Higgs and HH combinations at the CMS experiment

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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
    - Precise measurements of main H production XS and decay BR
    - Search for double-Higgs production
  - Measurement of H coupling to fermions and vector bosons
    - Probe anomalies from BSM contributions
    - HHVV coupling (c_{2V}) from VBF HH production
  - Probe properties of the H potential from H self-coupling λ
- Perspectives for HL-LHC
- Upcoming H+HH combination

Input Analysis

Main H production and decay channels covers with up to full Run 2 Dataset(2016-2018)

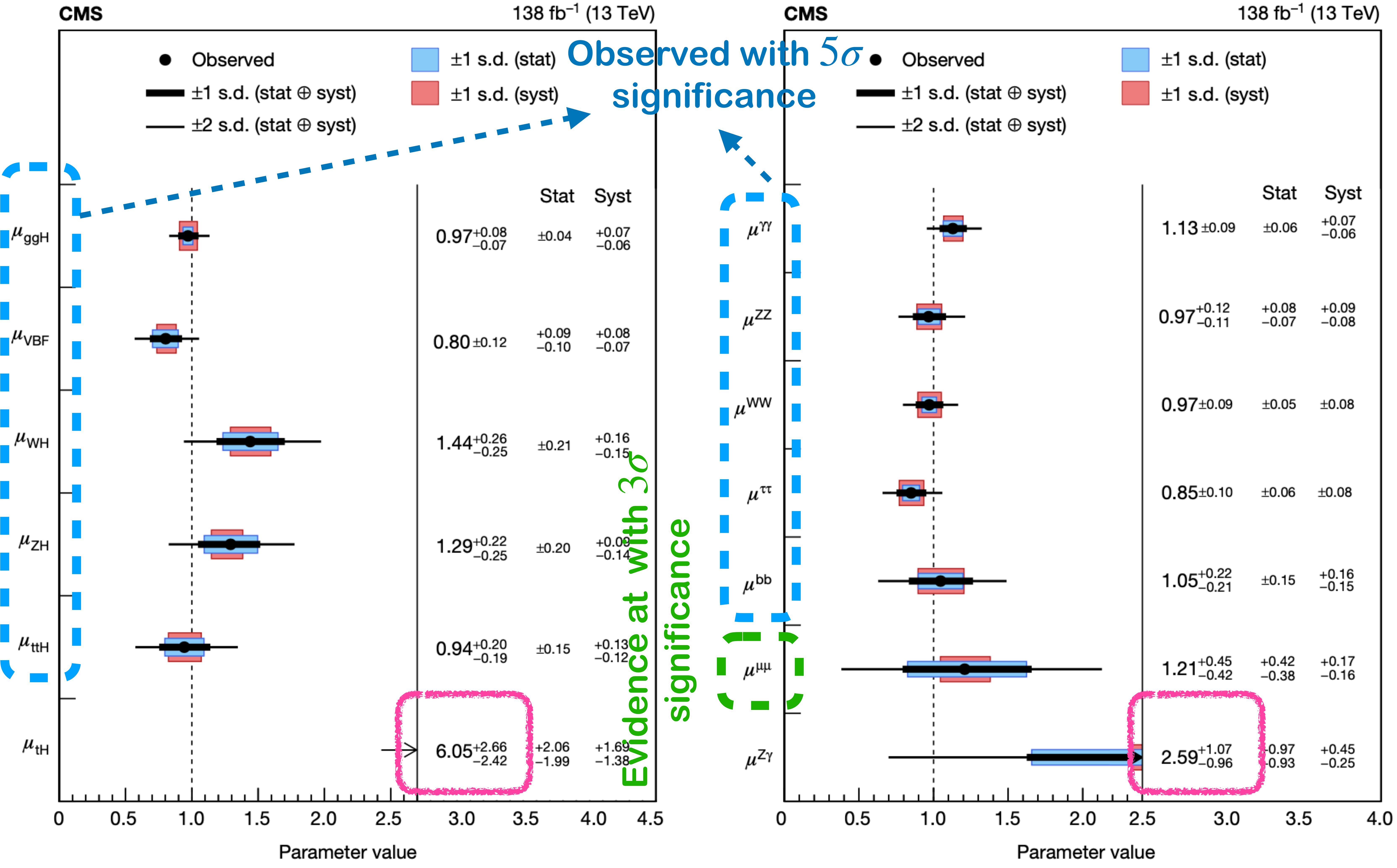
Single-Higgs											
Analyses	$H \to ZZ \to 4l$	$H \to bb$	$VH(H \to bb)$	$ttH(H \to bb)$	$ttH(multilepton)$	$H \to \mu\mu$	$H \to \gamma\gamma$	$H \to \tau\tau$	$H \to WW$	$H \to Z\gamma$	$H \to invisible$
Lumi	138	138	77	36	138	138	138	138	138	138	138

All channels use the full Run 2 data set
Additional publication with more channels($bbWW, WW\gamma\gamma$) are not included in this combination

Double-Higgs						
Process	$HH \to bb\gamma\gamma$	$HH \to bb\tau\tau$	$HH \to bbbb(resolved)$	$HH \to bbbb(boosted)$	$multilepton$	$HH \to bbZZ(4l)$
Production	ggHH/qqHH	ggHH/qqHH	ggHH/qqHH	ggHH/qqHH	ggHH/qqHH	ggHH

Test XS and BR compatibility with the SM

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

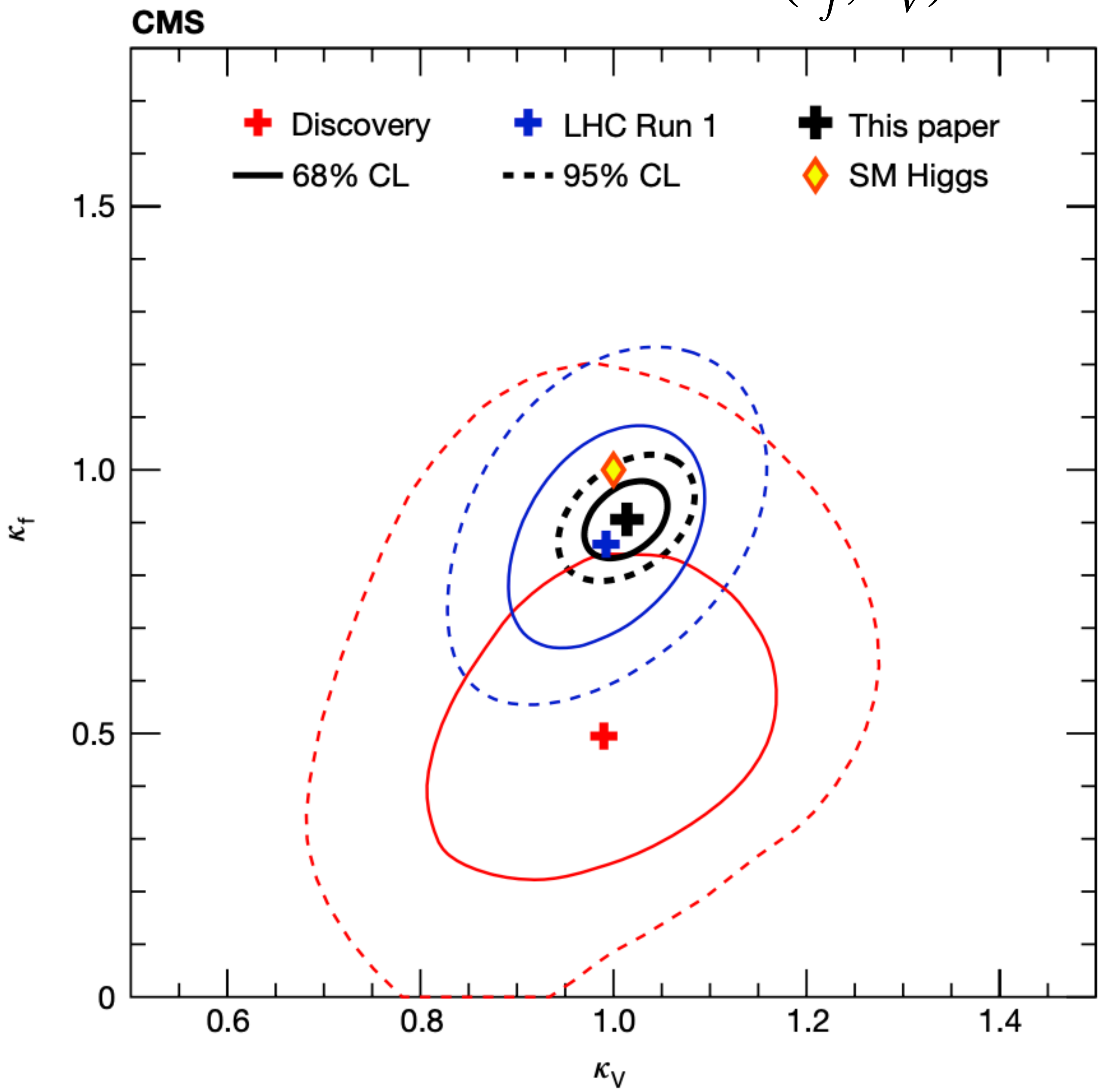


- ➡**Overall good compatibility with SM**
- ➡**Small excesses in μ_{tH} and in $\mu_{Z\gamma}$**
- ➡**Systematics uncertainties crucial for H measurements**
  - Reduce exp. Uncertainties with new or improved approaches
  - Need of more precise theory predictions

H couplings to fermions and vector bosons

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

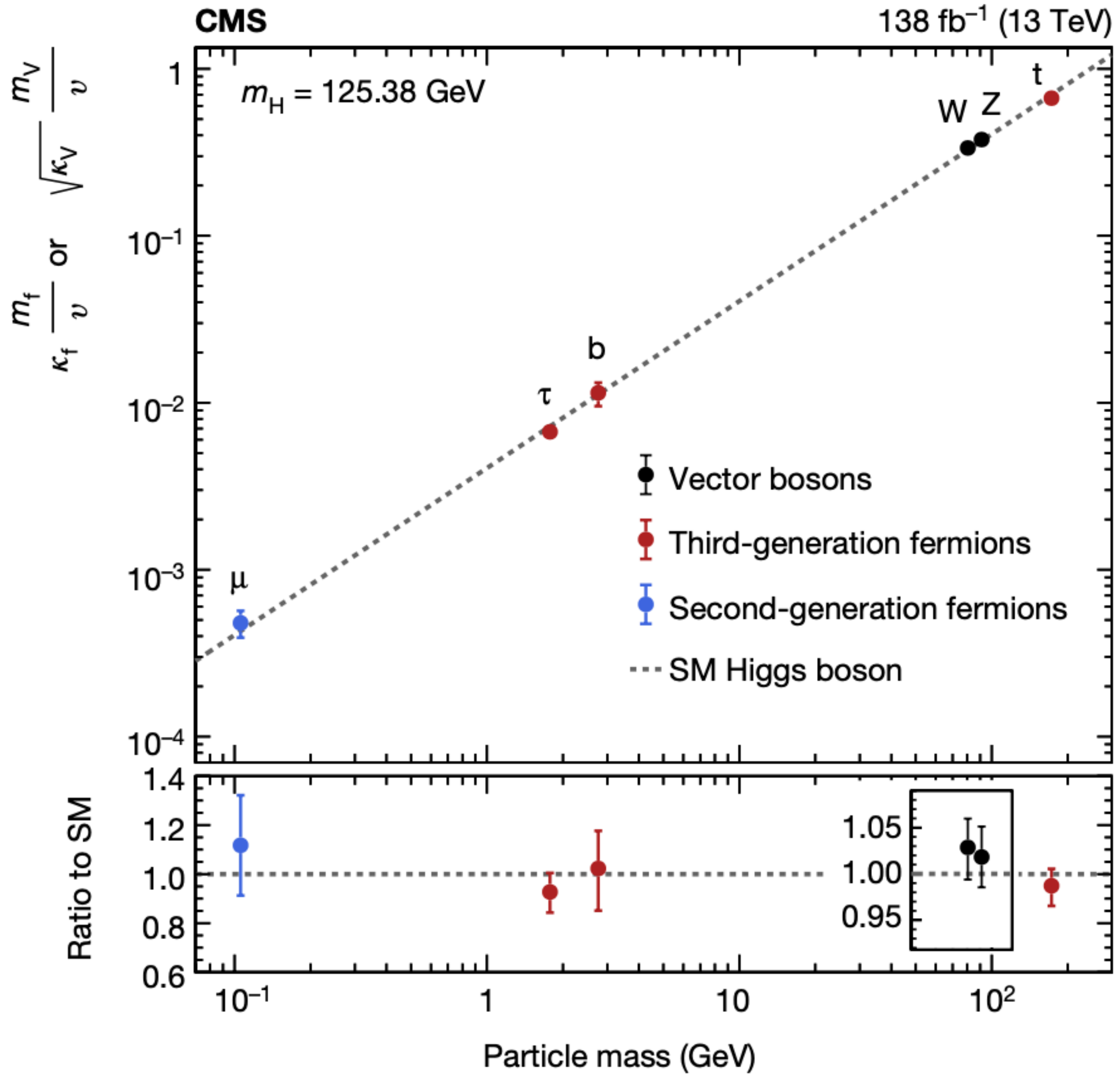
Likelihood scan of (κ_f, κ_V)



