Latest result on di-Higgs searches at the LHC

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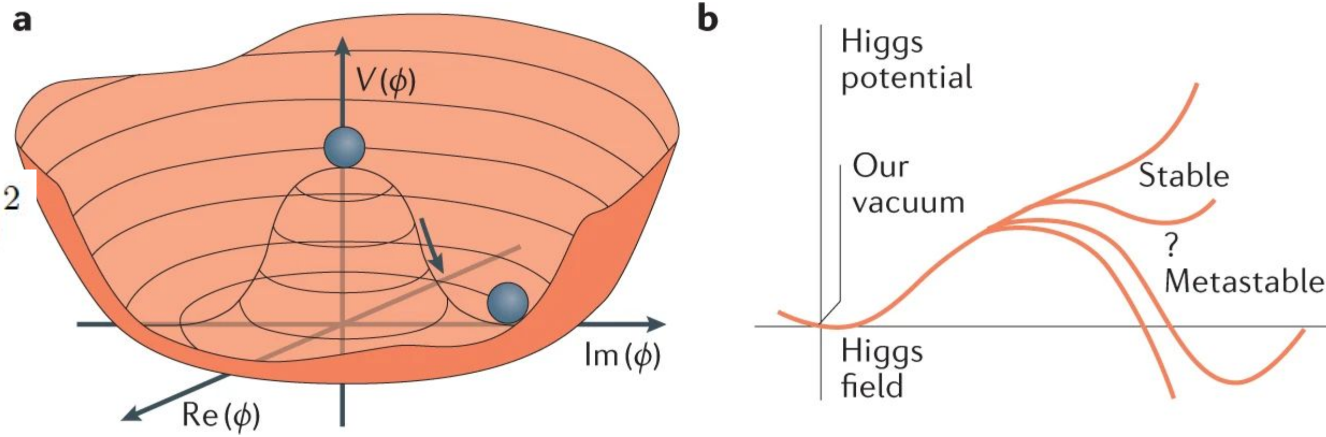
The Higgs mechanism

The **Electroweak symmetry breaking** mechanism has deep implications on particle physics and cosmology.
Measuring the Higgs self-coupling would provide a **strong test** of the Higgs mechanism of the Standard Model.

<u>The Higgs potential</u>

$$V\left(\phi^{\dagger}\phi\right) = \mu^2\phi^{\dagger}\phi + \lambda\left(\phi^{\dagger}\phi\right)^2$$



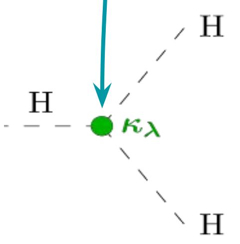
The **shape of the Higgs potential** has strong implications on the **stability of the universe.**

Measuring the Higgs self-coupling with di-Higgs

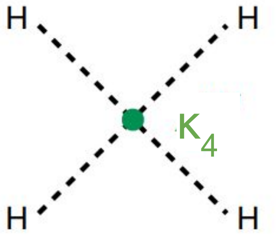
The Higgs self-coupling is one of the few parameters of the SM never directly measured.
Di-Higgs production allows for **measurement of the self-coupling λ** !
It can probe the shape of the **Higgs potential around the minimum**

$$V\left(\phi^\dagger\phi\right) = \mu^2\phi^\dagger\phi + \lambda\left(\phi^\dagger\phi\right)^2$$

Trilinear self-coupling



Quadrilinear self-coupling



<u>The EFT framework</u>

For more model-independent interpretations, the Lagrangian is parametrised with **coupling modifiers**:

$$\kappa_\lambda = \frac{\lambda}{\lambda_{\mathrm{SM}}}$$

Several **BSM theories** predict enhanced di-Higgs production, which would manifest as modifications in κ wrt. to their SM values

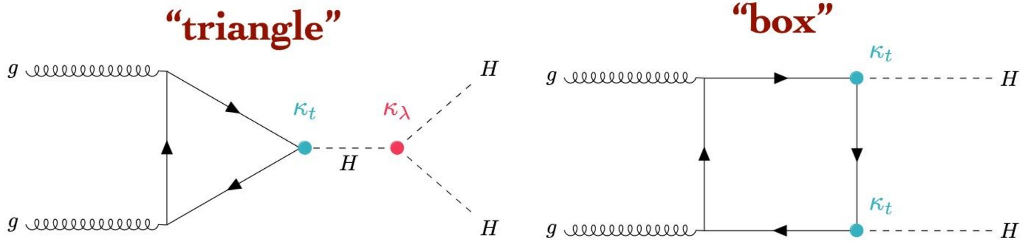
Di-Higgs production at the LHC : gluon-gluon fusion

$\sigma^{HH}_{ggF} = 31$ fb

$\sigma^{H}_{ggF} = 48$ pb

The main di-Higgs production at the LHC is **gluon-gluon fusion** (ggf).
It's cross-section is about **3 orders of magnitude lower** than that of **single-Higgs**.
About 4k HH events expected in the full Run2 LHC dataset

Two diagrams of ggf HH production

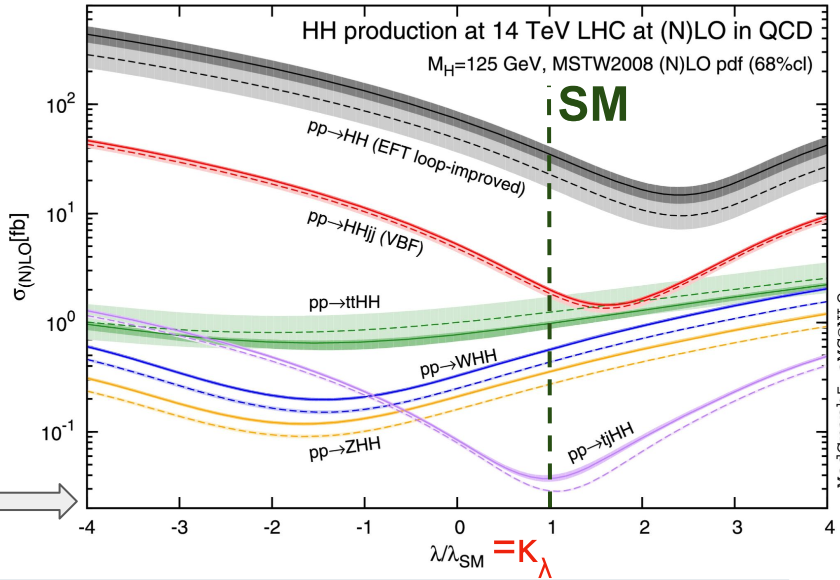


Strong **destructive interference** between the two diagrams, leading to very small HH cross-section.

