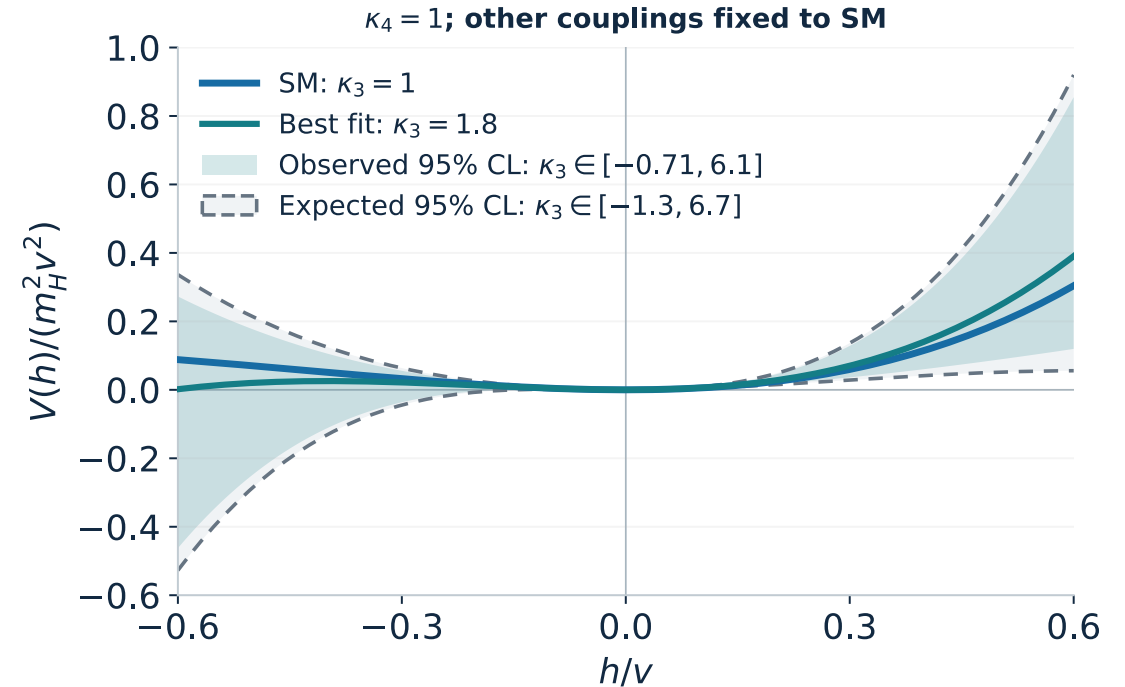


Higgs Self-Coupling

Probing the Higgs potential
with H, HH and HHH

Kunlin Ran
Fudan University



interpreted from LHC Run 2 HH combination, PRL 137 (2026) 131803

The Higgs field and particle masses

1. Electroweak symmetry breaking

In the SM, the Higgs potential selects a nonzero vacuum.

$$V_{\text{SM}}(\Phi) = \lambda \left(\Phi^\dagger \Phi - \frac{v^2}{2} \right)^2.$$

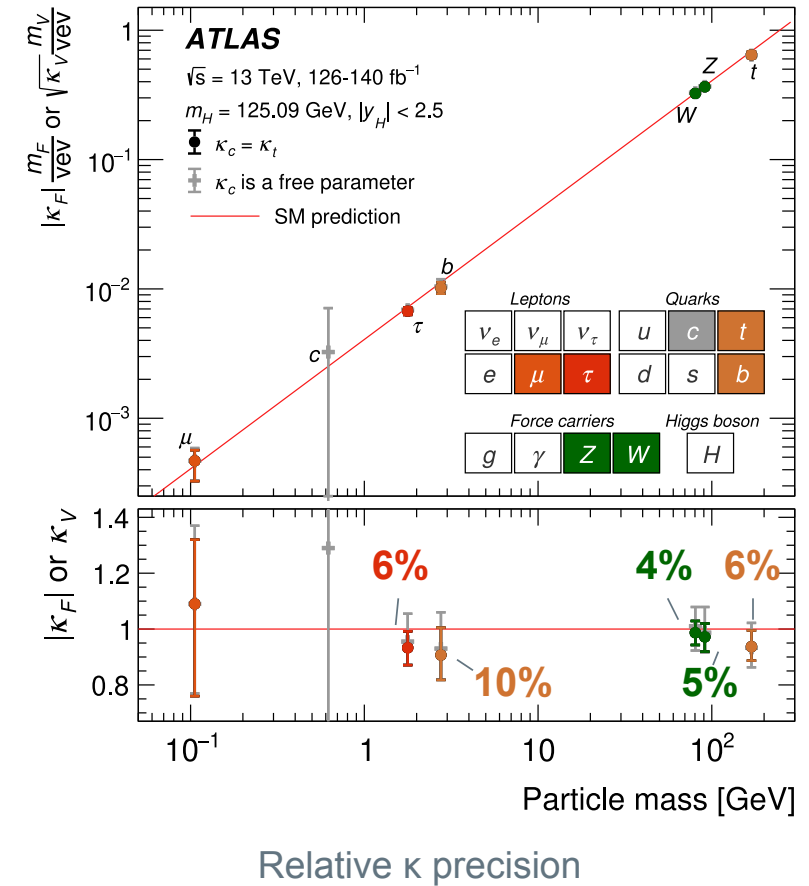
$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v+h \end{pmatrix}, \quad v \approx 246 \text{ GeV}.$$

The observed h is identified with the physical excitation about this vacuum.

2. Particle masses and Higgs couplings

Gauge and Yukawa interactions with the Higgs field generate W/Z and fermion masses.

$$g_{hff} = \frac{m_f}{v}, \quad g_{hVV} = \frac{2m_V^2}{v}.$$

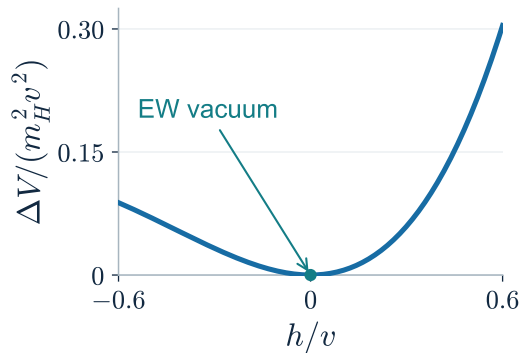


The SM coupling–mass relation is tested at 4–10% precision for W/Z and third-generation fermions.

The Higgs potential: mass and self-interactions

$$V(h) = \frac{1}{2}m_H^2 h^2 + \kappa_3 \frac{m_H^2}{2v} h^3 + \kappa_4 \frac{m_H^2}{8v^2} h^4 + \dots$$

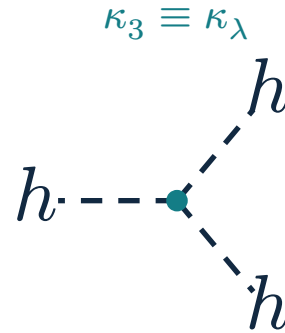
SM potential



$$m_H^2 = V''(0)$$

Curvature at the vacuum

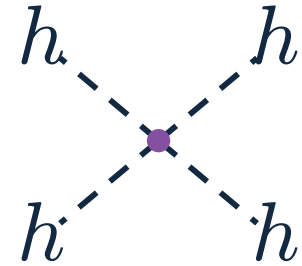
Three-Higgs vertex



$$g_{hhh} = V'''(0) = \kappa_3 \frac{3m_H^2}{v}$$

Direct sensitivity in HH.
Loop effects in single H.

Four-Higgs vertex



$$g_{hhhh} = V''''(0) = \kappa_4 \frac{3m_H^2}{v^2}$$

Direct sensitivity in HHH,
a much rarer process.

The SM predicts $\kappa_3 = \kappa_4 = 1$. Deviations would reveal new dynamics in the scalar sector.

Testing κ_3 and κ_4 probes the Higgs potential beyond its mass term.

Why measure the self-couplings?

The aim is an experimental test of the Higgs potential and its possible extensions.

Electroweak symmetry breaking

Test the self-interaction pattern predicted by the SM.

New scalar dynamics

Search for effects of additional fields or higher-dimensional interactions.

The early universe

Constrain models of the electroweak transition through finite-temperature predictions.

Three experimental handles

HH

Direct trilinear sensitivity

Rare production, destructive interference and coupling-dependent kinematics.

H

Loop sensitivity

Large samples and precision rates or spectra provide stringent tests of Higgs couplings to other SM particles.

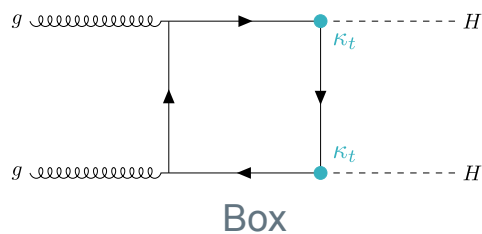
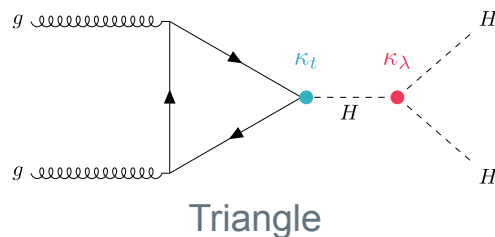
$H+HH$ combinations use the complementary dependence of direct and loop observables.

