μ = 1.002 ± 0.057 [± 0.036 (theory) ± 0.033 (exp.) ± 0.029 (stat.)]

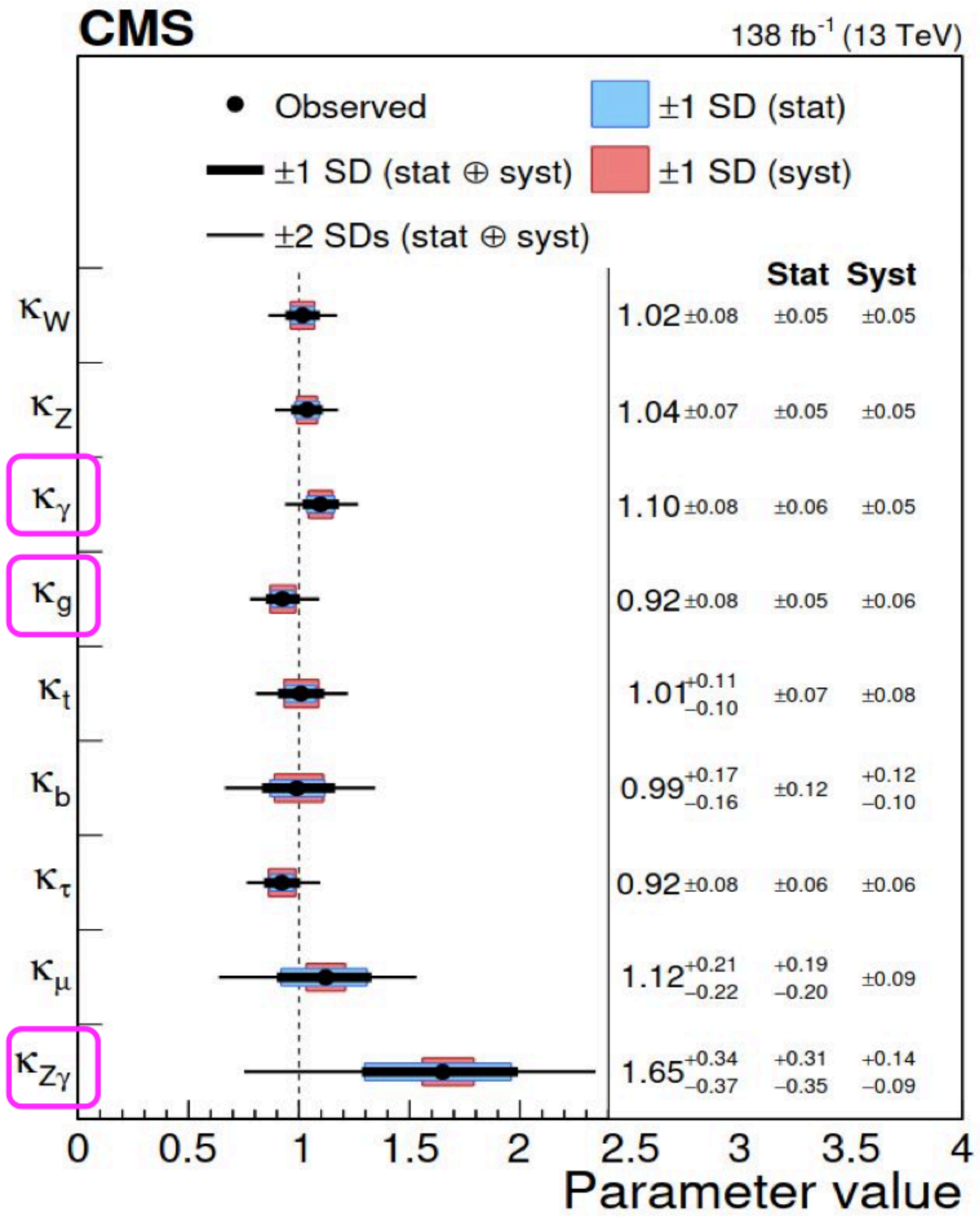
- Systematics uncertainties crucial for H measurements today and even more in future
  - Reduce exp. uncertainties with new or improved approaches
  - Need of more precise theory predictions

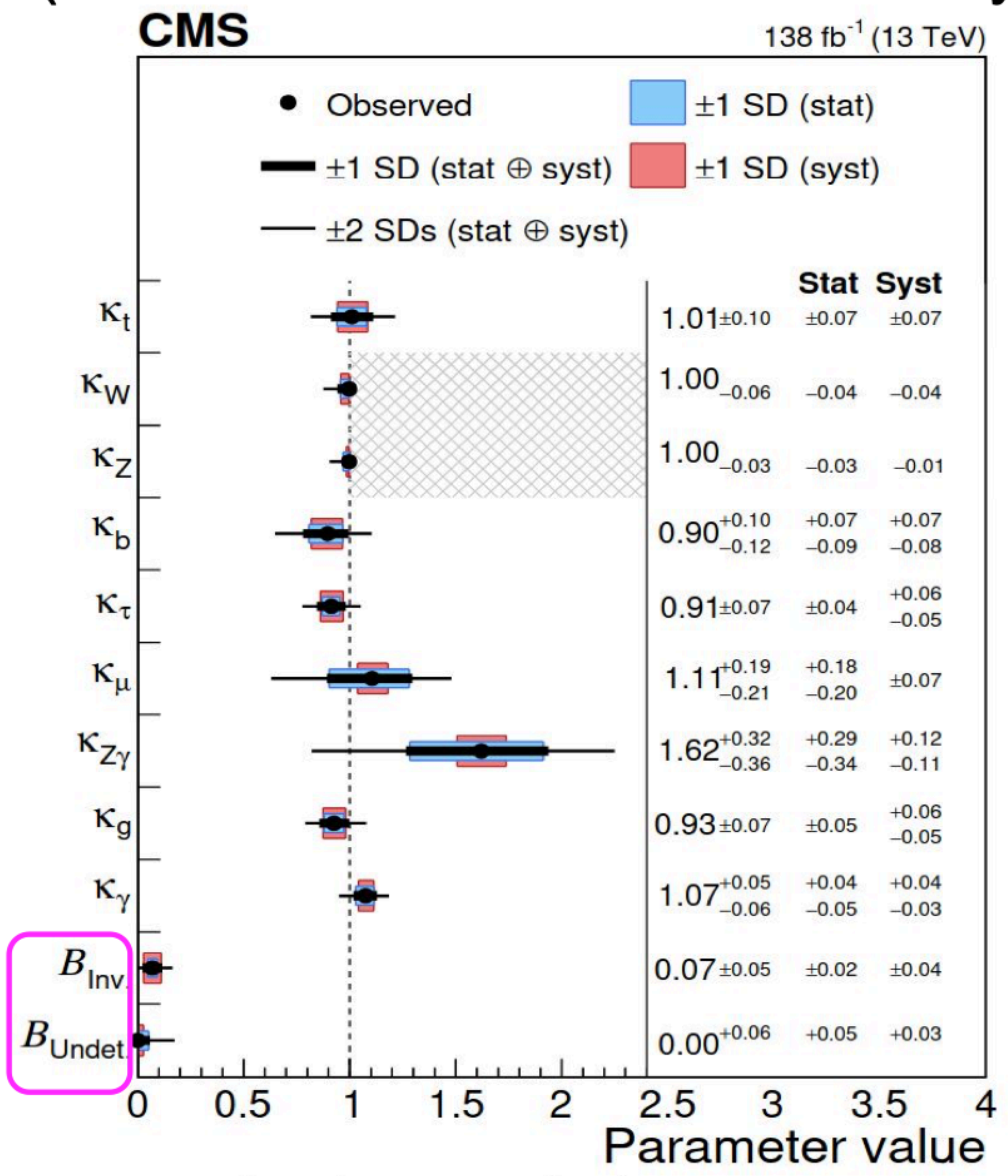
Test XS and BR compatibility with the SM



