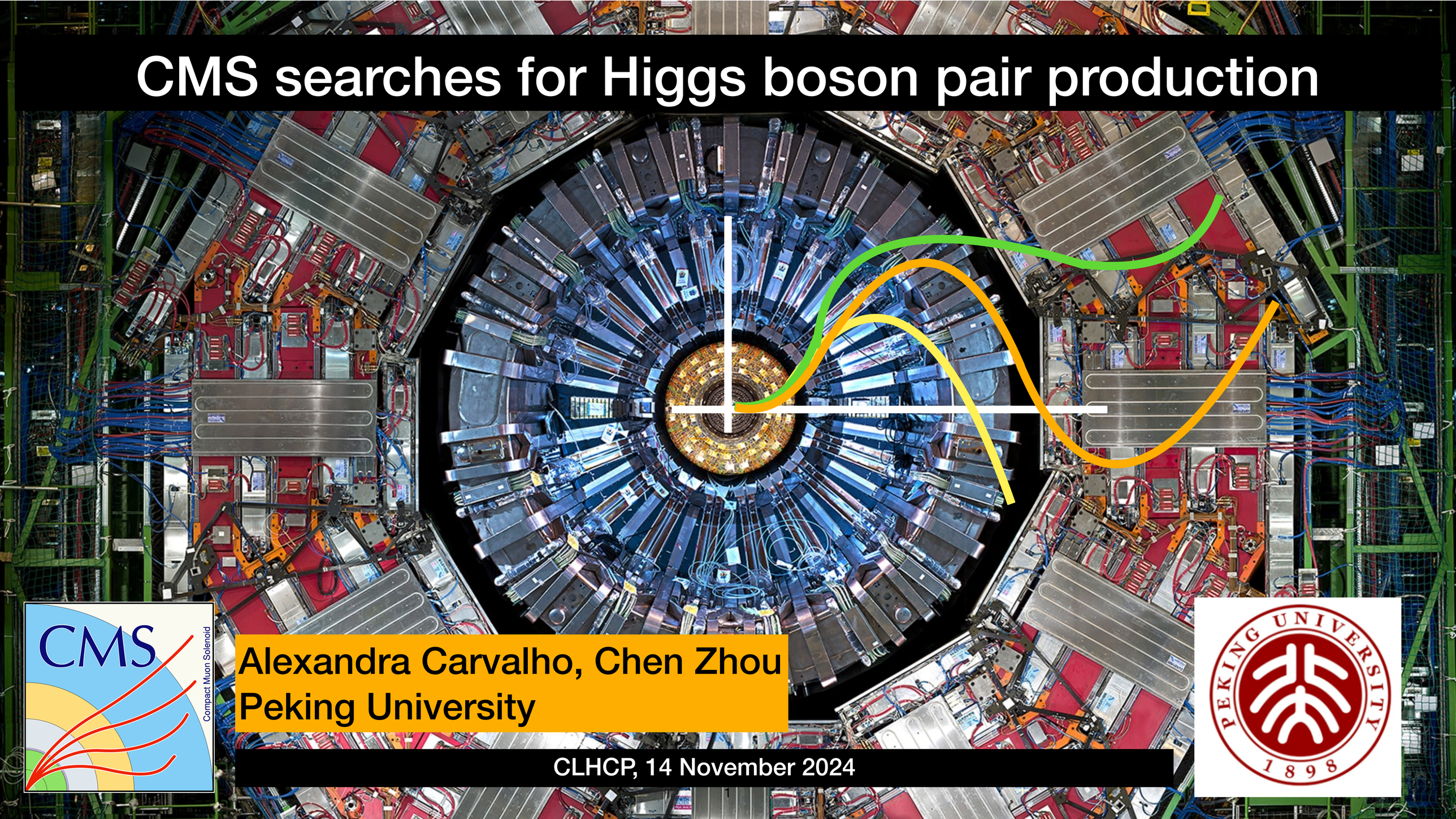
CMS searches for Higgs boson pair production



Alexandra Carvalho, Chen Zhou
Peking University

CLHCP, 14 November 2024

Why Higgs pairs?

- The Standard Model of particle physics is a formidable description of known matter and the three of four elementary forces in Nature
- The Higgs mechanism is the simplest way to unify ElectroWeak interactions

$$\Phi \equiv \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

$$V(\Phi^\dagger\Phi) = \mu^2\,\Phi^\dagger\Phi + \lambda\,(\Phi^\dagger\Phi)^2$$

In 2012 the H boson was discovered, leaving the H potential as the last unmeasured piece of the SM

- Given H boson mass is ~125 GeV, if $\lambda = 0.012$, **IF** the SM describes all that exists:
  - We 'predict' the masses of the photon, W and Z bosons. Keeping an elegant and renormalizable formulation for their interactions…

    … The measurement of the H potential is a closure of the SM, OR a door to understand physics behind it

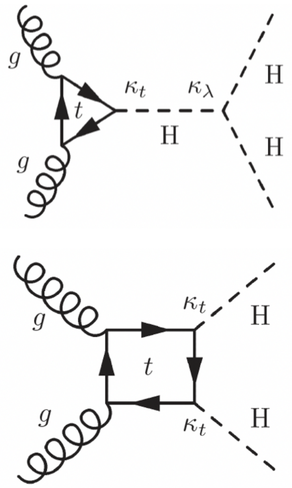
The search for non-resonant H boson pair production is the only direct method to probe λ at LHC

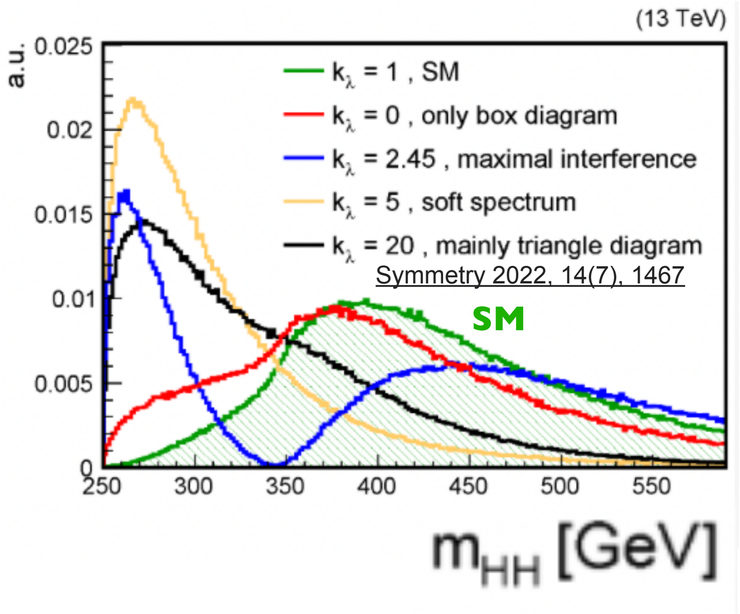
Higgs pairs in the Standard Model

The main production mechanisms at the LHC are gluon fusion (ggF) and vector boson fusion (VBF)

ggF: loop induced processes, destructive interference

σ_{ggF} (SM) = **31.05 fb**



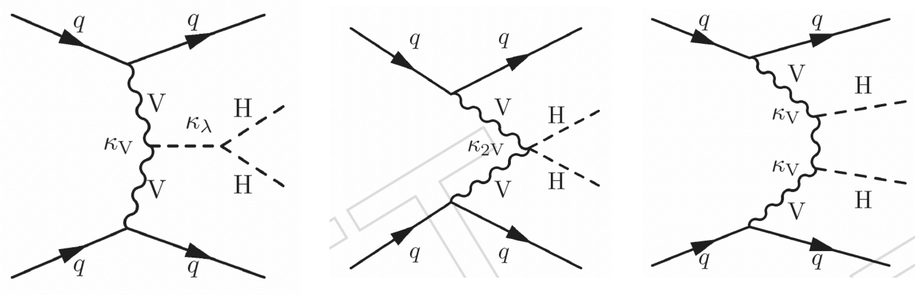


Deviations of κλ from the SM prediction:

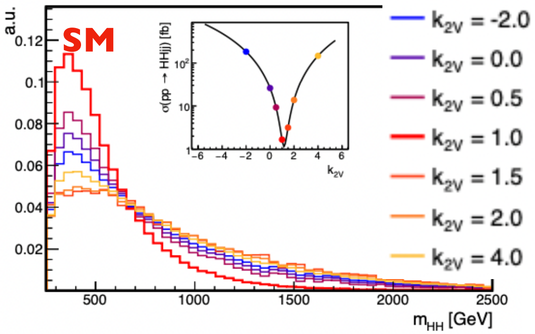
-> softer signal, cross section enhancements

VBF: tree-level process, The VVHH contact interaction is also probed

σ_{VBF} (SM) = **1.7 fb**



A measurement of k2V is also a test of the doublet structure of the H field !



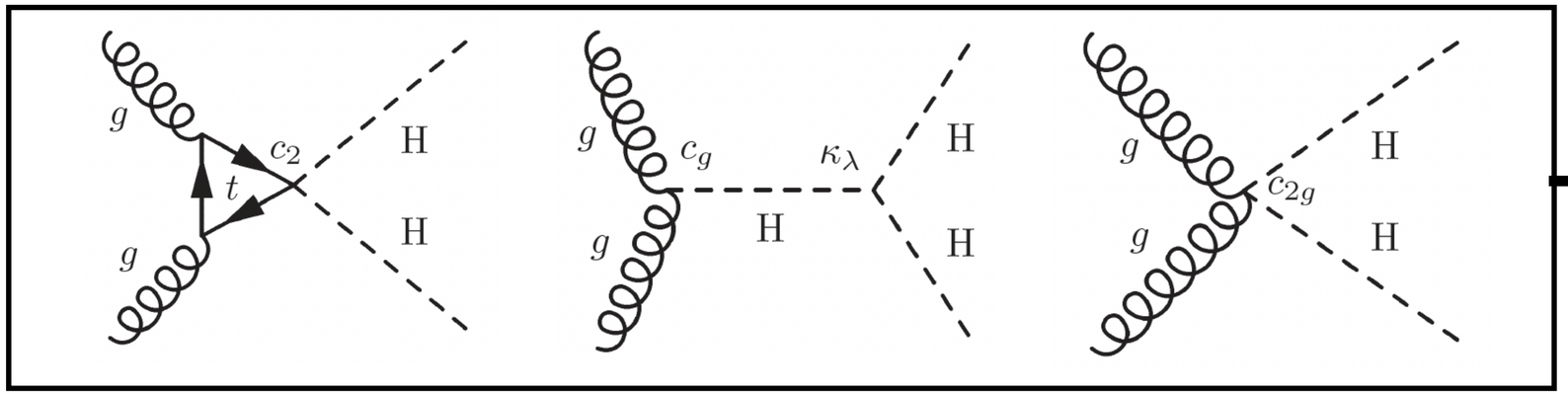
Deviations of κ2V from the SM prediction:

-> harder signal, cross section enhancements

Measurements of κλ and κ2V are entangled with κt and κV —> better measured in single H production

What if there is more than the SM interactions

- One possibility is that New physics induces other terms into the H potential
  - Other type of H couplings, specially on ggF production (BSM-like couplings)



More violent variations in signal topology and cross section variations [1,2]

- We approach the modeling of these in the Higgs EFT (HEFT) scenario

  => linear variation of couplings

- Two methods of search:
  - Upper limits in representative signal topologies (shape Benchmarks)
  - Parameter scans: We give priority to scan the ttHH coupling (c2)

    ==> deeply connected with κλ and κt in most complete theories

The CMS saga towards the H potential

H125 discovery July 2012

First non-resonant HH search
PRD 94 (2016) 5, 052012

κλ ~ [-17, 22]
19.7/fb @ 8 TeV

Several results in full run2 data!