HHH

Trilinear + quartic sensitivity

Direct access to the four-Higgs vertex; very small SM x-sec, with backgrounds much larger than the signal.

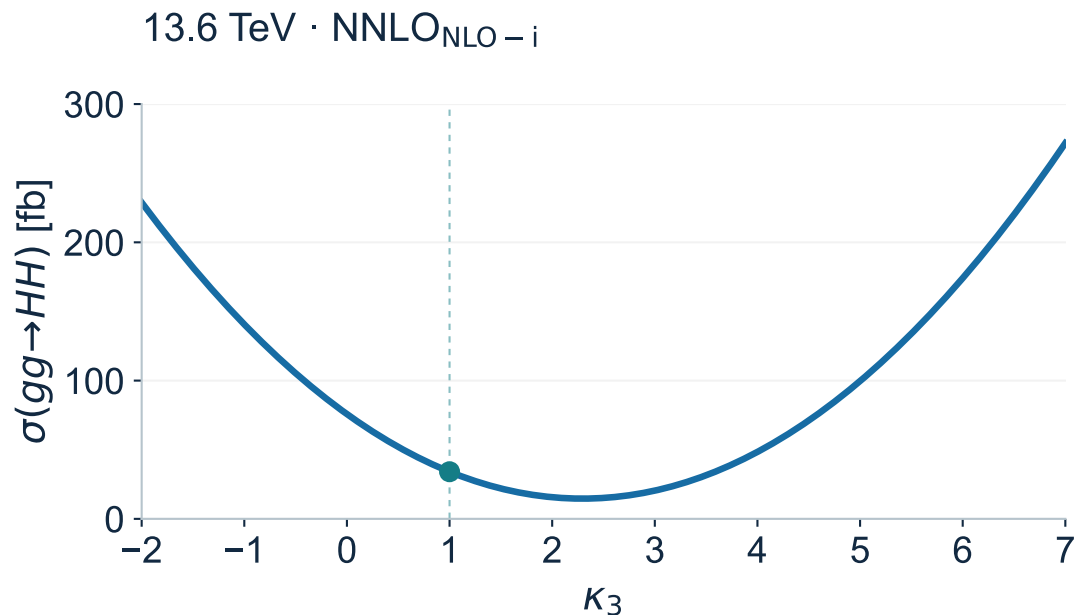
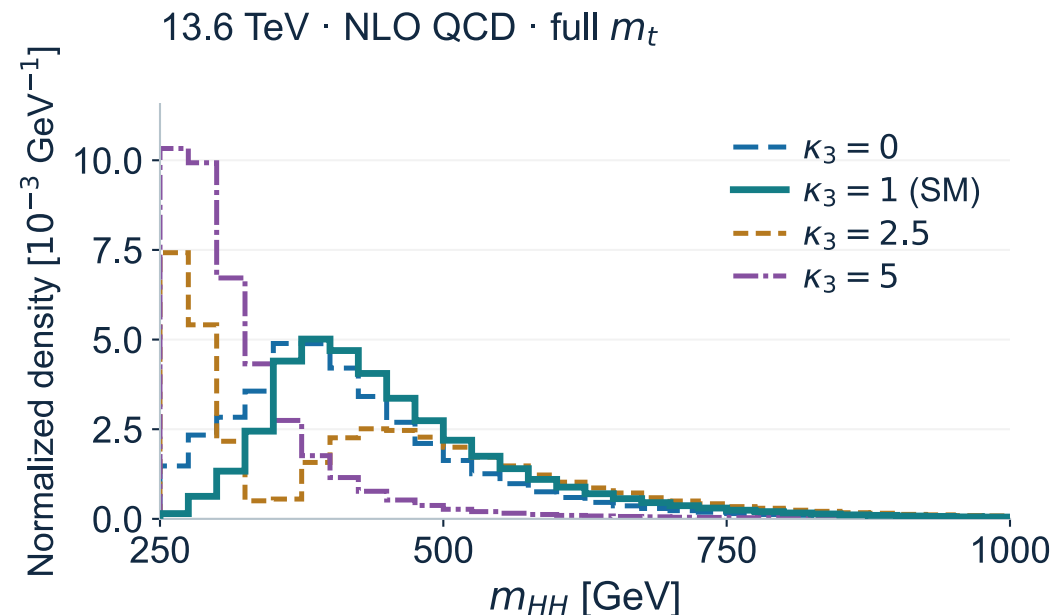
ggF HH: interference, rate and kinematics



LO ggF HH amplitude

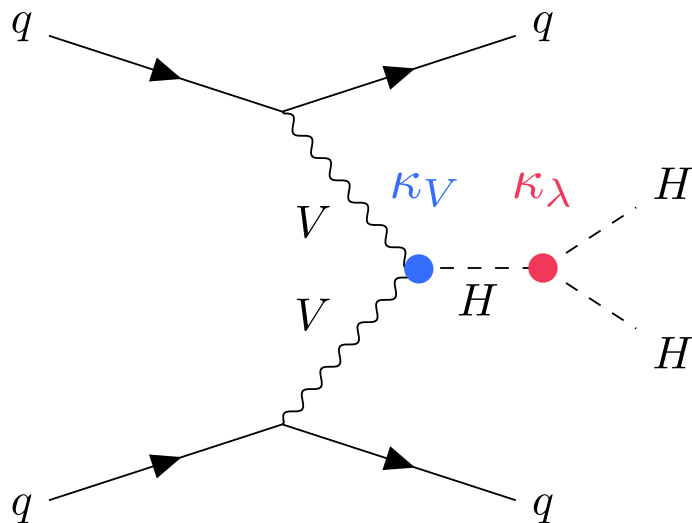
$$\mathcal{A}_{gg \rightarrow HH} = \kappa_t^2 \mathcal{A}_{\Box} + \kappa_t \kappa_3 \mathcal{A}_{\Delta}$$

Changing κ_3 alters both the yield and the kinematics.