H couplings with more general assumptions

Measurement assuming effective couplings for ggH, Hγγ, and HZγ → Assuming also H decays to invisible(≒missing p_T) & undetectable (≒non-closure of other BR's to unity)





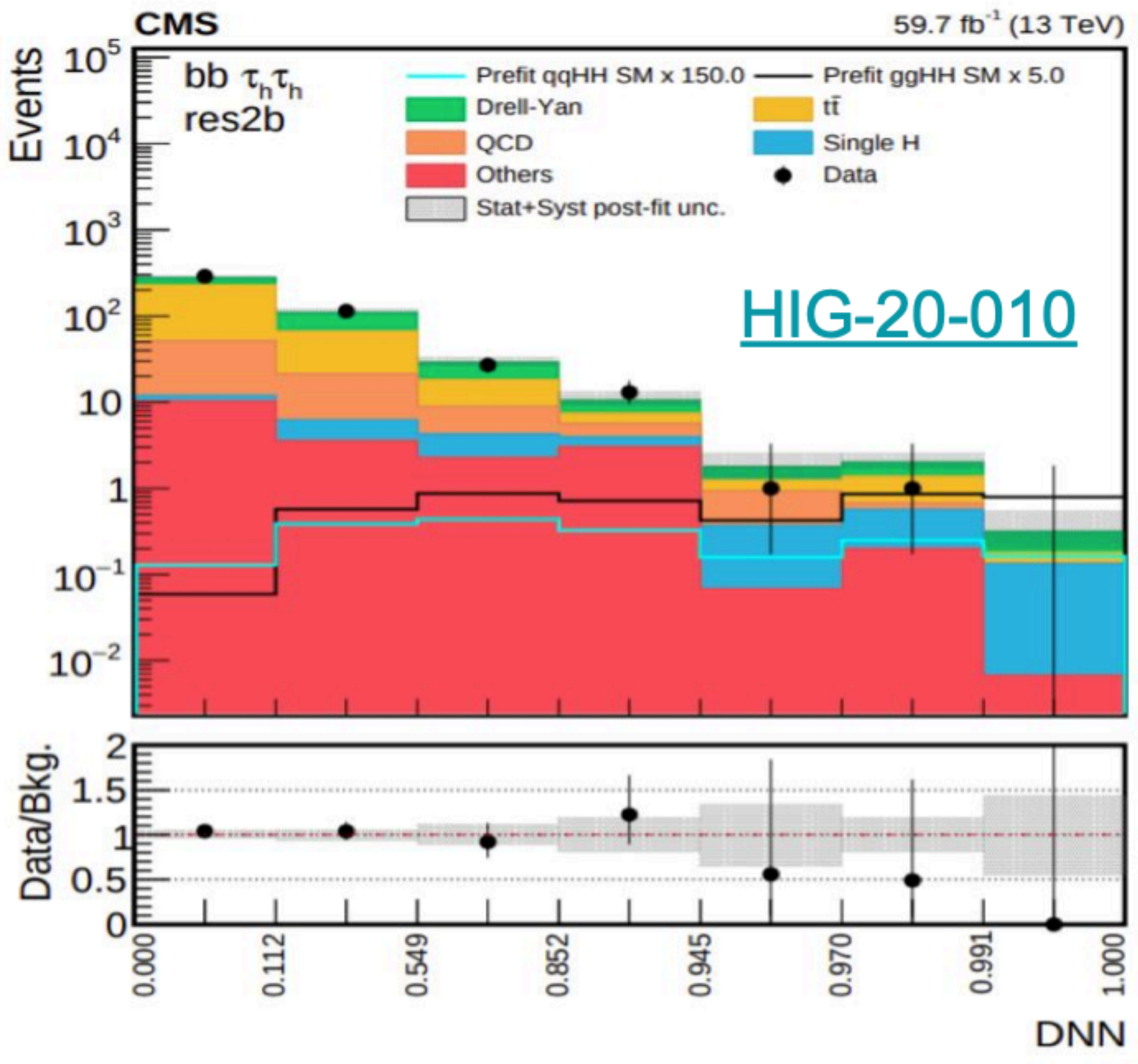
Stat. unc ≅ syst unc except for k_μ and and $k_{Z\gamma}$

Both invisible and undetectable BR's compatible with zero

What's new in full Run 2 HH searches @CMS?