Theory updates

Combination between single Higgs measurements and HH searches
arXiv:2407.13554, *accepted by PLB*

More channels!

More channels!

Theory updates

HEFT

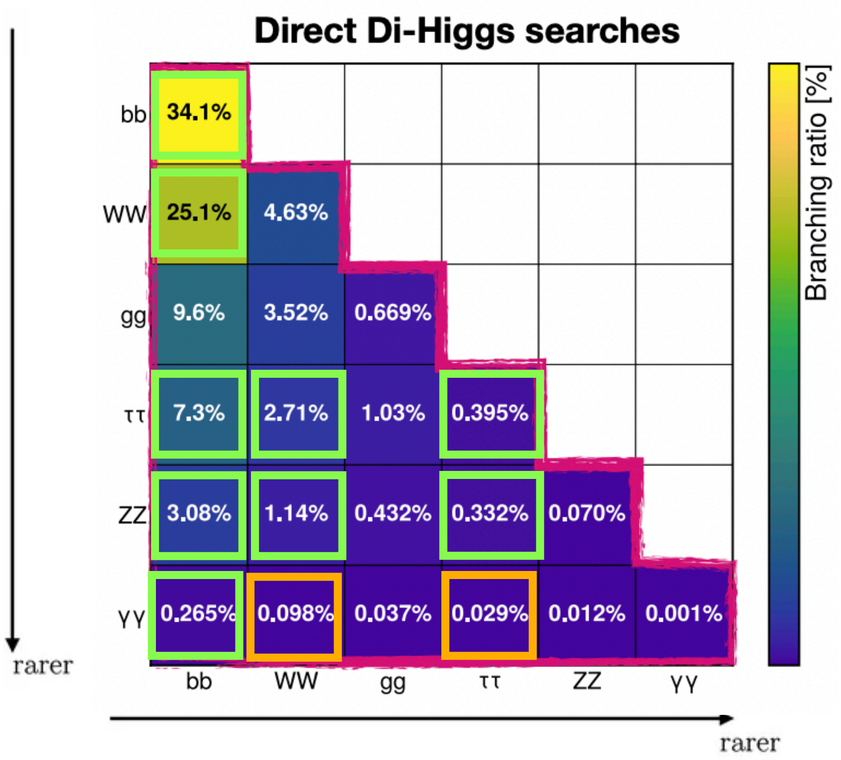
This talk

Legacy Combination CMS full Run 2 HH searches
PAS-HIG-20-011

κλ between [-1.4, 6.4] at 95% CL 138/fb @ 13 TeV

Input channels for CMS legacy HH combination

- We have a rich coverage of Higgs pairs final states and production modes



Final state		Reference
bbγγ	★●	JHEP 03 (2021) 257
bbττ	★●	PL B 842.137531
bbbb (resolved)	★●	PRL. 129.081802
bbbb (boosted)	★●	PRL. 131.041803
Multilepton	★●	JHEP 07 (2023) 095
bbZZ (4ℓ)	★	JHEP 06 (2023) 130
bbbb (VHH)	■	CMS-PAS-HIG-22-006
bbWW (leptonic)	★●	JHEP 07 (2024) 293
bbWW (hadronic)	★●	CMS-PAS-HIG-23-012
ττγγ	★●	CMS-PAS-HIG-22-012
WWγγ	★	CMS-PAS-HIG-21-014

Includes HEFT and shape-BM

Most added specially for this publication!

Nature
PRD 94 (2016) 5, 052012
PAS-HIG-20-011

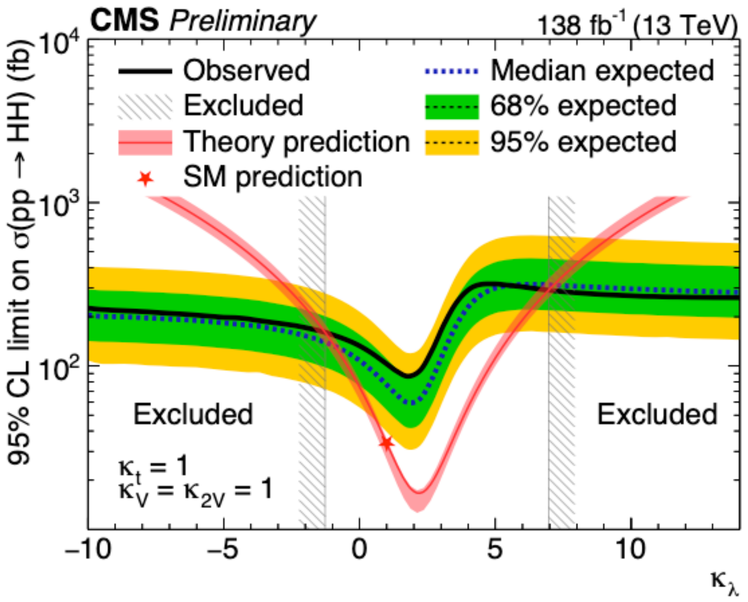
Production modes:
★ GGF
● VBF ■ V-associated

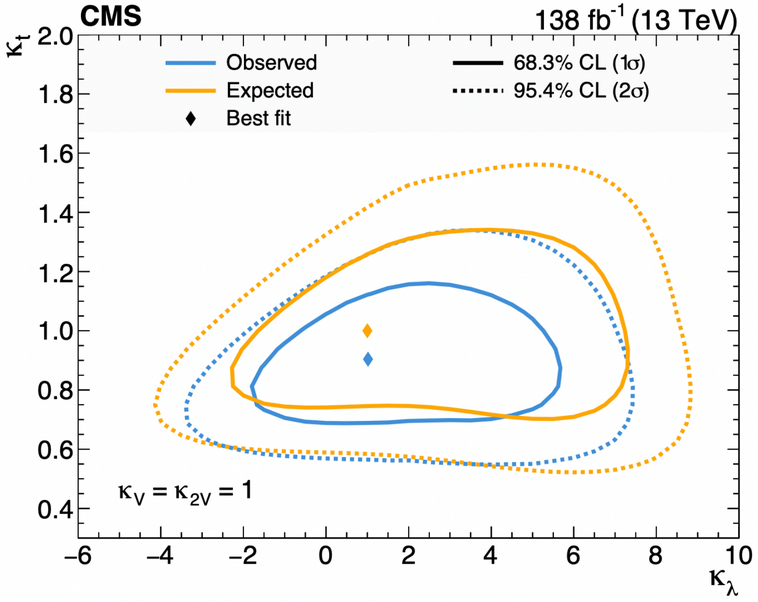
- There is no time to cover all channels, for an overview, I will talk about main channels and the brand new additions

The HH combination in the SM-like scenario (kl/kt)

PAS-HIG-20-011

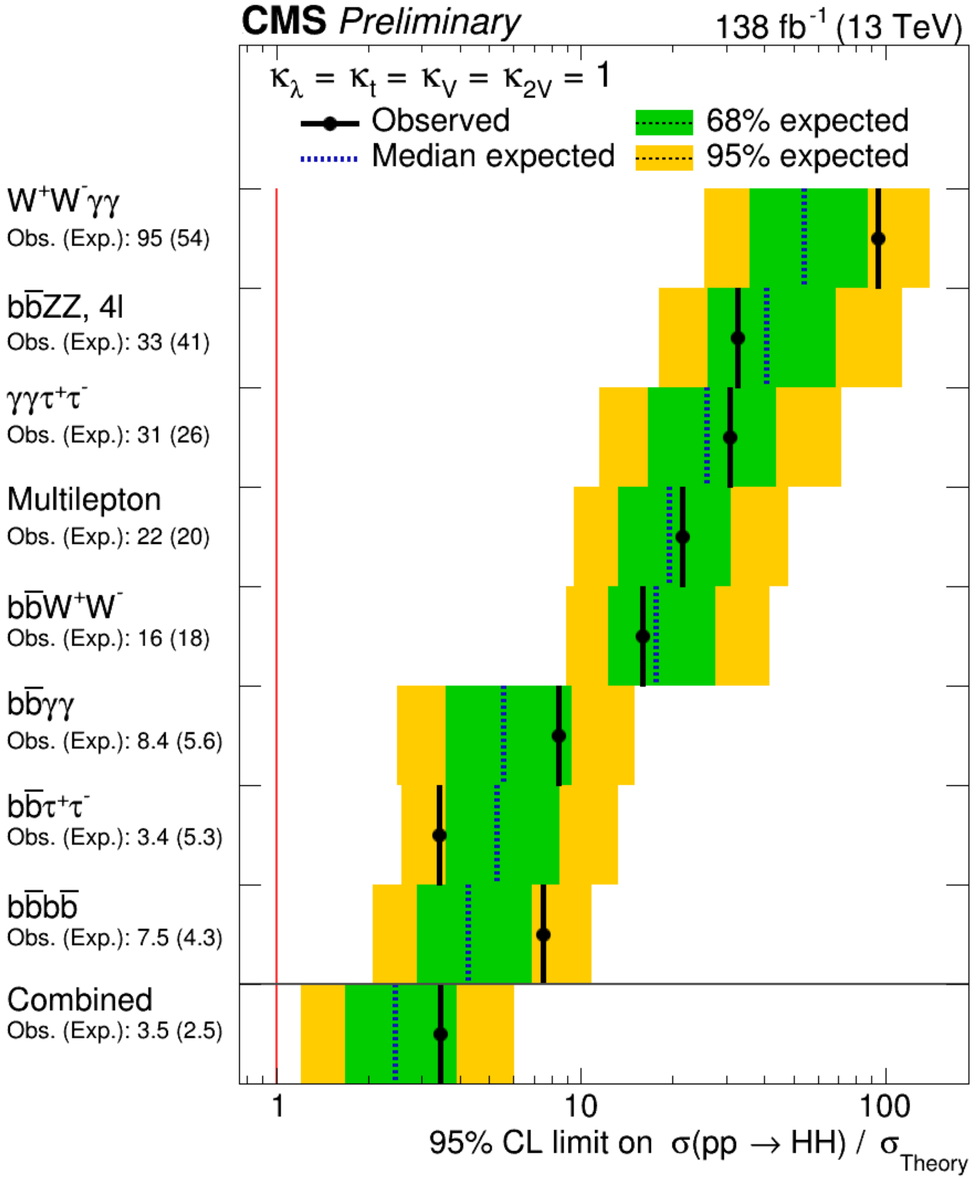
- The most complete CMS combination to date!
- Latest theory developments!
  - The constraints are dominated by the ggF production