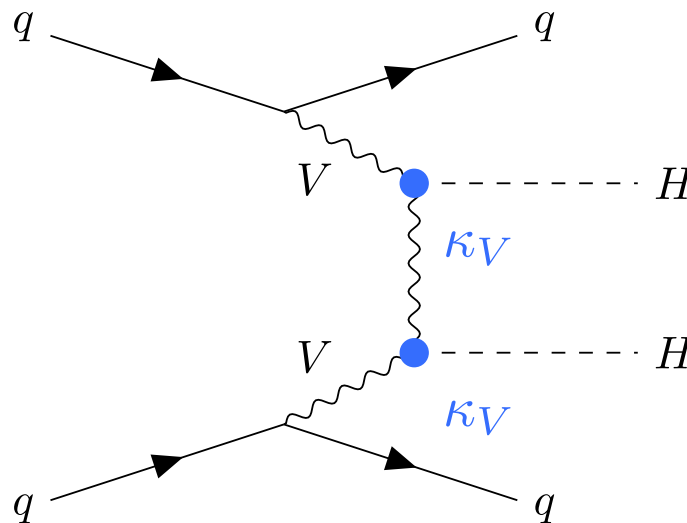


VBF HH: amplitudes and coupling dependence

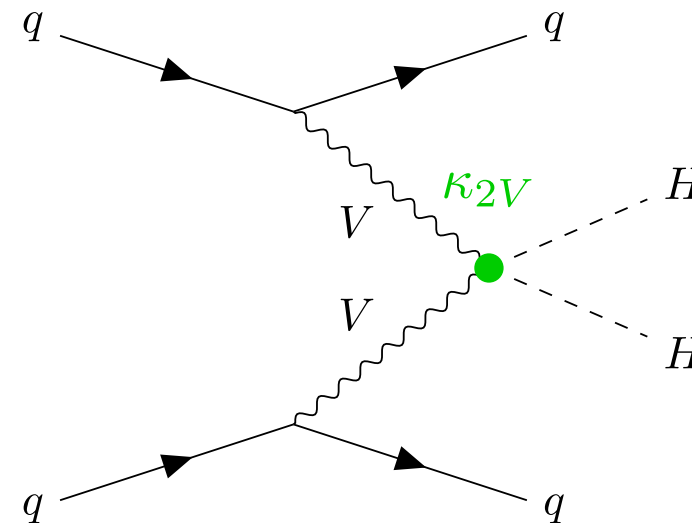
Higgs s-channel



Vector t/u-channel



Contact interaction

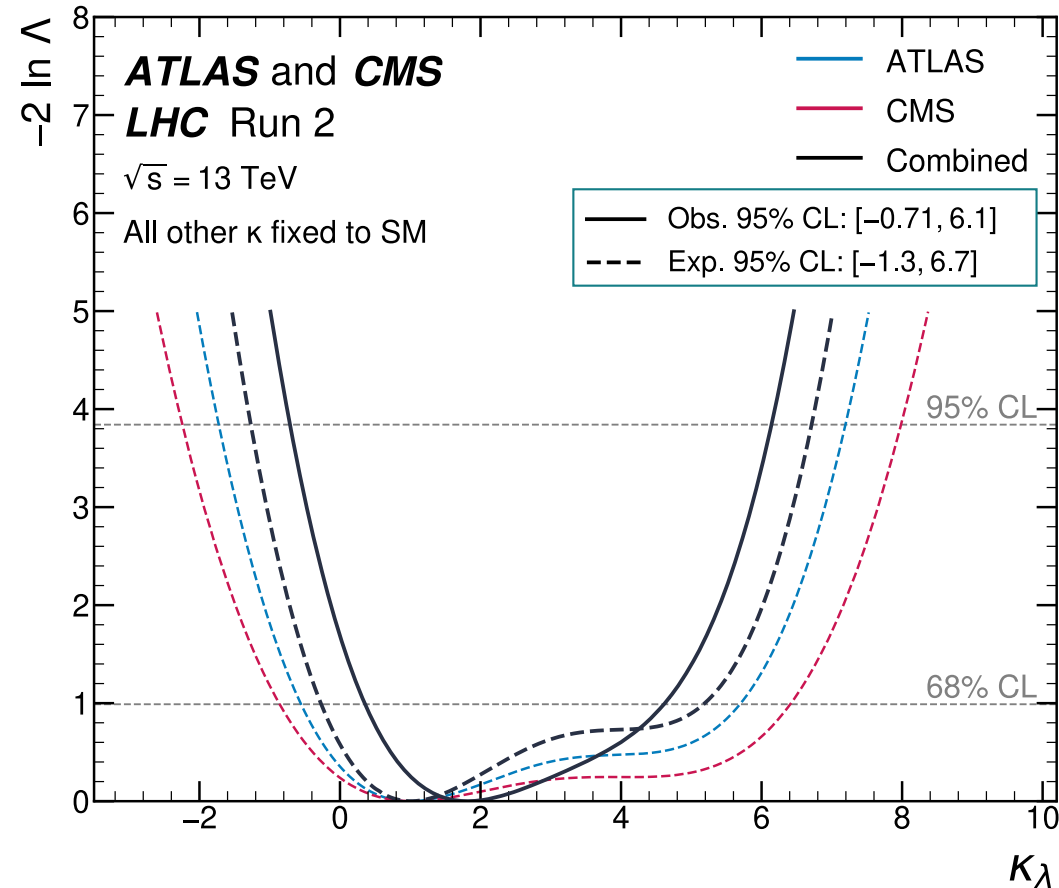


Tree-level scattering amplitude

$$\mathcal{A}(VV \rightarrow HH) = \kappa_V \kappa_3 \mathcal{A}_s + \kappa_V^2 \mathcal{A}_{t/u} + \kappa_{2V} \mathcal{A}_c$$

Different topologies weight ggF/VBF HH amplitudes and their interference differently.

ATLAS + CMS Run 2 HH combination



	Observed	Expected
$\hat{\mu}_{HH}$	$0.8^{+0.9}_{-0.7}$	$1.0^{+0.9}_{-0.8}$
Significance	1.1σ	1.3σ

This is the reference point; the following results add Run 3 data, new methods and complementary observables.

Recent results

November 2025–October 2026

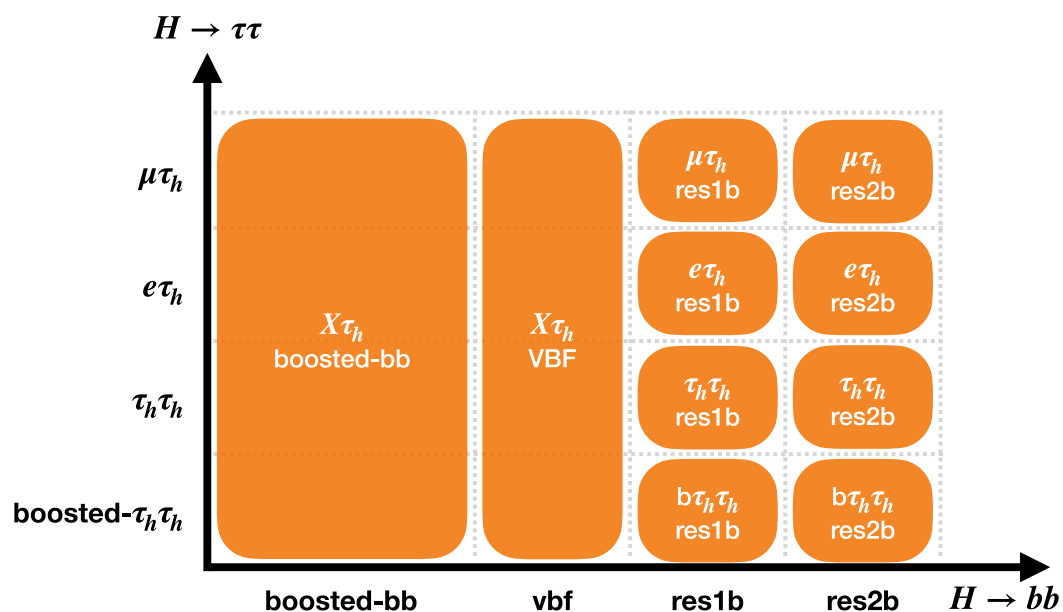
New measurements and complementary probes of the Higgs potential

CMS HH $\rightarrow$ bb $\tau\tau$: a Run 3 step forward

bb $\tau\tau$ combines a 7.3% branching fraction with identifiable τ decays.

172 fb $^{-1}$ Run 3 + 138 fb $^{-1}$ Run 2

New $\tau\tau$ +jet, b+ τ parking and VBF triggers extend HH signal acceptance.



τ identification

DeepTau / Boosted DeepTau

b tagging and boosted $H \rightarrow bb$ tagging

ParticleNet (2022–23), UParT (2024)

ParticleNet Xbb for boosted $H \rightarrow bb$

$H \rightarrow bb$ jet assignment

Retrained HH-bTag

VBF jet assignment

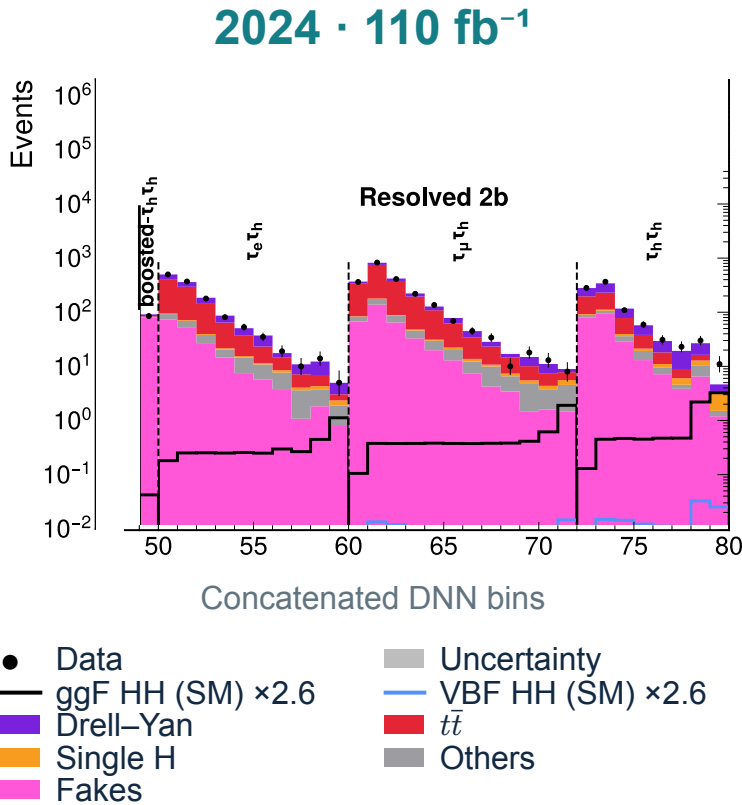
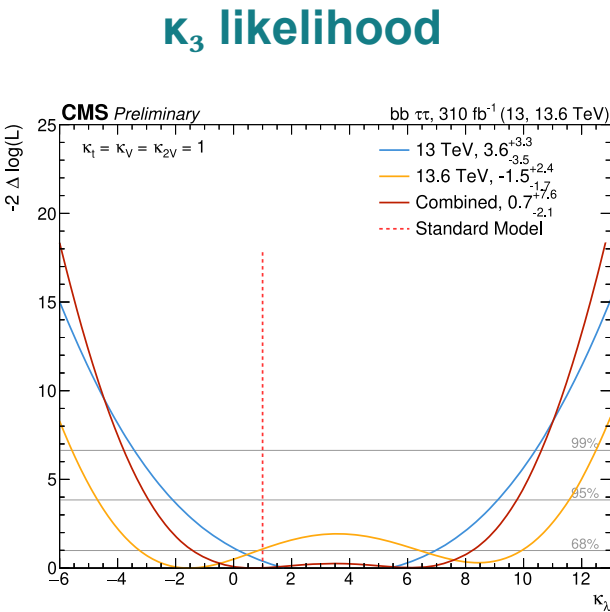
VBFJTAG

Neutrino regression improves $m_{\tau\tau}$.

