Institute of High Energy Physics
Chinese Academy of Sciences

Higgs and HH combinations at the CMS experiment

CLHCP 2022

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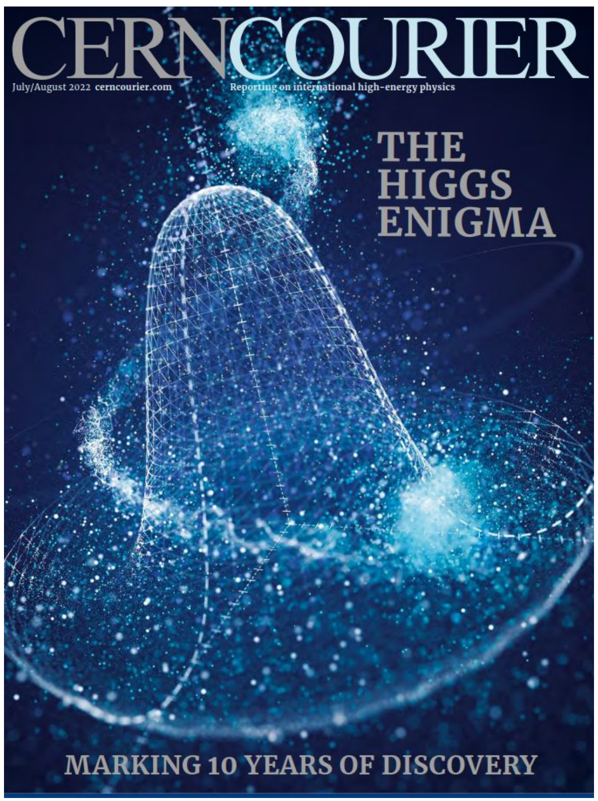
on behalf of the CMS Collaboration

Context and outline

Recently 10th anniversary of the Higgs boson discovery



- 138 fb^{-1} of CMS Run 2 dataset offers great potential for Higgs physics!
  - …and Run 3 data taking has just started
- From 2029 HL-LHC targeting 3000 fb^{-1} in ~10 years of operations

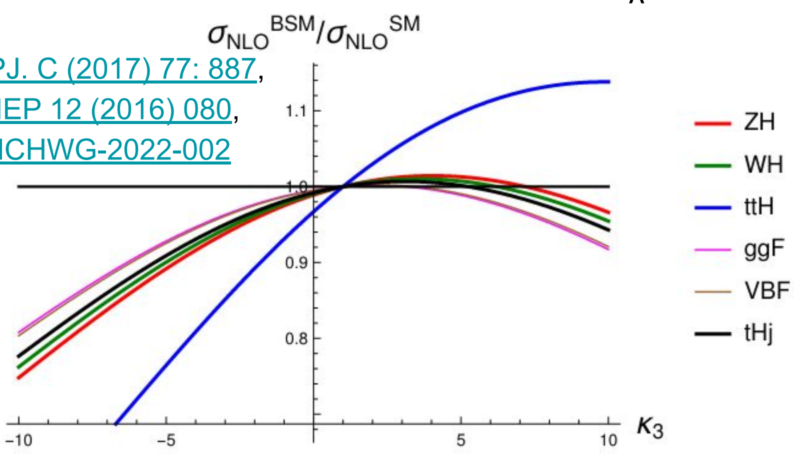
➢ In this presentation CMS results for
  - comb. of H measurements
  - comb. of double-Higgs searches
  - perspectives for HL-LHC

Target of Run 2 Higgs measurements and searches

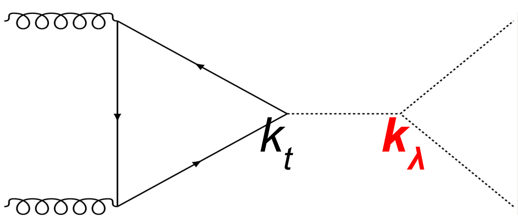
- ➢ Test compatibility with SM
  - ○ Precise measurements of the main H production XS and decay BR
  - ○ Search for double-Higgs production (HH)
- ➢ Measurement of H coupling to fermions and vector bosons
  - ○ Probe anomalies from BSM contributions
  - ○ HHVV coupling (c_{2V}) from VBF HH production
- ➢ Probe properties of the H potential from H self-coupling λ
  - ○ From HH or single-H via NLO EW corrections

Modification of total XS vs k_λ

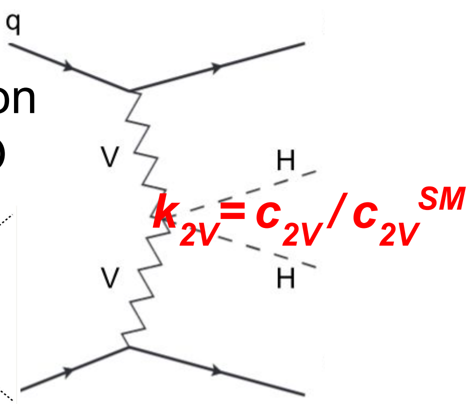
EPJ. C (2017) 77: 887, JHEP 12 (2016) 080, LHCHWG-2022-002



One of the ggF production (ggHH) diagrams at LO



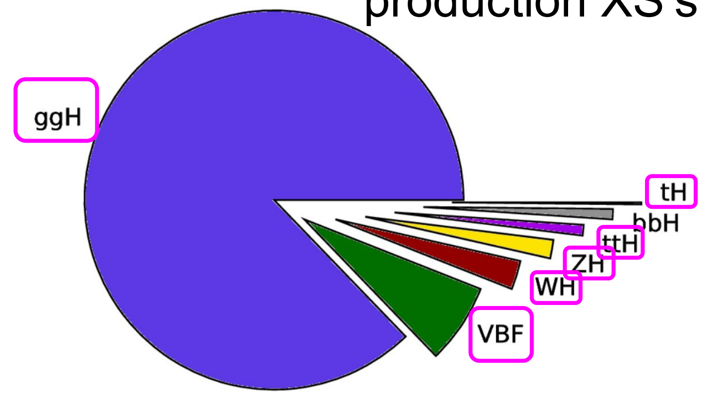
One of the VBF HH production diagrams at LO



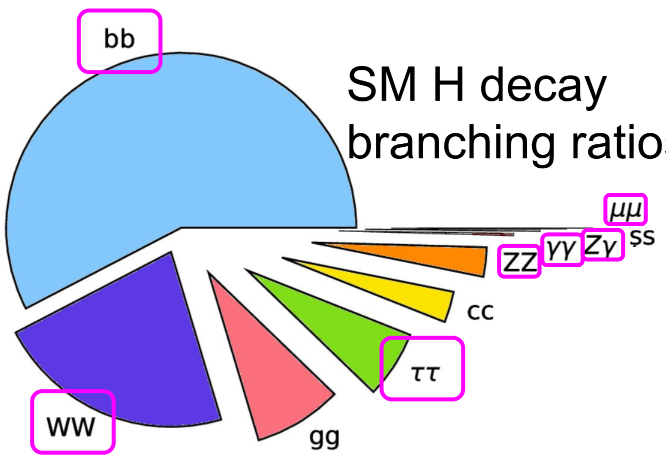
Analyses included in the H combination

Analyses	Integrated lumi (fb^{-1})
H(γγ)	138
H(ZZ→4l)	138
H(WW)	138
H(Zγ)	138
H(bb)	36(ttH) 77(VH) 138(ggH)
H(ττ)	138
ttH multilepton (ττ, WW, and ZZ)	138
H(μμ)	138
H(invisible)	138