Upper limit 3.5 (2.5) times SM
κλ between [-1.4, 6.4] at 95% CL

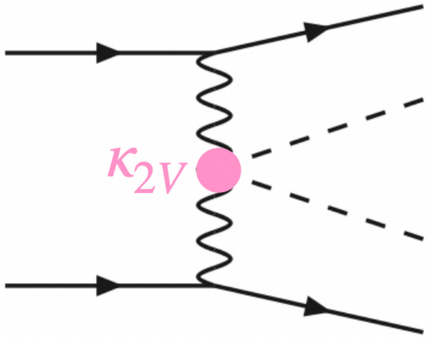
All results are compatible with the SM hyphothesis

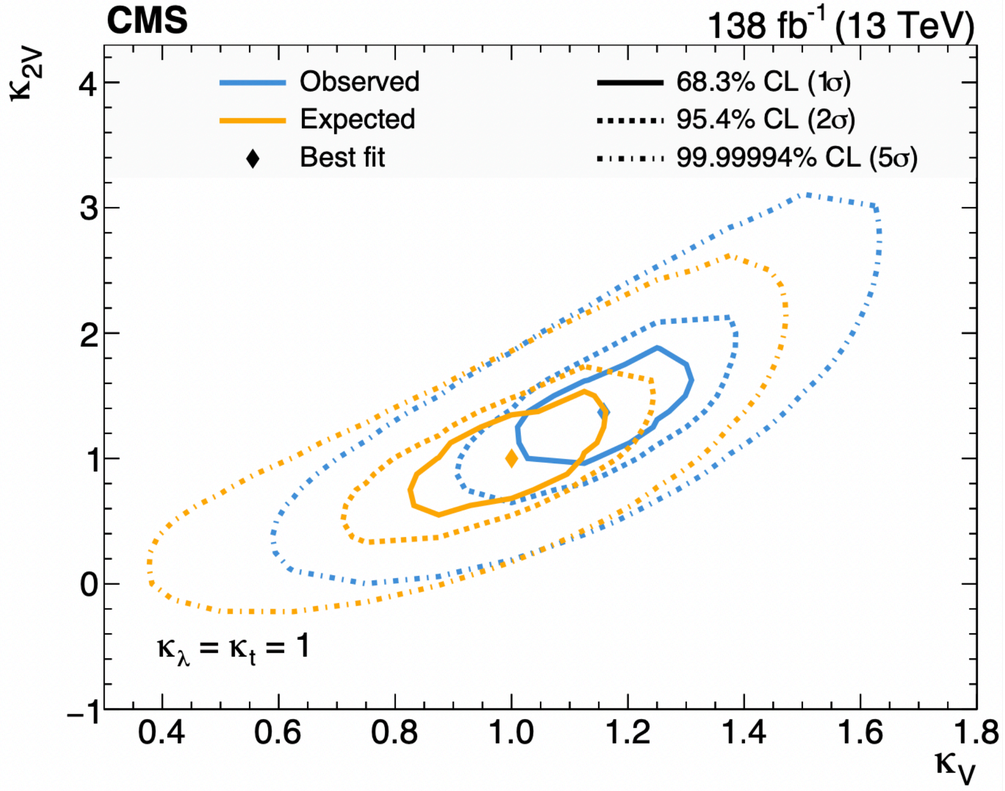


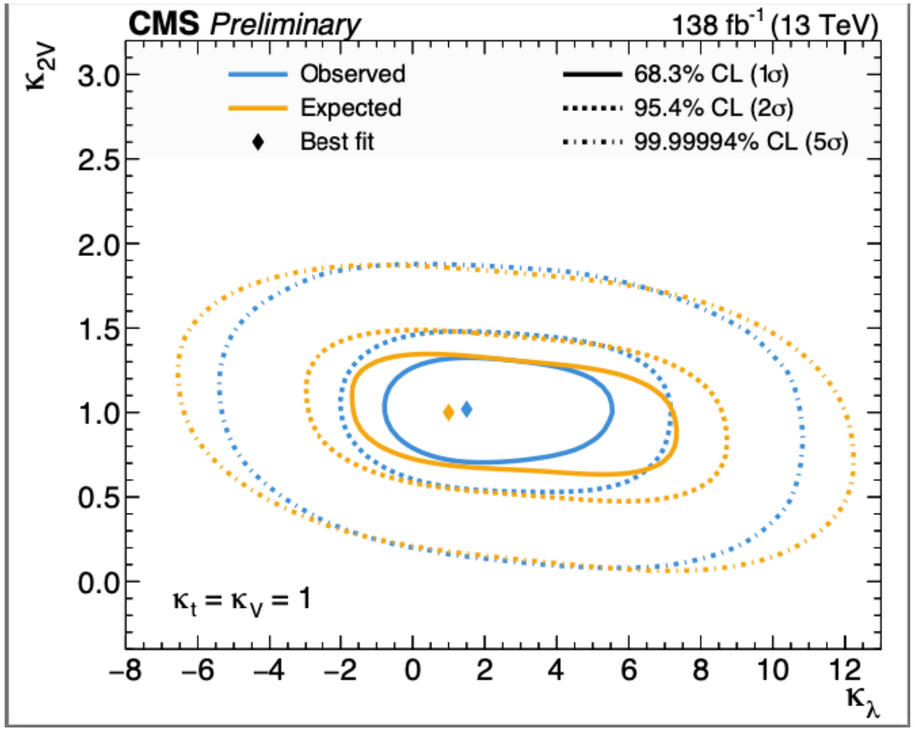
Results in SM-like scenario, coupling to vector bosons

PAS-HIG-20-011

- When considering the k2V coupling the constraints are dominated by the VBF channel







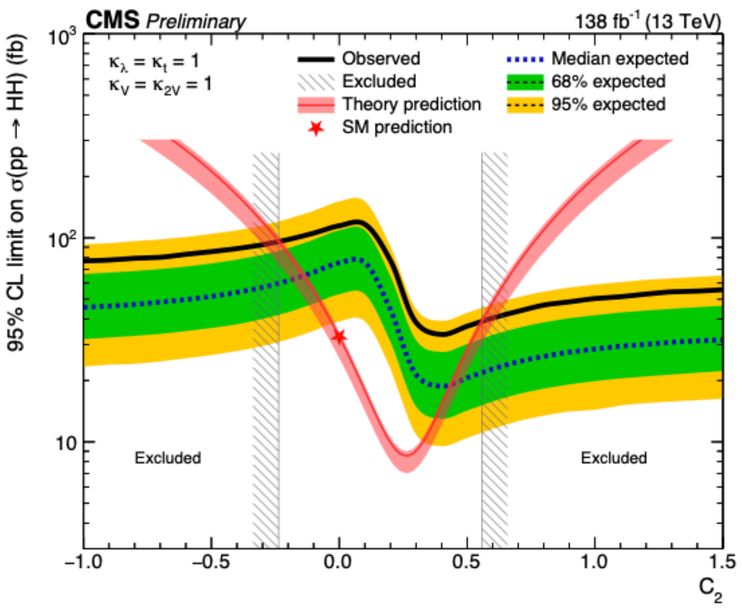
We prove the existence of the k2V coupling !!!

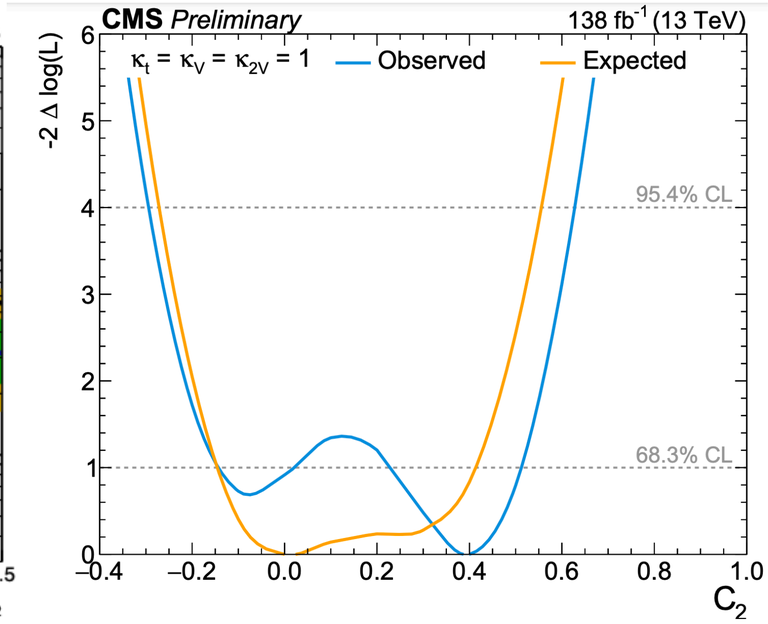
k2V = 0 is excluded at more than 5 sigmas to any value of kl or kV