Improved triggers, reconstruction and discrimination enhance HH and self-coupling sensitivity.

CMS HH → bbττ: fit and κ₃ limit

Separate ggF and VBF DNNs provide the distributions fitted across the signal regions.



Run 2+3 · μ_{HH} upper limit, 95% CL

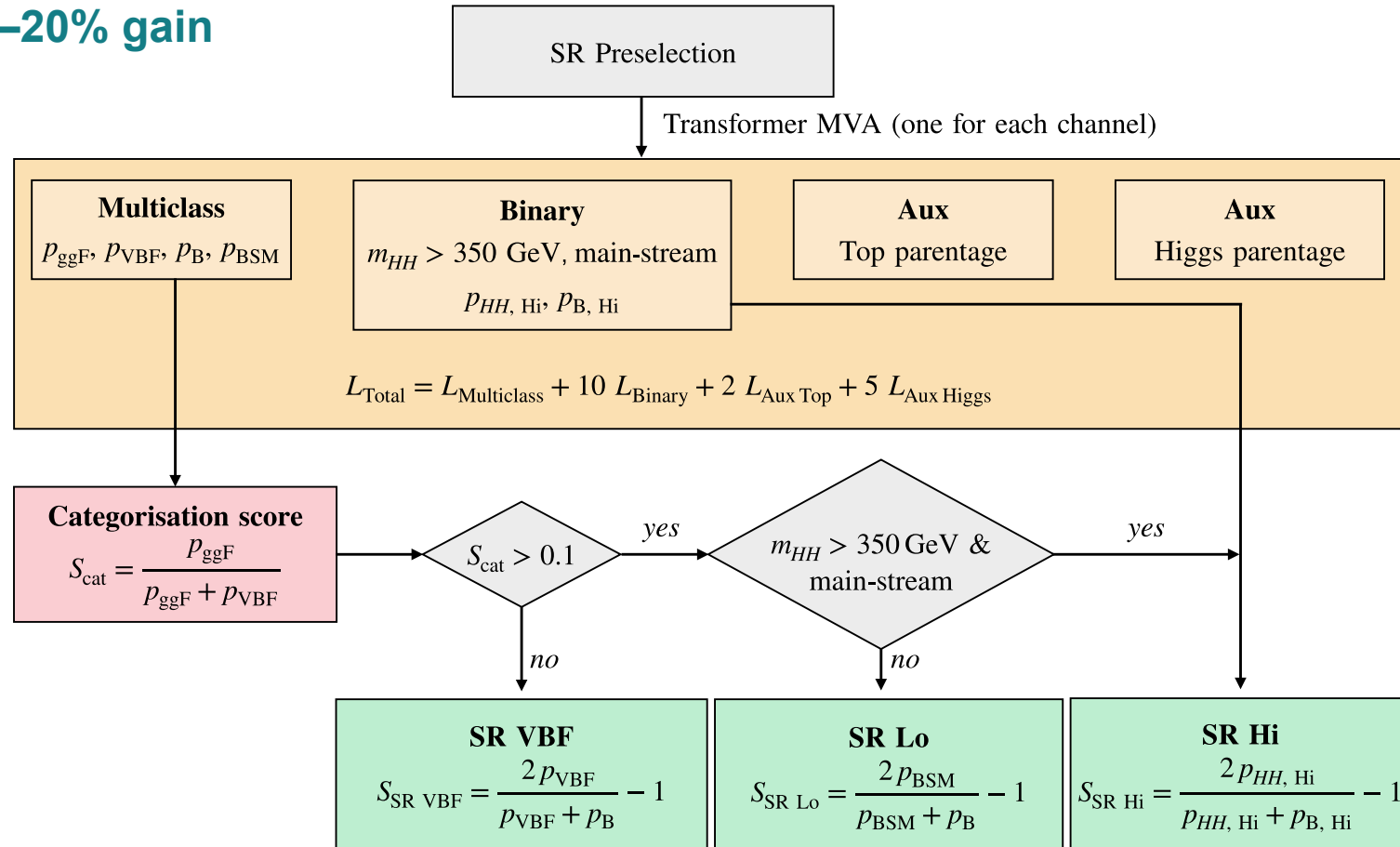
Observed 4.0 / Expected 3.0

κ₃, 95% CL

Dataset	Observed	Expected
Run 2 138 fb ⁻¹	[−1.7, 8.7]	[−2.9, 9.8]
Run 3 172 fb ⁻¹	[−4.1, 11.2]	[−2.2, 9.2] −10% vs Run 2
Run 2+3	[−2.5, 9.4]	[−1.5, 8.4] −22% vs Run 2

ATLAS HH → bbττ: categorisation strategy

New classifier: 15–20% gain in HH sensitivity



SR Hi targets SM HH, SR Lo adds κ_3 sensitivity, and SR VBF probes $\kappa_2 \text{V}$.

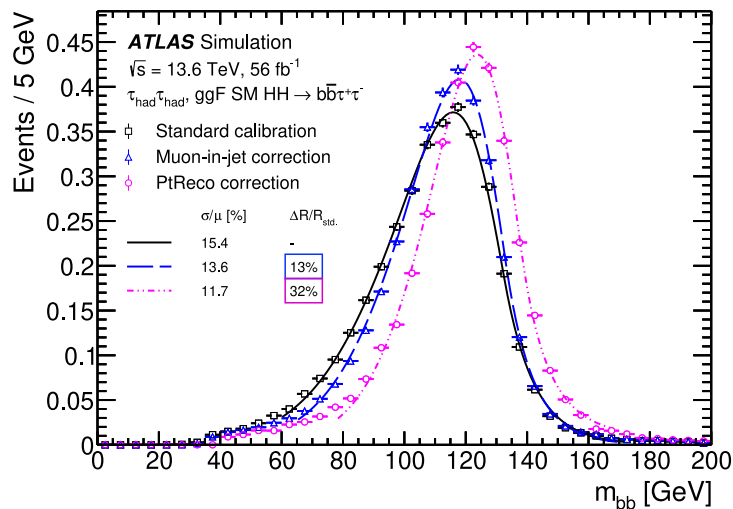
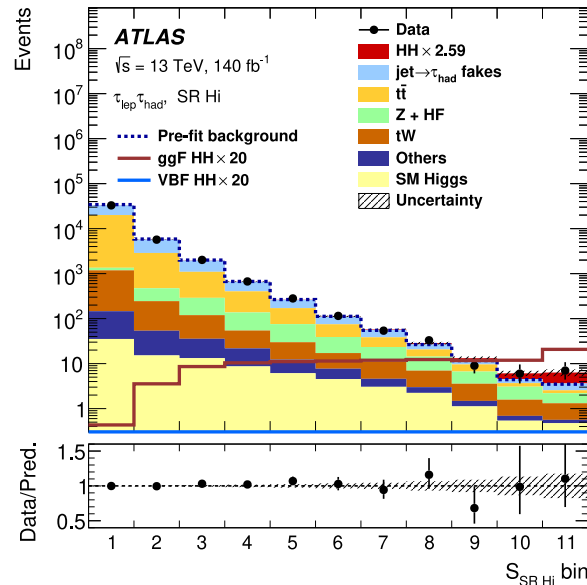
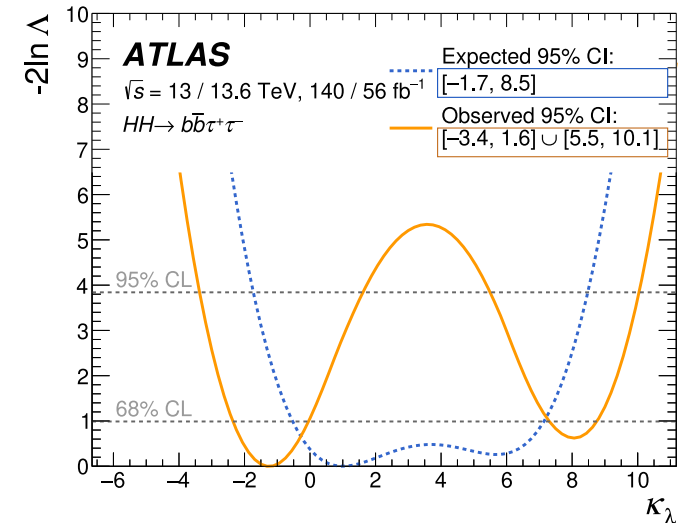
ATLAS HH $\rightarrow$ bb $\tau\tau$: signal strength and κ_3 limit

140 fb $^{-1}$ Run 2 (reanalysed) + 56 fb $^{-1}$ Run 3

Triggers: Run 3 delayed-stream data from lower-threshold di- τ and additional di-b-jet triggers extend $\tau_{\text{had}}\tau_{\text{had}}$ acceptance.