Relative SM H production XS's



SM H decay branching ratios

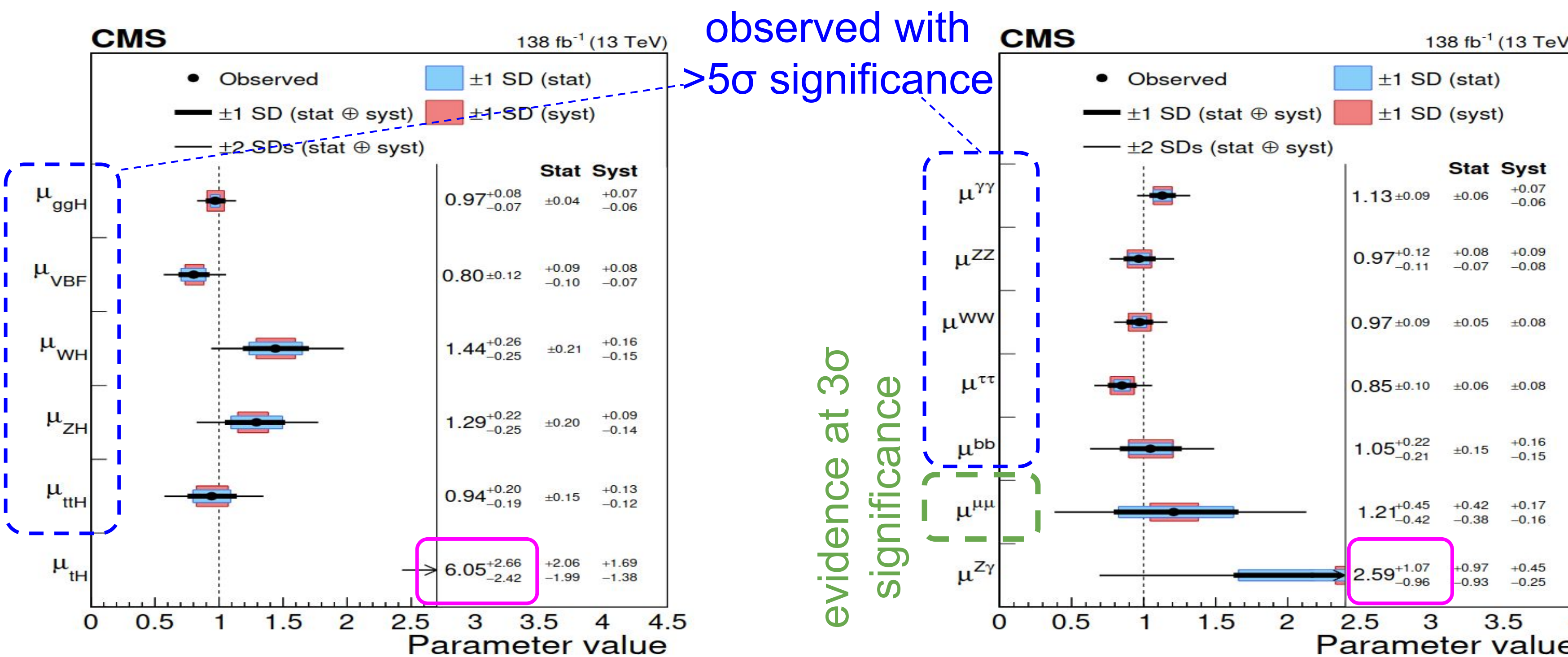


- Main H production and decay channels covered with up to full Run 2 dataset (2016-2018)

Test XS and BR compatibility with the SM

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



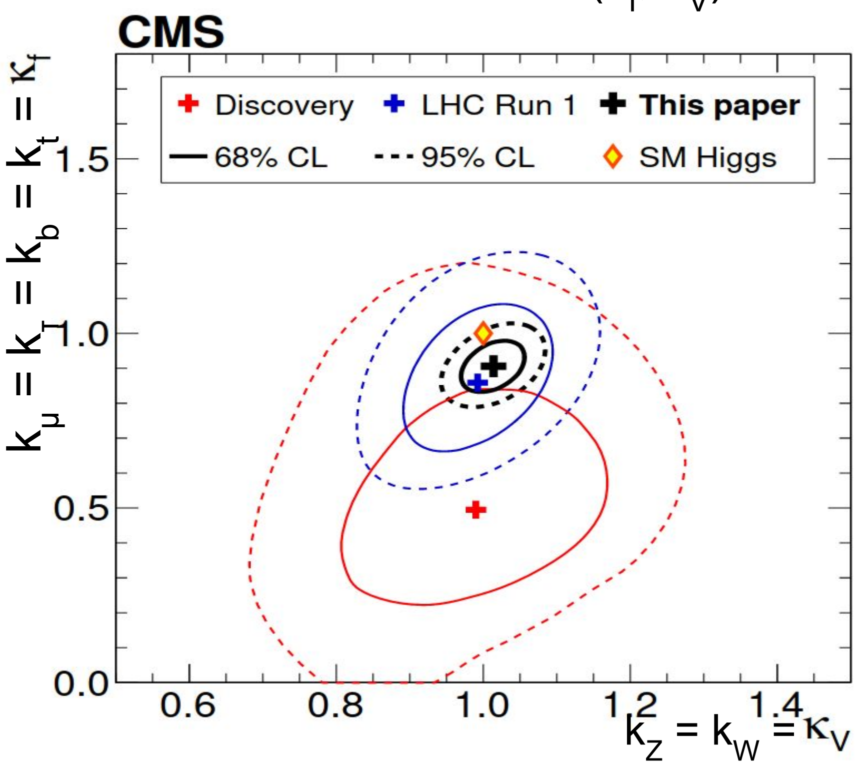
- ➢ Overall good compatibility with SM
  - ○ Small excesses in μ_{tH} and in $\mu_{Z\gamma}$→interesting to see with Run 3 data

H couplings to fermions and vector bosons

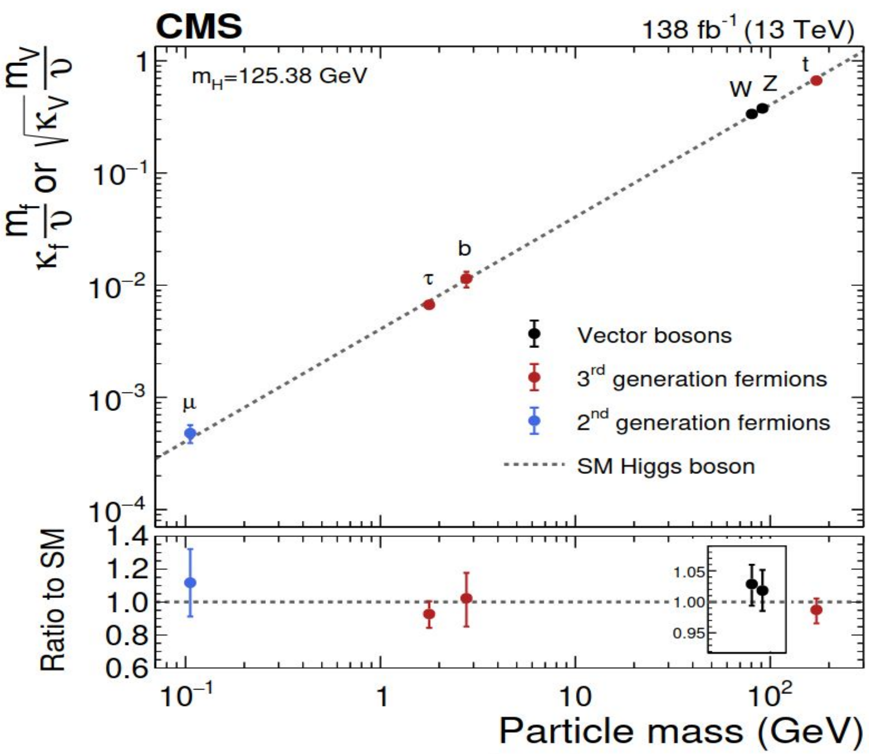
- Coupling modifiers k to quantify couplings deviations from SM predictions

$$\sigma(i \to \mathrm{H} \to f) = \sigma_i(\vec{\kappa}) \frac{\Gamma_f(\vec{\kappa})}{\Gamma_H(\vec{\kappa})}$$

Likelihood scan of (k_f, k_V)



H couplings vs particle mass



- Compatibility with SM within 10%
- ~5✕ improvement wrt discovery

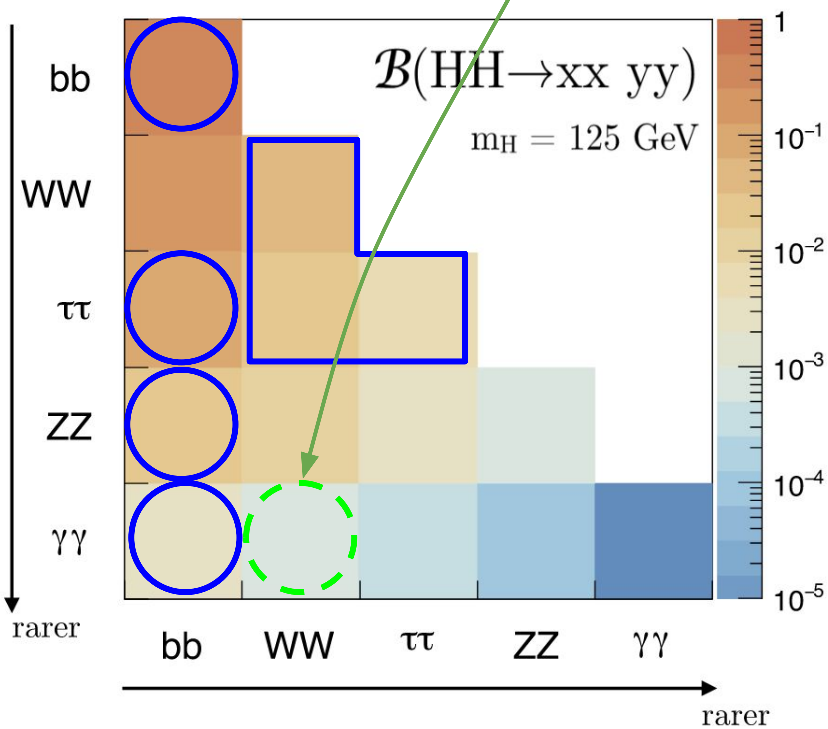
- Agreement with SM for masses within 0.1 - 200 GeV