Exploiting the different kinematics between the triangle and box diagrams is expected to improve the sensitivity to κ_λ.

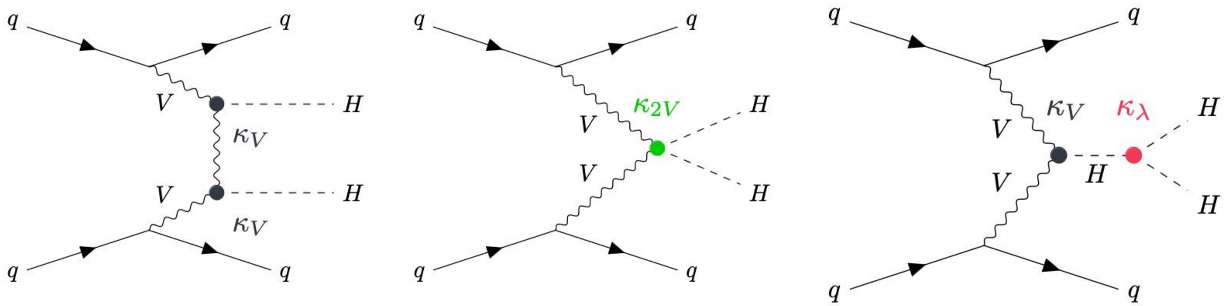
BSM effects can enhance the HH cross-section

HH cross-sections as function of κ_λ



Di-Higgs production by Vector Boson Fusion (VBF)

Similarly to single-Higgs, HH can be produced by **fusion of vector bosons** at proton colliders:



Can measure κ_{2V}, the coupling of HH with 2 vector bosons (W/Z)

Advantages:

- **tagging with two forward jets** in final state
- no colour connection between VBF jets, leading to reduced central hadronic activity wrt backgrounds

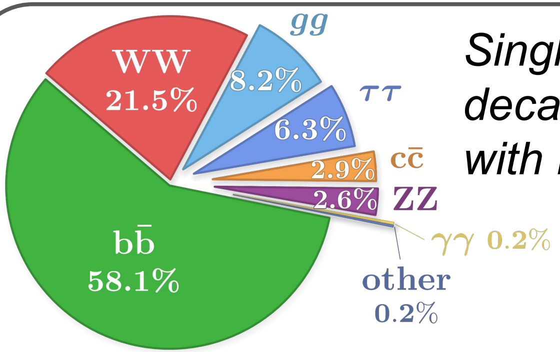
Inconvenients:

- lower cross-section than gluon-fusion $\sigma^{HH}_{VBF} = 1.7$ fb (by about 1 order of magnitude)

Also rarer production modes :

- association with top pair
- association with W/Z

HH search channels overview



Single-Higgs decays modes with BR

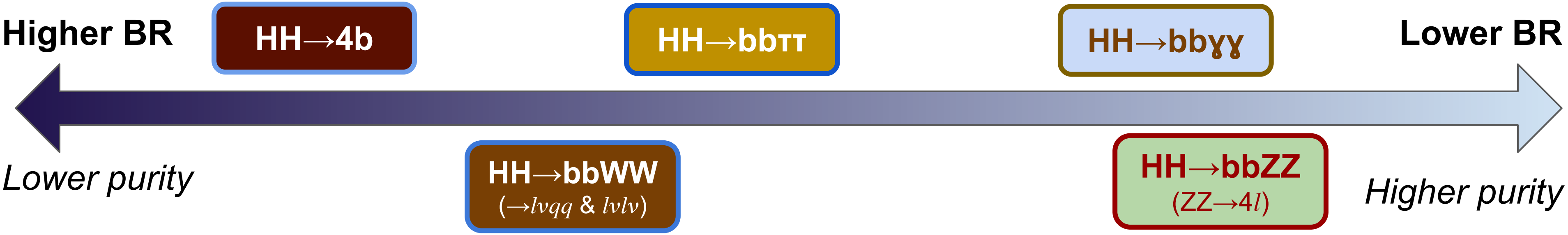
	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

Matrix of di-Higgs decays with BR

All circled decays are included in the CMS HH combination

Di-Higgs searches have to strike a **compromise between purity** of final state and **branching ratio**

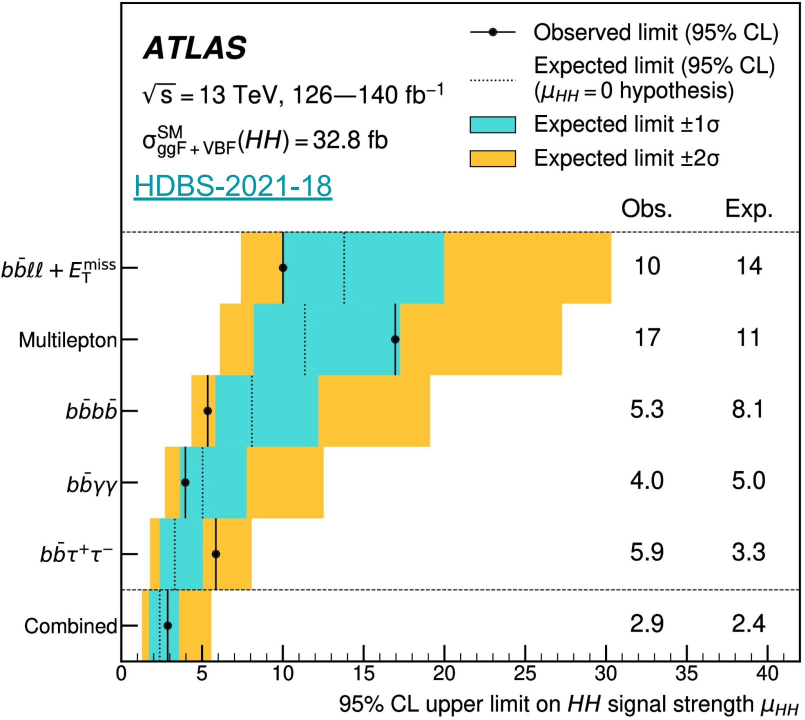
There is no single golden channel : **combination is key!**