➡Compatibility with SM within 10%

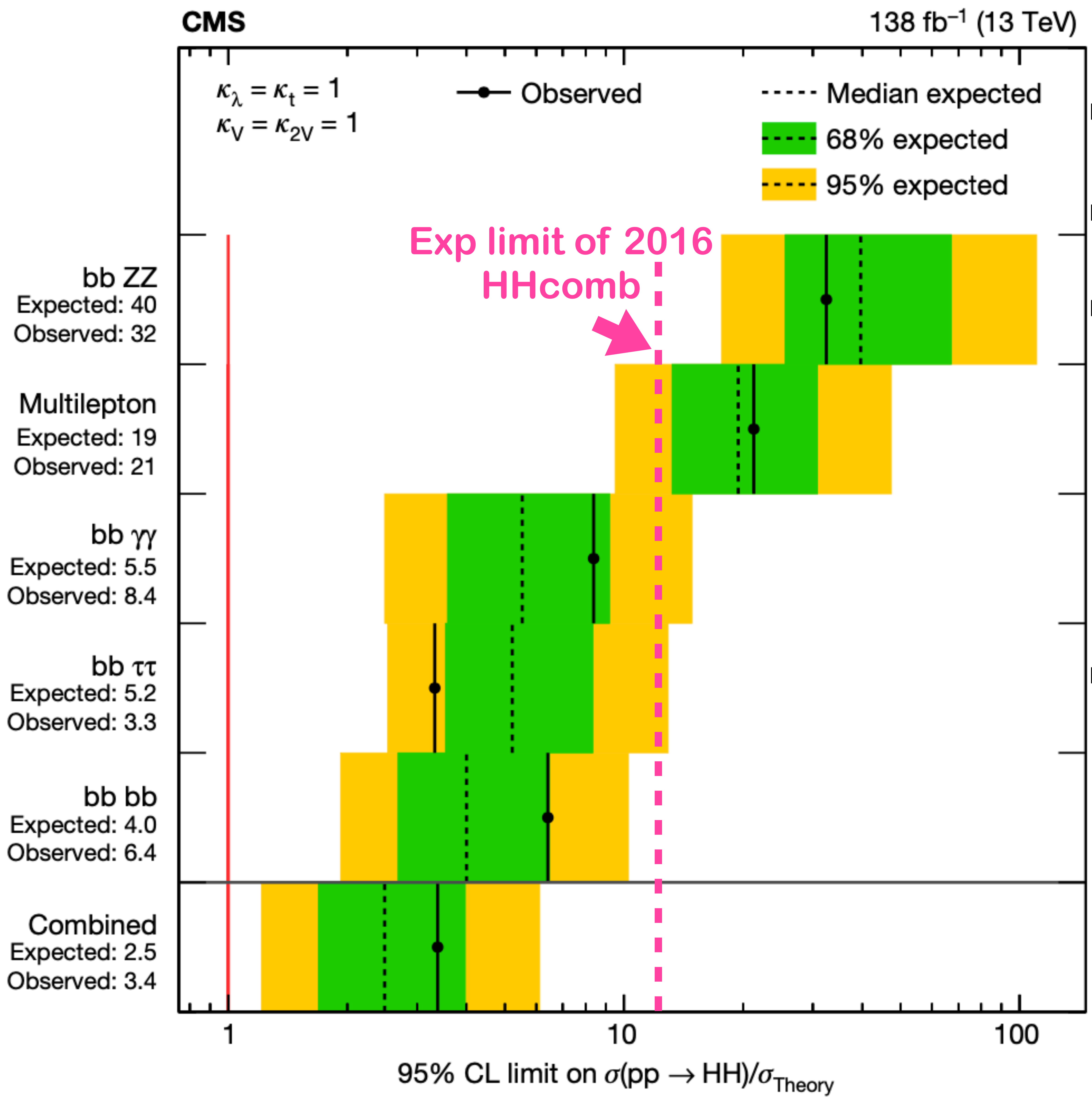
➡Around 5 times improvement w.r.t discovery

H couplings VS particle mass



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

Upper limit on HH signal strength

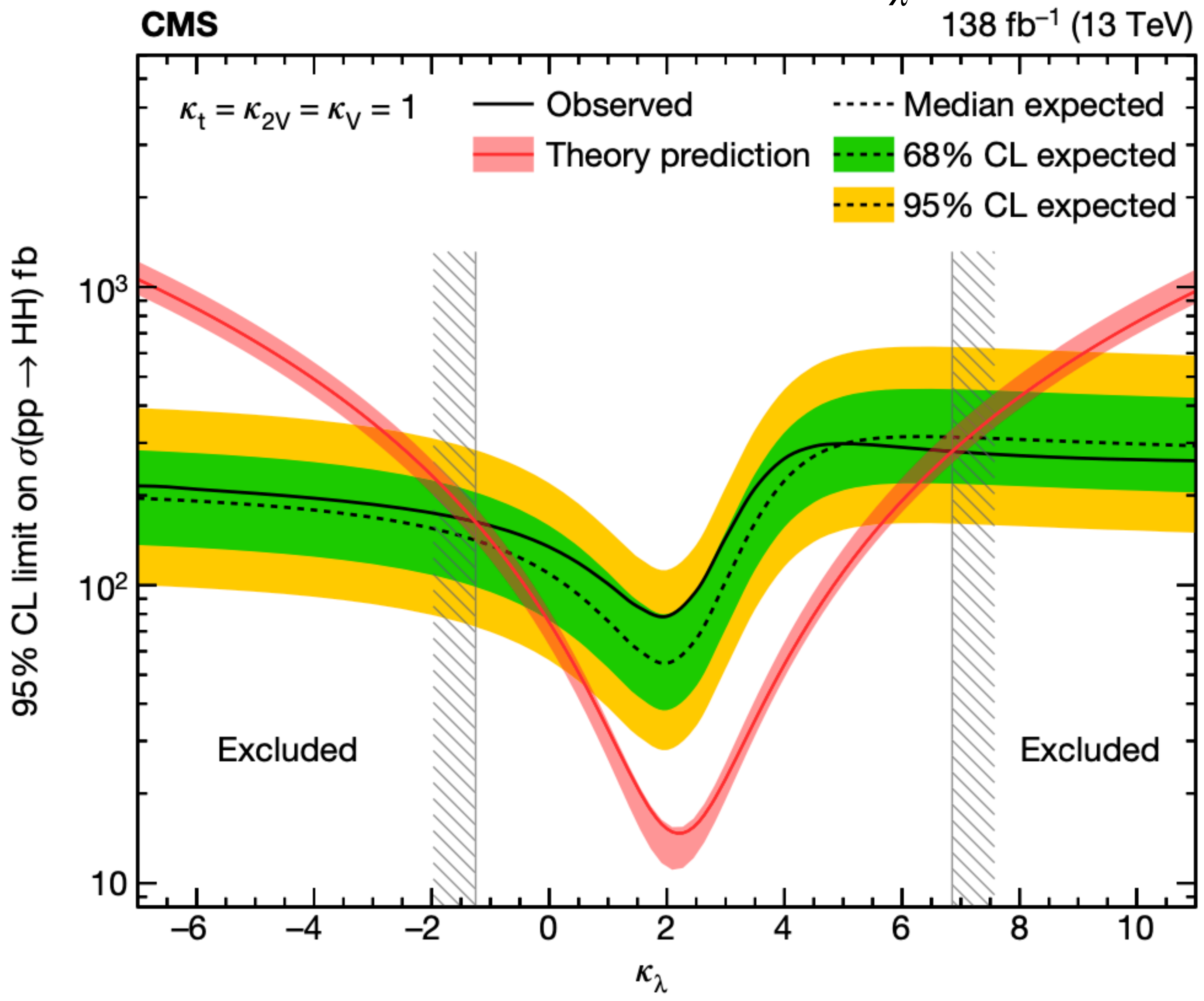


- ➡Obs(exp) upper limit on $\mu_{HH} = 3.4(2.5)$
- ➡No deviations from SM observed
- ➡2.5 time better than 2016 result scaled by Lumi
  - Extensive usage of ML tools + boosted topologies
- ➡HH will be one of the most exciting results of Run3
  - Scaling by end of Run3 and combing with ALTAS vary to 1!

Constraints on κ_λ

- **Observed results compatible to SM predictions**

Limit on HH XS vs κ_λ



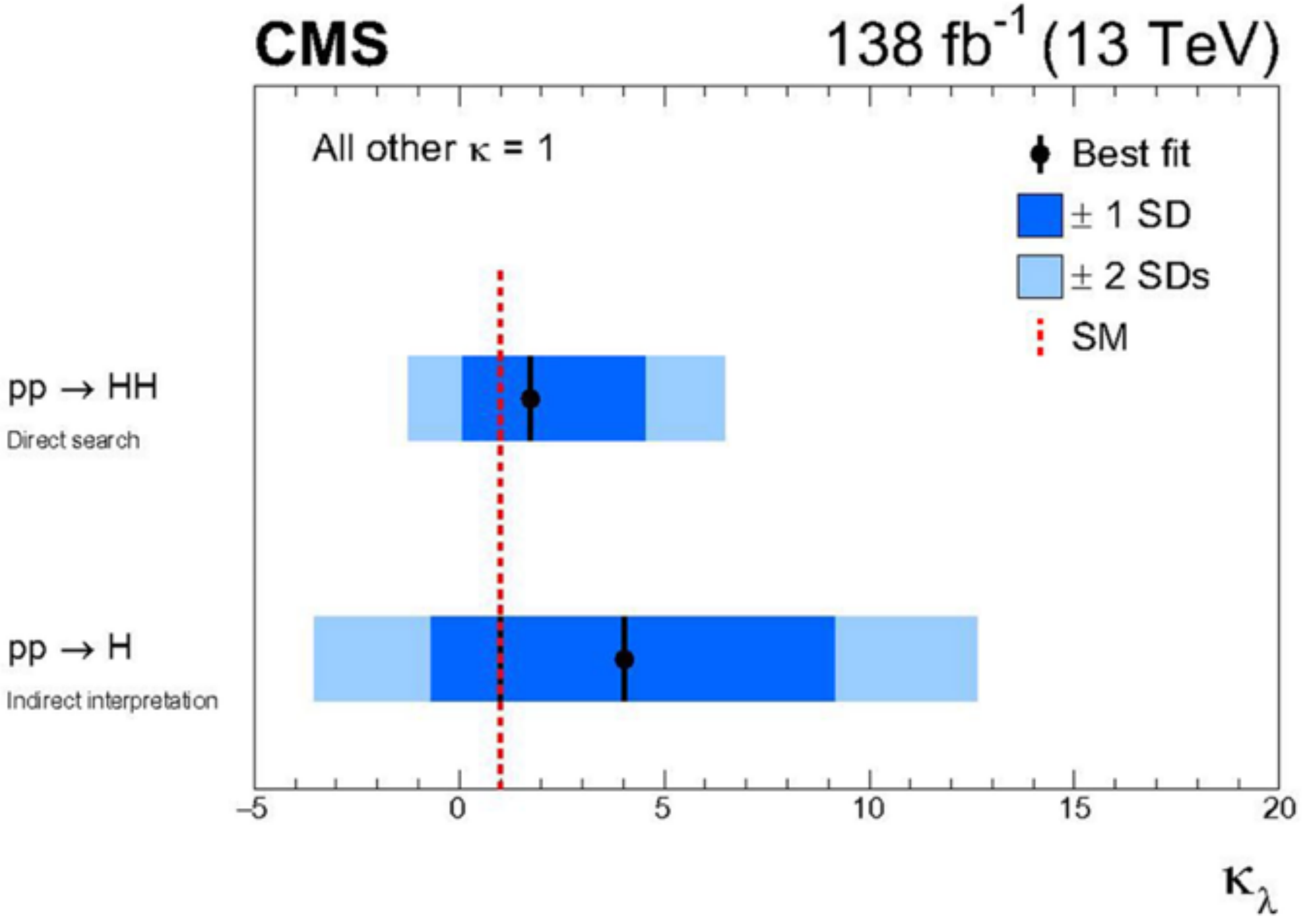
Obs. $\kappa_\lambda \in [-1.3, 6.9]$

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**

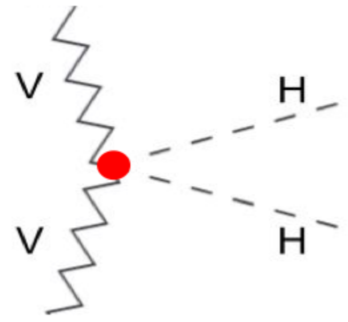
κ_λ measurement from HH vs from single-H



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

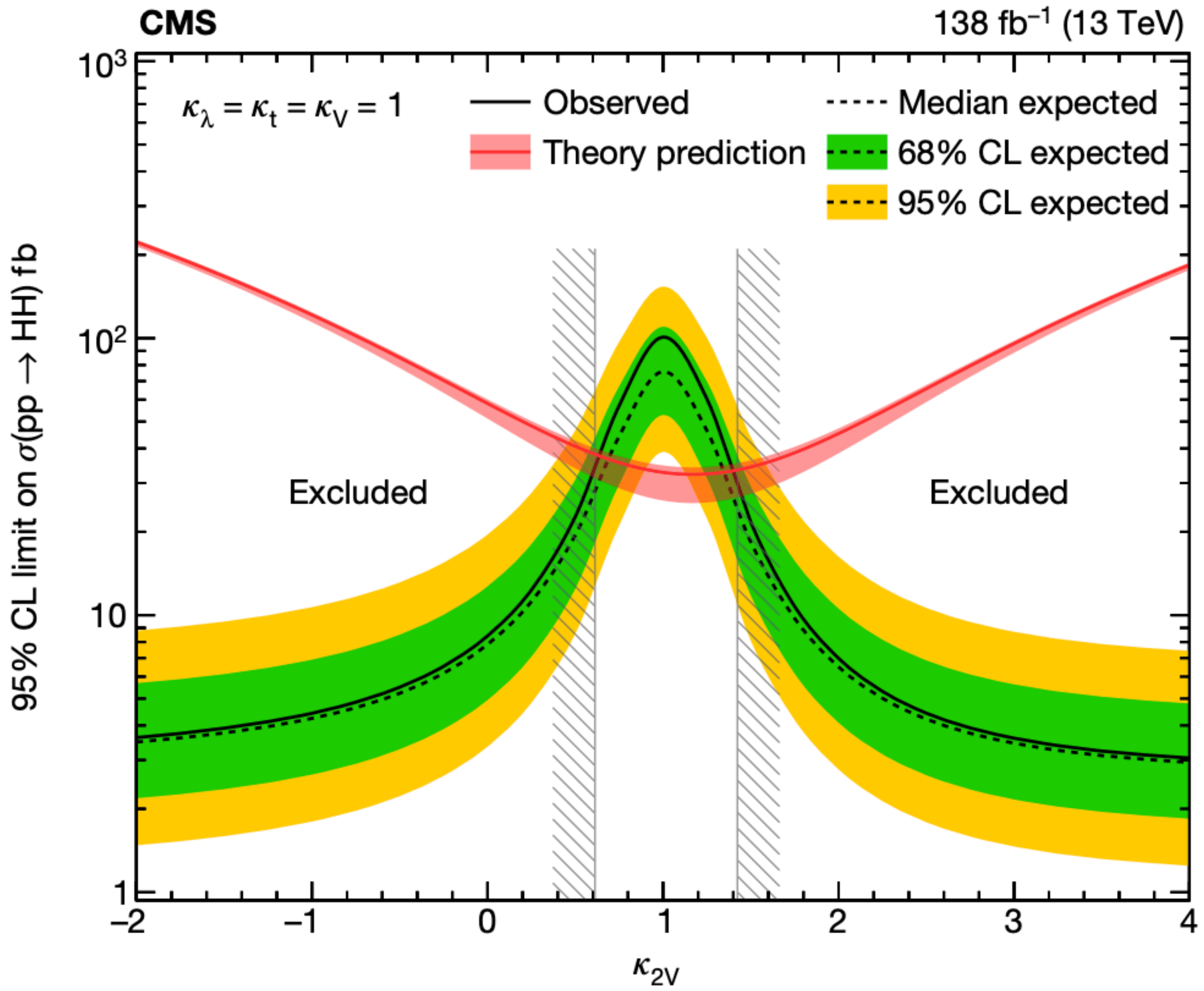
- **Ultimate κ_λ results with Run 2 dataset will be updated soon by combining H+HH**