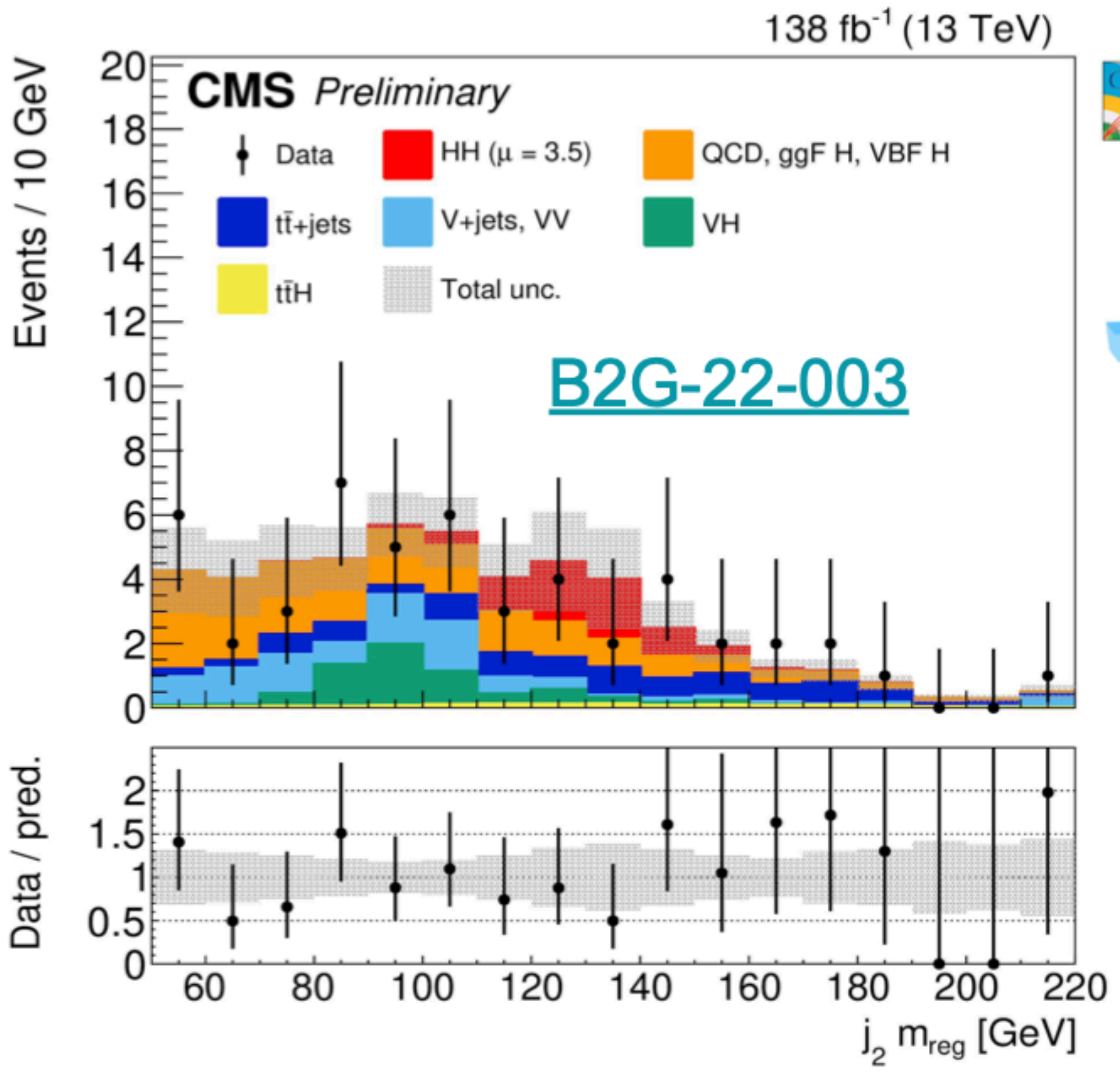
- Improvement wrt HH searches with 2016 dataset much larger than gain in integrated luminosity

Extensive usage of ML tools

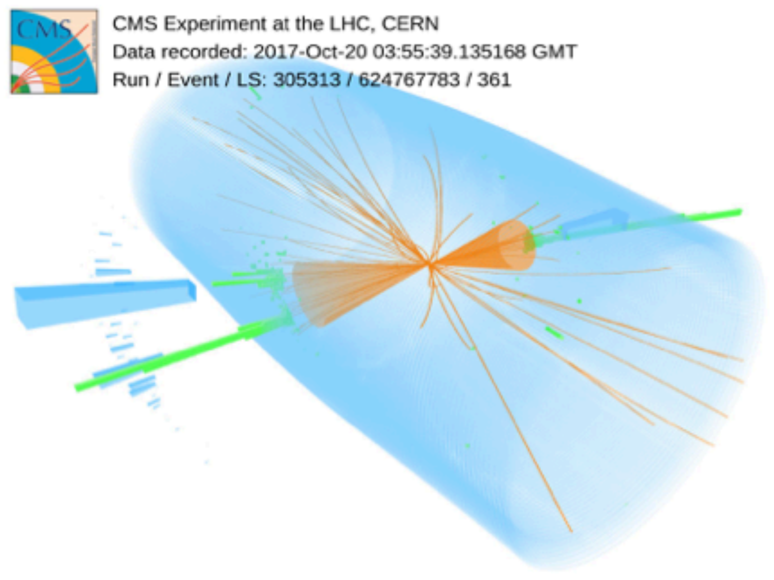


DNN score for resolved ggHH($bb\tau_h\tau_h$) category

Boosted topologies



Regressed mass of one AK8 jet in a ggHH(4b) boosted category



Boosted ggHH→4b event candidate

+ Selections targeting VBF HH production mechanism
+ New final states, e.g. multilepton