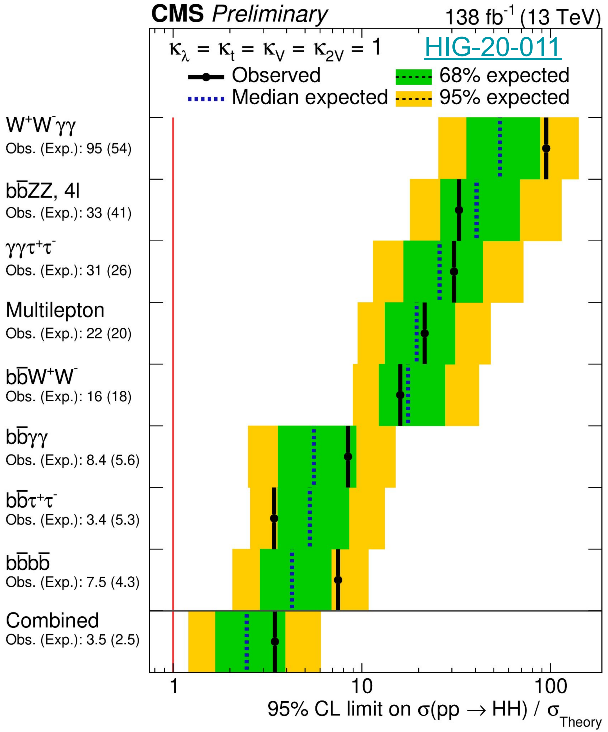


Latest HH combinations

No single channel drives the sensitivity : **combination of final states** is important !

Signal strength of HH measured by ATLAS and CMS





Observed limits

ATLAS

$$\sigma_{HH} < 2.4\,\sigma^{SM}_{HH}$$

CMS

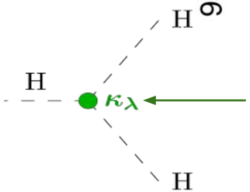
$$\sigma_{HH} < 3.5\,\sigma^{SM}_{HH}$$

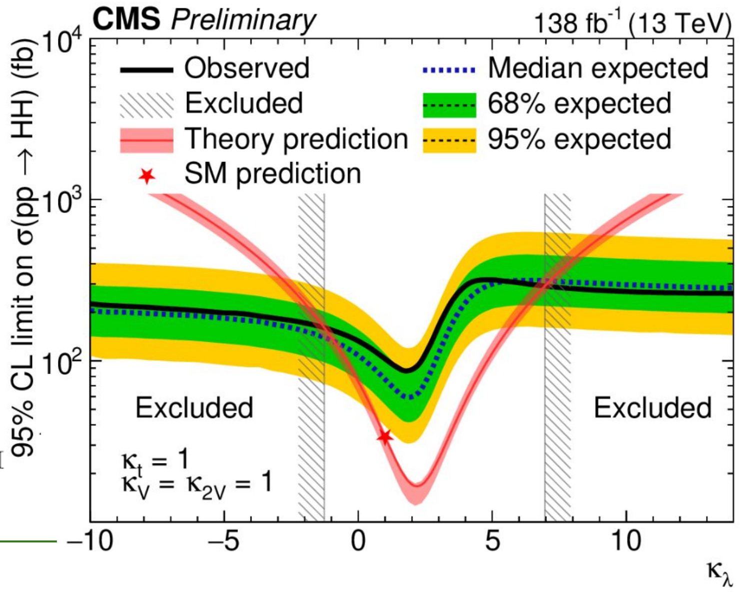
Full Run2 data is not enough for observation of HH

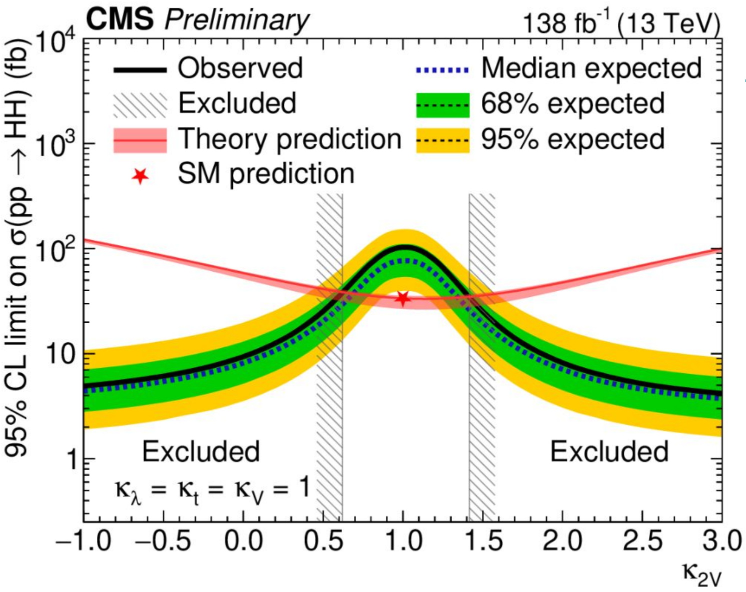
Most sensitive analyses: **HH→4b** **HH→bbττ** **HH→bbγγ**

Anomalous couplings results (combination)

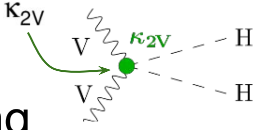
The interpretation using **anomalous couplings** allows for model-independent probes of BSM effects