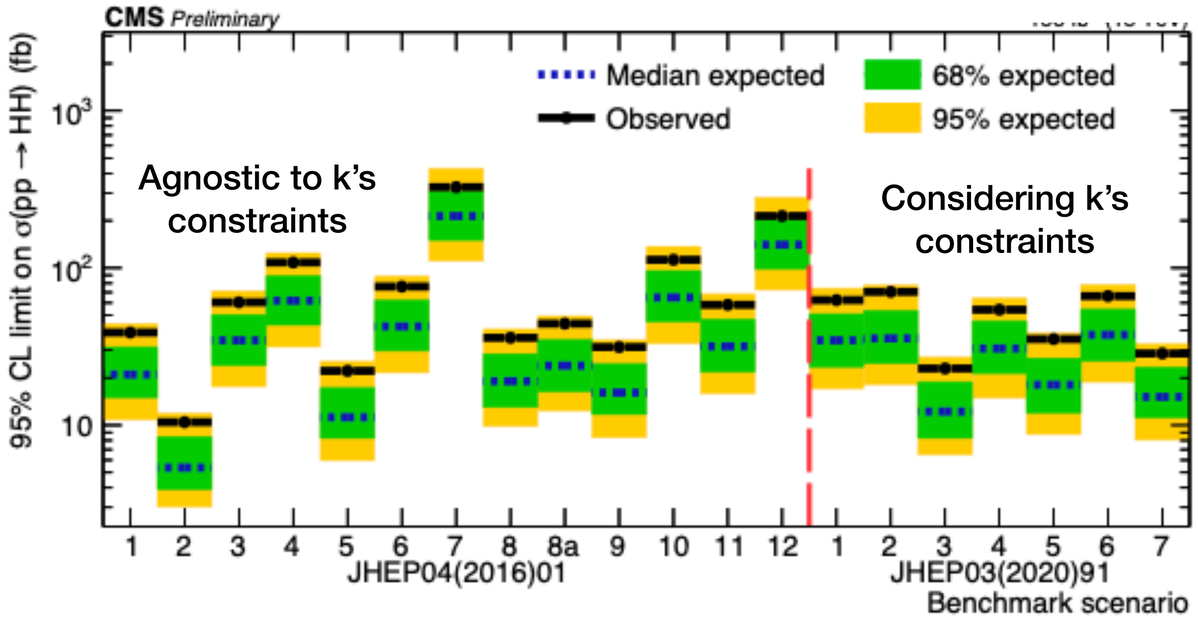
Results in BSM-like scenario

PAS-HIG-20-011

- Constraint in c2 between [-.0.23 0.63] @ 95% CL
  - Slight preference to c2 ~ 0.4,
    - Statistically compatible with the SM (c2 = 0)







- Shape benchmarks: Despite limits variating more than one order of magnude due signal topology variations, no excess is found

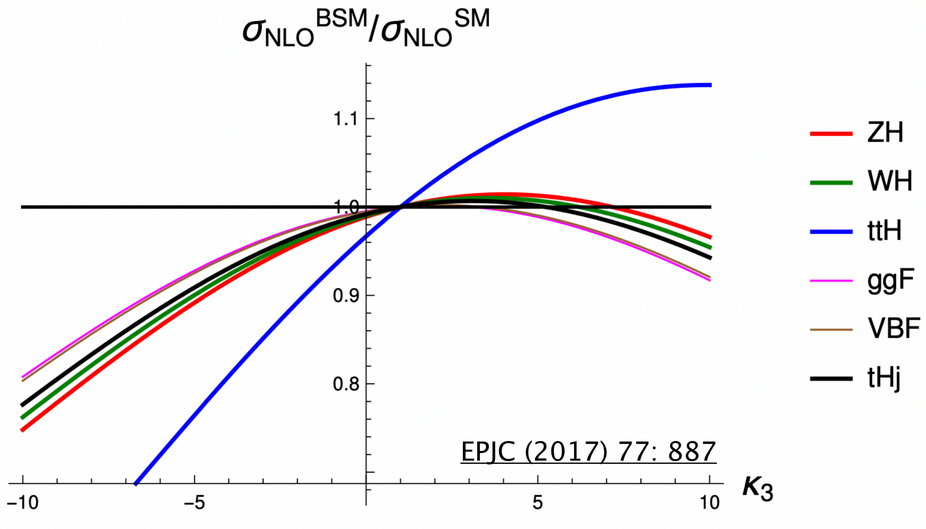
Stay tunned for more results with scans involving ttHH coupling in HEFT !!!

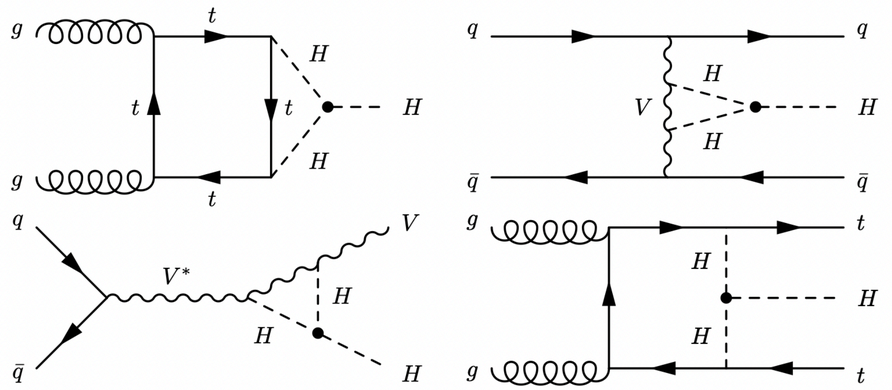
Adding indirect constrants

arXiv:2407.13554, *accepted by PLB*

Measurements of κλ and κ2V are entangled with κt and κV —> better measured in single H production

- That is not the whole history
  - At one loop the single H production (with much higher cross section) and decay is sensitive to variations in kλ **





- Changes signal topology and production rates
  - Signal topology modifications can be modelled when the search is made considering an specific glanularity on fit (Simplified Template Cross Sections - STXS)

Ultimate precision on the H potential in the SM scenario in a given dataset can only be achieved considering a global fit including all H and HH production modes

** These effects are considered in the HH combination regarding single H contamination on HH analyses

H + HH combination

arXiv:2407.13554, *accepted by PLB*

- This result was made prior to the HH legacy combination
  - The main channels for H pair production are considered
  - Several production and decay modes for single H production are considered
    - A few including glanularity sufficient to consider a differential dependency in kl

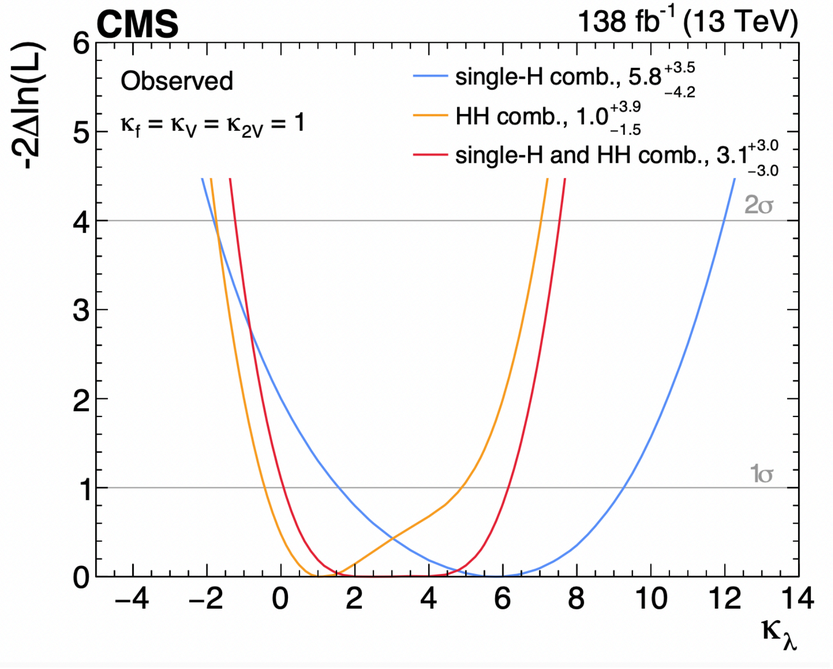
Analysis	Integrated luminosity (fb^{-1})	Targeted H production modes	Maximum granularity
$H \to 4l$	138	ggF, VBF, VH, $t\bar{t}H$	STXS 1.2
$H \to \gamma\gamma$	138	ggF, VBF, VH, $t\bar{t}H$, tH	STXS 1.2
$H \to WW$	138	ggF, VBF, VH	STXS 1.2
$H \to$ leptons ($t\bar{t}H$)	138	$t\bar{t}H$	Inclusive
$H \to b\bar{b}$ (ggF)	138	ggF	Inclusive
$H \to b\bar{b}$ (VH)	77	VH	Inclusive
$H \to b\bar{b}$ ($t\bar{t}H$)	36	$t\bar{t}H$	Inclusive
$H \to \tau\tau$	138	ggF, VBF, VH	STXS 1.2
$H \to \mu\mu$	138	ggF, VBF	Inclusive