Constrains on κ_{2V}



- Observed results compatible to SM predictions

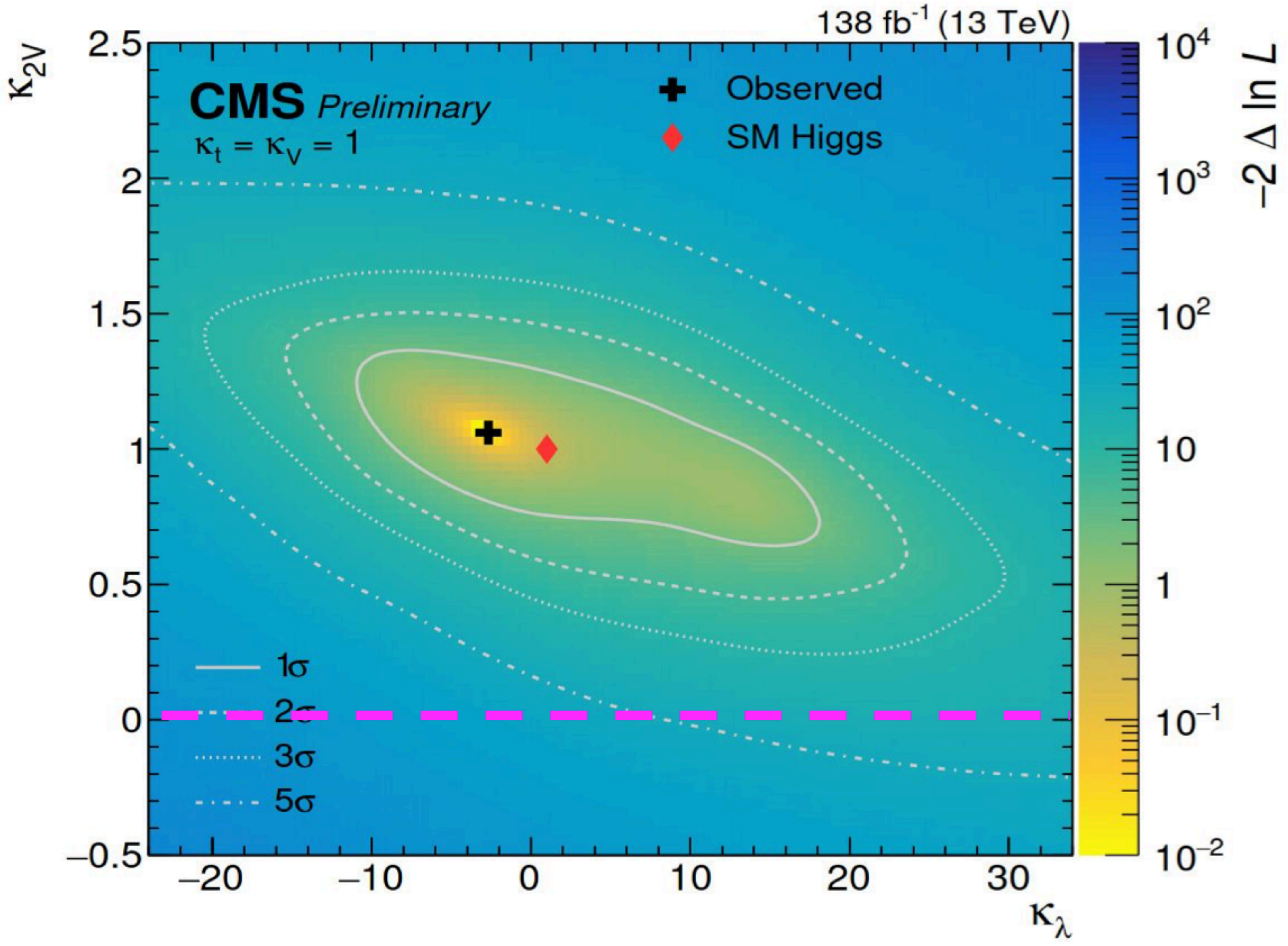
Limit on VBF HH XS vs κ_{2V}



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

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

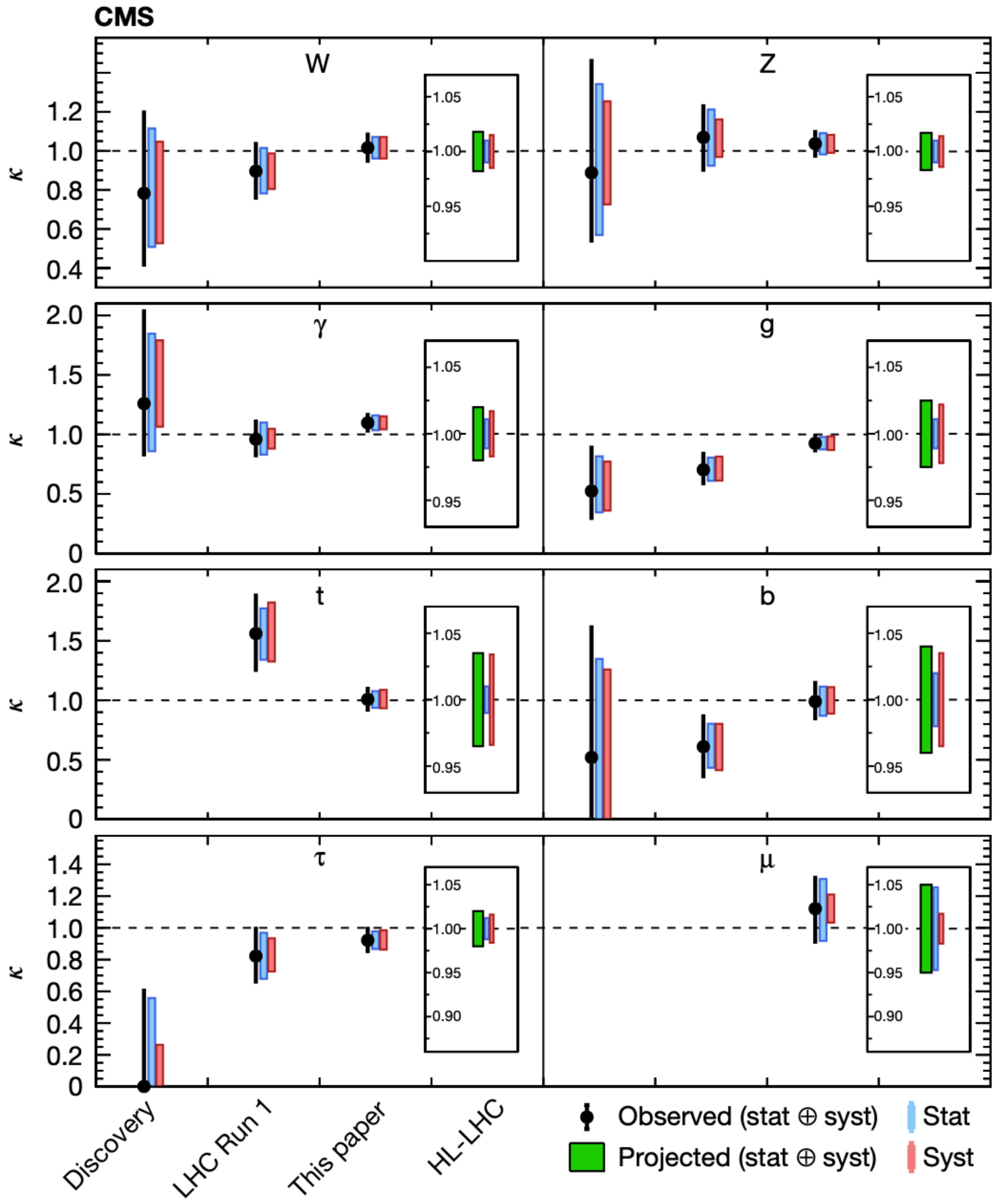
Likelihood scan of $(\kappa_\lambda, \kappa_{2V})$ with considering only boosted HH(4b)



➡$\kappa_{2V} = 0$ 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**

Upcoming H+HH Combination

- Measurement of Higgs trilinear self-coupling lambda is a fundamental test of SM($\kappa_\lambda = \kappa/\kappa_{SM}$)
- Get ultimate Run2 results With H+HH combination in CMS
- Include new HH channels (e.g HH(bbWW)), update single-H to STXS in some channels (e.g H(WW))
- Status: Approval talk, will be public soon → HIG-23-006

Summary

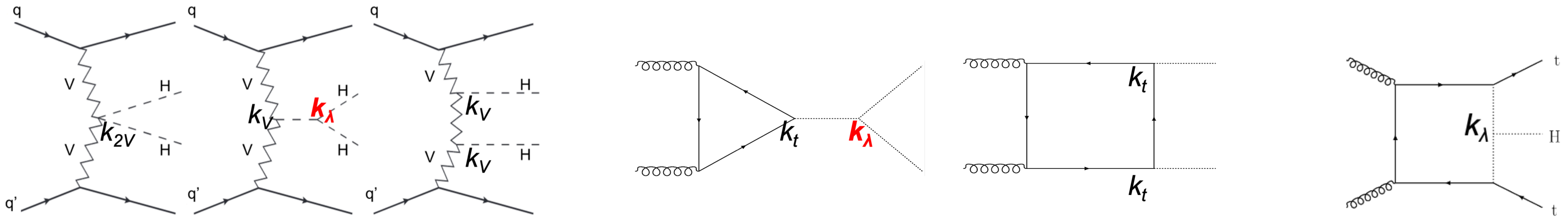
- H and HH combination provide fundamental extensive tests of SM
- Good compatibility of observations with SM predictions
- Statistical uncertainties comparable to systematics ones for main H production and decay channels
- Exclusion of $k_{2V} = 0$ for any value of k_V observed at 5σ significance assuming
- At HL-LHC high-precision tests of the SM and potential for HH observation
- Upcoming H+HH combination will be public soon

Thanks !

Backup

Why a H and HH Combination

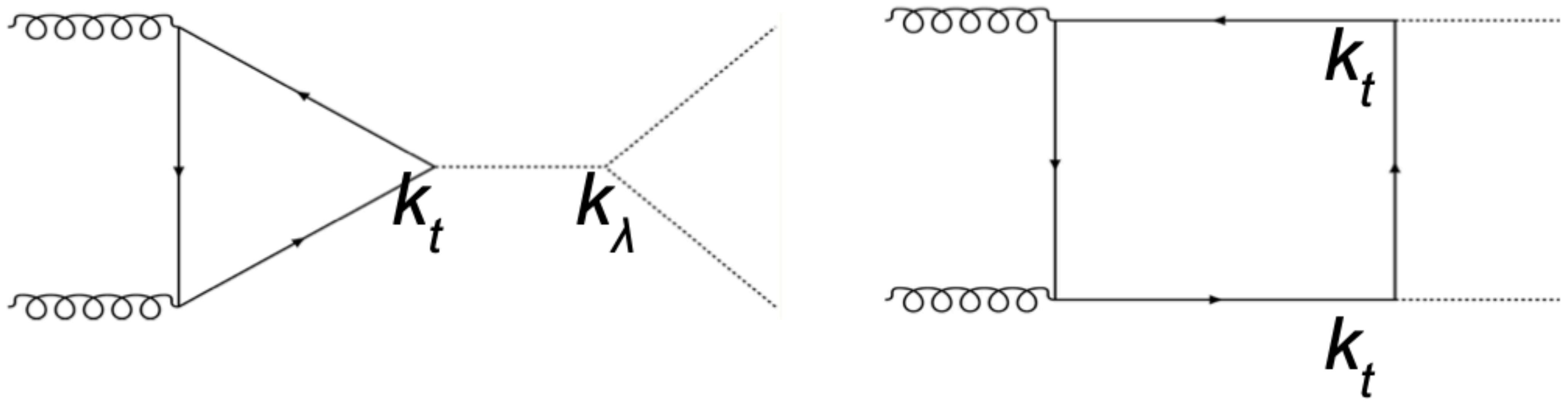
- $138fb^{-1}$ of CMS Run 2 dataset offers great potential of Higgs physics
- Measurement of Higgs trilinear self-coupling lambda is a fundamental test of SM($\kappa_\lambda = \kappa/\kappa_{SM}$)
- κ_λ accessible from both HH and single-H XS measurements
- BSM expected to introduce changes in more than one coupling, HH has better κ_λ sensitivity but single-H provides constrain other Higgs couplings
  - More general statements about κ_λ