Reconstruction: GN2 b tagging and muon-in-jet + p_T -reco corrections improve b-jet reconstruction.

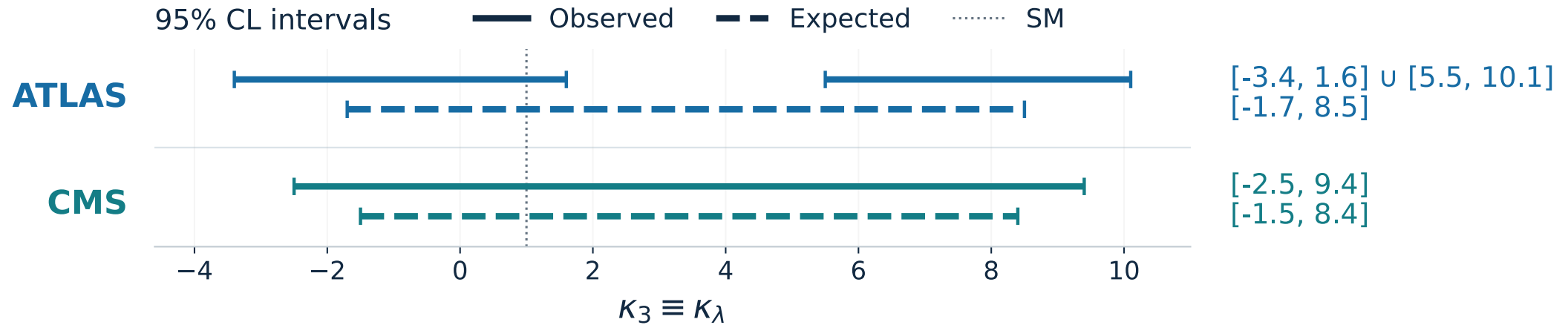
Expected κ_3 95% CL interval: $\approx 15\%$ narrower vs previous Run 2 analysis.



$$\mu_{HH} = 2.6^{+1.4}_{-1.0}$$

Significance: Observed 2.6σ / Expected 1.2σ

HH $\rightarrow$ bb $\tau\tau$: comparing the κ_3 limit range



ATLAS · 196 fb⁻¹

Reanalysed Run 2, including SM + $\kappa_3=5$ training and SR Lo.

HH sensitivity gains vs previous ATLAS:
classifier 15–20%; flavour tagging $\approx 10\%$.

The ATLAS excess splits the observed κ_3 interval.

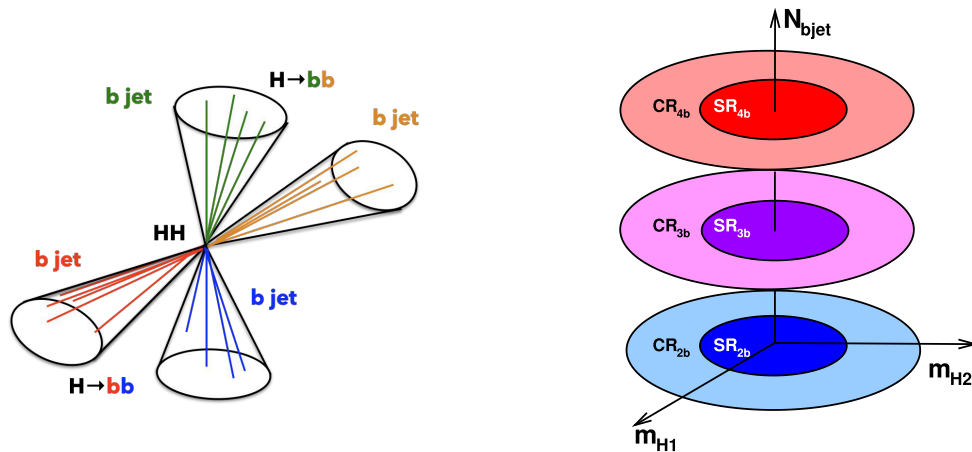
CMS · 310 fb⁻¹

More Run 3 data, dedicated triggers and expanded boosted categories.

CMS HH $\rightarrow$ 4b: Run 3 regions and QCD modelling

4b combines the largest HH branching fraction ($\approx 34\%$) with reconstructible Higgs candidates.

Resolved: 4 AK4 jets



ParticleNet: b tagging + jet p_T regression.

Jet p_T resolution: **10–25% better.**

m_{bb} resolution: **$\approx 20\%$ better.**

QCD: sideband-trained $2b \rightarrow 4b$ weights.

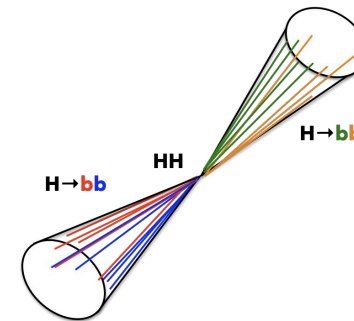
Resolved $\rightarrow$ ggF / VBF $\rightarrow$ **classifier fit**

Merged HPSR events are removed from the resolved sample to ensure orthogonality.

Run 2 resolved reanalysed: $\approx 25\%$ better expected HH limit.

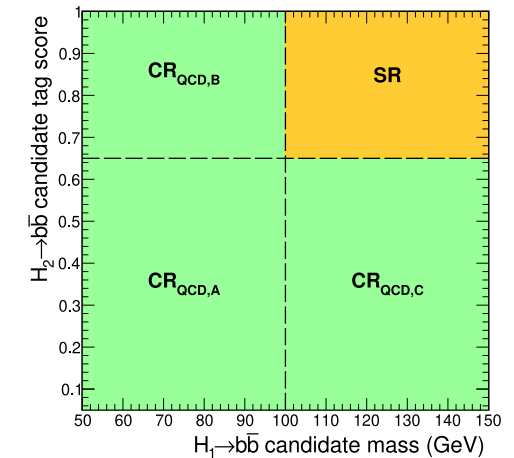
CMS partial Run 3 HH $\rightarrow$ 4b, arXiv:2604.27044

Merged: 2 AK8 jets



GloParT: bb tagging + mass regression.
 $\approx 6\%$ resolution improvement over soft-drop.
QCD: reweight tag-sideband data.

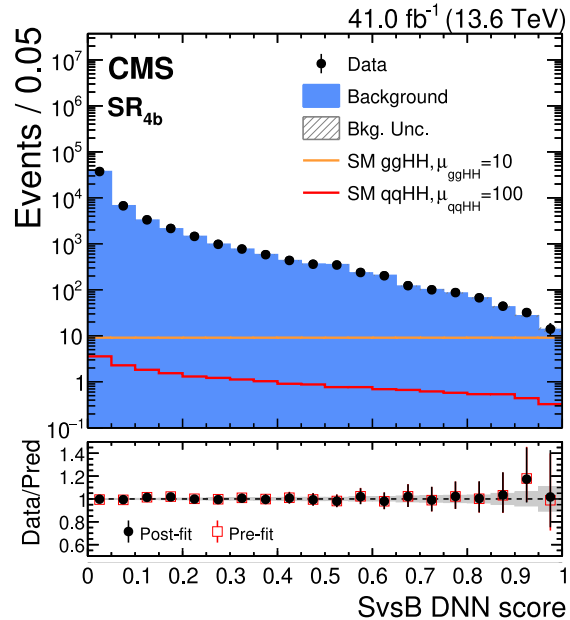
Merged $\rightarrow$ ggF / VBF $\rightarrow$
high-purity SR (HPSR) $\rightarrow$ **mass fit**



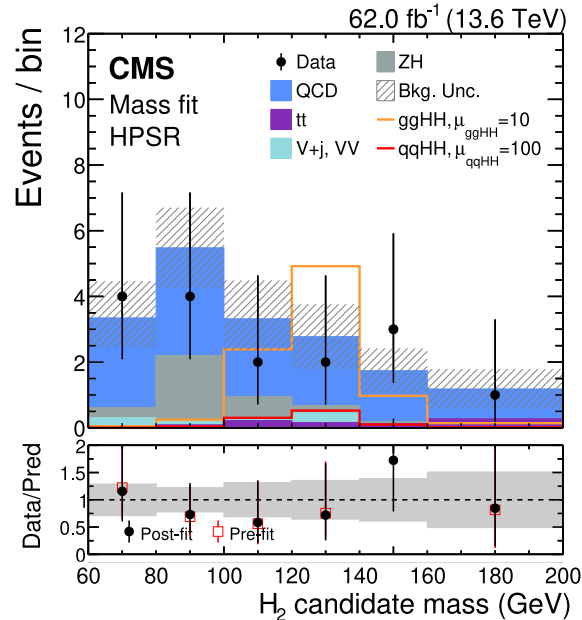
CMS HH $\rightarrow$ 4b: signal strength and κ_3 constraints