Explored HH channels at CMS

- H→bb: large BR & bkg rejection from heavy-flavour jet ID
- H final states with leptons, γ, or τ_h: efficient bkg rejection

ch's included in HIG-22-001

New! See Chu Wang talk

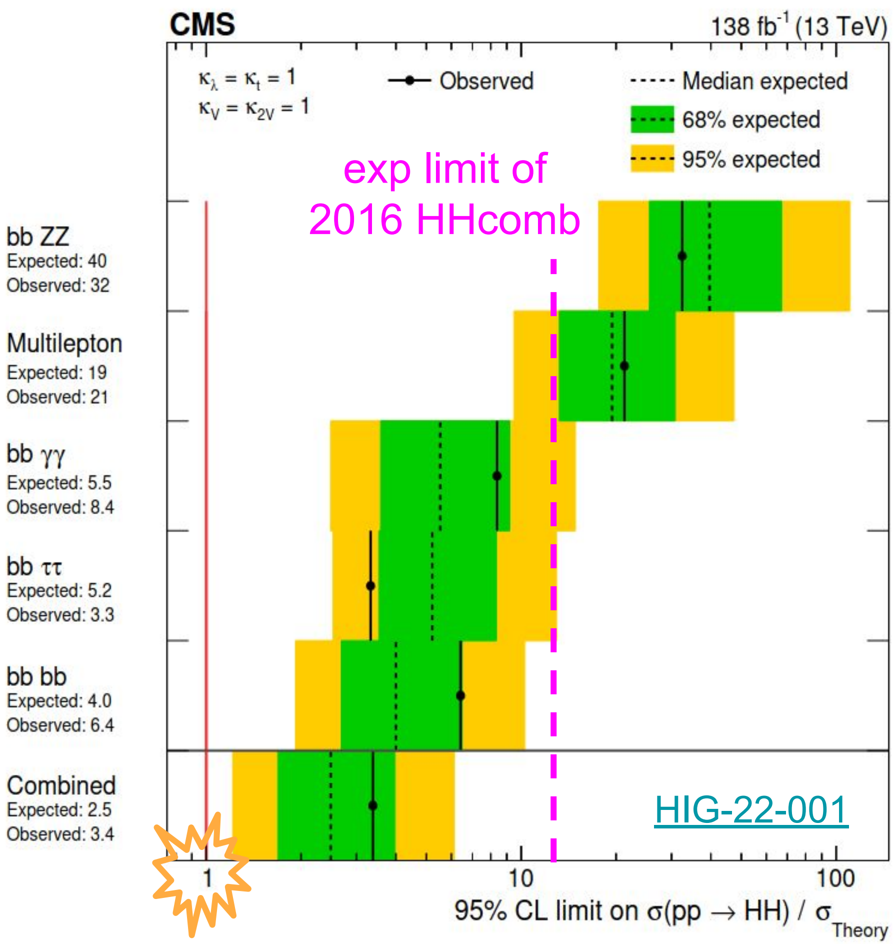


➢ No HH golden channel
  - Channel sensitivities are complementary

➢ Many final states covered

Upper limit on HH signal strength

- No deviations from SM observed



Obs(exp) upper limit on μ_{HH} of 3.4(2.5)

- 2.6 times better than 2016 result scaled by lumi
  - Extensive usage of ML tools + boosted topologies
- HH will be one of the most exciting results of Run 3
  - Scaling by end of Run 3 and combining with ATLAS very close to 1!!!

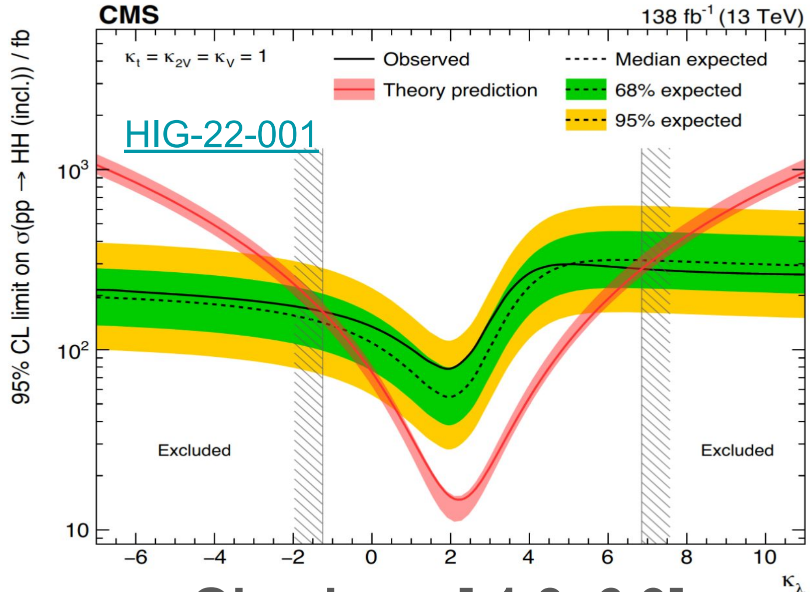
ATLAS preliminary Run 2 HHcomb
Obs(exp) U.L. on μ_{HH} of **3.1**(3.1)

Constraints on k_λ

ATLAS preliminary Run 2 HHcomb
Obs. $k_\lambda \in [-1.0, 6.6]$
Exp. $k_\lambda \in [-1.2, 7.2]$

- Observed results compatible to SM predictions

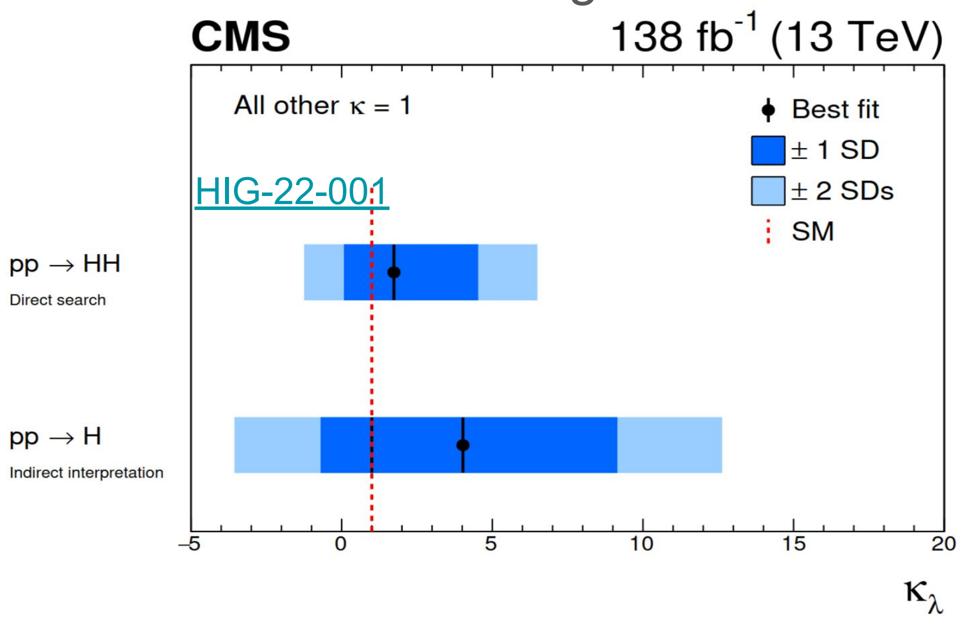
Limit on HH XS vs k_λ



Obs. $k_\lambda \in [-1.3, 6.9]$
Exp. $k_\lambda \in [-0.9, 7.0]$

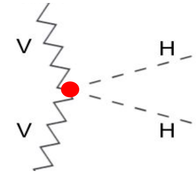
➢ Close to exclusion of $k_\lambda = 0$
  - Possible with Run 3 data or with Run 2 HHcomb of CMS+ATLAS