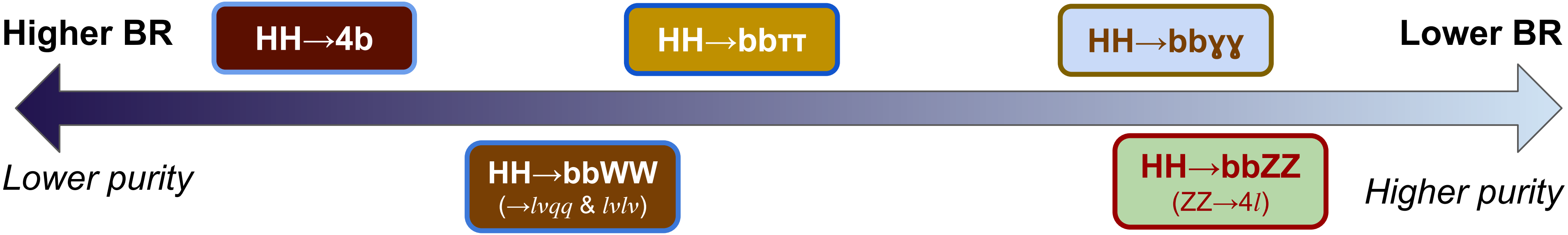
HIG-20-011



All other couplings are fixed at their SM value

The latest CMS combination **allows excluding κ_{2V}=0** at 95% C.L. (→showing existence of VVHH coupling), thanks to the **VBF channels**

Overview of main analysis channels

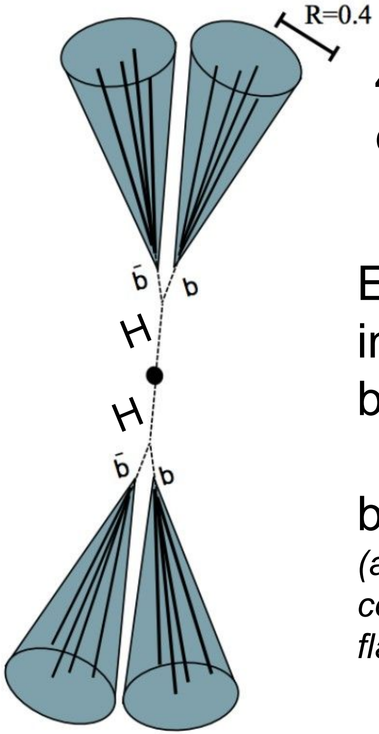


HH→4b

Largest branching fraction, but **very large background** from QCD and $t\bar{t}$

2 kinematic regimes : resolved & boosted

Resolved



4 **small-radius** (AK4) **containing one b jet**

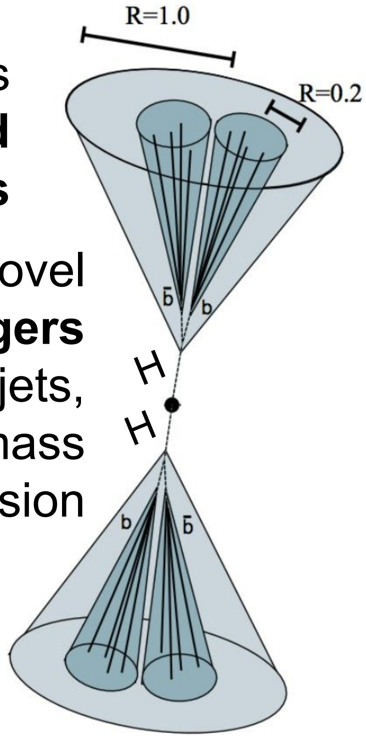
Each jet is independently b-tagged

b-jet mass regression
(account for different composition of heavy vs light flavour jets)

Boosted

2 **large-radius** jets **containing merged H→bb decays**

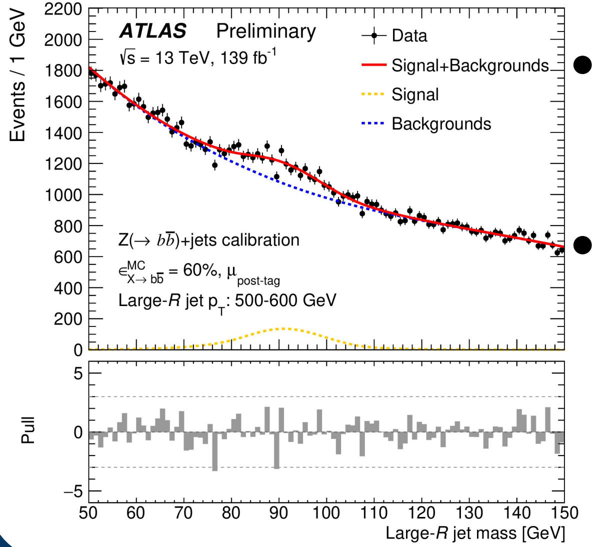
Novel **Machine Learning taggers** targetting H→bb jets, including jet mass regression



Novel analysis techniques for HH→4b

Calibrating H→bb jet taggers is crucial for HH searches, as it is often the **leading systematic** uncertainty on boosted searches.
Very large background makes calibration a difficult task

ATLAS calibration of H→bb tagger on Z→bb and Z(→bb)ɣ events



- $Z\to ll$ events are used to determine the pre-tag yield
- $Z\to b\bar{b}$ events are used at high p_t for post-tag yield, with $Z(\to b\bar{b})\gamma$ at lower p_t

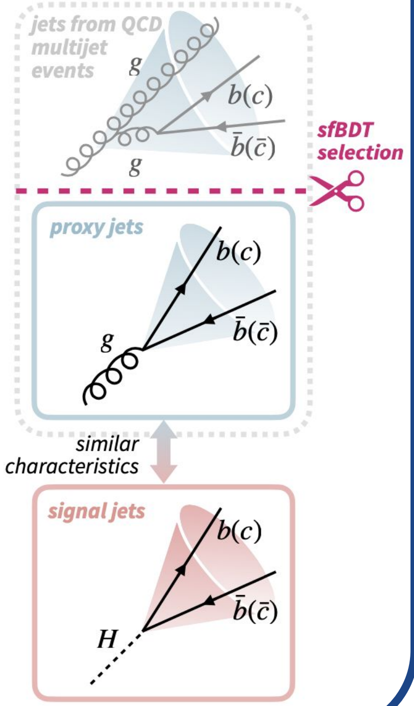
ATLAS PUB-21-035

CMS calibration of H→bb tagger on gluon→bb events

$g\to b\bar{b}$ jets are used as **proxy** for H→bb:

- Use a BDT to extract $g\to b\bar{b}$ from QCD multijet events
- Perform tag&probe to extract scale factors

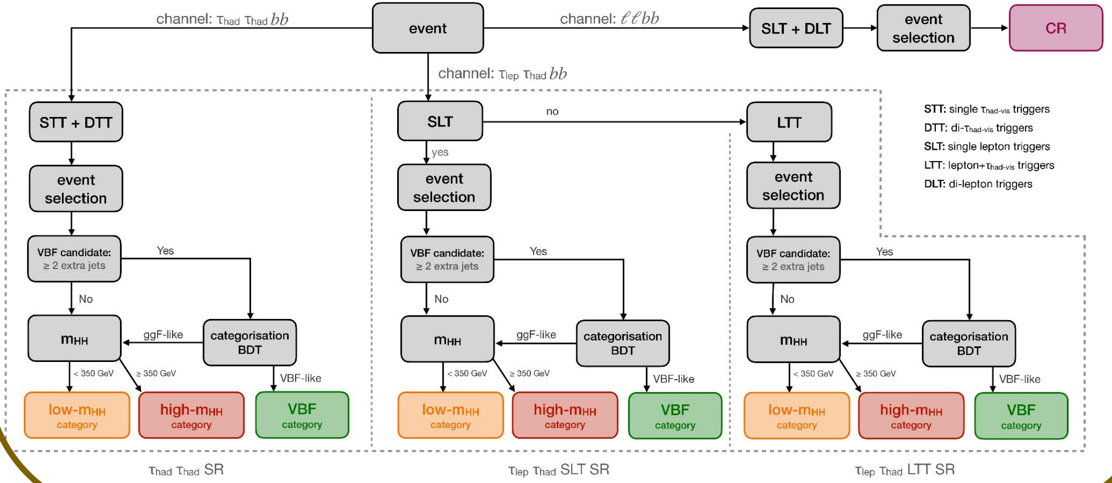
CMS DP-2022/005



HH→$bb\tau\tau$ Good **compromise between branching ratio and purity** of final state

Complex analysis targetting 3 ττ pair decay modes, in both ggf and VBF production modes

ATLAS analysis flow, showing the 8 different triggers used



<u>Multiple uses of machine learning techniques:</u>

- b-jet identification
- hadronically decaying tau lepton identification
- ggF vs VBF classification
- final discriminant

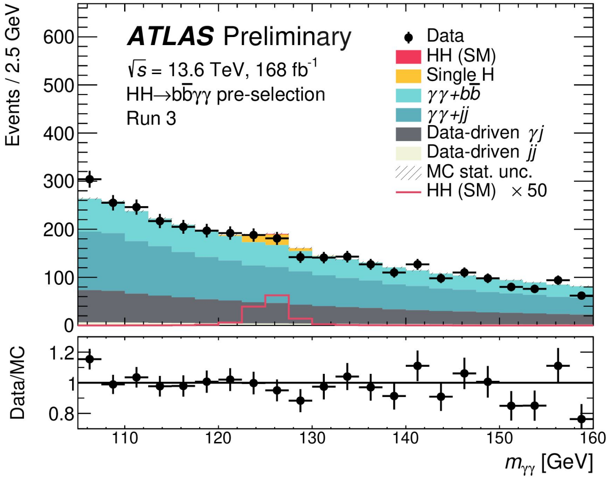
<u>Trigger strategy developments:</u>

- dedicated VBF triggers
- b-tagging at trigger level
- enhanced tau identification