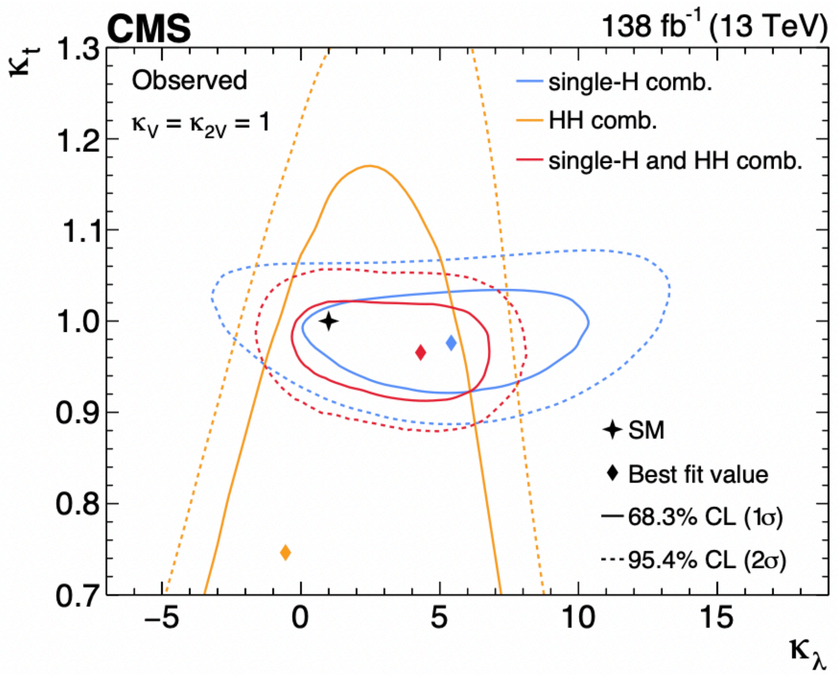
H + HH combination

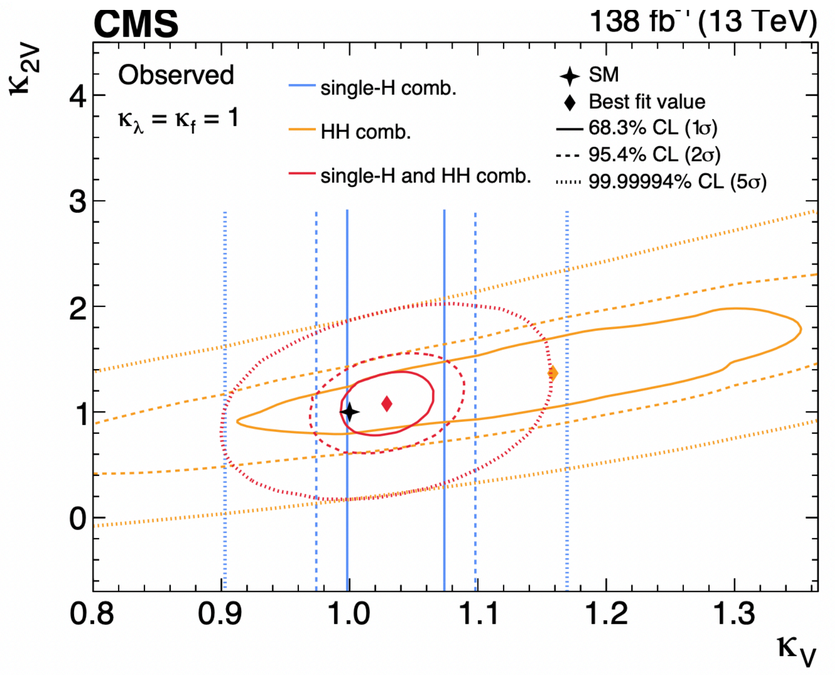
arXiv:2407.13554, *accepted by PLB*

- In a combined measurement we are able to
  - Achieve a better precision on kl
    - Also under minimal assumptions on the other H couplings

Hypothesis	Best fit $\pm1\sigma$ Expected	Best fit $\pm1\sigma$ Observed
Other couplings fixed to SM	$1.0^{+4.6}_{-1.7}$	$3.1^{+3.0}_{-3.0}$
Floating (κ_V, κ_{2V}, κ_f)	$1.0^{+4.7}_{-1.8}$	$4.5^{+1.8}_{-4.7}$
Floating (κ_V, κ_t, κ_b, κ_τ)	$1.0^{+4.8}_{-1.8}$	$4.7^{+1.7}_{-4.1}$
Floating (κ_V, κ_{2V}, κ_t, κ_b, κ_τ, κ_μ)	$1.0^{+4.8}_{-1.8}$	$4.7^{+1.7}_{-4.2}$

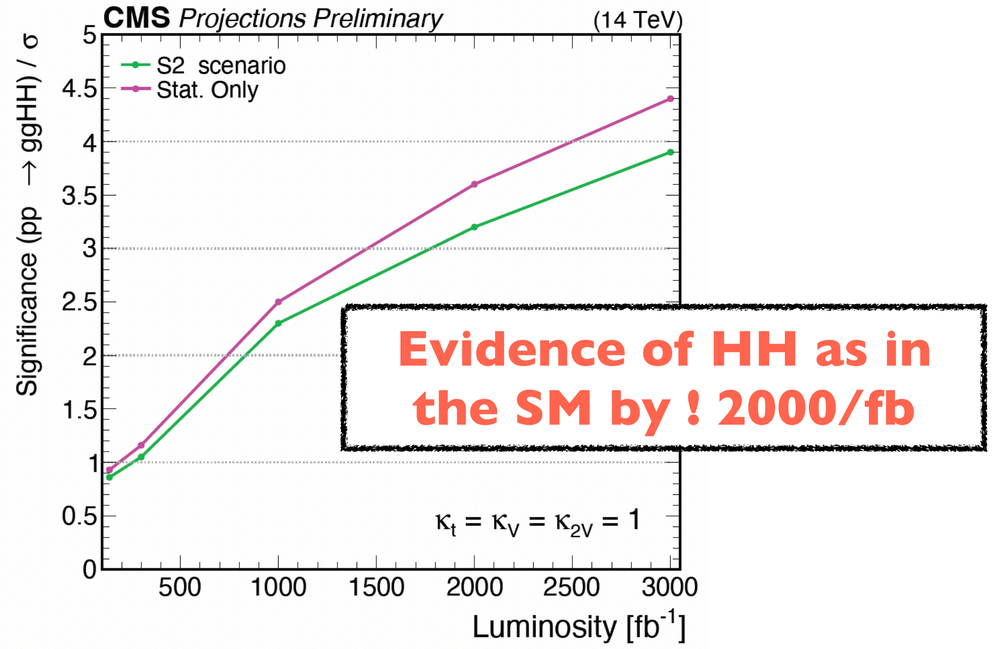




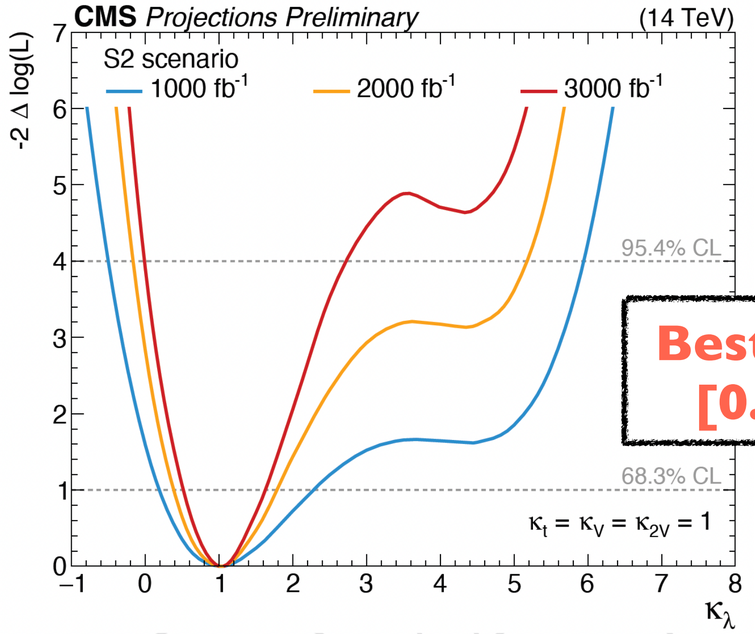


Conclusions

- The measurement of the H potential is one of the key physics topics in High Energy Physics
- That is achieved directly by the searches for H pairs at LHC
- CMS performed several searches for H pairs
  - Brand new results form the legacy combination from using full Run 2 data!



Evidence of HH as in the SM by ! 2000/fb



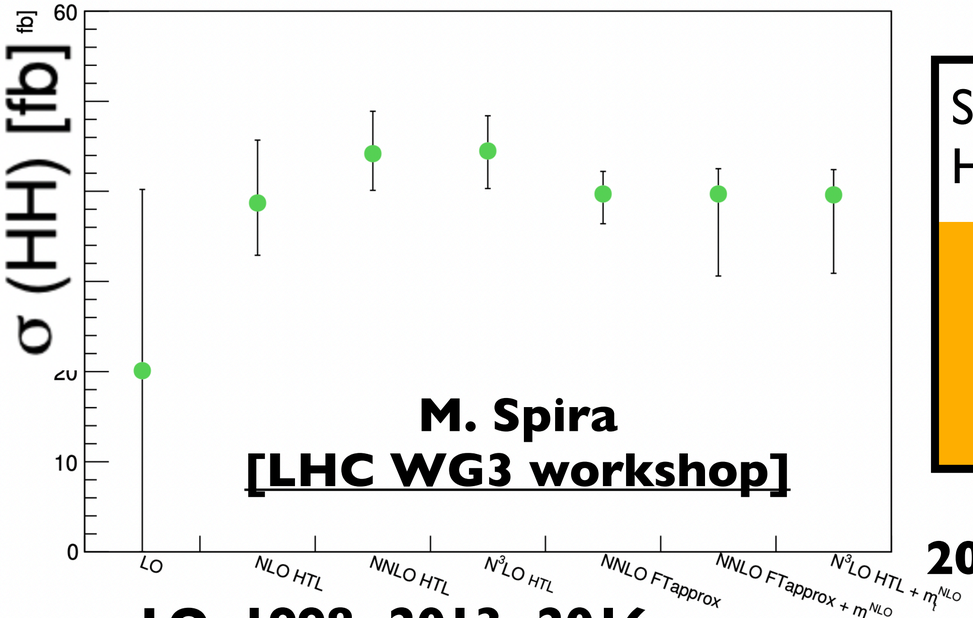
Best fit on κλ between [0.5, 0.6] @ 1 sigma

The theory saga on ggF signal modelling

- GGF H pair production is an one loop process,, making its simulation challenging
  - First modelled using form factors to emulate the loop [year]
  - Full model at NLO precisions to SM-like processes [year]
    - Including BSM-like processes in HEFT [year]

ADD years/ links refs

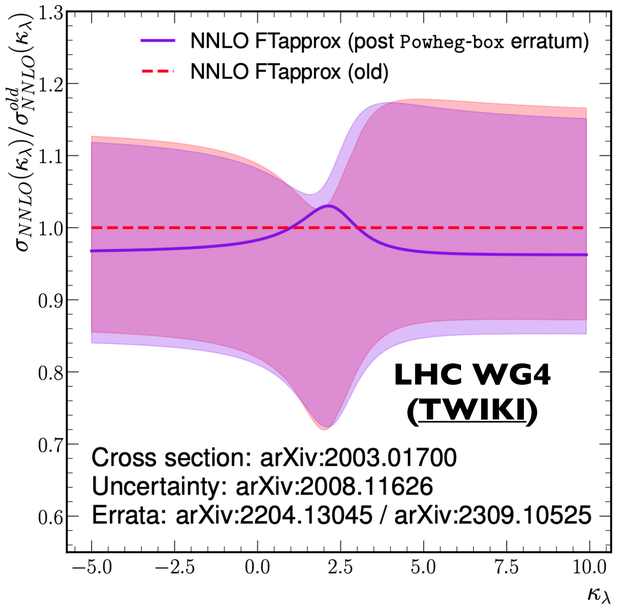
- Total cross-section computation had evolved considerably in the last years



State of art: N3LO w/ Heavy top mass approx.