Search for non-resonant HH production

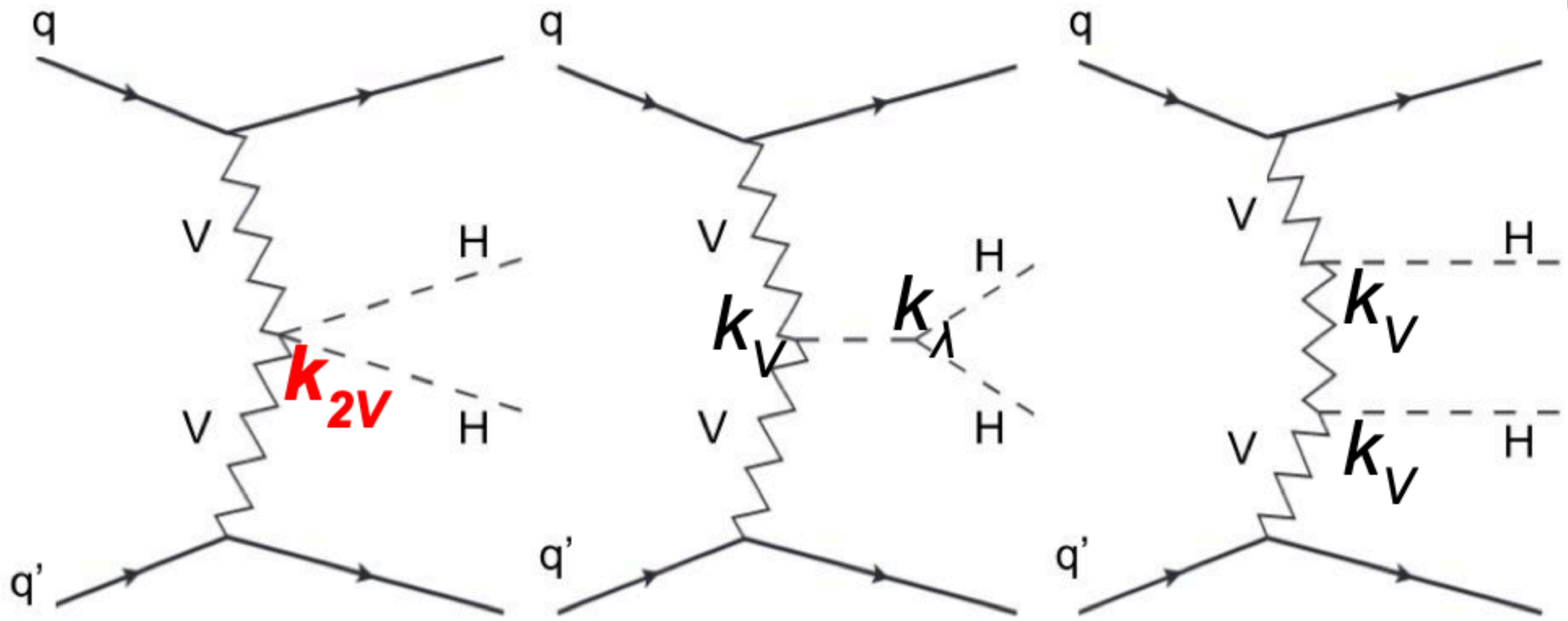
- HH production is sensitive to the Higgs trilinear coupling λ
- VBF HH is sensitive to c_{2V} coupling $\rightarrow$ $k_{2V} = c_{2V} \;/\; c_{2V(SM)}$

ggF production (ggHH) diagrams at LO

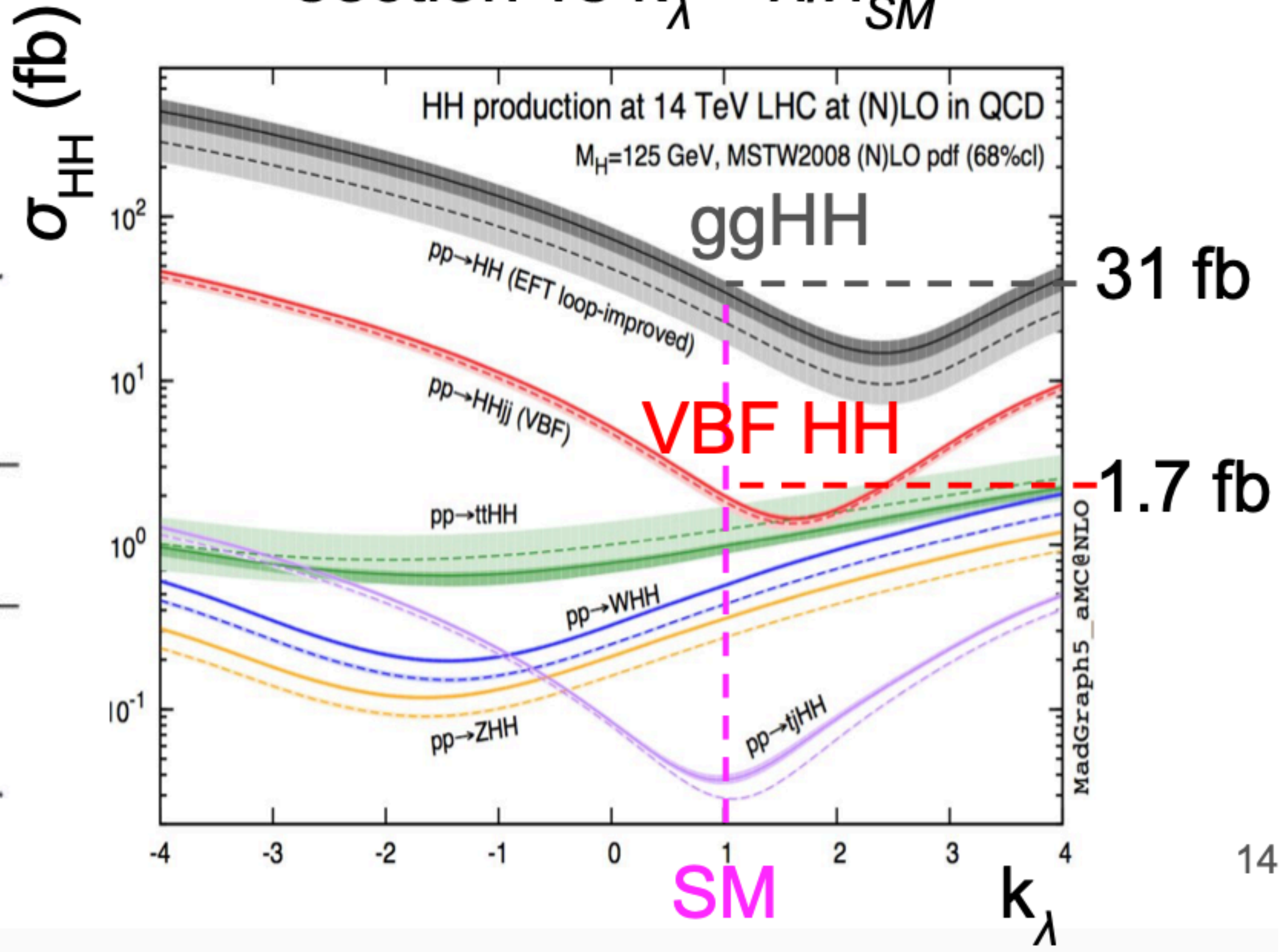


Fundamental tests of SM

VBF HH production diagrams at LO



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



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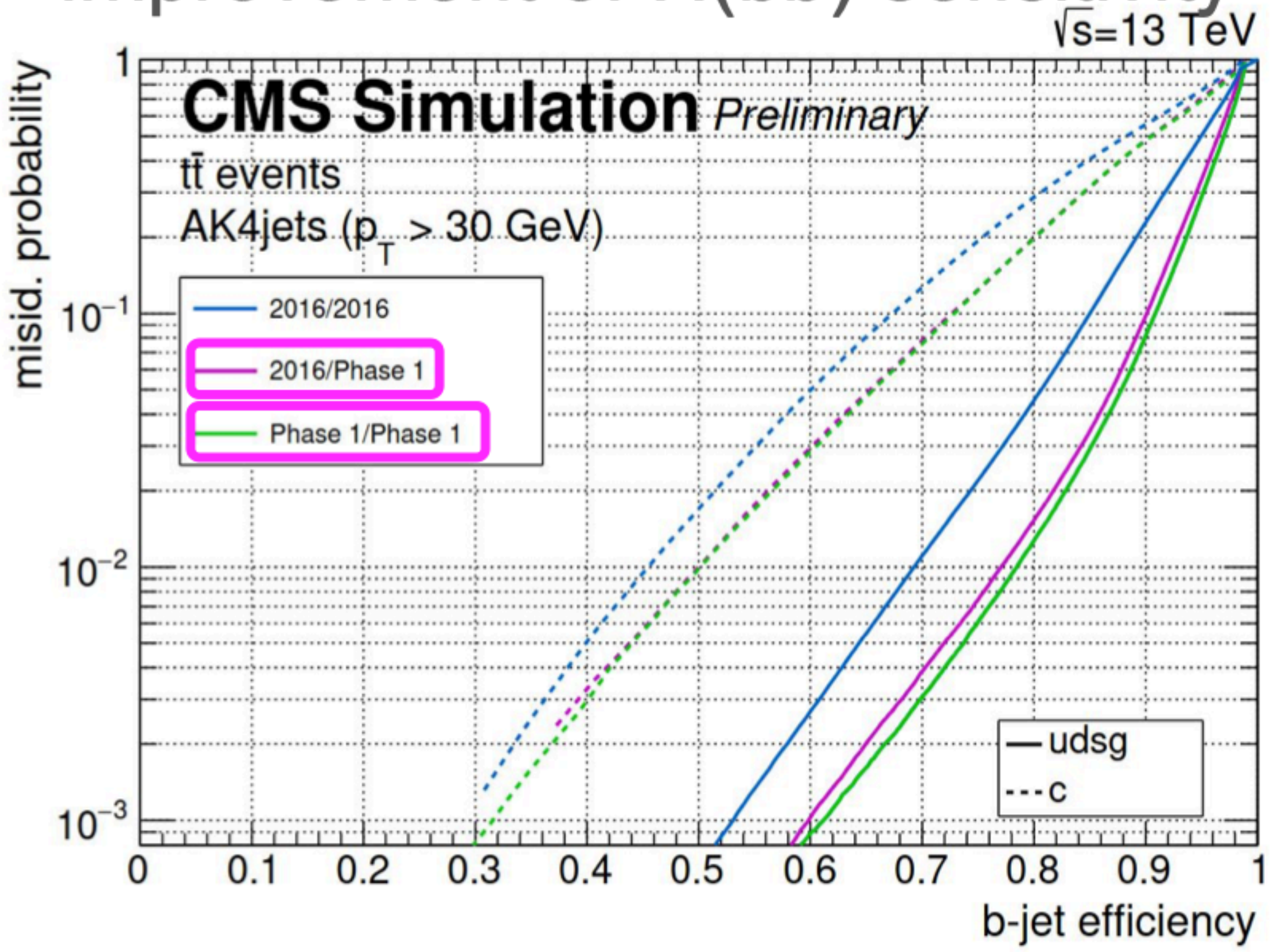
Improvements during Run 2