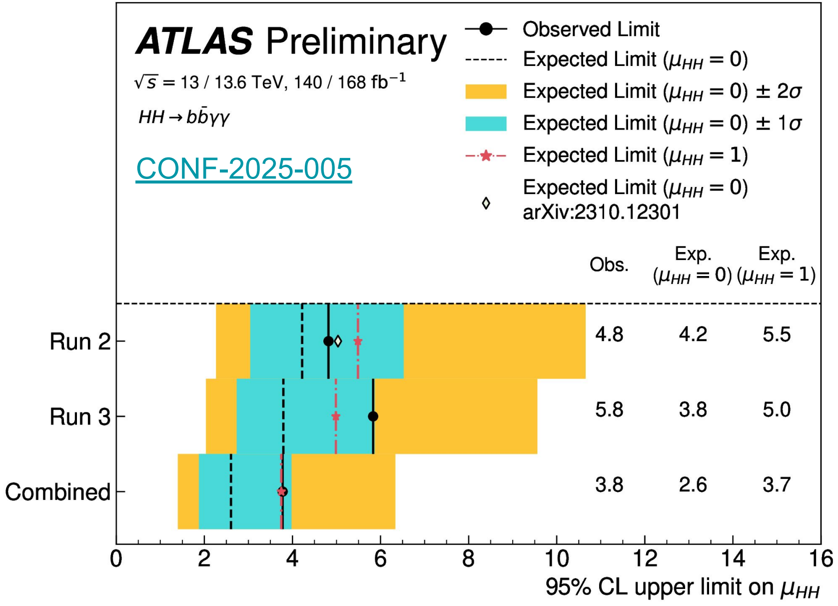
ATLAS : HDBS-19-27
CMS : HIG-20-010

HH→bbγγ

Very low branching ratio but mass resolution on H→γγ is very good



Latest ATLAS result ***combining Run2 and early Run3*** *(2022 to 2024)*



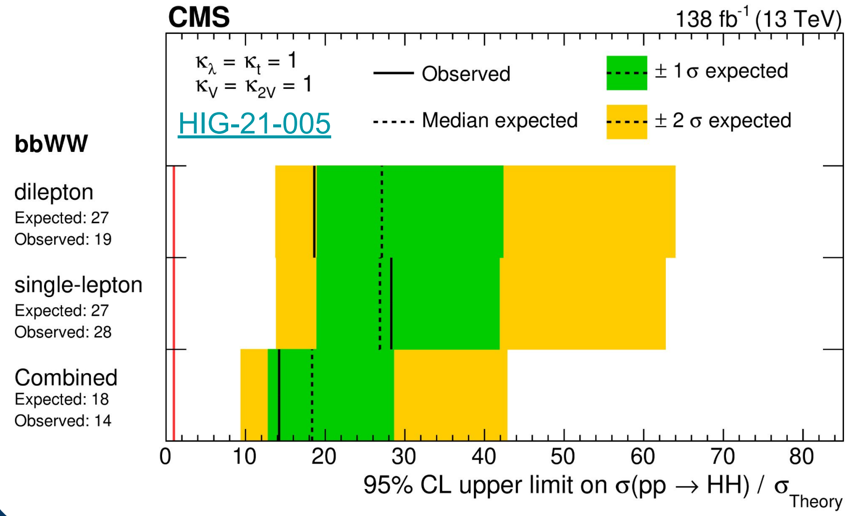
Re-analysis of Run2 data with new analysis techniques brought a ~20% increase in sensitivity on the same dataset !

Using:

- more advanced **ML techniques for b-tagging** (based on transformers architecture)
- a new **kinematic fit** to improve the invariant masses resolution

Other analysis channels

HH→bbWW (to 1 or 2 leptons)



HH→bbZZ(→4 leptons)

Very pure final state but extremly small cross-section

ATLAS : HDBS-2019-04 CMS : HIG-20-004

Multilepton analyses

- to W pair and/or τ pairs
- to γγττ

ATLAS HDBS-2019-04
CMS HIG-21-002

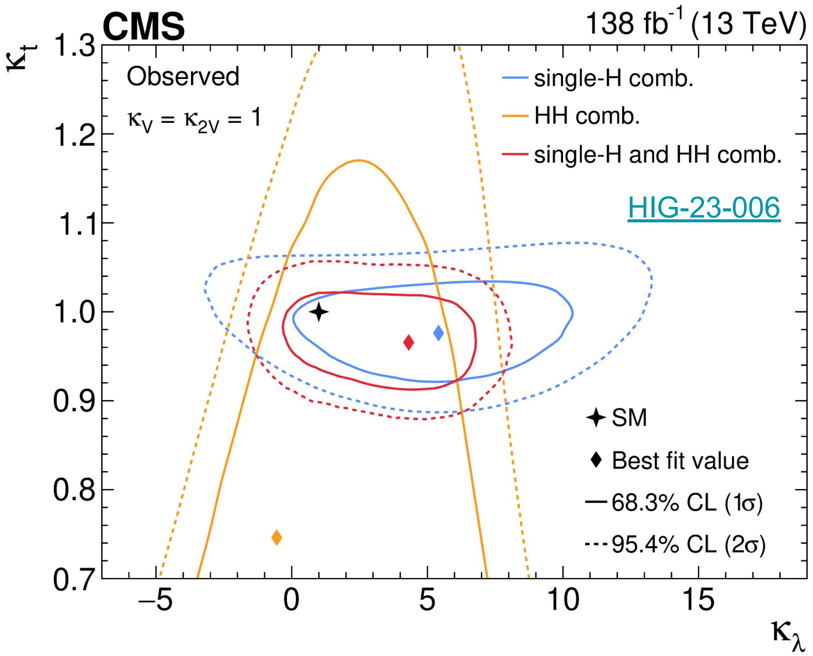
Many different channels to bring some **additional sensitivity** to the search for di-Higgs

Combinations and future

Combination of single & di-Higgs

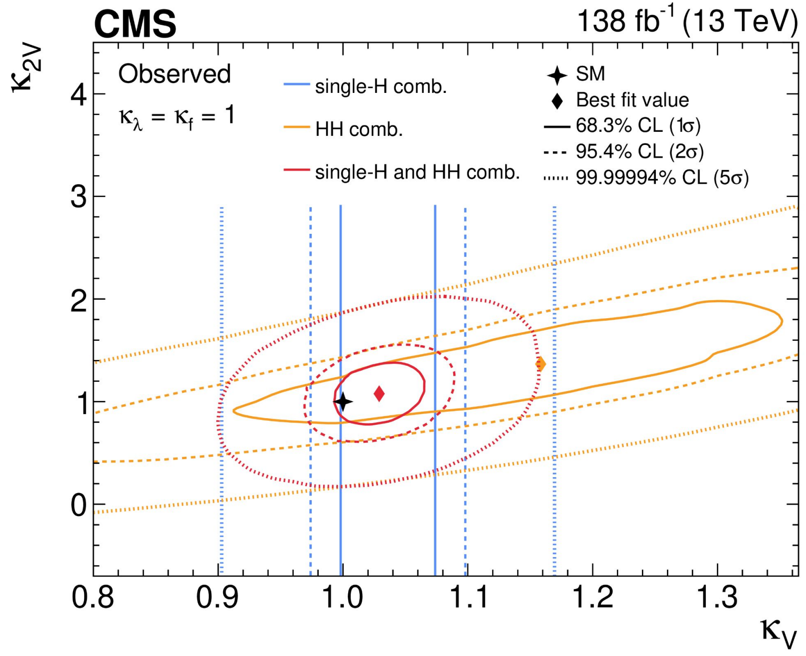
Combining single-Higgs and di-Higgs brings **complementarity to constraints**