138 fb $^{-1}$ Run 2 + 62 fb $^{-1}$ Run 3

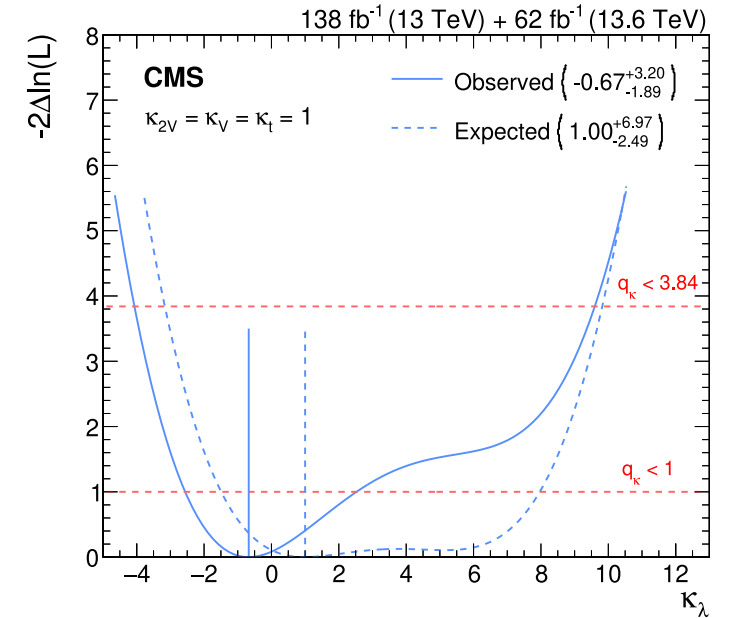
Resolved



Merged HPSR



κ_3 likelihood · Run 2+3



Run 2+3 · μ_{HH} upper limit · 95% CL
Observed 4.7 / Expected 2.8

κ_3 , 95% CL	Observed	Expected
Run 3	[-3.4, 9.7]	[-4.3, 10.9]
Run 2+3	[-4.1, 9.6]	[-3.2, 9.8]
		-14% vs Run 3

Complementary topologies enable a more complete and precise study of HH $\rightarrow$ 4b.

CMS HH $\rightarrow$ bbWW: dilepton

Dilepton · 62 fb⁻¹, 13.6 TeV

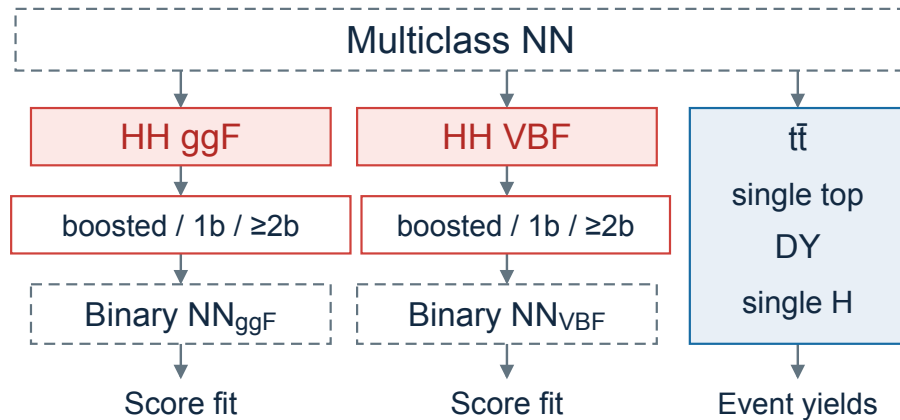
bbWW has a sizeable HH branching fraction ($\approx 25\%$); two isolated leptons suppress multijet backgrounds.

Extra ee/e+jet triggers with looser isolation.

Signal yield: +5% in ee, +1% in e μ .

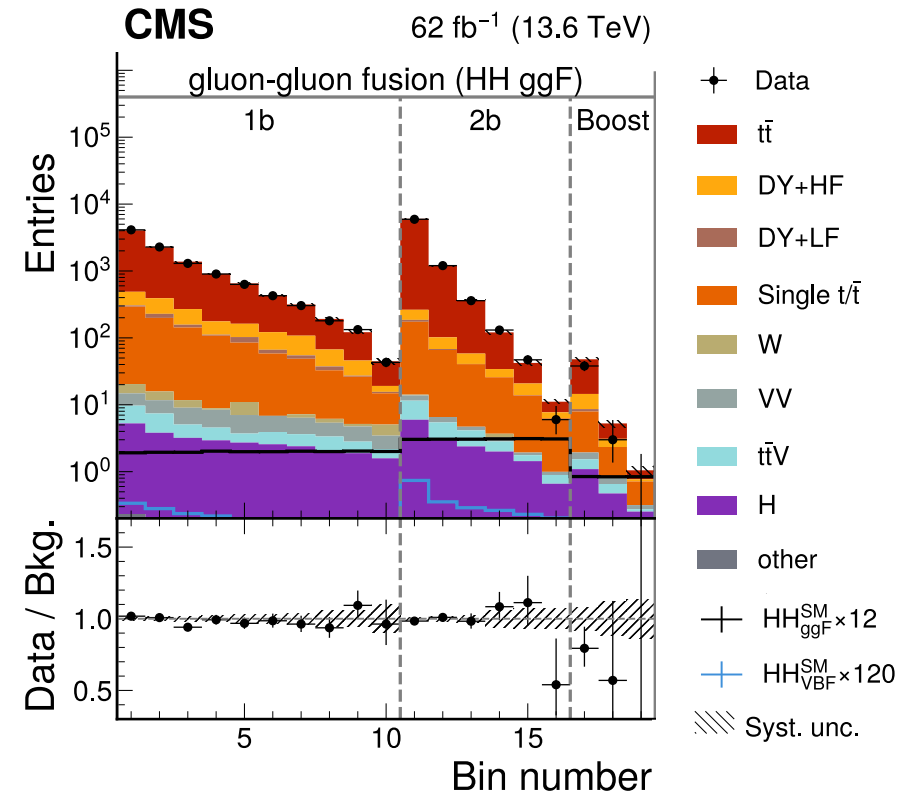
ParticleNet: AK4 b jets and boosted H $\rightarrow$ bb.

Staged multiclass + binary NNs: $\approx 50\%$ sensitivity gain at matched luminosity.



κ_3 , 95% CL

Observed [−9.1, 15.7]



Expected [−13.3, 19.8]

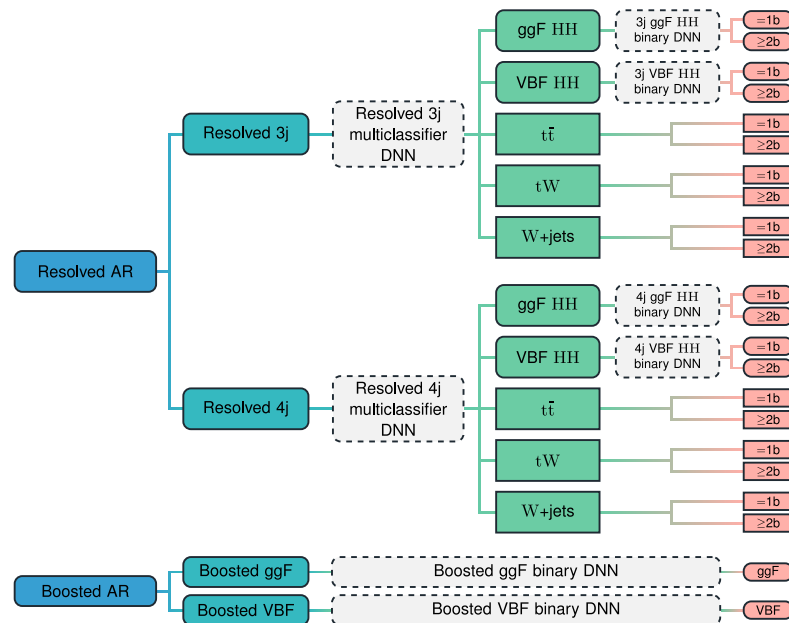
CMS HH $\rightarrow$ bbWW: single lepton and DL+SL combination

SL: 62 fb $^{-1}$, 13.6 TeV

SL retains $\approx 35\%$ of bbWW decays and adds hadronic-W kinematic information.

b tagging: DeepJet $\rightarrow$ ParticleNet

H $\rightarrow$ bb: resolved AK4 jets or a boosted AK8 jet.