CMS detector upgrades

- e.g. new Si pixel detector → ×2 improvement of H(bb) sensitivity

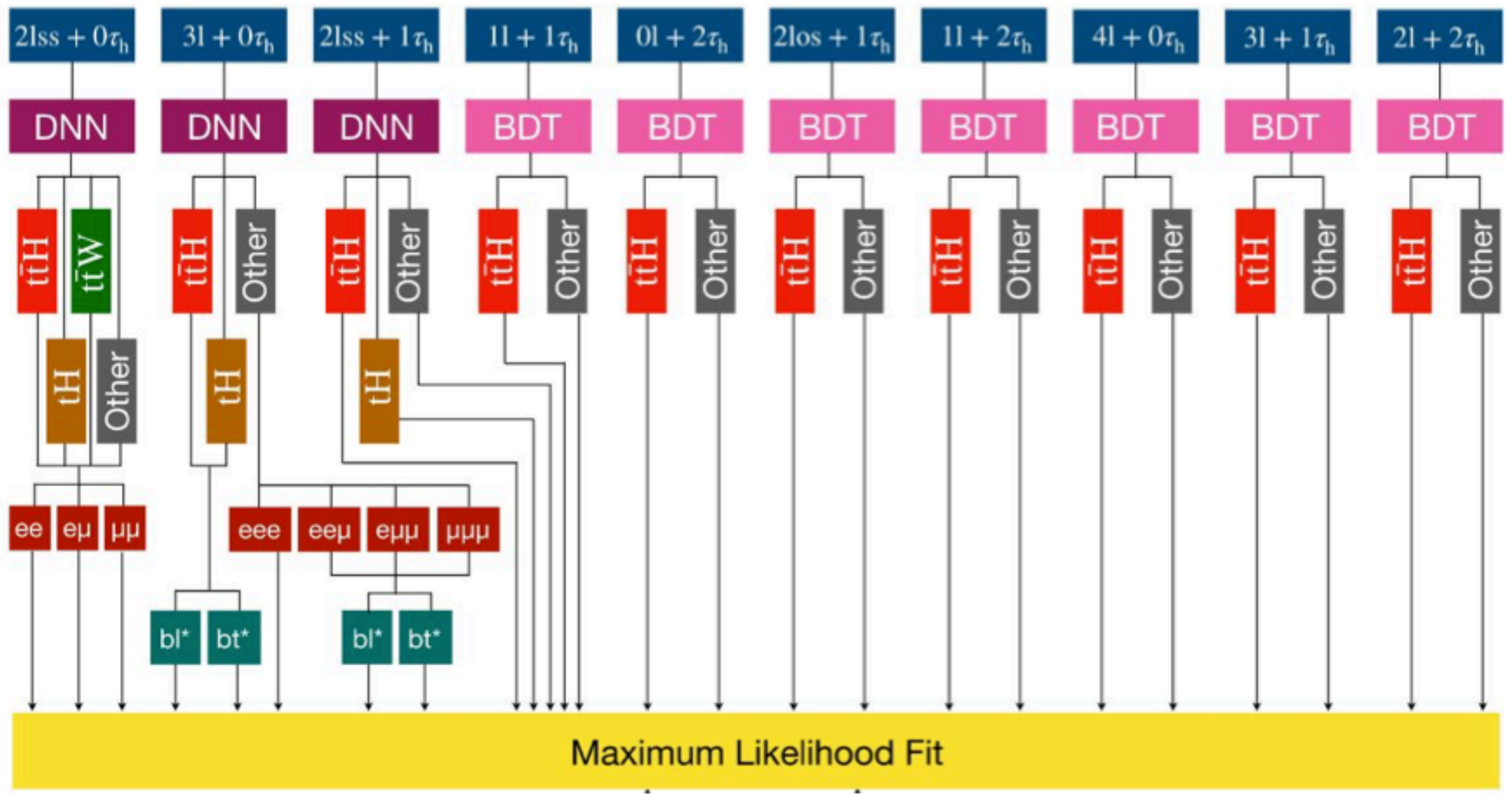


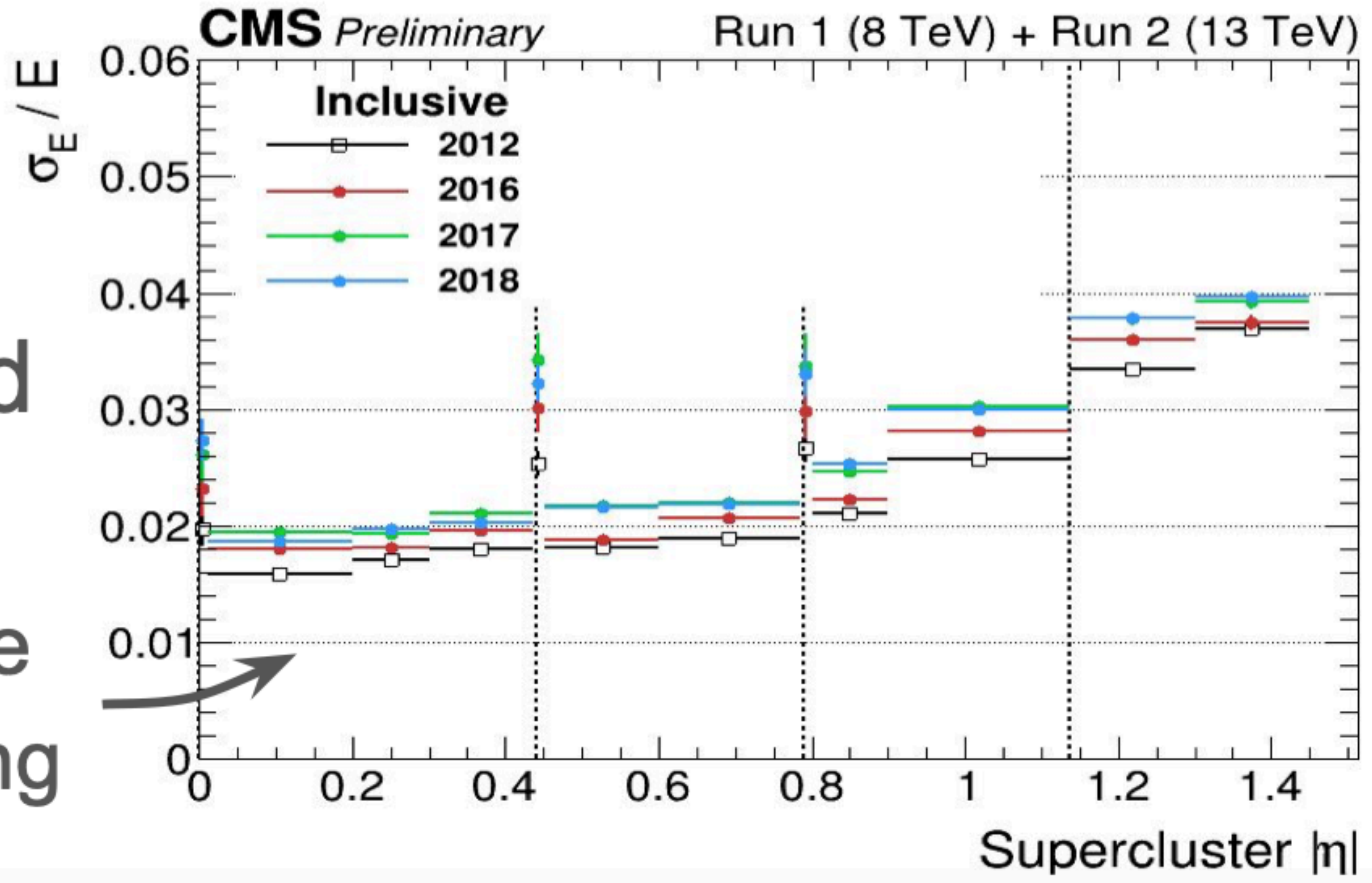
Optimized detector calibration and physics objects reco

- e.g. stable e/γ energy resolution despite higher pile-up and ECAL detector ageing

Extensive usage of ML

ttH multilepton analysis workflow





Evolution since discovery

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

$\mu = 0.87 \pm 0.23$ [dominated by stat.]

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

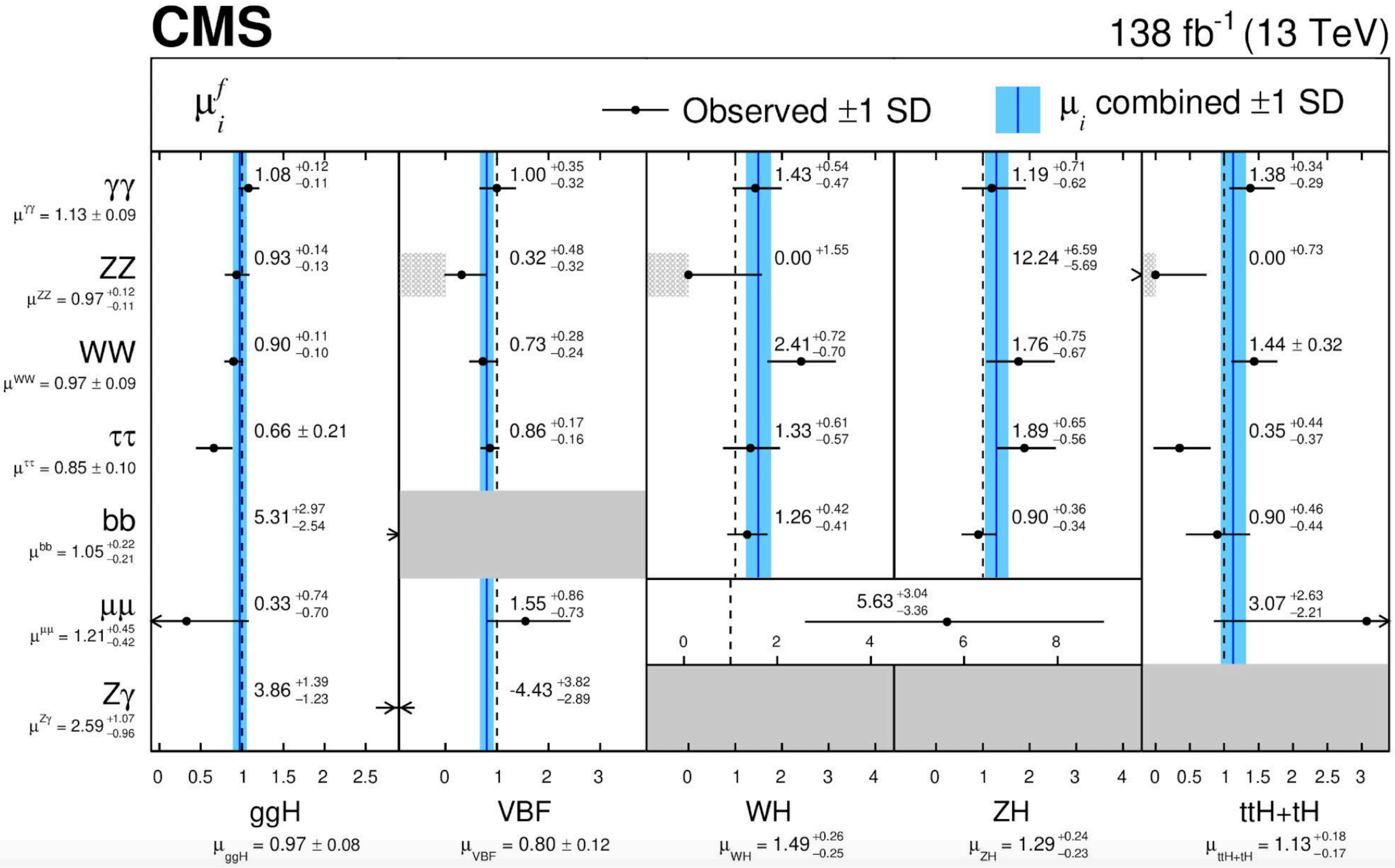
$\mu = 1.00 \pm 0.13$ [+0.08/-0.07 (theory) ± 0.07 (exp.) ± 0.09 (stat.)]

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

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

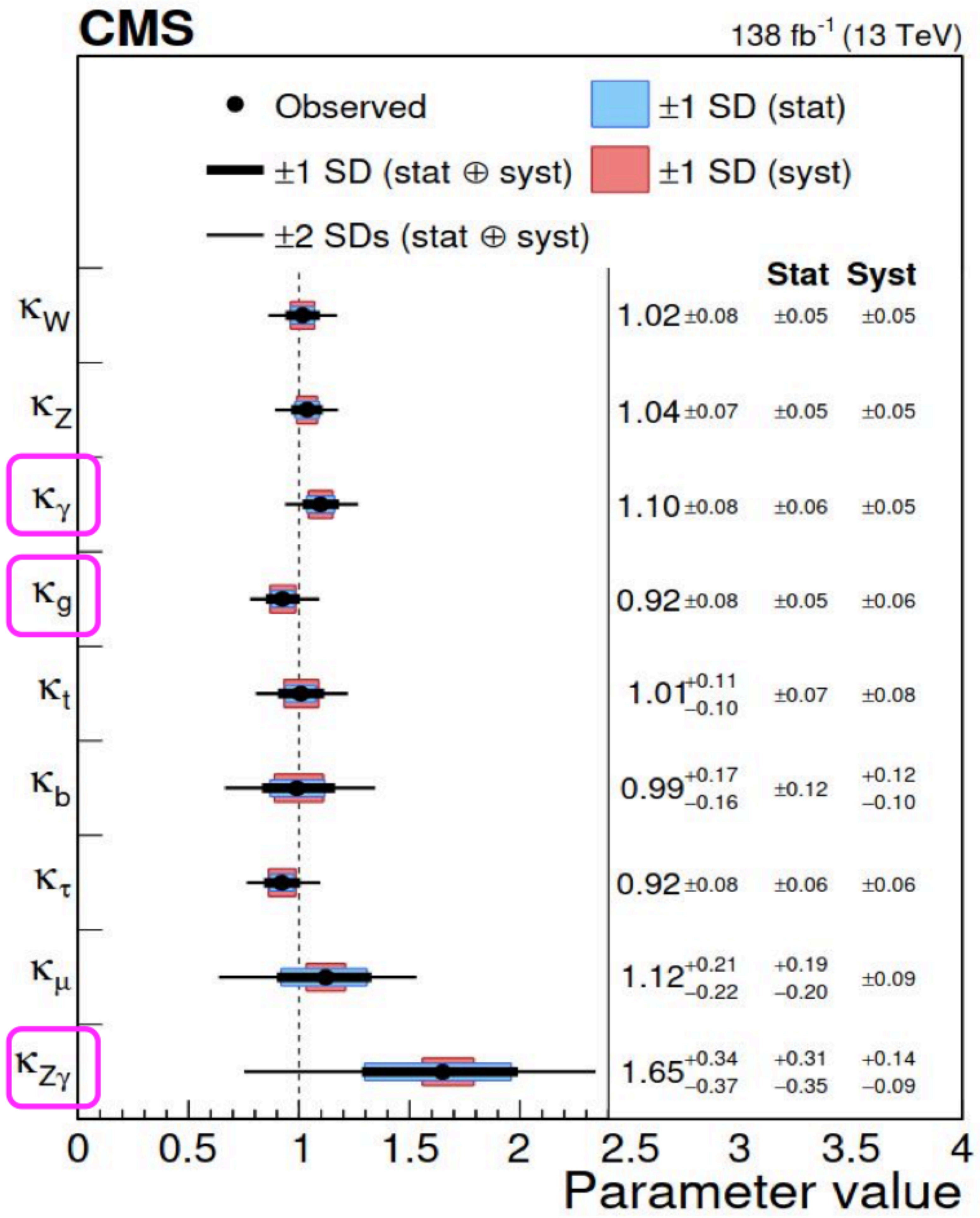
- ➢ Systematics uncertainties crucial for H measurements today and even more in future
  - Reduce exp. uncertainties with new or improved approaches
  - Need of more precise theory predictions

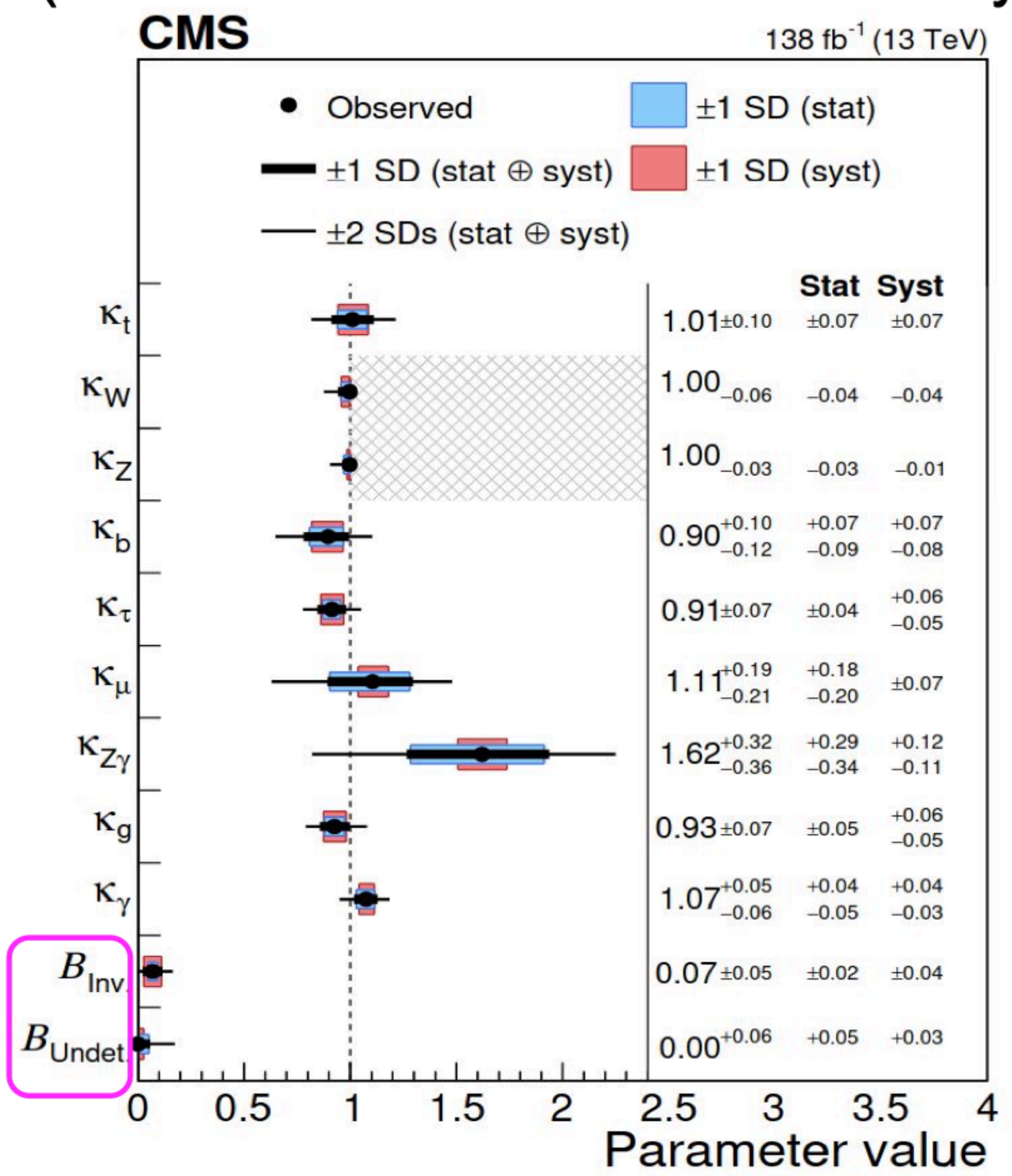
Test XS and BR compatibility with the SM