k_λ measurement from HH vs from single-H



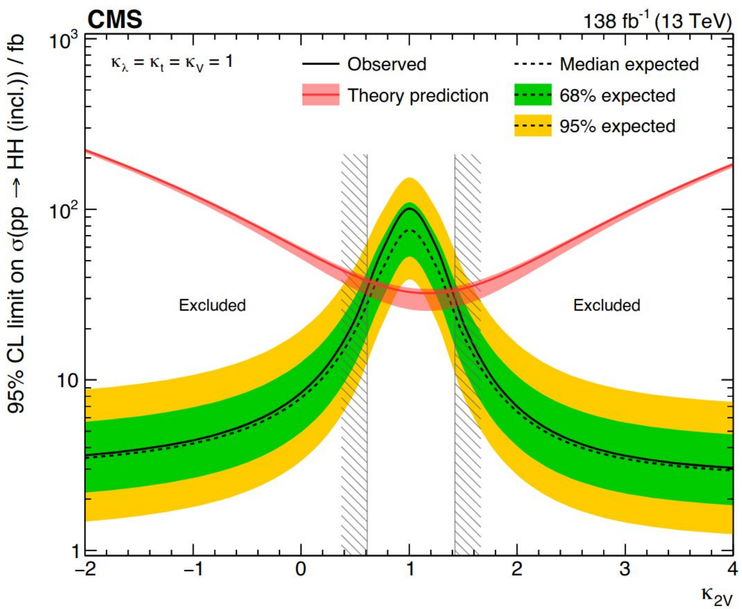
➢ First CMS measurement of k_λ from single-H exploiting differential effects on XS

Constraints on k_{2V}



- Observed results compatible to SM predictions

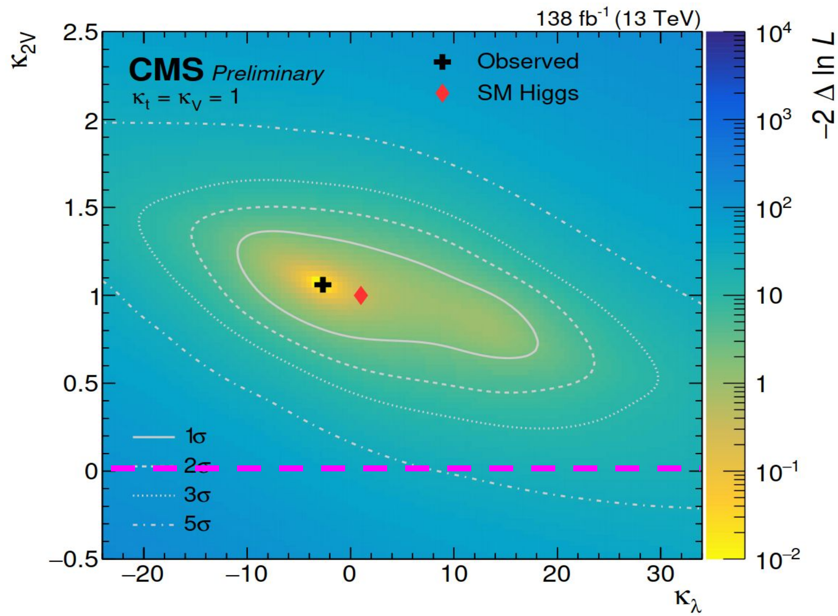
Limit on VBF HH XS vs k_{2V}



Obs. k_{2V} ∈ [0.61, 1.42]

Exp. k_{2V} ∈ [0.60, 1.37]

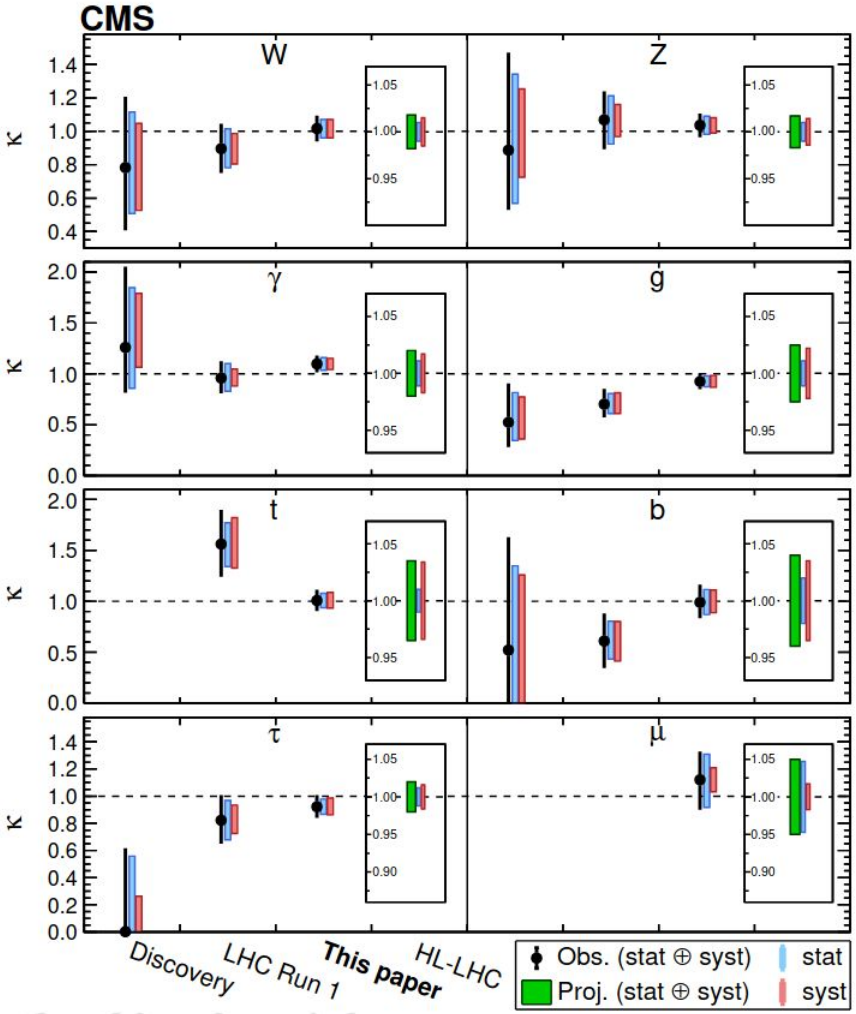
Likelihood scan of (k_λ, k_{2V}) considering only boosted HH→4b



➢ $k_{2V} = 0$ excluded at >5σ assuming $k_\lambda = k_t = k_V = 1$

➢ $k_{2V} = 0$ excluded at >3σ for any value of k_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 3000 fb^{-1} of U.L. on $\mu_{HH} < 1$
  - ○ Evidence of SM HH expected with 4σ from CERN YR
  - ○ Further improvement possible through new techniques & ideas→observation?
- ➢ Potential for more extensive tests of SM, e.g. EFT

Summary

- H & HH comb's provide fundamental extensive tests of SM
- Good compatibility of observations with SM predictions
  - μ_H = 1.002 ± 0.057 and μ_{HH} < 3.4 @ 95% C.L.
  - Precision better than 10% for most of the considered H couplings
- Statistical uncertainties comparable to systematics ones for main H production and decay channels
- $k_{2V} = 0$ excluded at >5σ assuming $k_\lambda = k_t = k_V = 1$
- At HL-LHC high-precision tests of the SM and potential for HH observation

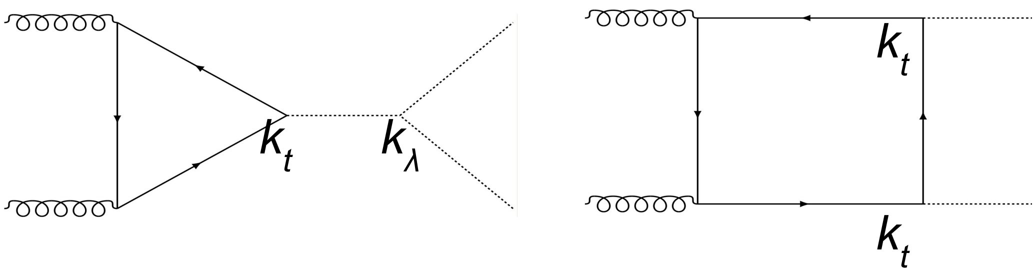
Great progresses in understanding the Higgs boson since its discovery and exciting times ahead!