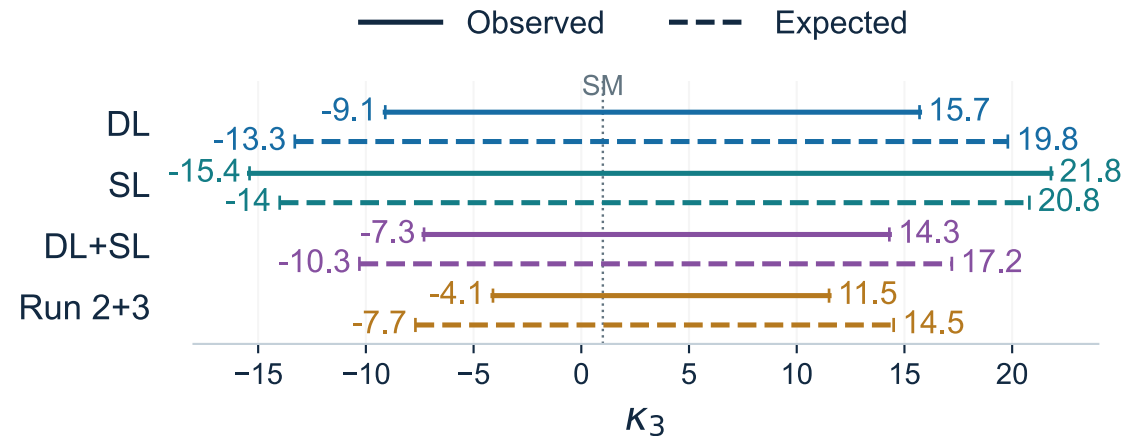


Compared with DL, additional jets introduce assignment ambiguities.

Fake-factor data-driven method for fake and non-prompt backgrounds.

Run 2+3: $\mu_{HH} < 7.8$ obs. / 12 exp., 95% CL

κ_3 , 95% CL



Run 2 κ_3 (SL+DL), 95% CLs: Obs. $[-7.2, 13.8]$ / Exp. $[-8.7, 15.2]$

Adding Run 2 to Run 3 DL+SL narrows the expected κ_3 95% CL interval by $\approx 19\%$.

Single Higgs: loop sensitivity in production and decay

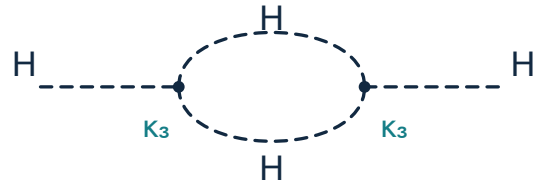
Large H samples constrain κ_3 through small, process- and kinematics-dependent electroweak effects.

$$\frac{X(\kappa_3)}{X_{\text{SM}}} = Z_H^{\text{BSM}} \left[1 + (\kappa_3 - 1) \frac{C_1^X}{K_{\text{EW}}^X} \right], \quad X = \sigma_i \text{ or } \Gamma_f$$

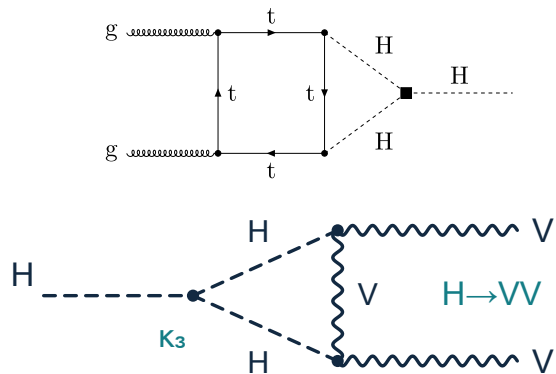
$$Z_H^{\text{BSM}} = \frac{1}{1 - (\kappa_3^2 - 1) \delta Z_H}$$

Common external-Higgs factor;
 C_1 varies with process and kinematics.

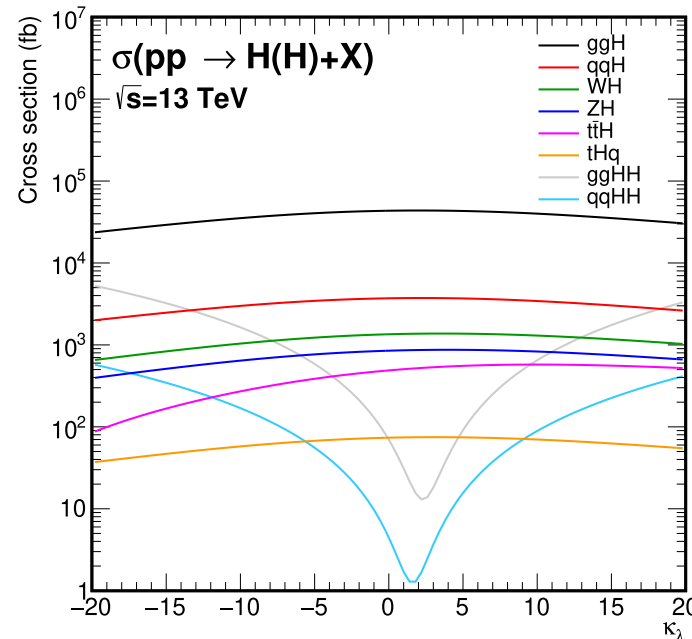
Universal wave-function



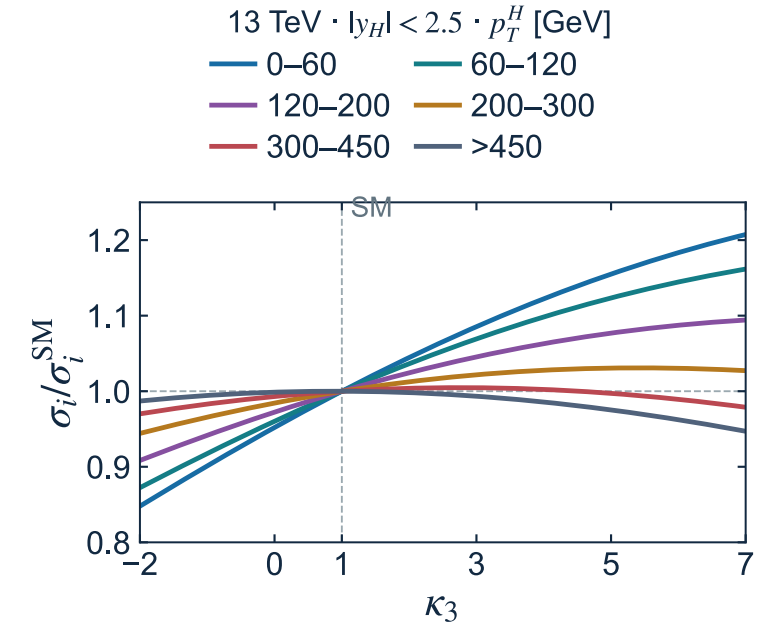
Process-dependent C_1



Inclusive x-sec



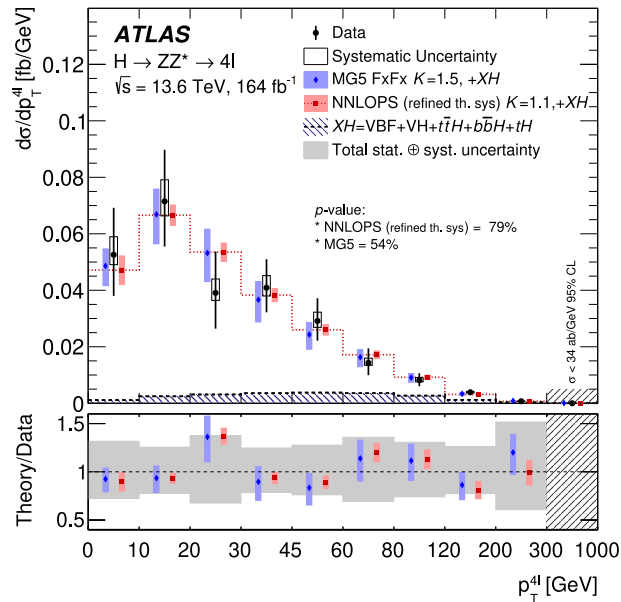
$t\bar{t}H$ STXS



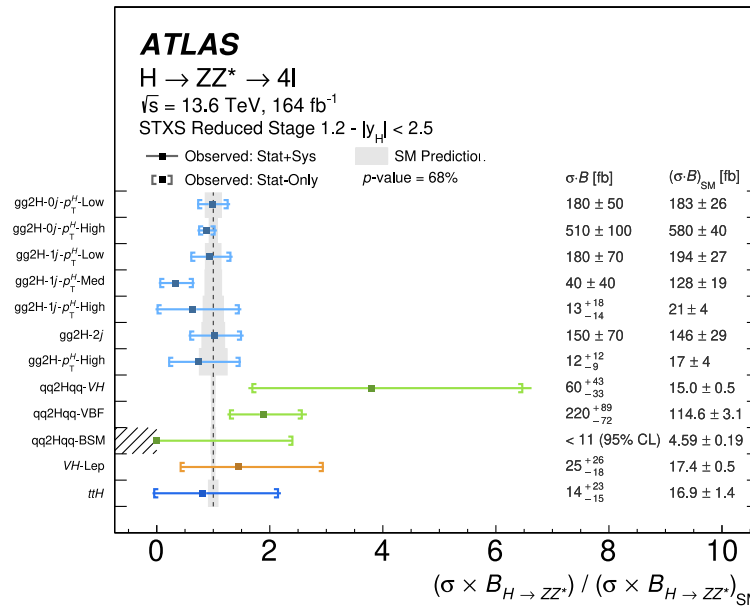
ATLAS $H \rightarrow 4\ell$: differential versus STXS

Bin-wise C_1 and universal Z_H reweighting for each production mode.
 κ_3 dependence of $\Gamma(H \rightarrow 4\ell)$ and Γ_H is included.