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 $k_{Z\gamma}$

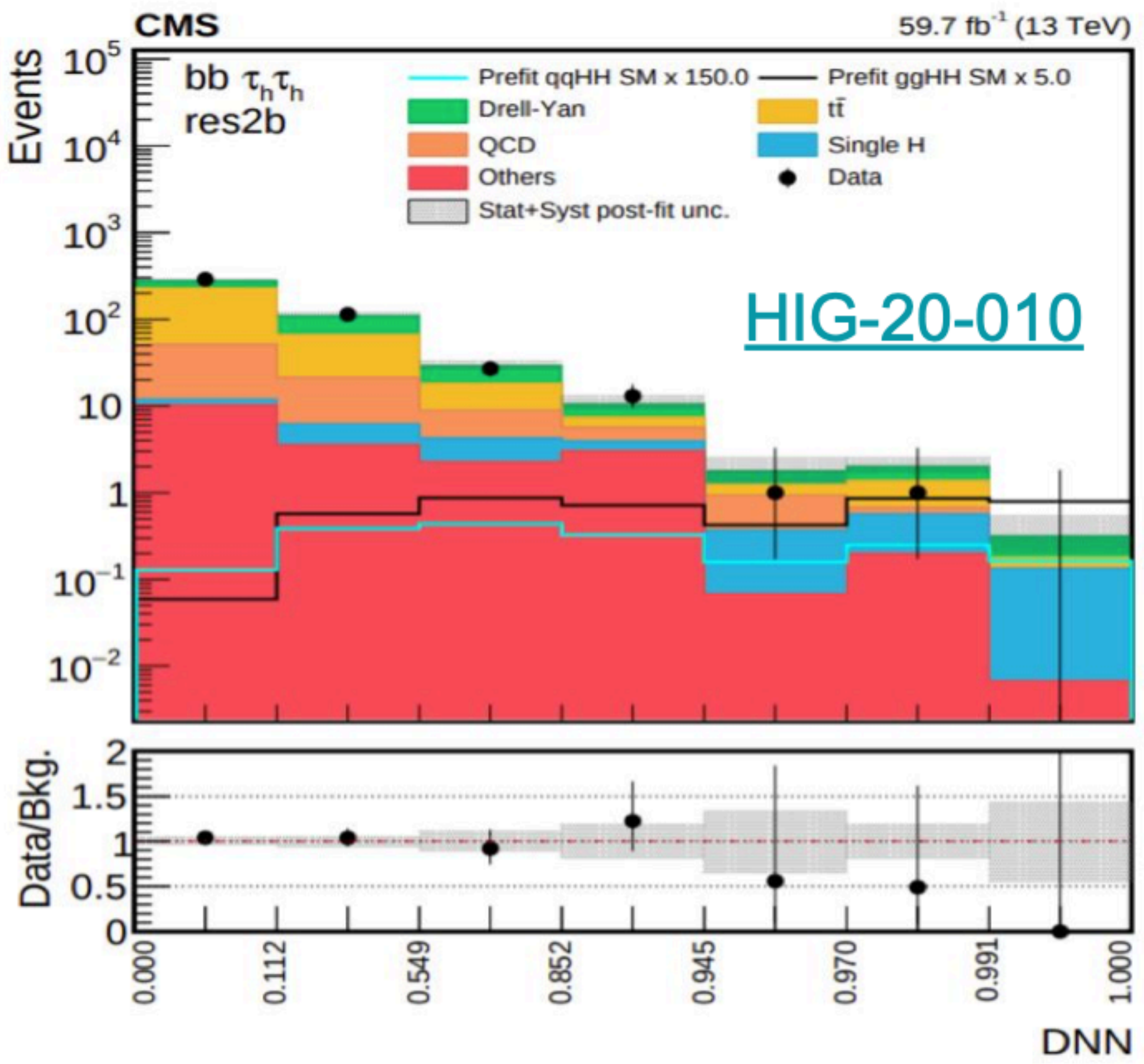
Both invisible and undetectable BR's compatible with zero

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

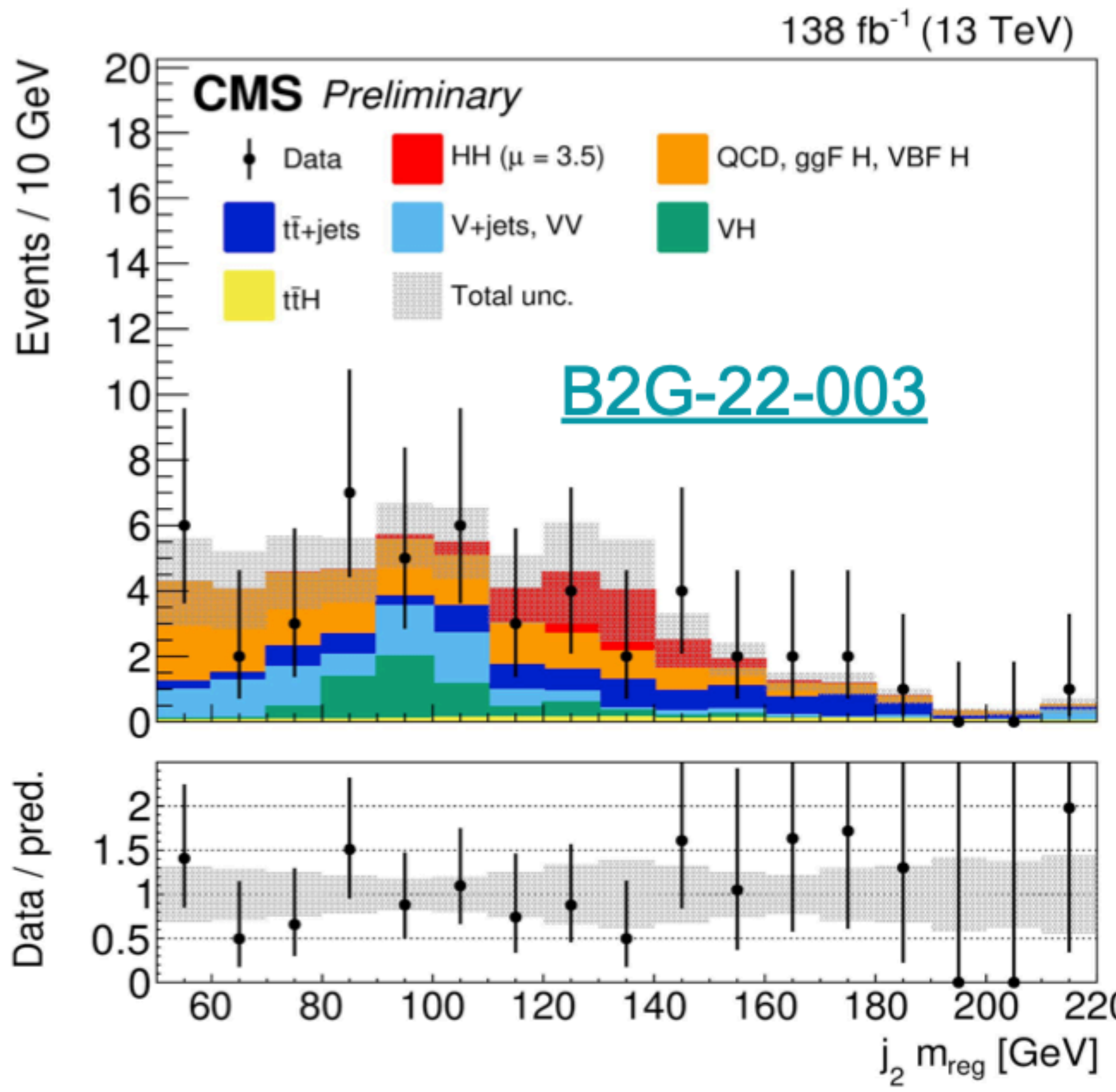
- Improvement wrt HH searches with 2016 dataset much larger than gain in integrated luminosity

Extensive usage of ML tools

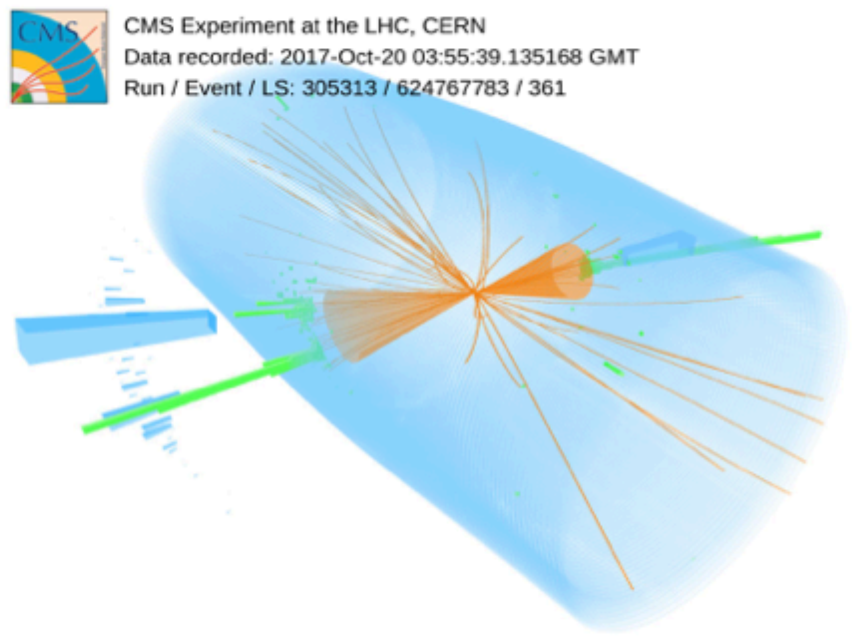
Boosted topologies



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



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



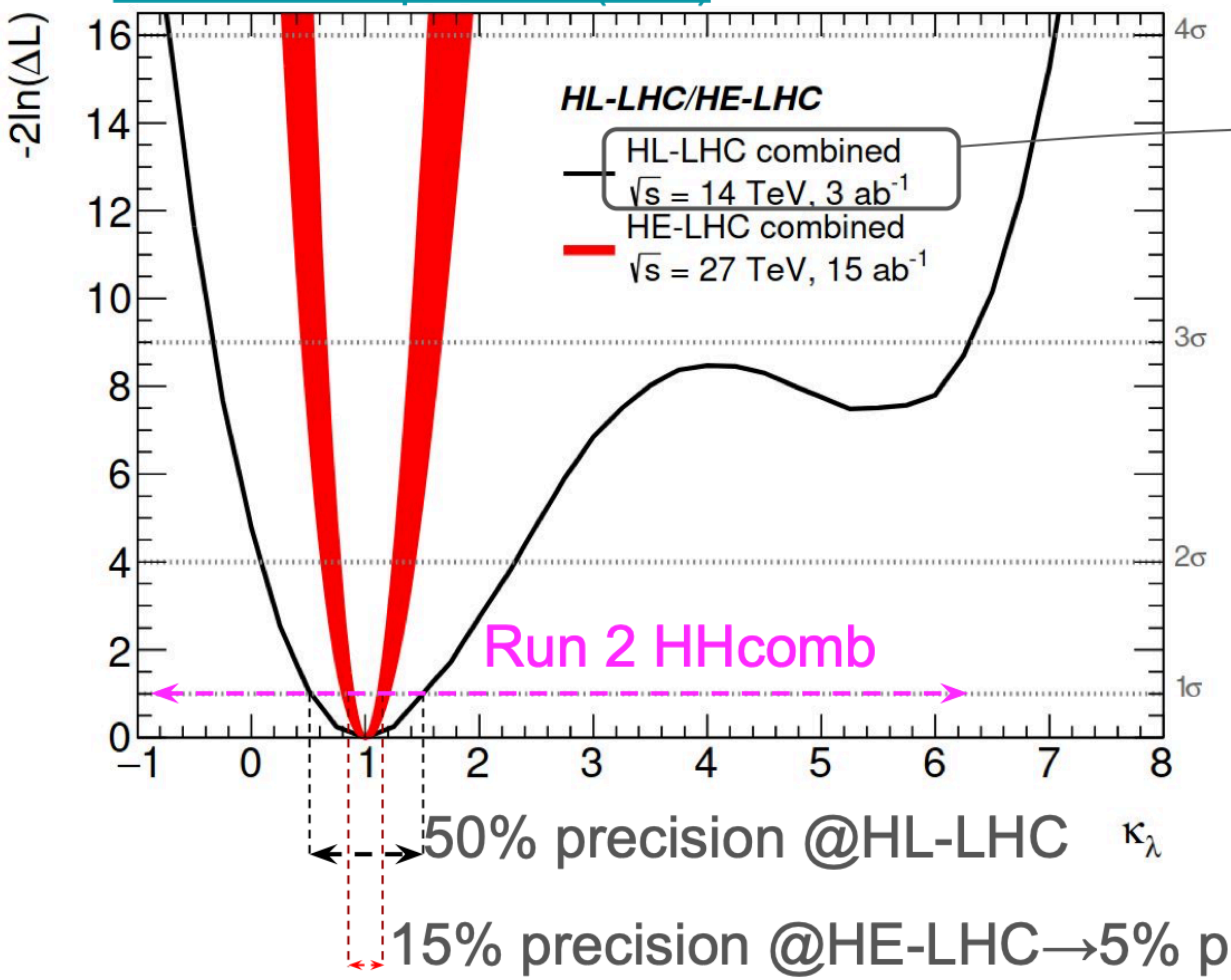
Boosted ggHH→4b event candidate

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

Outlook for the future

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

CERN Yellow report Vol. 7 (2019)