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Outlook for the future

Projection of ATLAS+CMS combination of HH searches @HL-LHC and HE LHC

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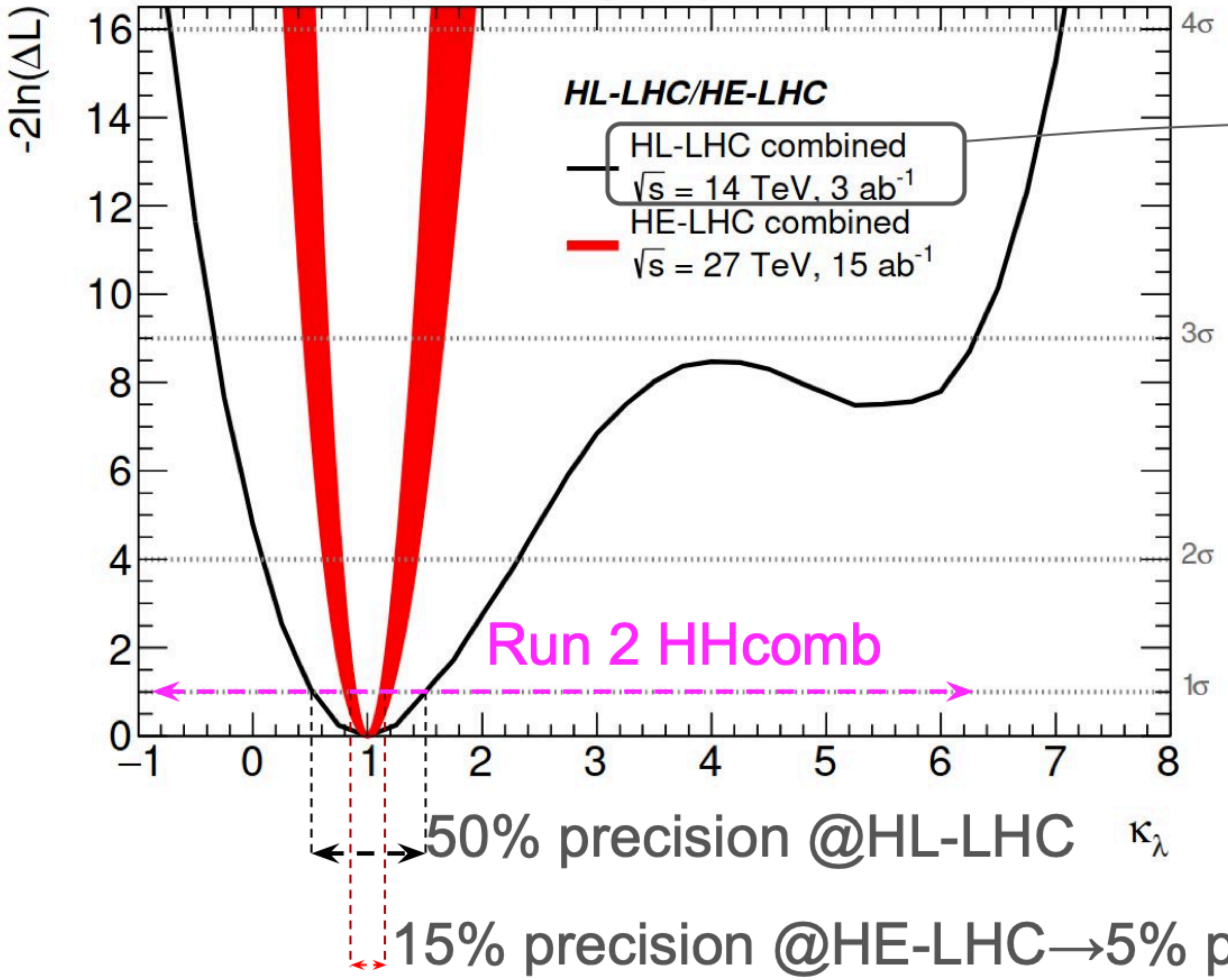


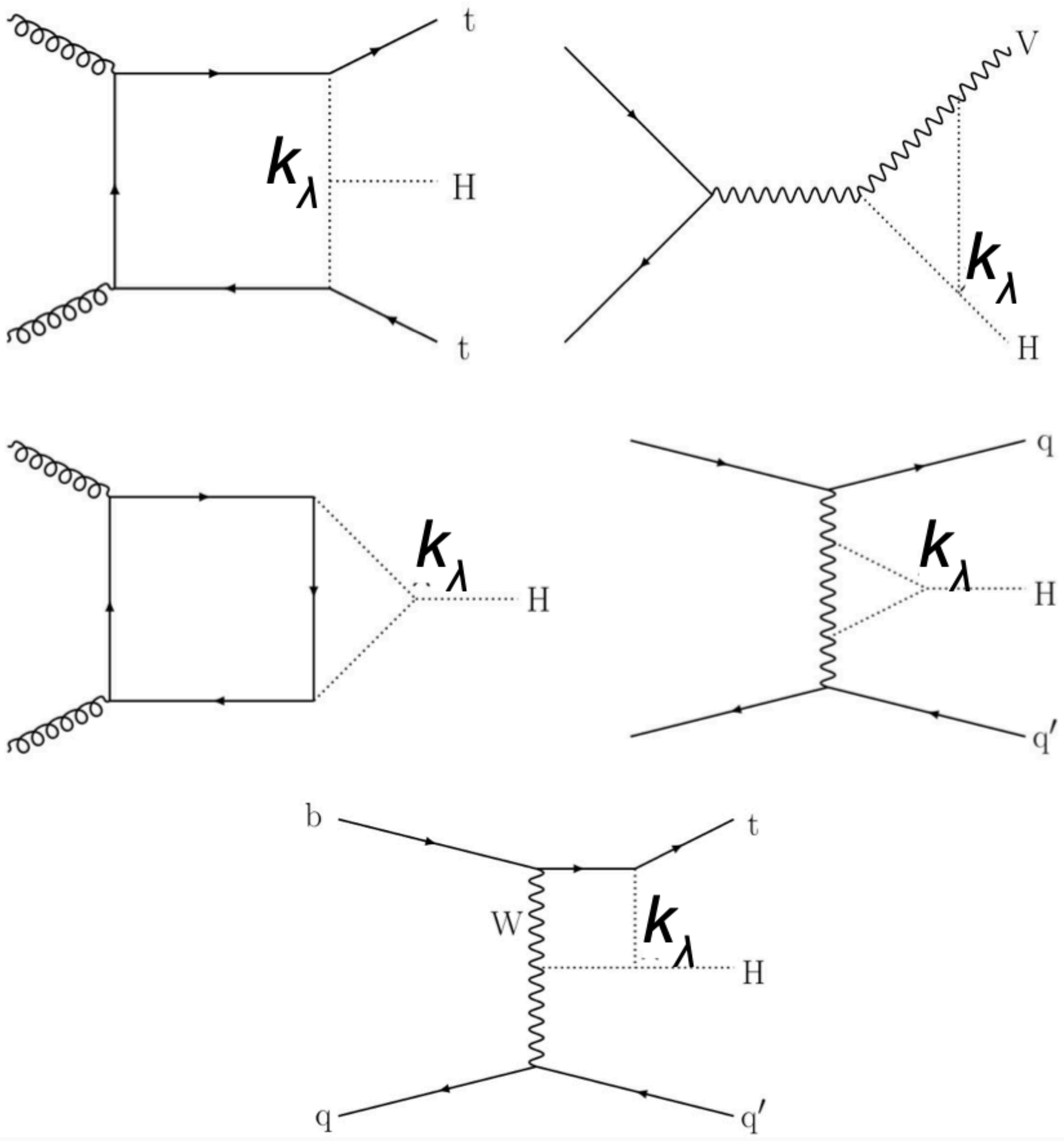
- Evidence of SM HH expected with 4σ
- Further improvement possible through new techniques & ideas→observation?