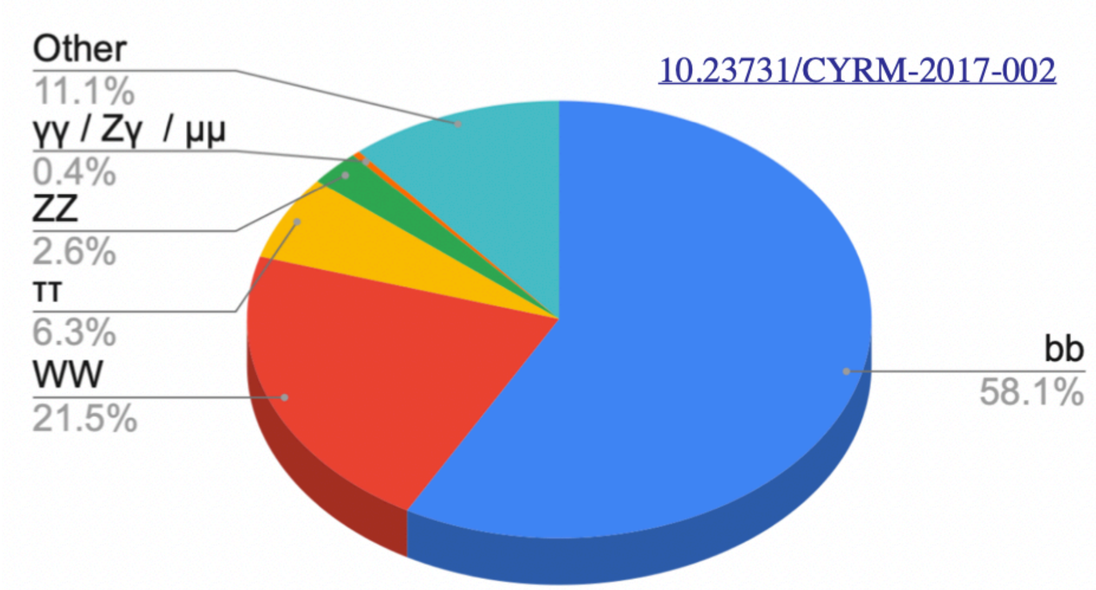
Still needs evolving: Uncertainties in top mass dominate the uncertainty

We use N3LO with top mass effects, That got sligtly updated since last comb.



How to look for Higgs bosons?

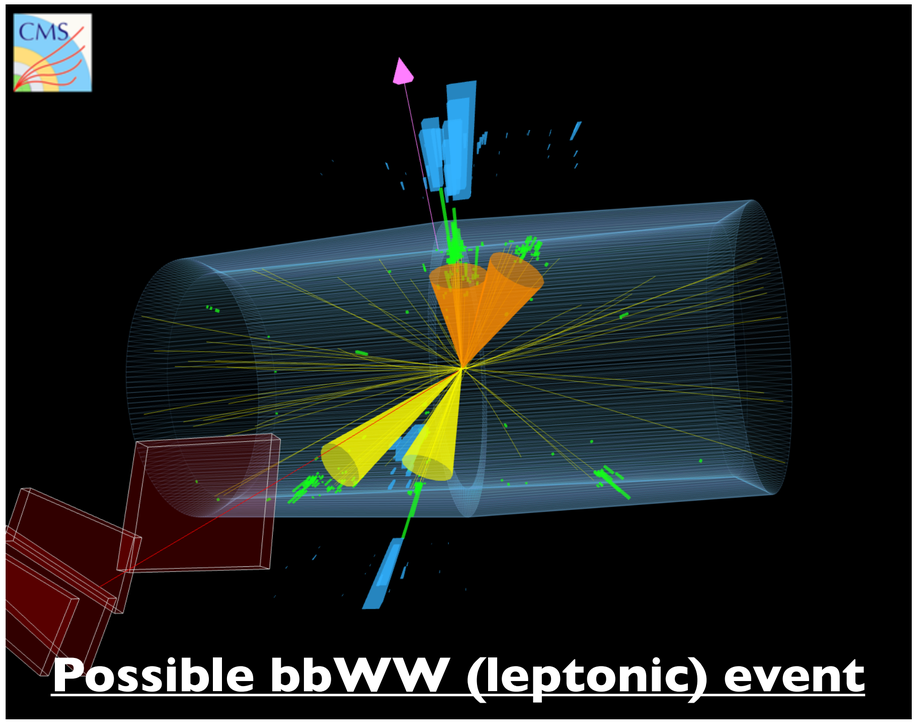
- Higgs boson decays:



- Decays to photons and b-jets are fully reconstructable
- Most of the final states that involve a lepton also involve a non-identifyable neutrino and loss of information
  - To recover, Multivariative (MVA) is imperative

Balance between resolution, reconstructebility and branching ratio define each channel importance

- At CMS we can identify as objects:
  - Photons, electrons and muons are clean (low BKG) signatures
  - Jets and hadronic tau leptons hold big portion of branching ratio (BR)



Possible bbWW (leptonic) event

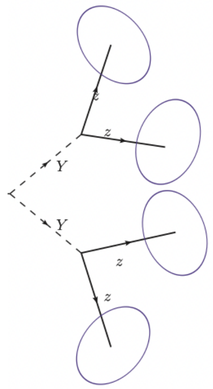
4b final state

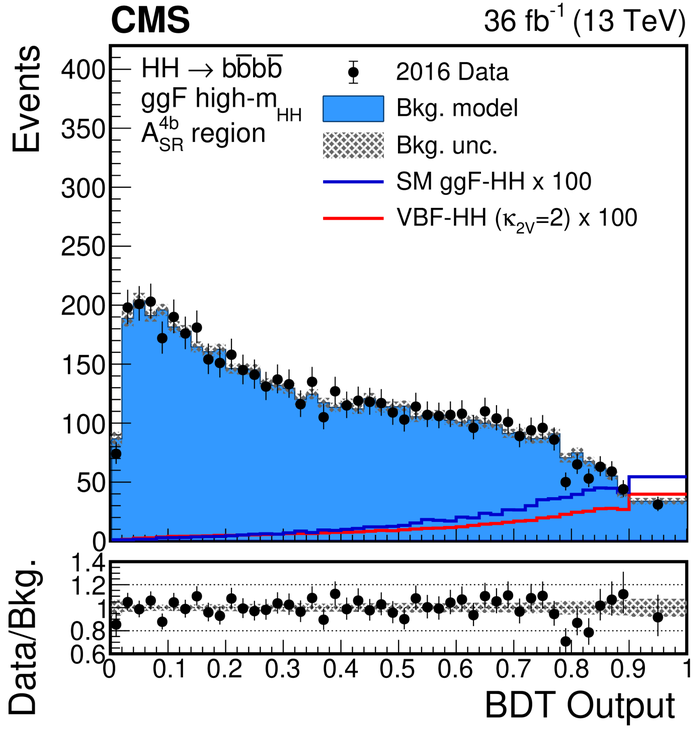
Largest Br = 34% X Large QCD bkg

Four resolved jets

PRL 129.081802

- b-jet identification with deep NN [ref.]
- Fully data-driven background estimation
-
- Simultaneous fit of:
  - MVA for ggF
  - mHH for VBF





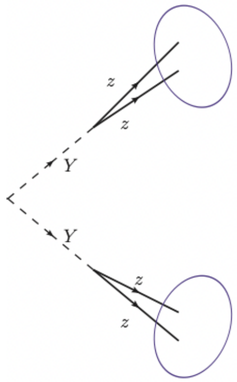
Fully boosted

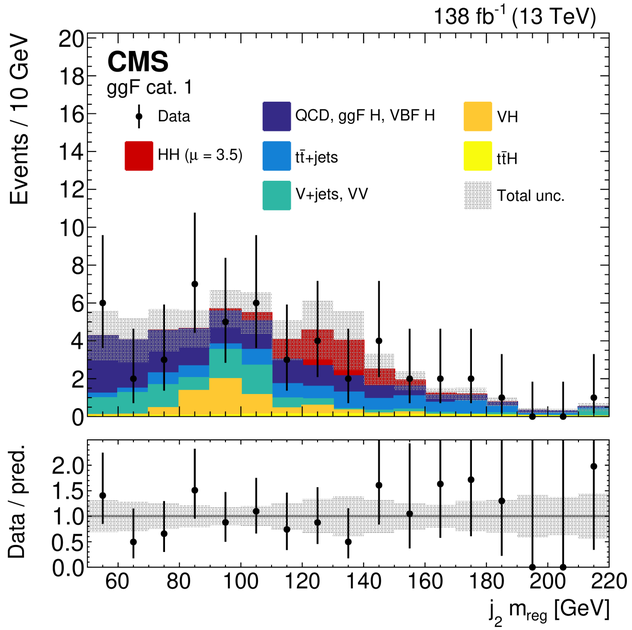
PRL 131.041803

- Select events with energetic two large-cone jets
- ID with GraphNN-based jet flavour [ref.]

==> Considerably BKG reduction

- Simultaneous fit of :
  - Sub-lead. H for ggF
  - mHH for VBF





Specially good constraining anomalous qqHH and ttHH couplings !