κ_t VS κ_λ



Di-Higgs brings some additional constraint on κ_λ

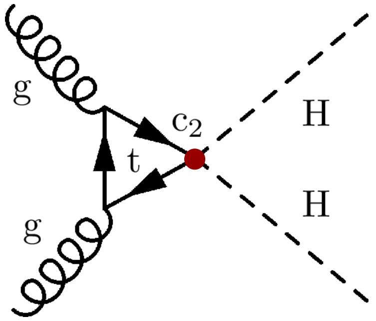
κ_{2V} VS κ_V



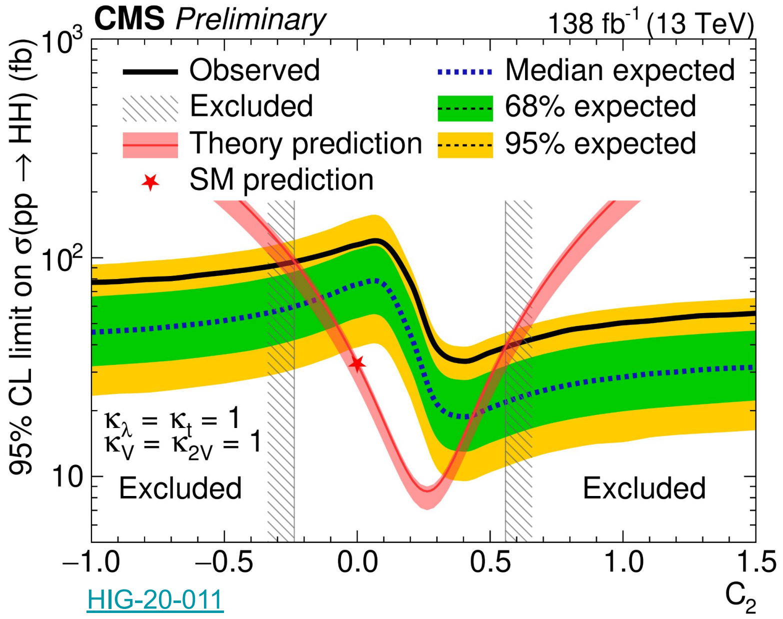
Only di-Higgs can constrain κ_{2V}, whilst single Higgs constrains κ_V better

Anomalous couplings interpretations

Di-Higgs searches can also be used to **probe anomalous couplings** not predicted by the Standard Model, such as the c_2 coupling between two Higgses and two top quarks



Higgs effective field theory (**HEFT**) “benchmarks” are also probed : these are sets of modified couplings where **more than one coupling is varied at a time**.



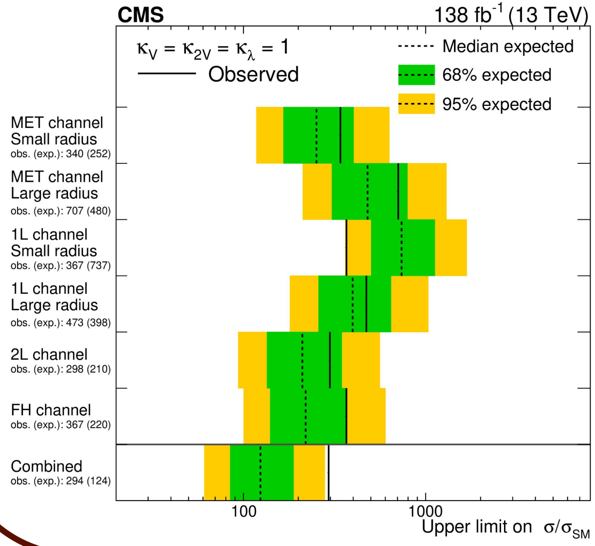
HIG-20-011

Future analysis directions

New decay channels and production modes, with smaller cross-section:

Di-Higgs production in association with a vector boson

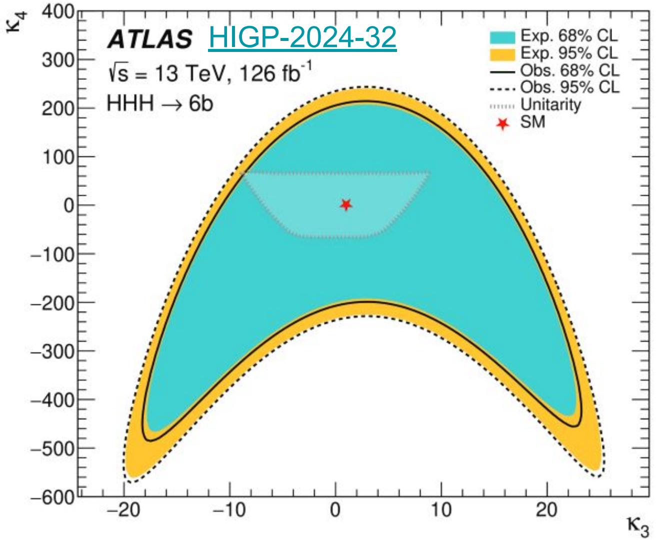
CMS VHH (HH→4b) HIG-22-006



Triple-Higgs production

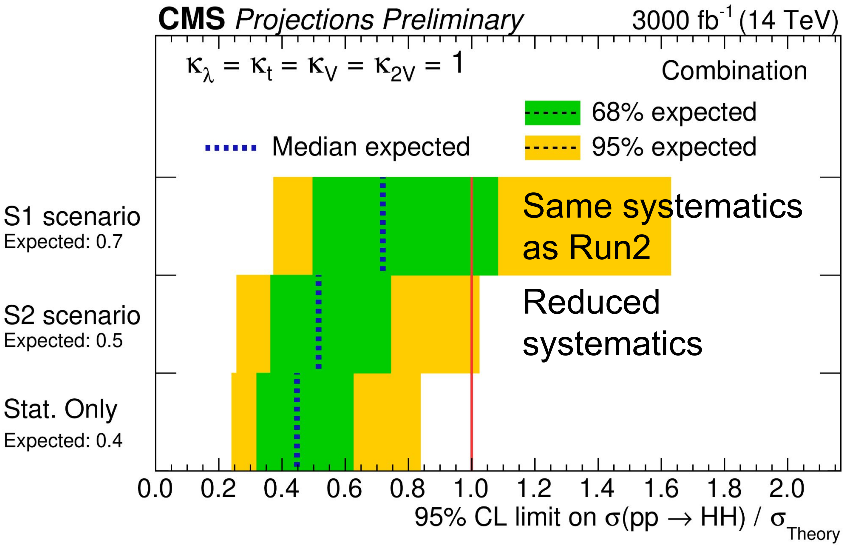
Can **constrain the Higgs quartic coupling.** However, cannot set strong constraints at LHC due to extremly low cross-section