15% precision @HE-LHC→5% precision with 100 TeV & 30 ab^{-1}

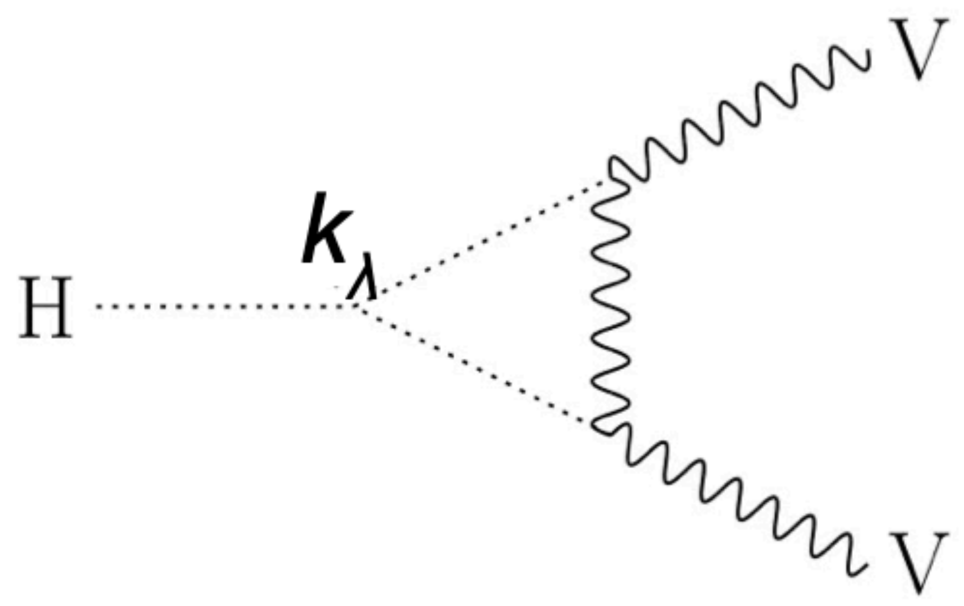
Trilinear self-coupling in single-H mechanisms

- k_λ-dependent NLO electroweak corrections to single-H XS and BR

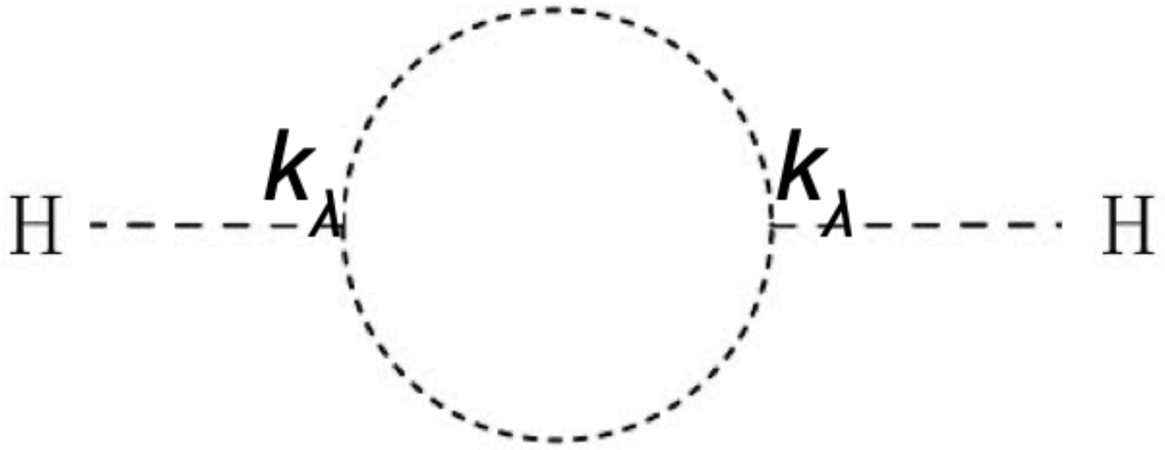
Examples of k_λ-dependent diagrams for single-H prod. mechanisms $O(k_\lambda)$