When combining both results overlap is removed with priority to keep events in the boosted region

bbγγ and bbττ

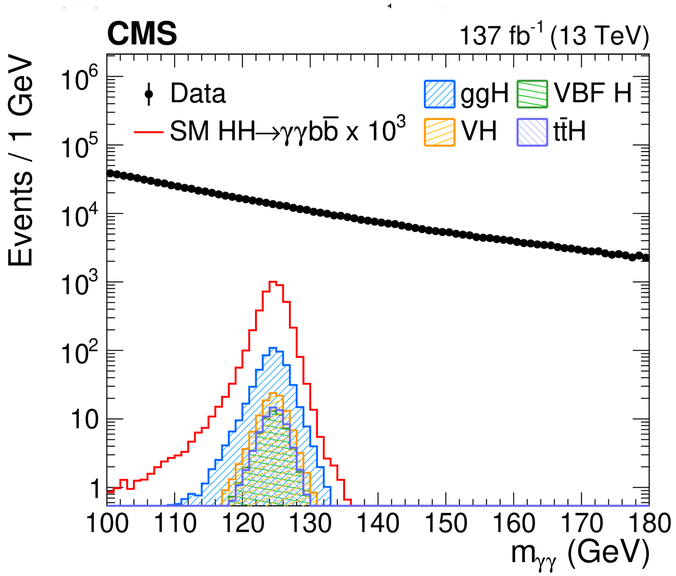
smaller BR X Better BKG control

bb γγ

BR ~ 0.3%

JHEP 03 (2021) 257

- MVA separates main BKGs
- 2D fit on $m_{\gamma\gamma}$ and m_{bb} in bins of m_{HH}
  - Data-driven fit estimate strictly falling remaining BKG



- Attention to SH peaking BKGs in $m_{\gamma\gamma}$
  - Separate area to constraint it on the fit

Excellent Hγγ resolution + fully reconstructable = possibility of separate mHH areas

bbττ

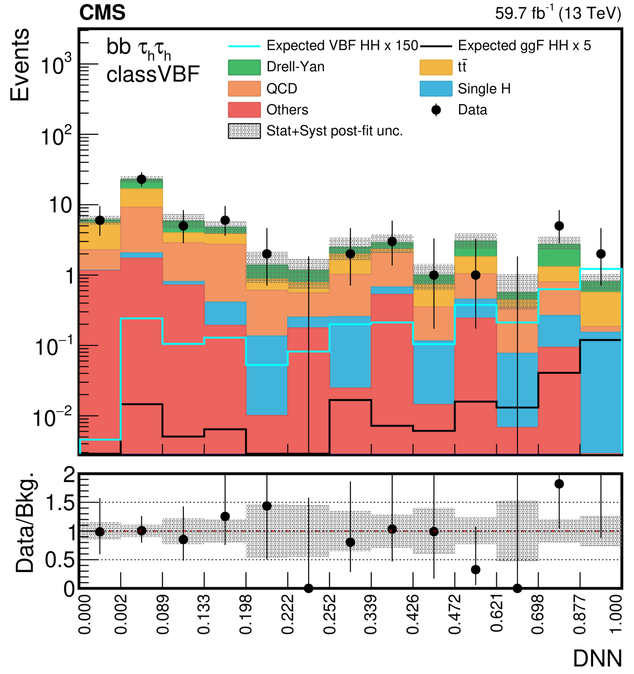
BR ~ 7.3%

PRB 842.137531

- b-jet identification with deep NN [ref.]
- τ ID with deep NN developed to this ana. [ref.]

==> Considerably BKG reduction

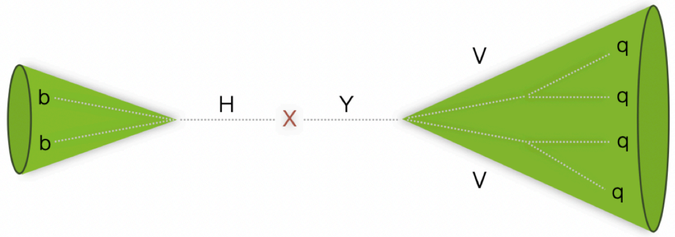
- Multiclassification MVA separates main BKGs,
- fit on this MVA to extract signal



Considers events with merged-jet Hbb
3rd best channel to constrain anomalous qqHH and second best constraining the ttHH coupling !

Newcomers: bb VV hadronic

CMS-PAS-HIG-23-012



Fully-merged

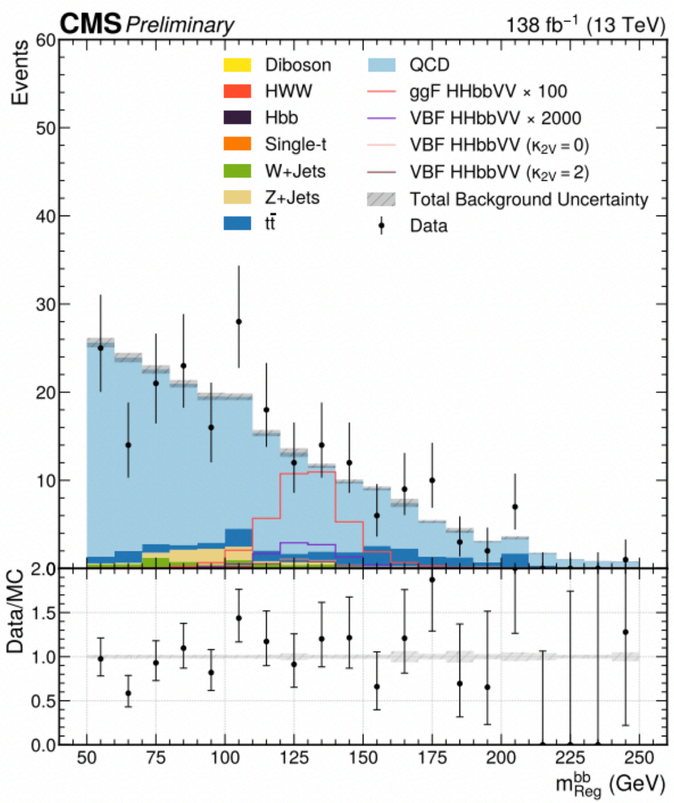
Large Br = 28% X Large QCD bkg

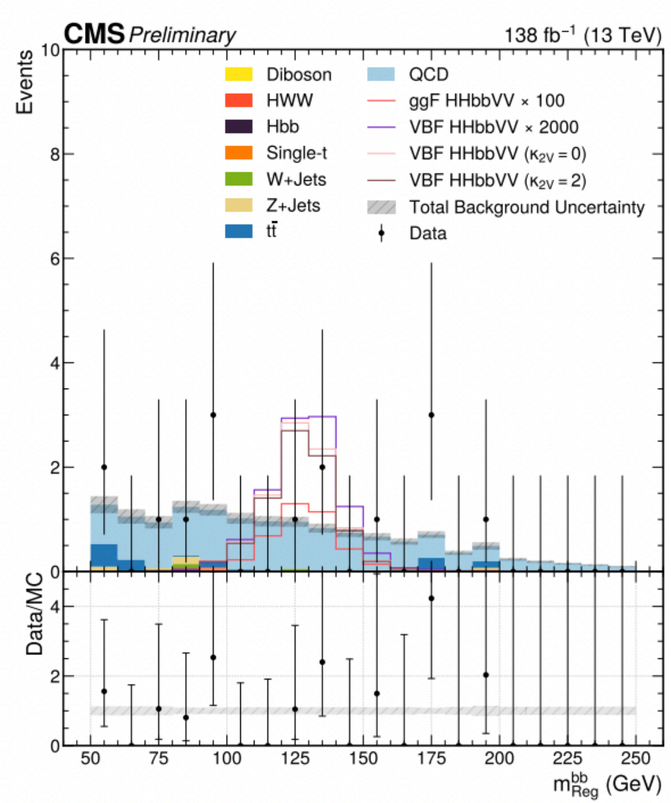
- b-jet identification with deep NN [ref.]
- V → 4 jets ID with deep NN developed to this ana. [ref.]

==> Considerably BKG reduction

- Data-driven QCD estimation
- MVA separates ggF and VBF production from BKGs
  - V → 4 jets tagger used on selection
  - Fit on reconstructed m_{bb}

2rd best channel to constrain anomalous qqHH !