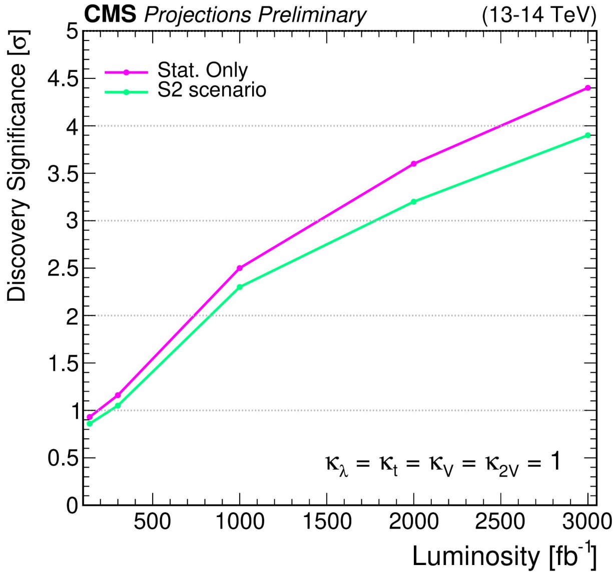
ATLAS HHH→6b search



HL-LHC projections

High-Lumi LHC will bring a projected **3000fb^{-1} of integrated luminosity.**
It is expected that this will allow **evidence of di-Higgs production** when combining all the decay channels.
With significantly improved analysis techniques and combination with ATLAS, it might be possible to claim discovery of di-Higgs at the end of HL-LHC.





Latest CMS projections

HIG-20-011

including channels :

- $bb\gamma\gamma$
- $bb\tau\tau$
- 4b (resolved & boosted)
- VHH ($\rightarrow$4b)
- bbWW
- bbZZ (leptonic & hadronic)
- multilepton
- $WW\gamma\gamma$
- $\tau\tau\gamma\gamma$

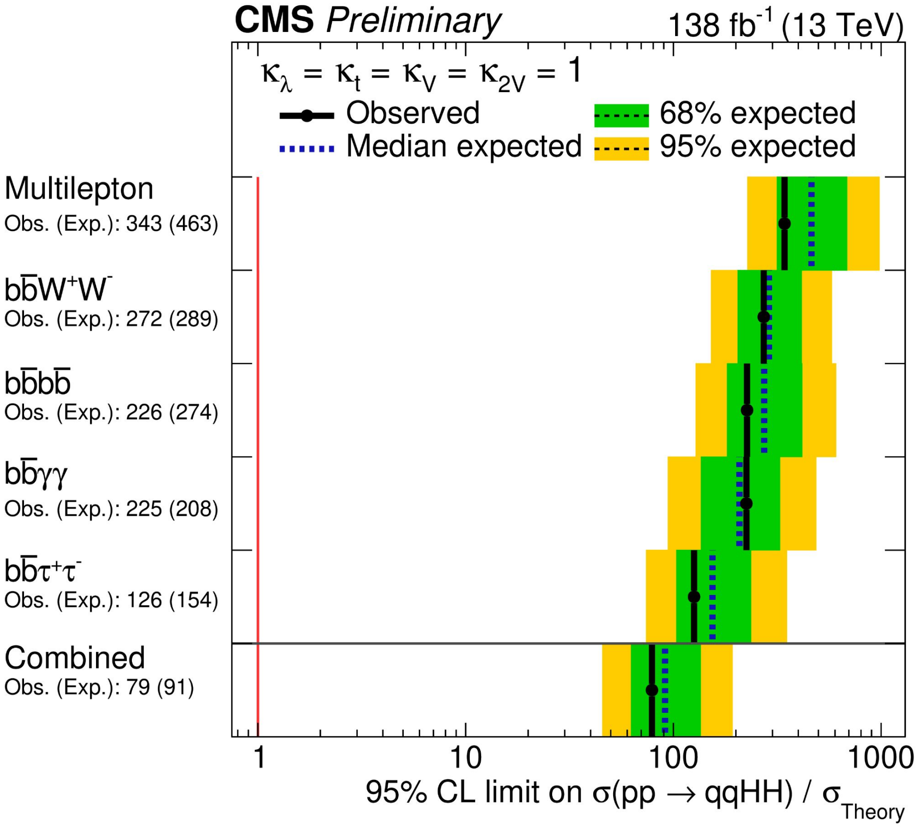
Conclusion

- Observing the **Higgs boson self-coupling** is one of the main target of the next decade at the LHC
- The upper limit on di-Higgs cross-section is currently at 2-3 times the SM expectation
- The self-coupling κ_λ is constrained around $-1 < \kappa_\lambda < 6$
- The **absence of VVHH coupling is excluded** (κ_{2V} != 0)

- Limits on di-Higgs are still statistically dominated, but more data is foreseen
  - analysis of the Run3 dataset is well underway, with already significantly more integrated luminosity accumulated wrt. Run2
  - High-Lumi LHC will bring an unprecedented amount of data
- **Innovative analysis techniques** are steadily improving the sensitivity, bringing us closer to observation of di-Higgs production

Backup

VBF results



CMS Preliminary
138 fb^{-1} (13 TeV)
$\kappa_\lambda = \kappa_t = \kappa_V = \kappa_{2V} = 1$
Observed
Median expected
68% expected
95% expected
Multilepton
Obs. (Exp.): 343 (463)
$b\bar{b}W^+W^-$
Obs. (Exp.): 272 (289)
$b\bar{b}b\bar{b}$
Obs. (Exp.): 226 (274)
$b\bar{b}\gamma\gamma$
Obs. (Exp.): 225 (208)
$b\bar{b}\tau^+\tau^-$
Obs. (Exp.): 126 (154)
Combined
Obs. (Exp.): 79 (91)
1
10
100
1000
95% CL limit on $\sigma(pp \to qqHH) / \sigma_{Theory}$

2D scans of anomalous couplings