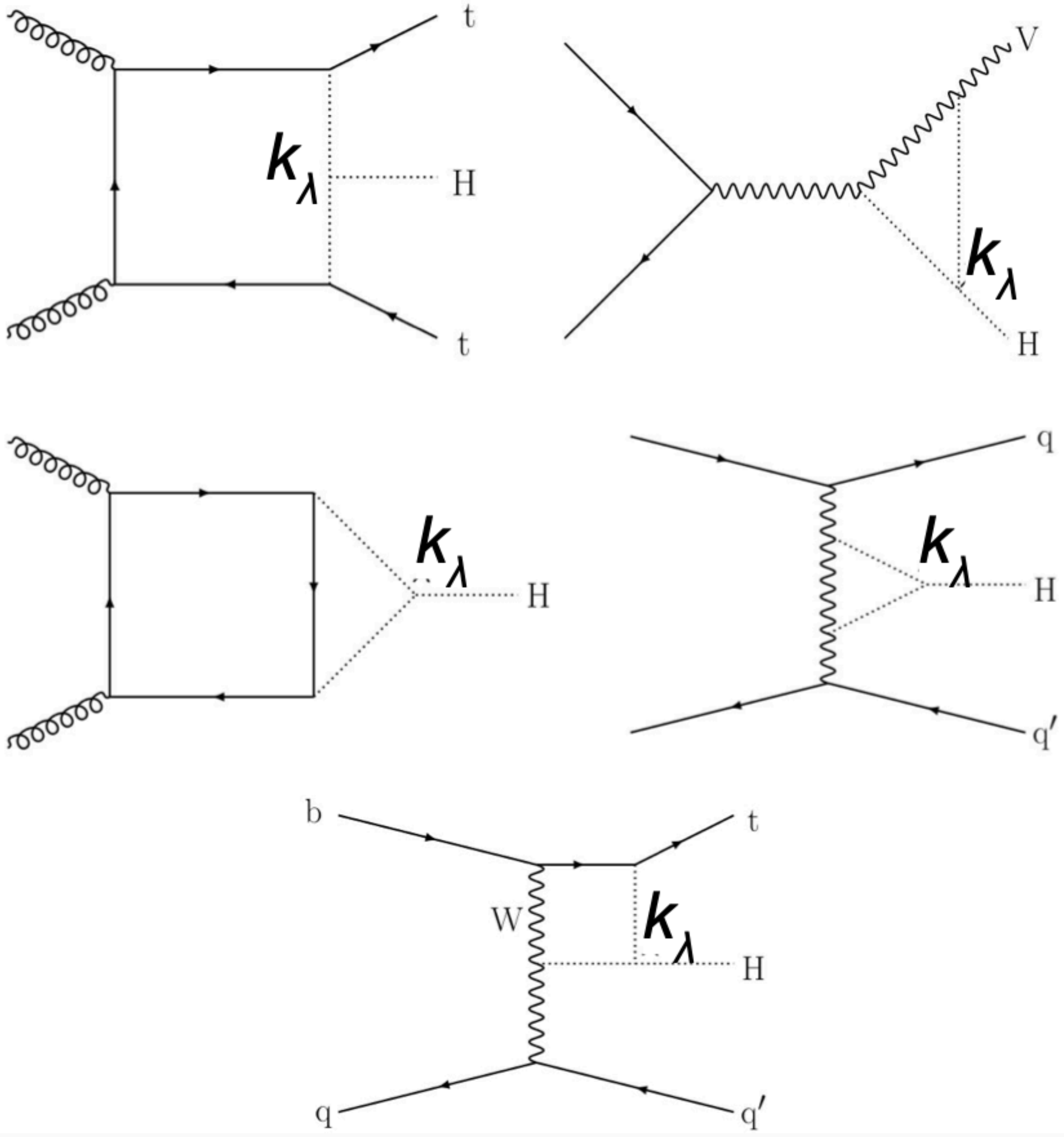
- Evidence of SM HH expected with 4σ
- Further improvement possible through new techniques & ideas→observation?

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

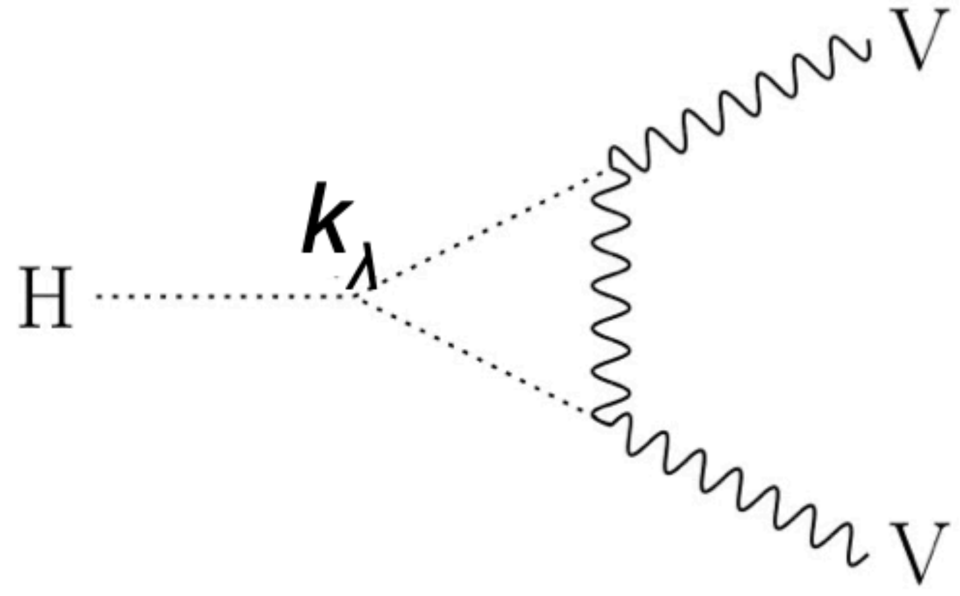
Trilinear self-coupling in single-H mechanisms

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

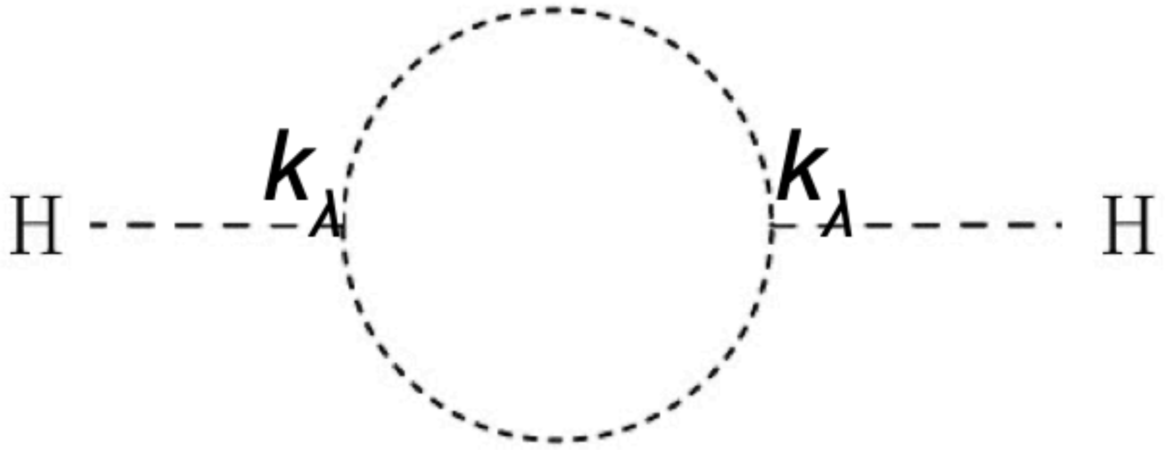
Examples of k_λ-dependent diagrams for single-H prod. mechanisms $O(k_\lambda)$