BACKUP

Search for non-resonant HH production

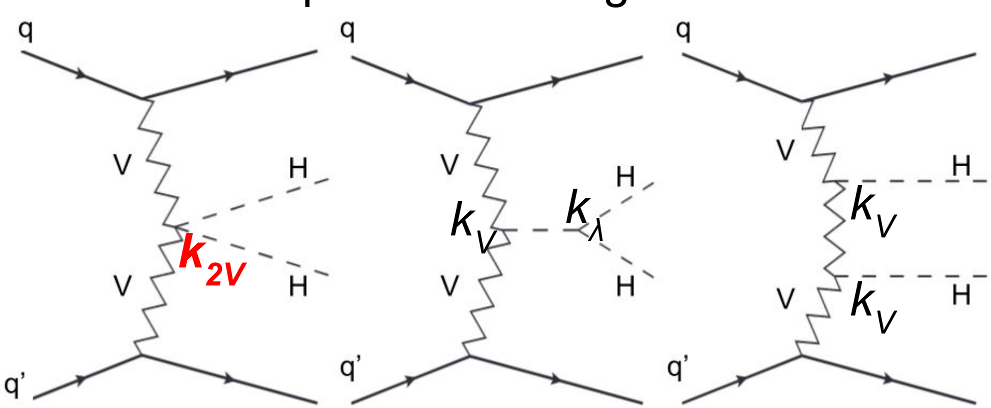
- HH production is sensitive to the Higgs trilinear coupling λ
- VBF HH is sensitive to c_{2V} coupling → $k_{2V} = c_{2V} / c_{2V(SM)}$

ggF production (ggHH) diagrams at LO

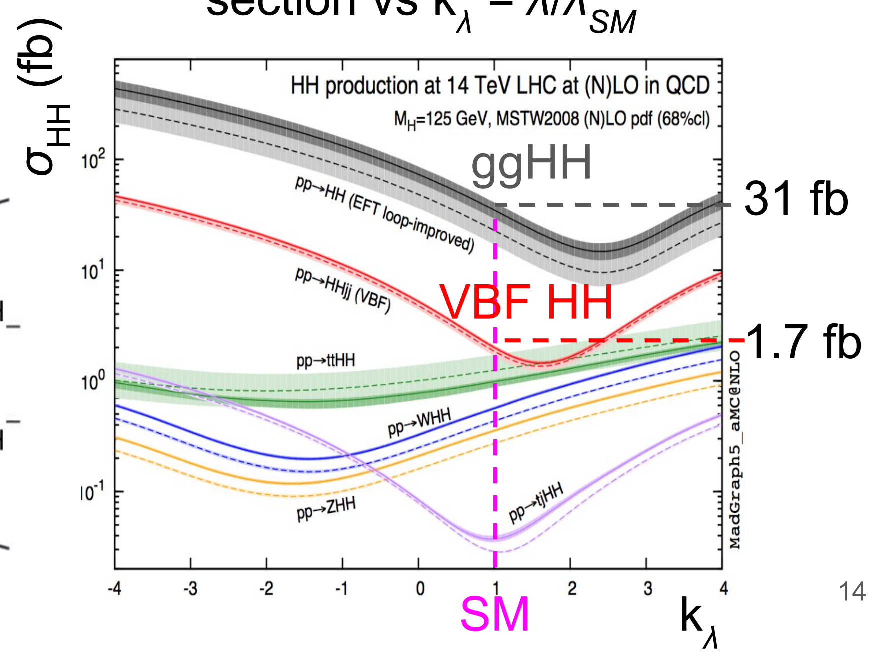


Fundamental tests of SM

VBF HH production diagrams at LO



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



Analyses included in the combination

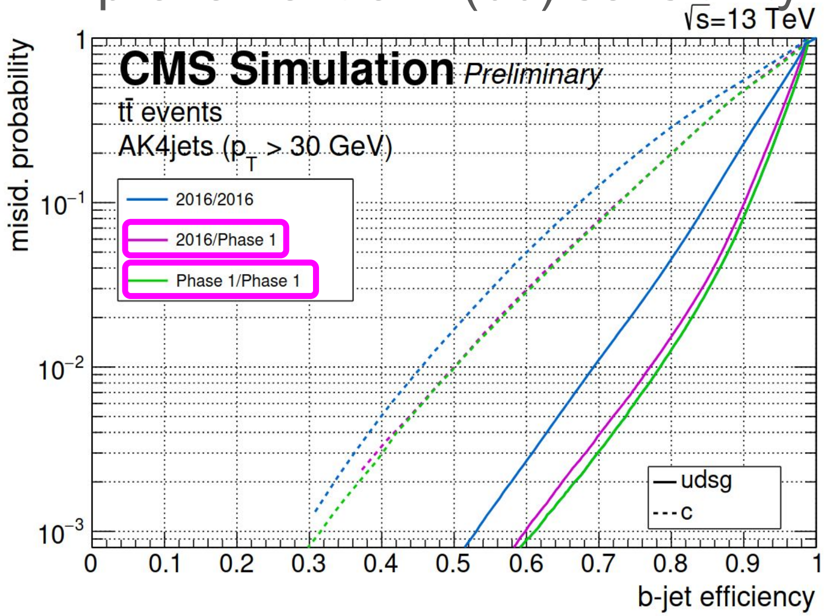
Analyses	Integrated lumi (fb^{-1})	ggH	qqH	VH	ttH & tH
H(γγ)	138	X	X	X	X
H(ZZ→4l)	138	X	X	X	X
H(WW)	138	X	X	X	
H(ττ)	138	X	X	X	
ttH multilepton(ττ, WW, and ZZ)	138				X
H(Zγ)	138	X	X	X	X
H(bb)	36(ttH) 77(VH) 138(ggH)	X	X	X	X
H(μμ)	138	X	X	X	X
H(invisible)	138	X	X	X	

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

Improvements during Run 2

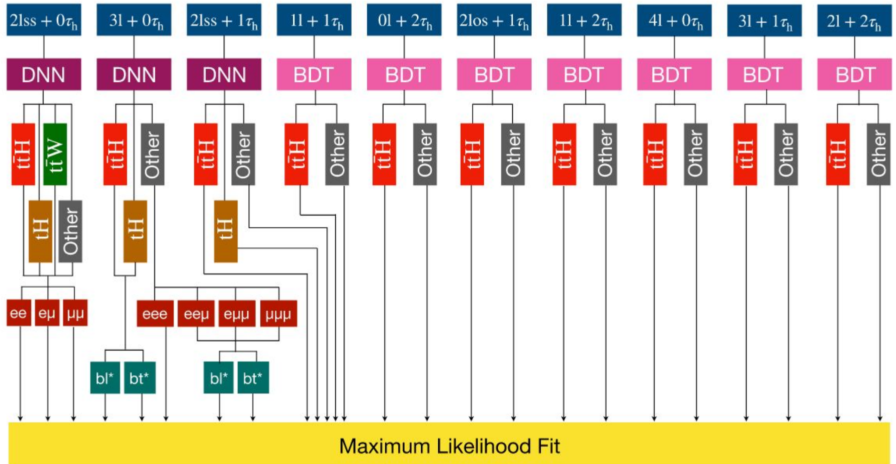
CMS detector upgrades

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



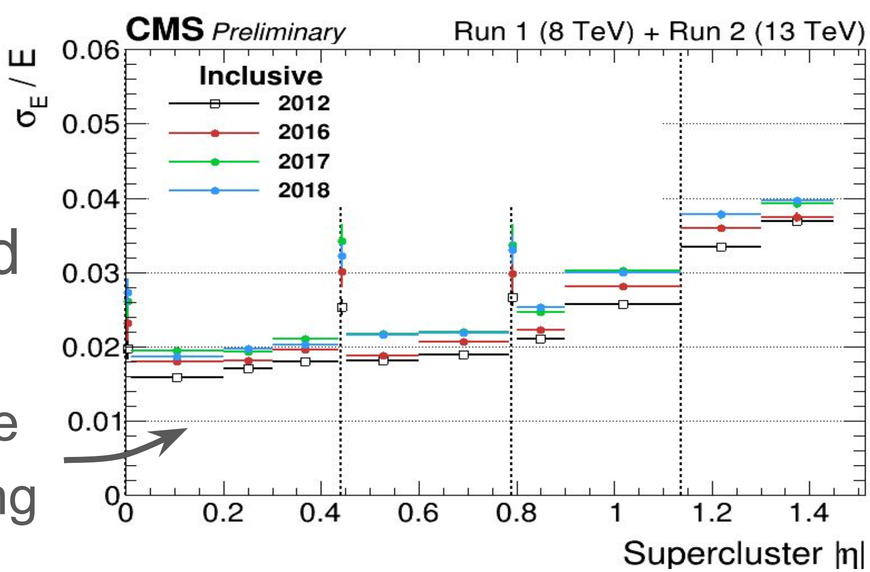
Extensive usage of ML

ttH multilepton analysis workflow



Optimized detector calibration and physics objects reco

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



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)