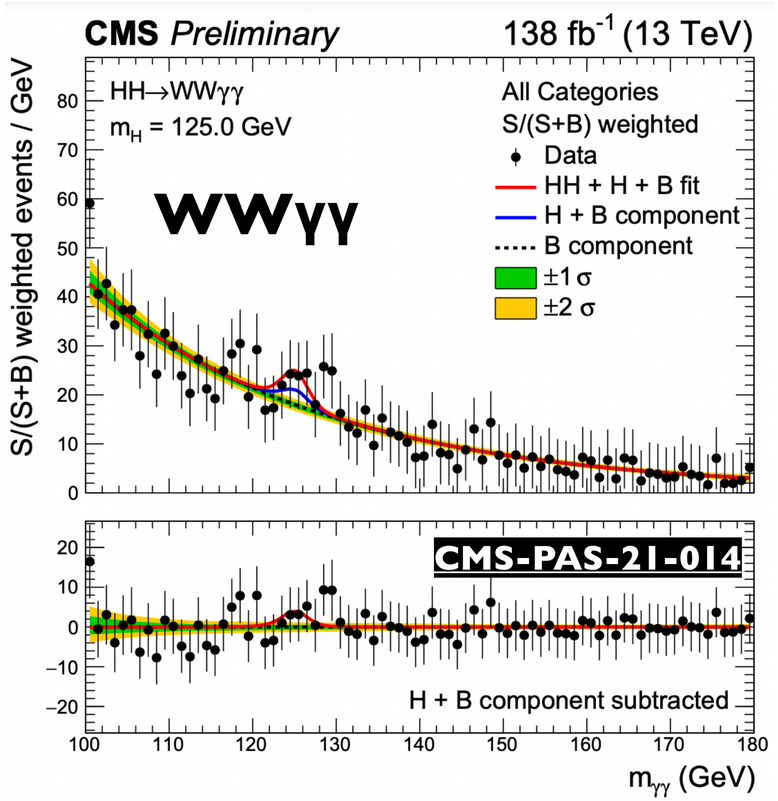


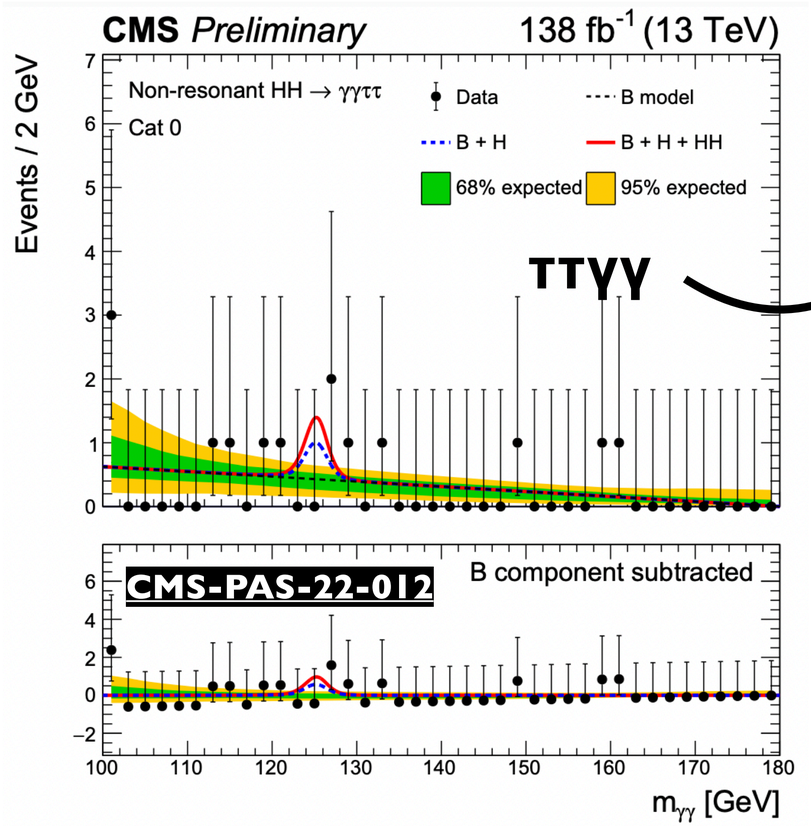


Newcomers: WWγγ and ttγγ

- MVA separates main BKGs
- Fit on $m_{\gamma\gamma}$ and m_{bb} in bins of m_{HH}
  - Data-driven estimate of strictly falling remaining BKG

Explore excellent Hγγ resolution, closing all HH decays possibilities





Despite the tiny BR (0.03%) still produces an upper limit of ~ 30 times the SM

On channels complementarity

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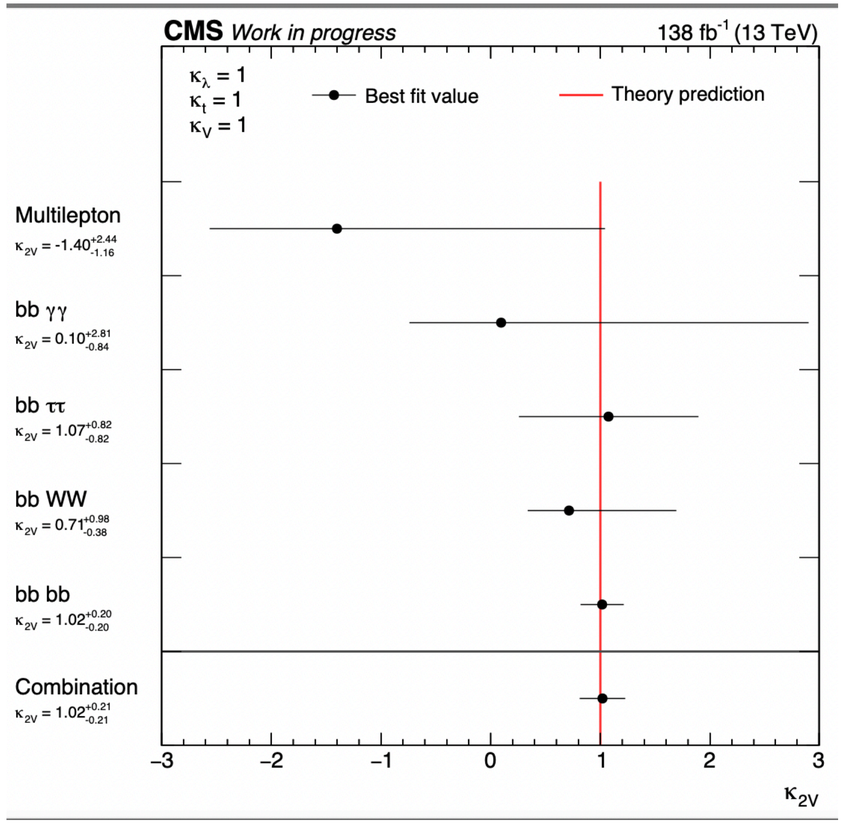
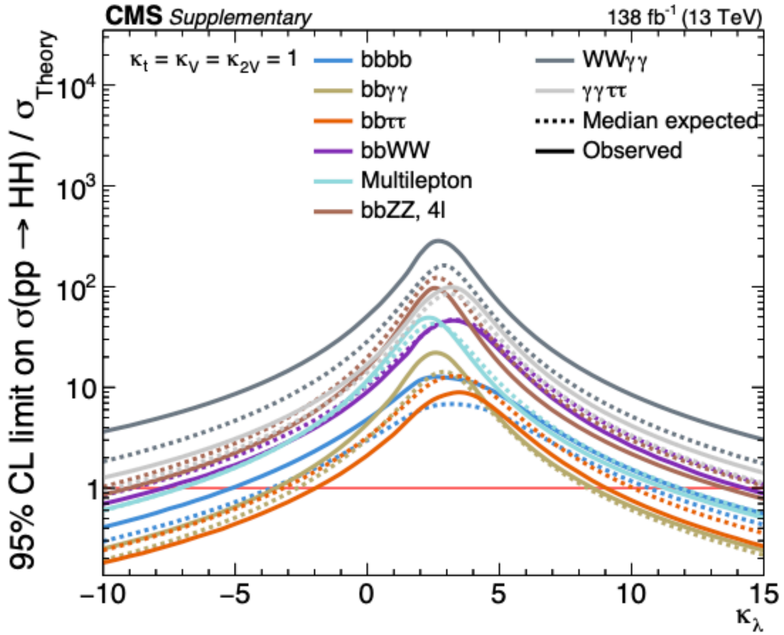
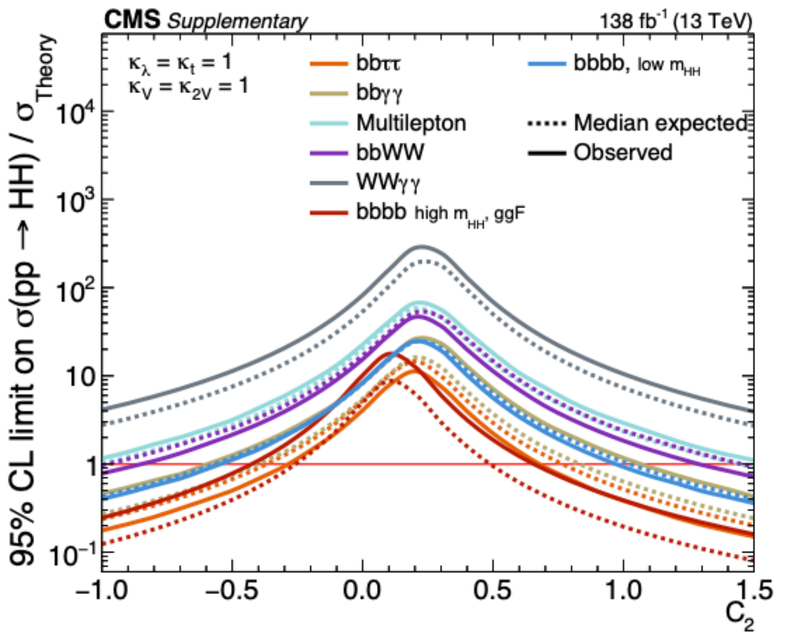
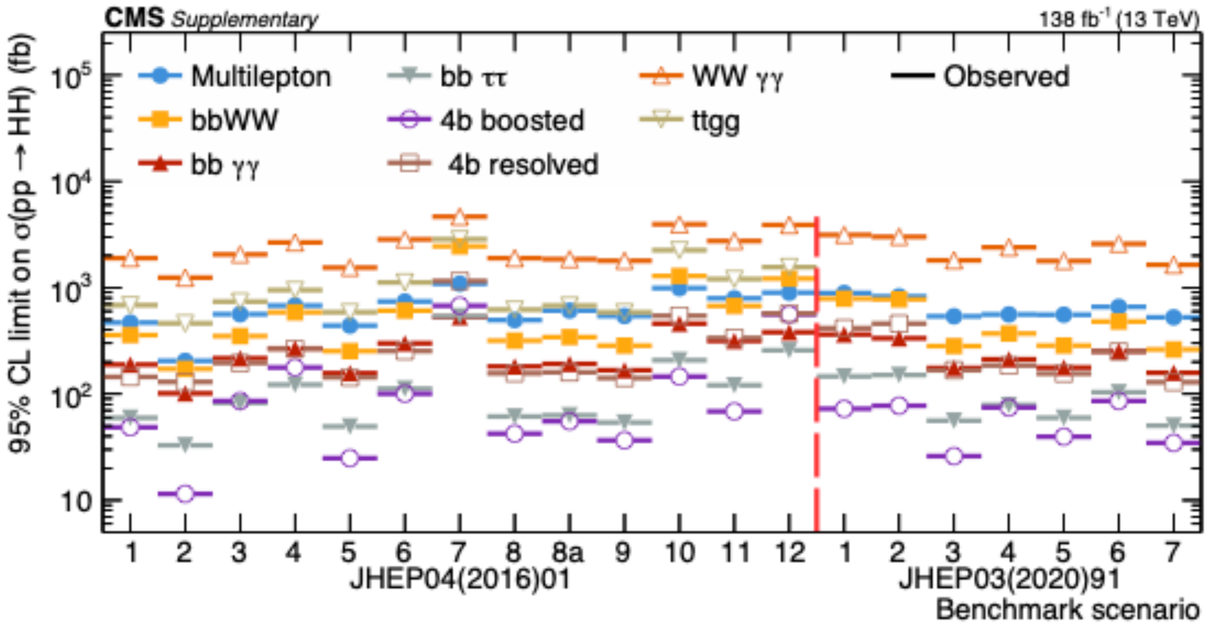
Need improvement if we want to add as add. Material









On channels complementarity

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In the constraints of κλ and c2 we clearlly see that the combined measurement gains from channels complementarity