Example of k_λ-dependent diagrams for H→VV decay



One universal correction for H wave-function renormalization $O(k_\lambda^2)$



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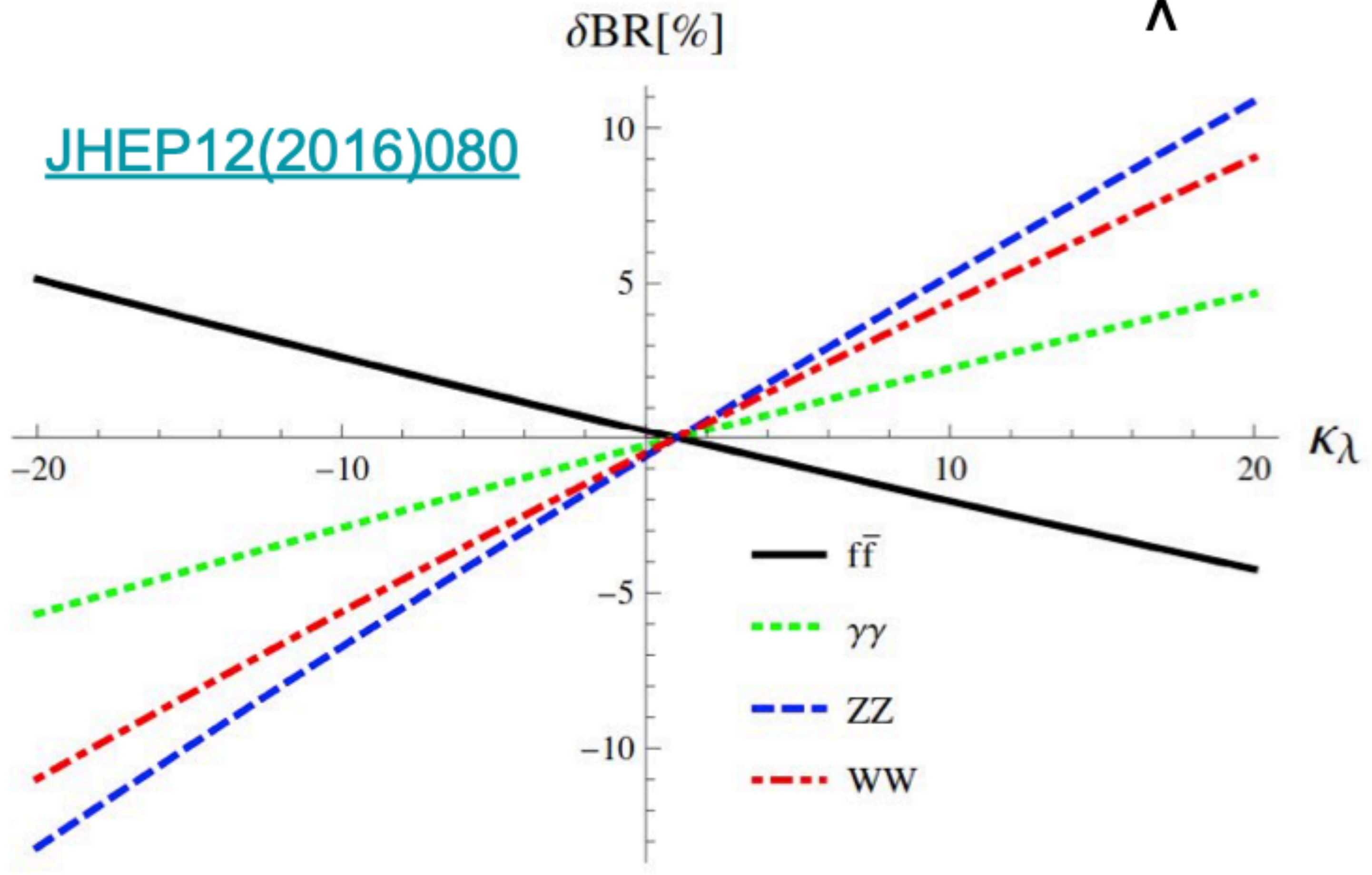
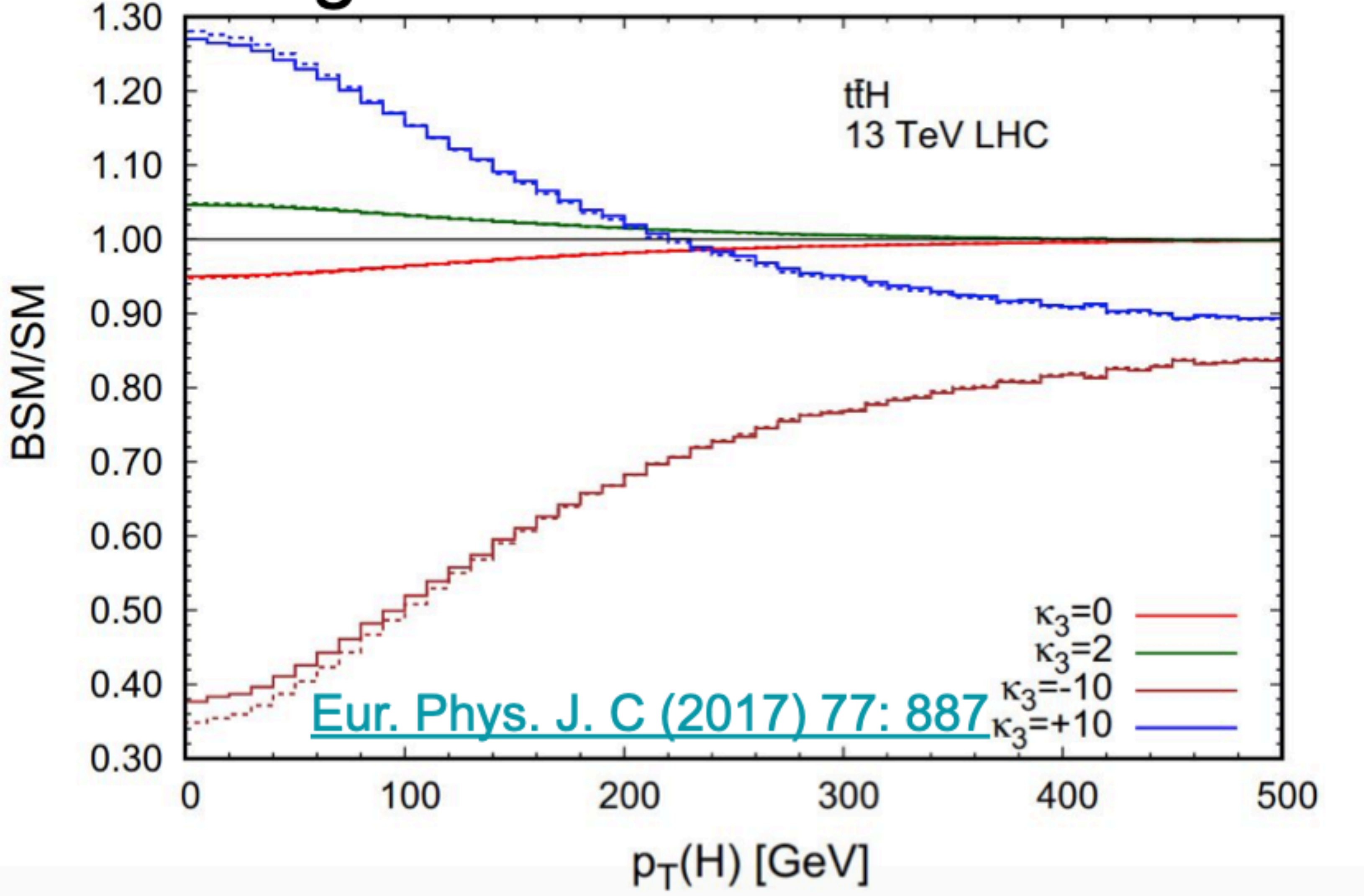
Effect of k_λ corrections on Higgs XS and BR