Example of k_λ-dependent diagrams for H→VV decay

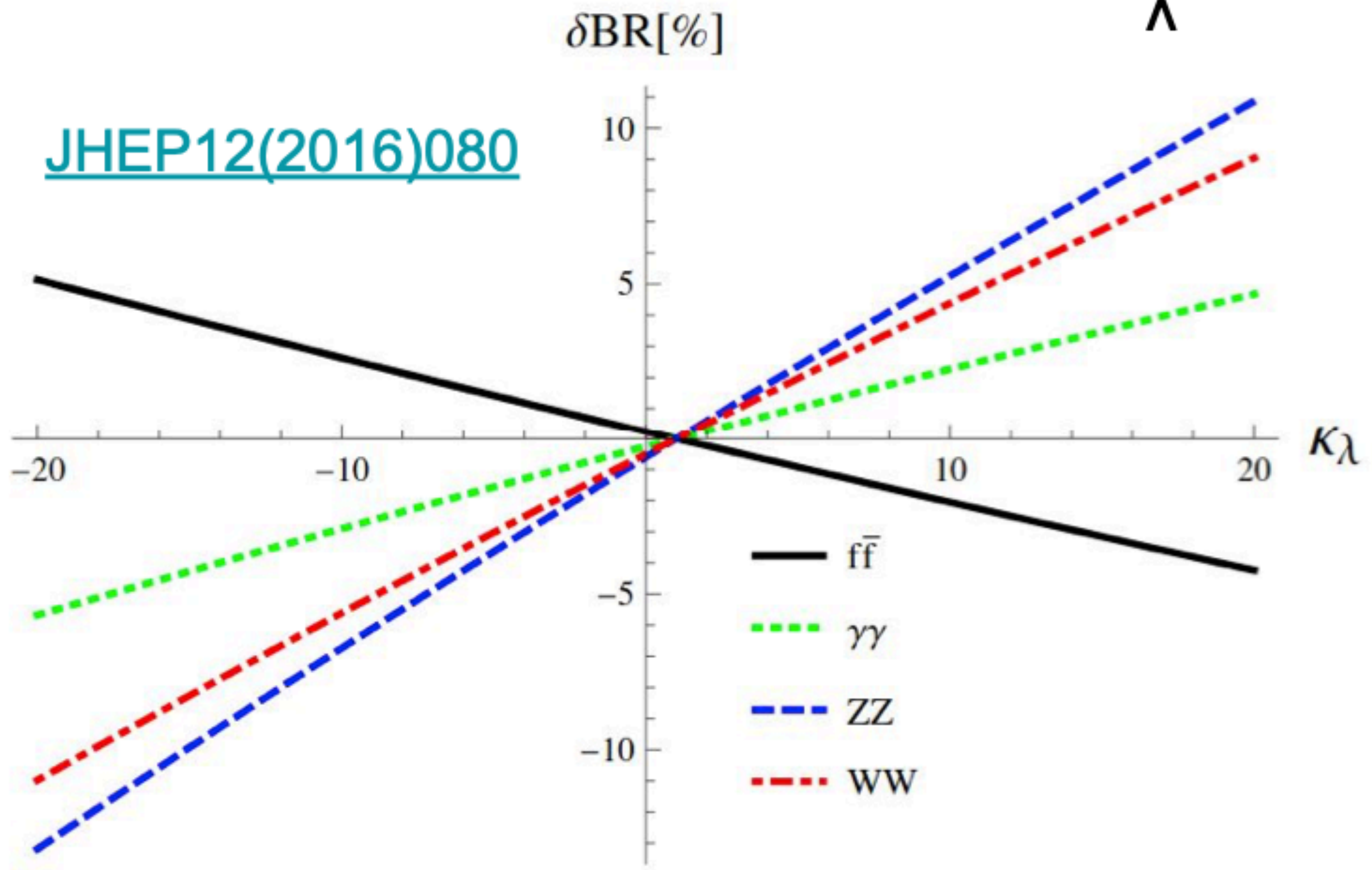


One universal correction for H wave-function renormalization $O(k_\lambda^2)$

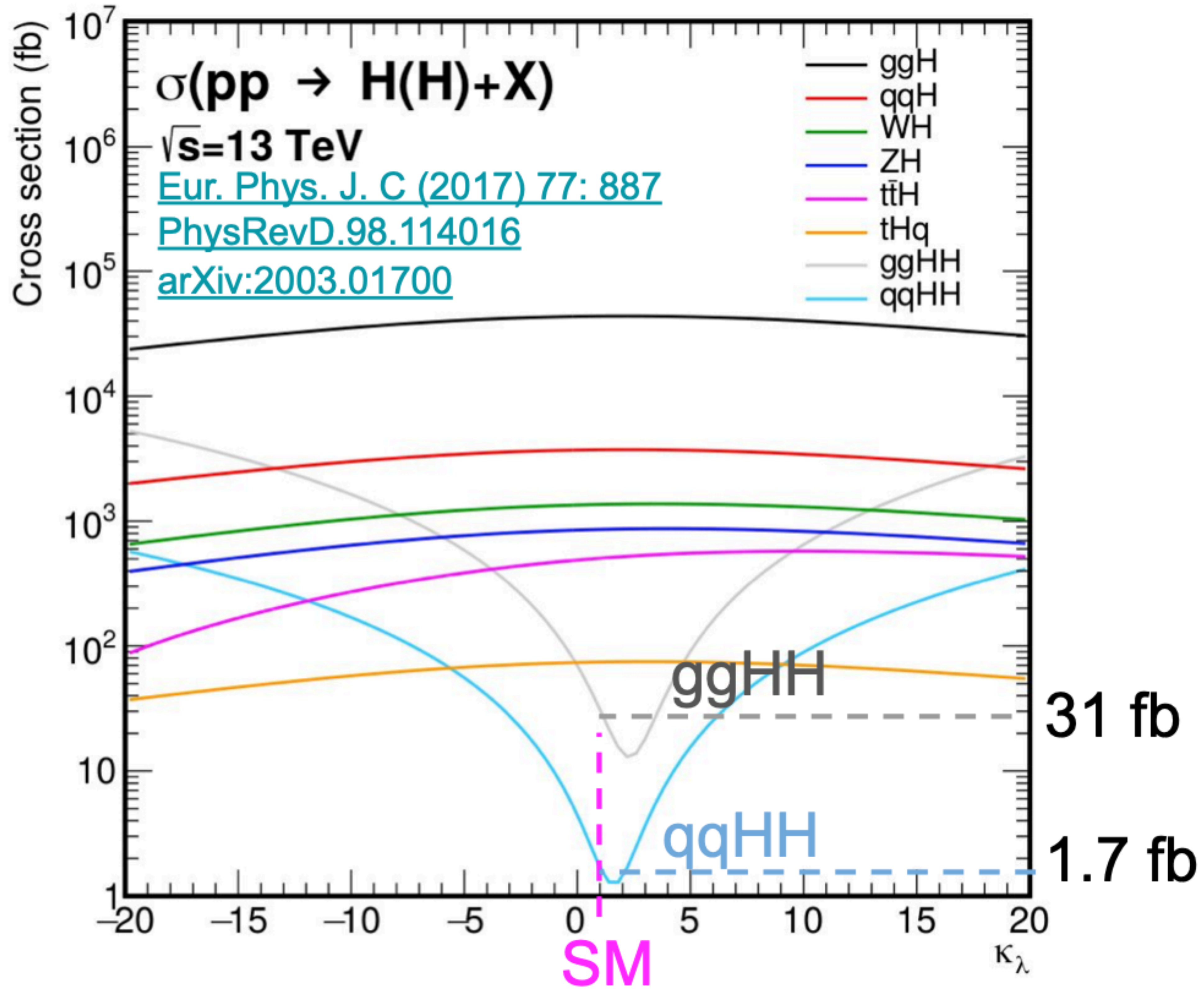


Effect of k_λ corrections on Higgs XS and BR

Modification of H BR vs k_λ



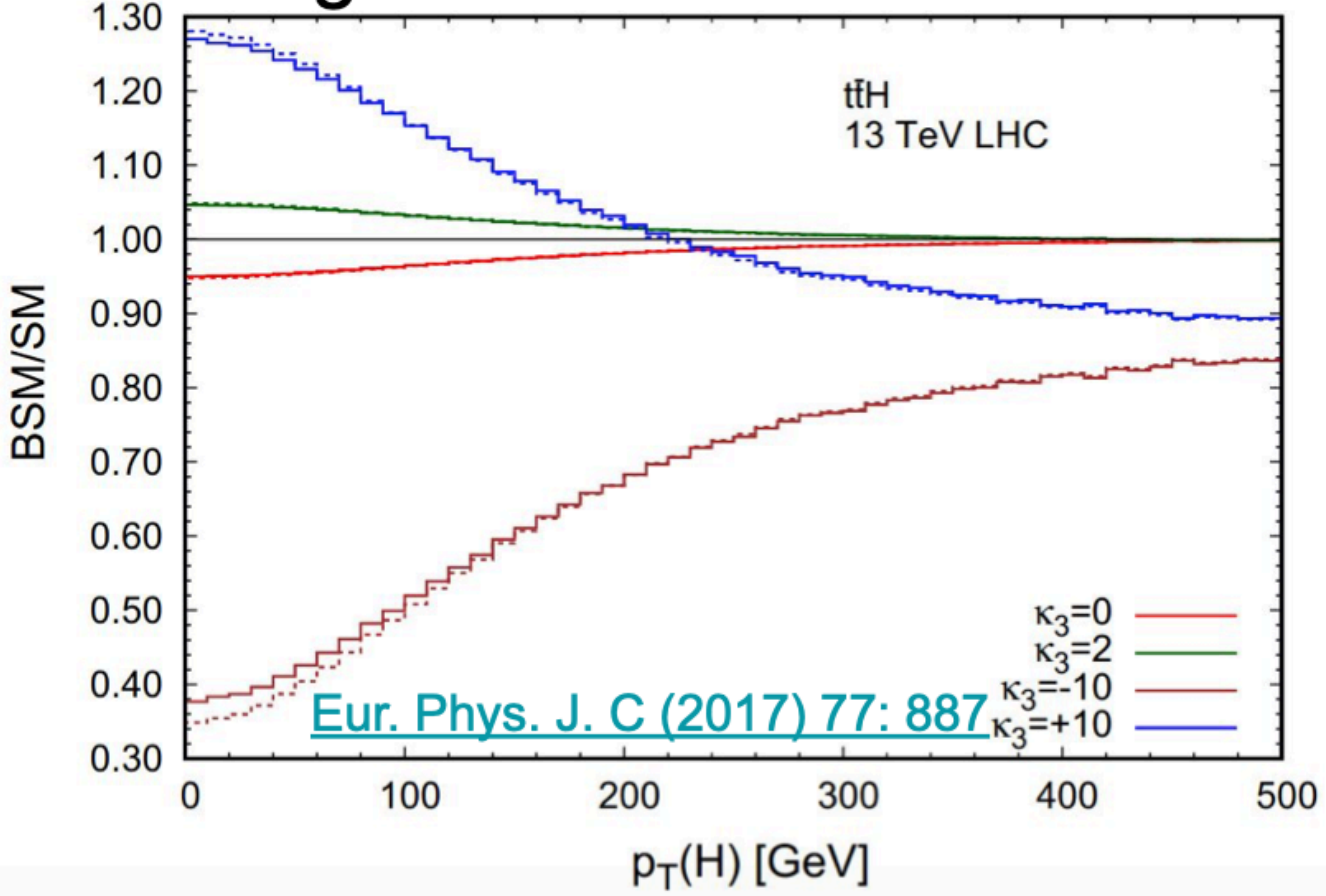
Modification of total XS vs k_λ



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

Modification of differential. XS

- Larger variations for VH and ttH



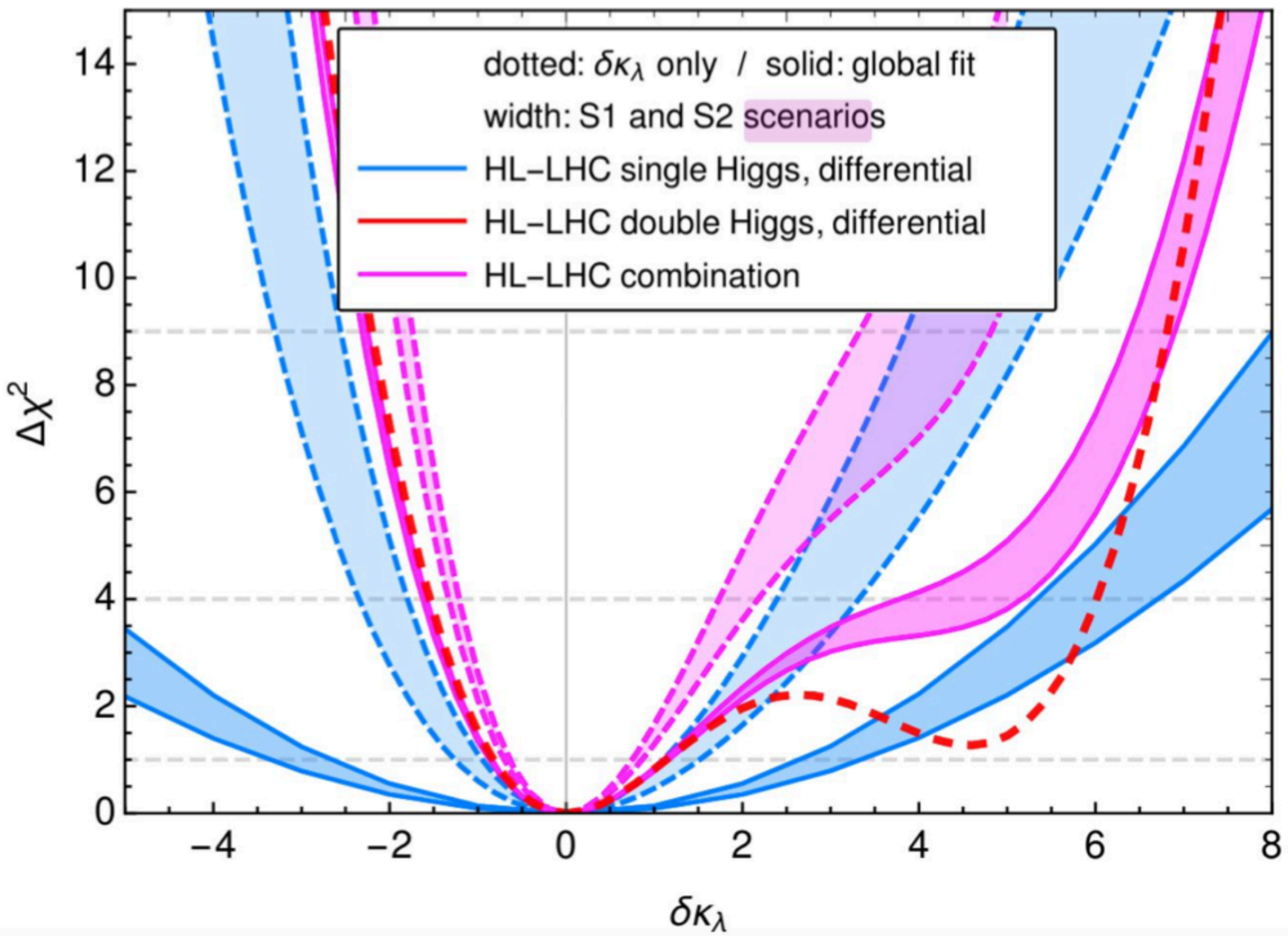
Global fit

- 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

[CERN Yellow report Vol. 7 (2019)]



➢ Challenging because of overlap between single-H and HH selections

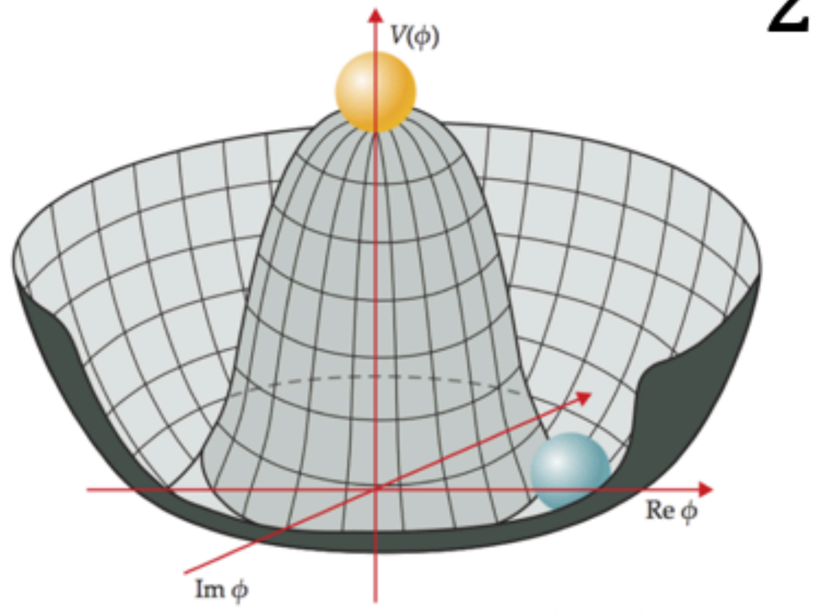
➢ NOT impossible! [ATLAS preliminary result]

Introduction

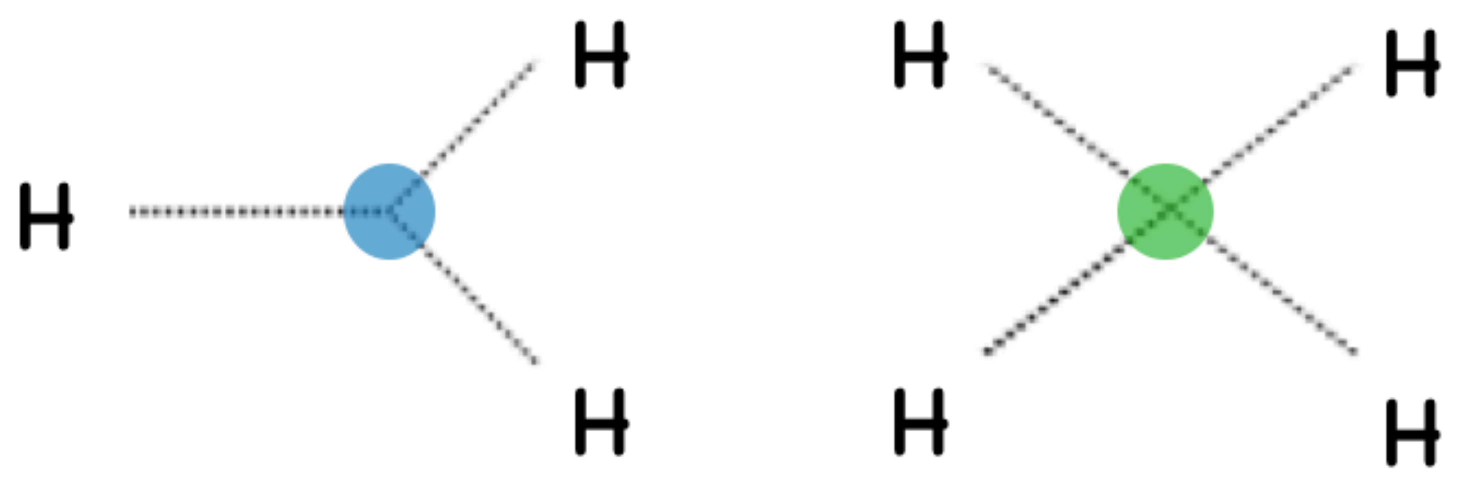
- Higgs boson self-coupling (λ) is a crucial missing element to complete the picture about Higgs boson
- λ measurement provides:
  - a fundamental test of SM and has important physics implications (e.g. stability of the universe)
  - a probe of the Higgs field potential shape
- Deviation of the coupling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

We focus on the trilinear coupling !

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



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



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