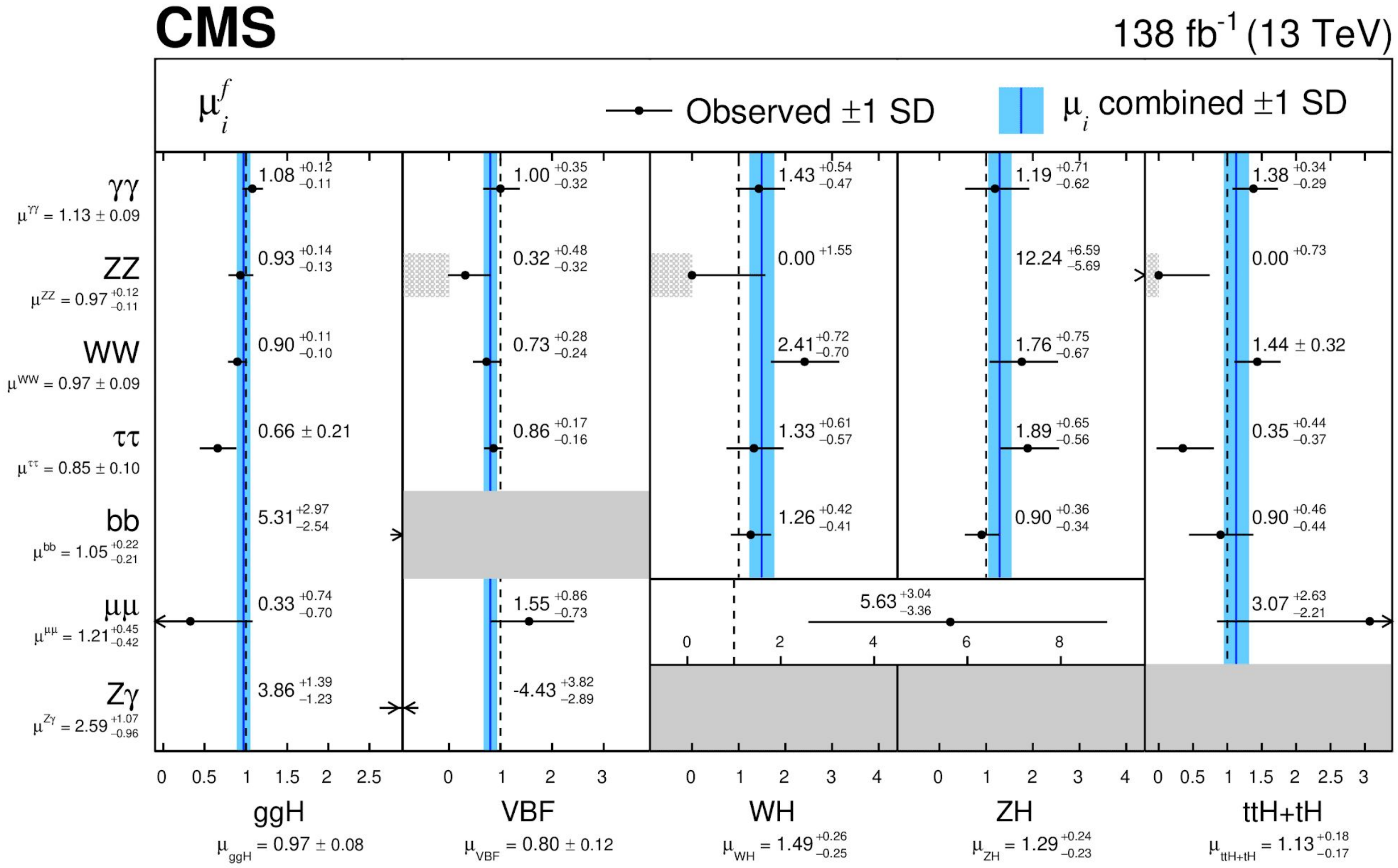
$\mu = 1.00 \pm 0.13$ [+0.08/-0.07 (theory) ± 0.07 (exp.) ± 0.09 (stat.)]

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

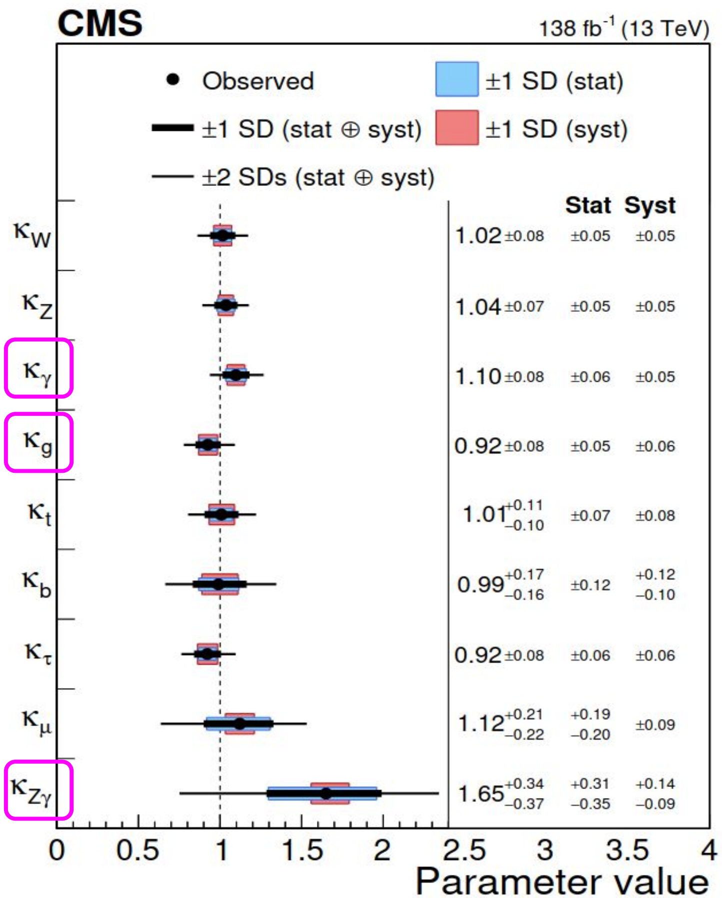
Test XS and BR compatibility with the SM

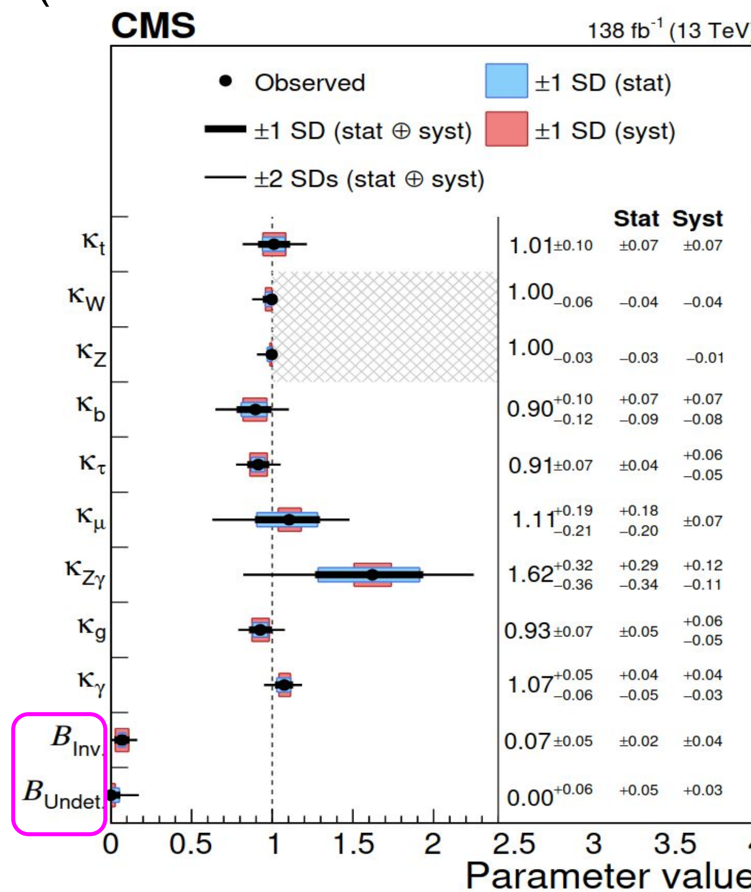


➢ Good compatibility with SM for main H production & decay

H couplings with more general assumptions

Measurement assuming effective couplings for ggH, Hɣɣ, and HZɣ → 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 $k_{Z\gamma}$