Modification of H BR vs k_λ

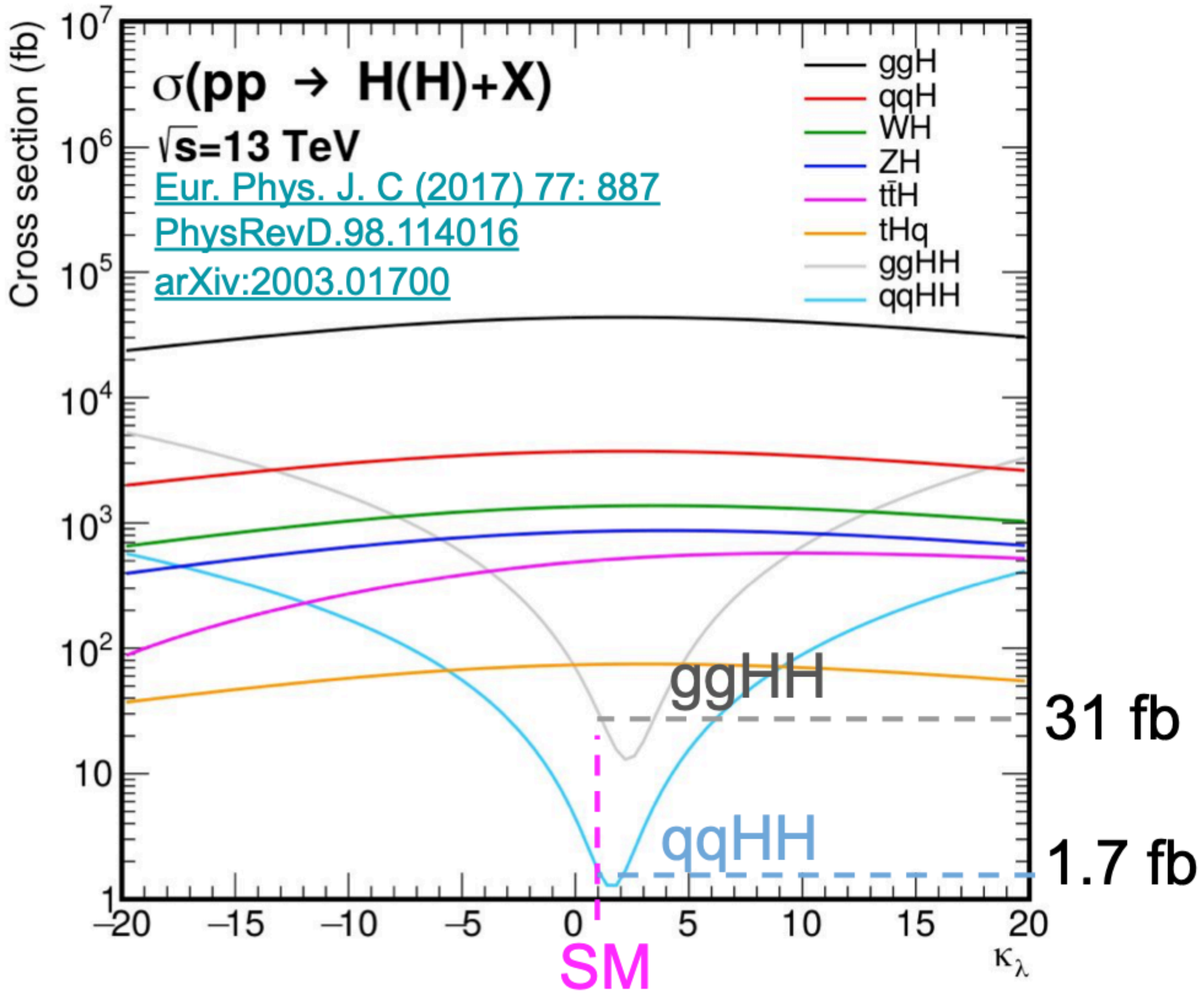


Modification of differential. XS

- Larger variations for VH and ttH



Modification of total XS vs k_λ



- Effect on double-H @LO →large variation
- Around SM single-H XS's are larger than double-H

Global fit

- BSM phenomena affecting k_λ should reasonably introduce deviations in other H couplings
  - ➢ Simultaneous fit of all H couplings
  - ➢ Complementarity of constraints from single-H and HH fully exploited in their combination

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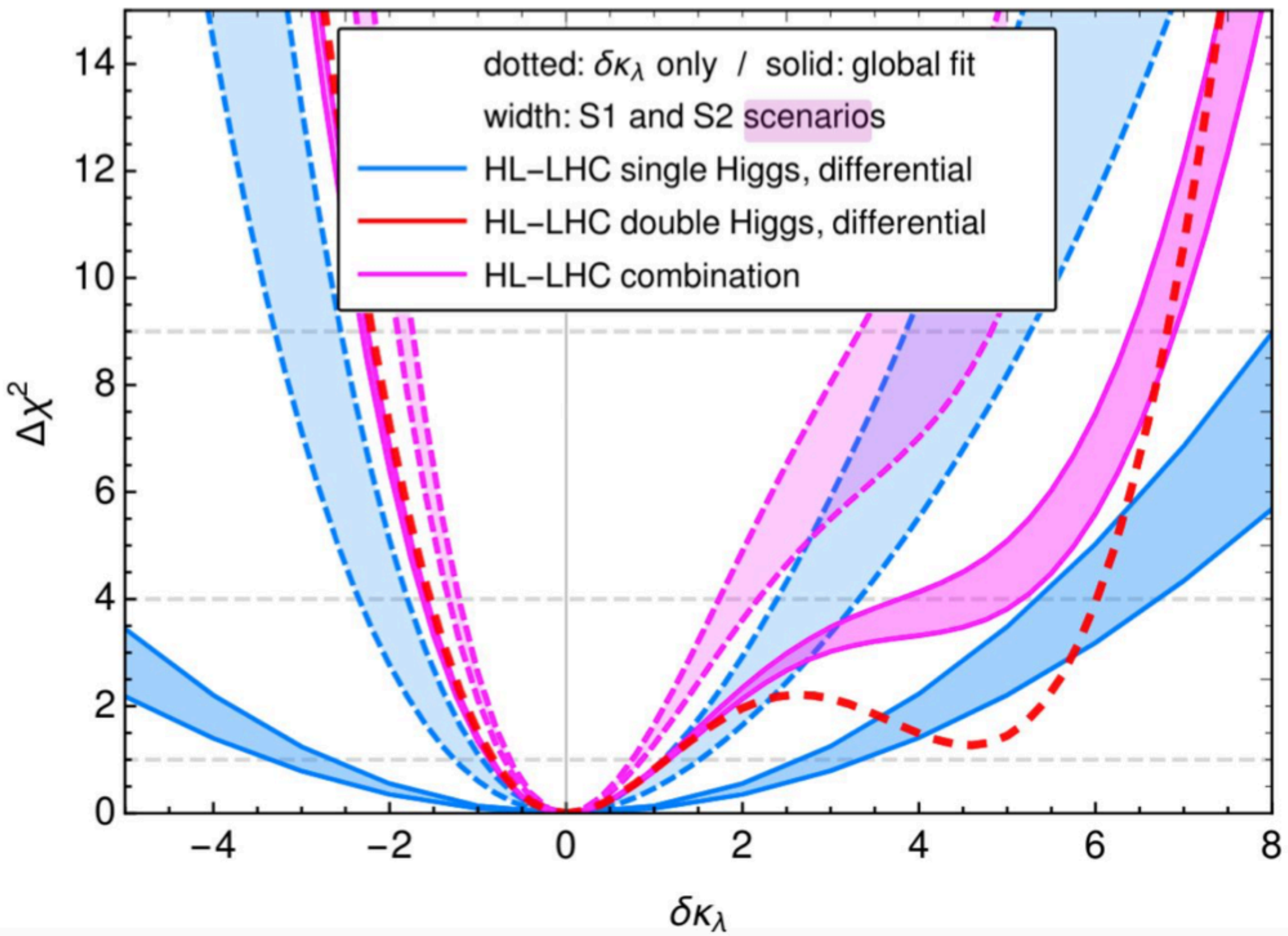