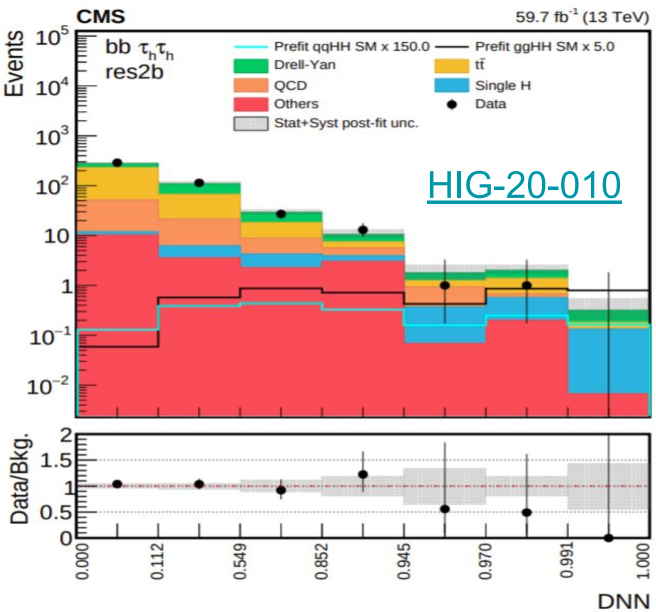
Both invisible and undetectable BR's compatible with zero

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

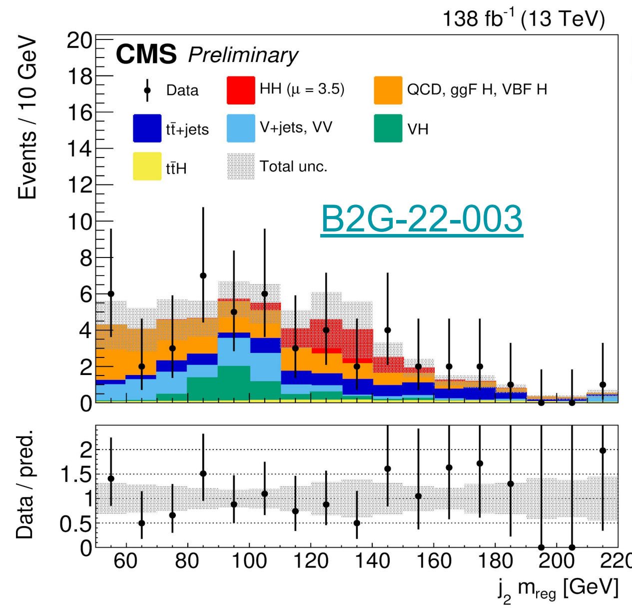
- Improvement wrt HH searches with 2016 dataset much larger than gain in integrated luminosity

Extensive usage of ML tools

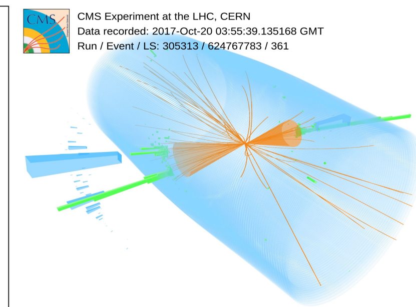
Boosted topologies



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

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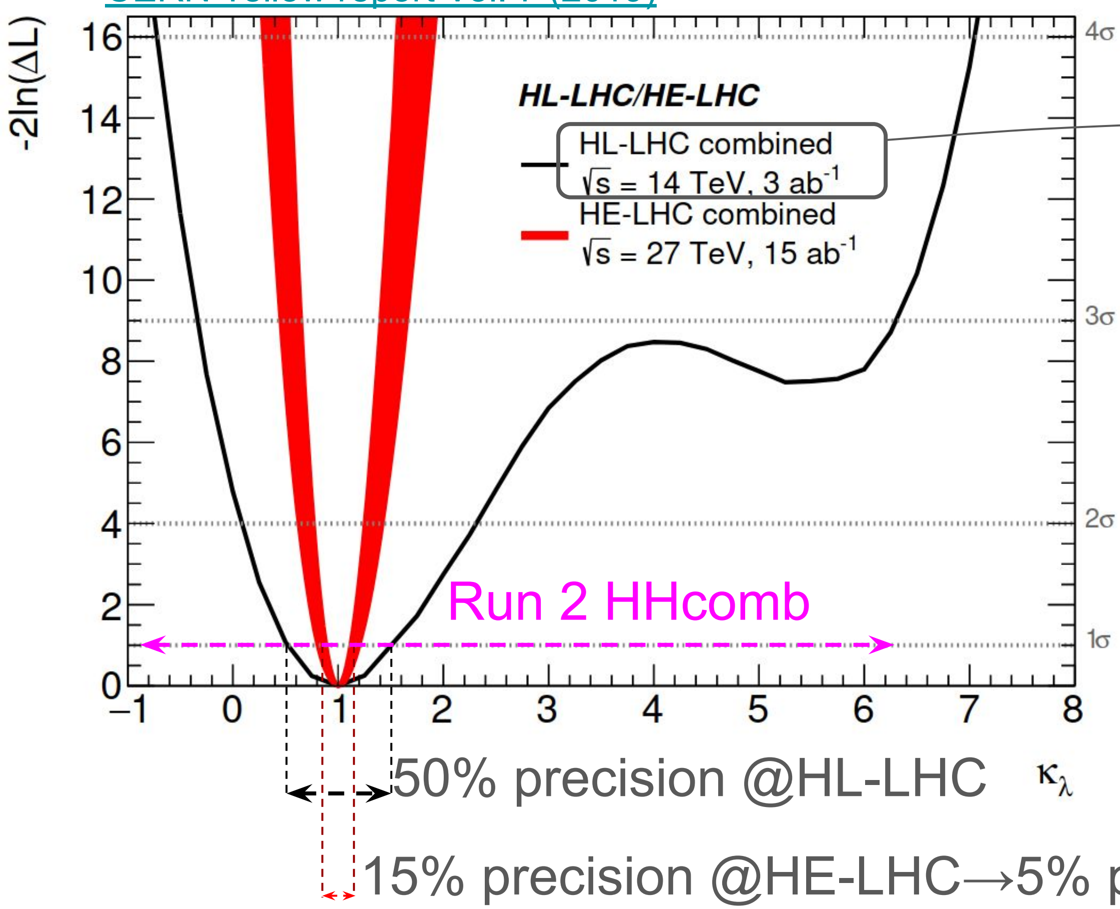


50% precision @HL-LHC

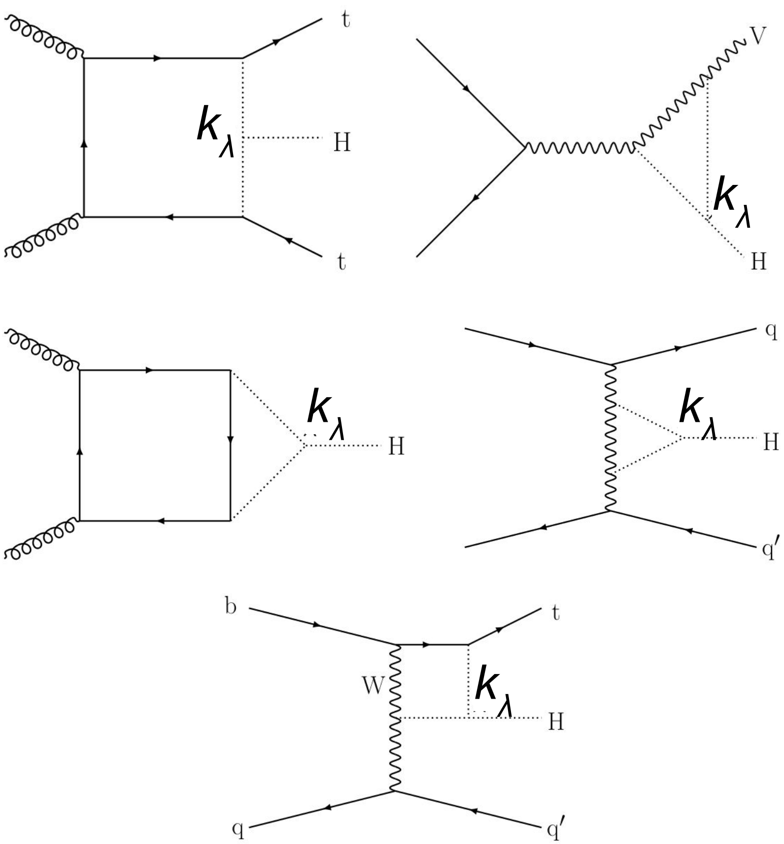
15% precision @HE-LHC→5% precision with 100 TeV & 30 ab^{-1}

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

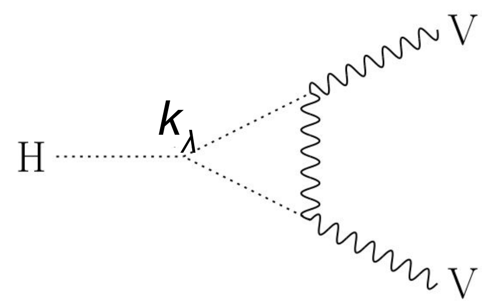
Trilinear self-coupling in single-H mechanisms

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

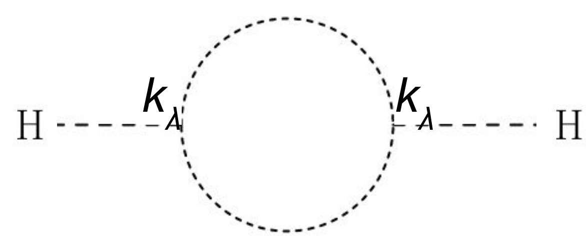
Examples of k_λ-dependent diagrams for single-H prod. mechanisms $O(k_\lambda)$



Example of k_λ-dependent diagrams for H→VV decay

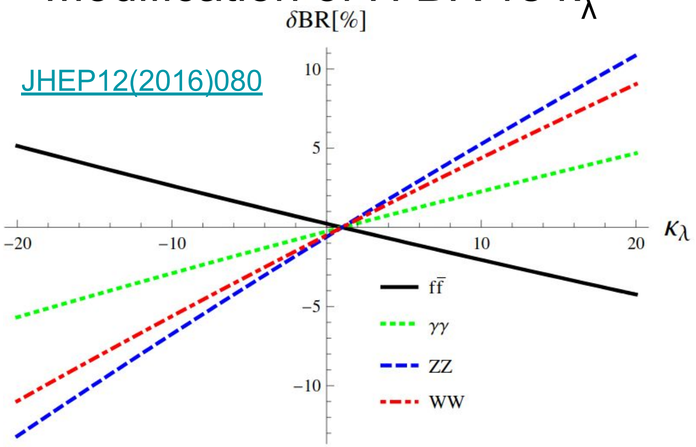


One universal correction for H wave-function renormalization $O(k_\lambda^2)$

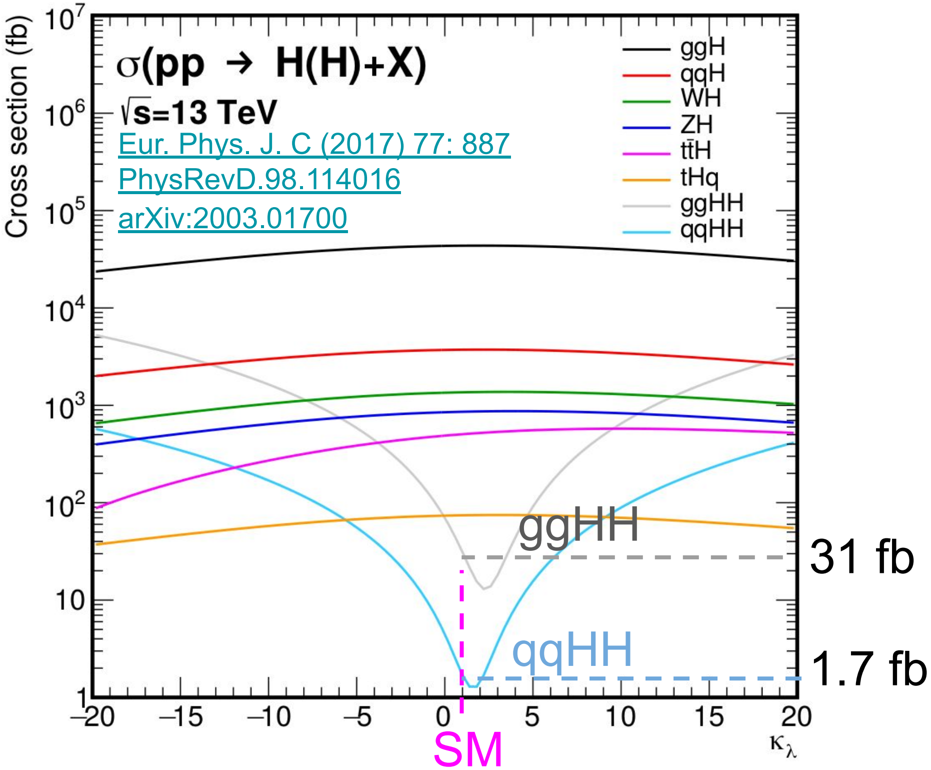


Effect of k_λ corrections on Higgs XS and BR

Modification of H BR vs k_λ

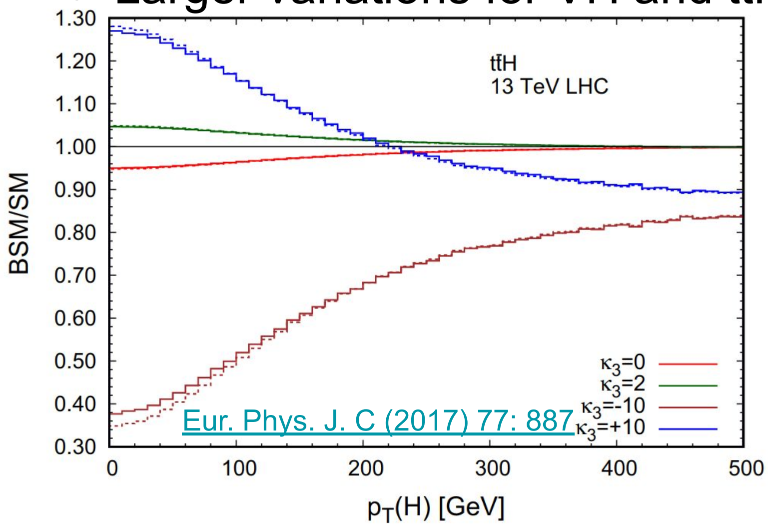


Modification of total XS vs k_λ



Modification of differential. XS

- Larger variations for VH and ttH



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

See also [JHEP 1709 (2017) 069]

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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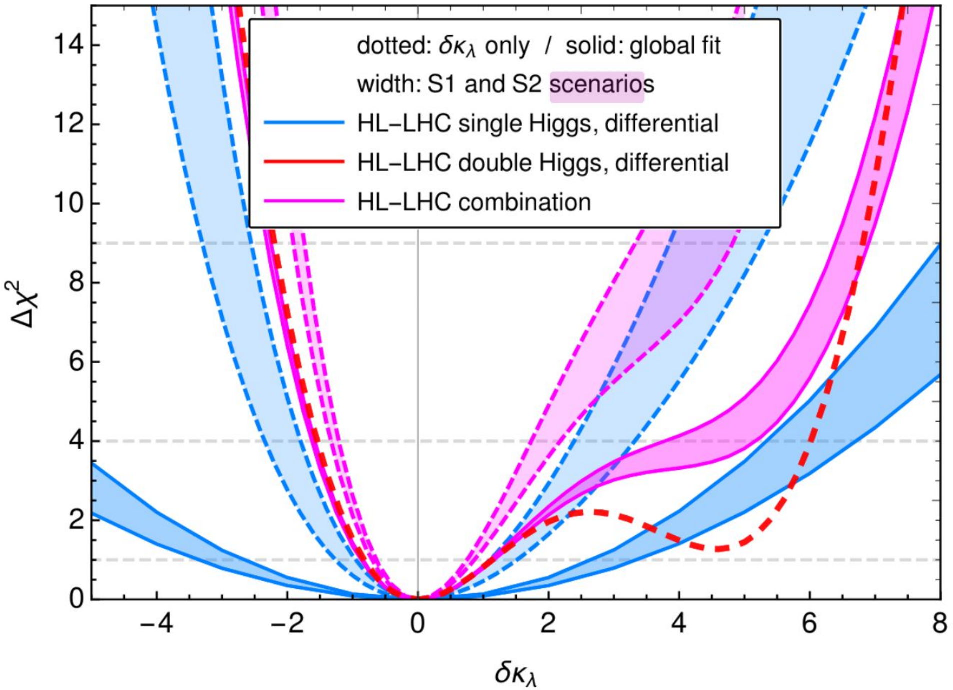

- ➢ Challenging because of overlap between single-H and HH selections
- ➢ NOT impossible! ATLAS preliminary result