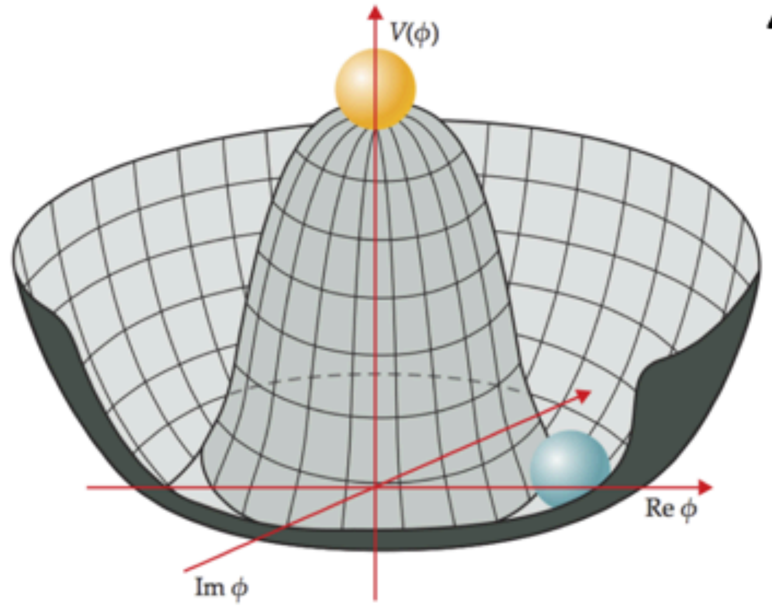
- ➢ Challenging because of overlap between single-H and HH selections
- ➢ NOT impossible! ATLAS preliminary result

Introduction

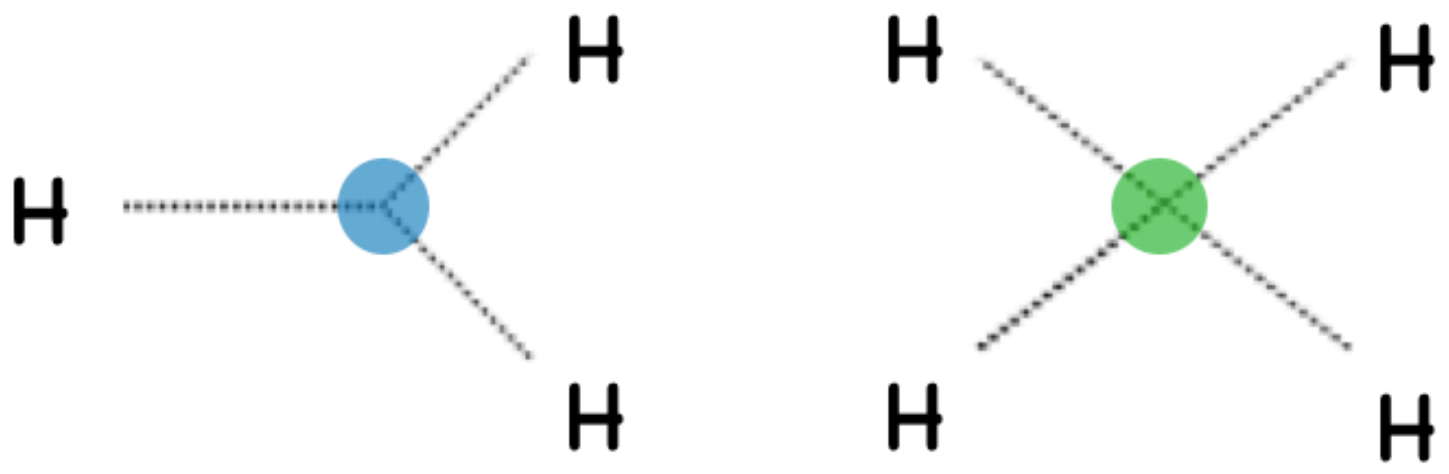
- Higgs boson self-coupling (λ) is a crucial missing element to complete the picture about Higgs boson
- λ measurement provides:
  - a fundamental test of SM and has important physics implications (e.g. stability of the universe)
  - a probe of the Higgs field potential shape
- Deviation of the coupling strength from SM is characterized by the coupling modifier: $\kappa_\lambda = \lambda/\lambda_{SM}$

We focus on the trilinear coupling !

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



Self-coupling arises from Higgs field potential expansion around its v.e.v.



H trilinear coupling $\lambda = m_h^2/2v^2$ with v = Higgs boson v.e.v.