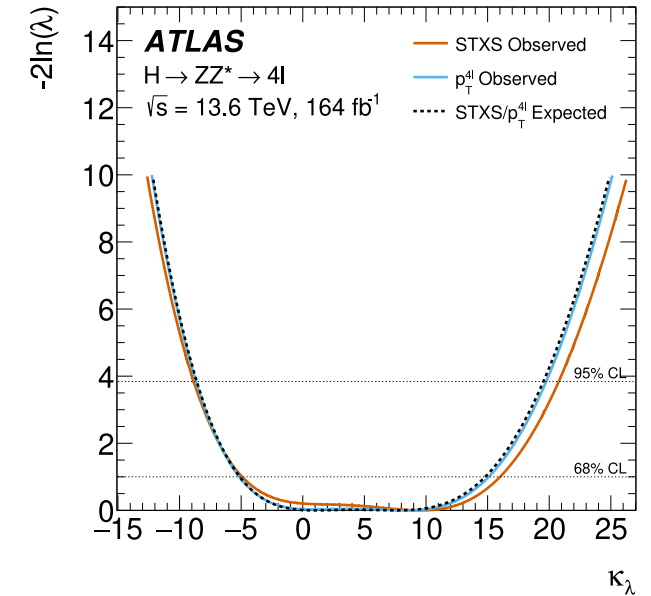
Differential $p_T^{4\ell}$



STXS bins



κ_3 likelihood



κ_3 , 95% CL
 Differential
 STXS

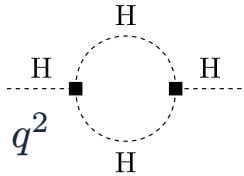
Observed
 $[-8.8, 19.9]$
 $[-9.0, 20.9]$

Expected
 $[-8.8, 19.9]$
 $[-8.8, 19.9]$

CMS off-shell $H \rightarrow 4\ell$: a new kinematic probe

Off-shell spectra add distinct loop information; the κ_3 interpretation is conditional on the EFT setup.

Physics and fit



$$\mathcal{O}_6 = (\Phi^\dagger \Phi)^3$$

$$\kappa_3 \approx 1 + \bar{c}_6$$

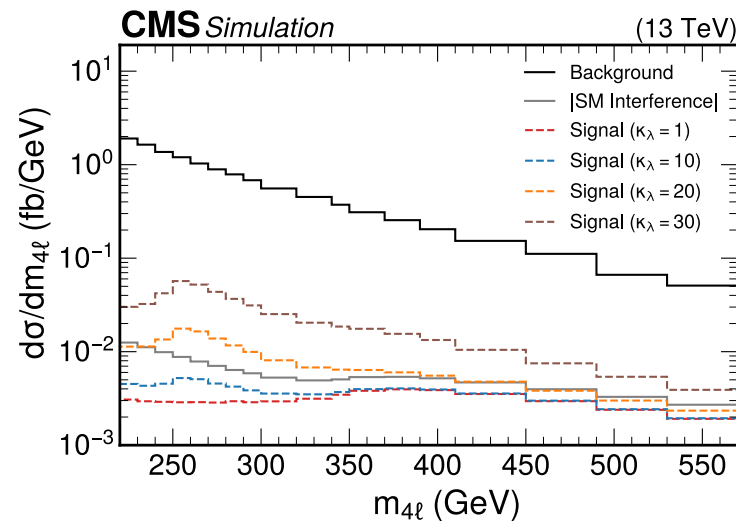
After EWSB, $\mathcal{O}_6$ shifts the h^3 interaction.

$$\nu_b = B_b + \mu S_b(\kappa_3) + \sqrt{\mu} I_b(\kappa_3)$$

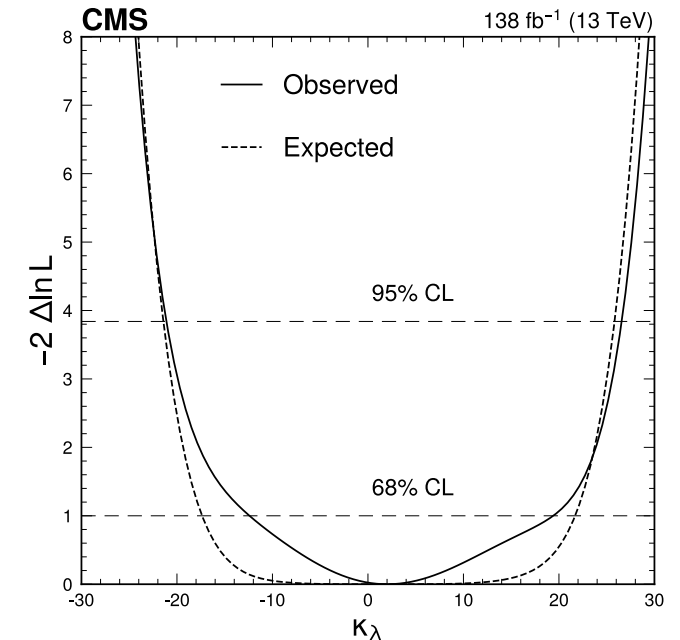
μ is profiled, relaxing the absolute-rate constraint.

The HH loop threshold near $m_{4\ell} \approx 2m_H$ reshapes the off-shell spectrum.

$m_{4\ell}$ spectrum



κ_3 likelihood



κ_3 , 95% CL

Observed
[-21, 27]

Expected
[-21, 26]

This is the first off-shell κ_3 constraint in this CMS analysis.

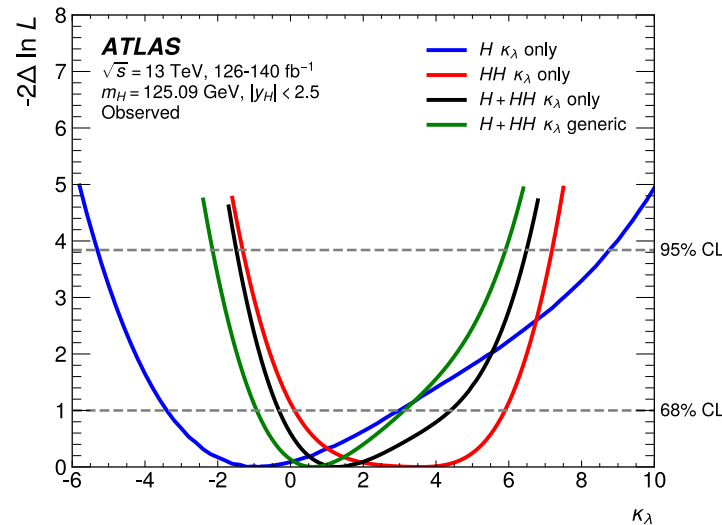
It tests a different kinematic regime from on-shell rates and HH production.

ATLAS H+HH: complementarity in one likelihood

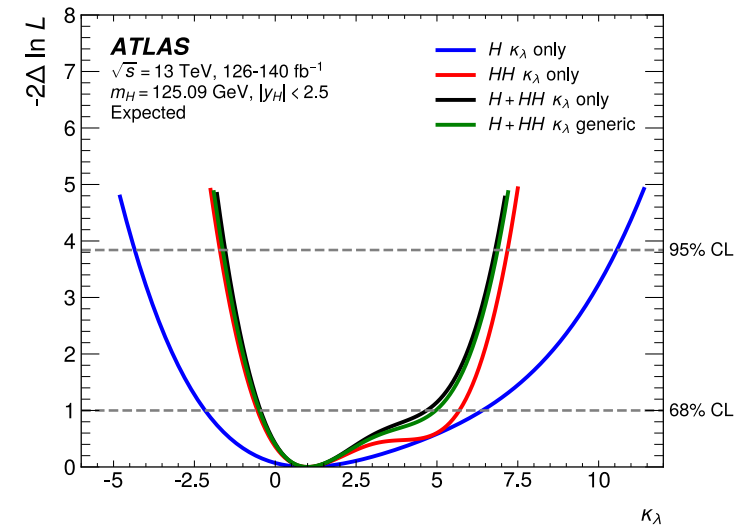
Run 2, up to 140 fb^{-1}

Generic: $\kappa_V, \kappa_t, \kappa_b, \kappa_\tau$ profiled.

Observed likelihood



Expected likelihood



κ_3 , 95% CL	Single H, κ_3 only	HH, κ_3 only	H+HH, κ_3 only	H+HH, generic
Observed	$[-5.3, 8.8]$	$[-1.3, 7.2]$	$[-1.5, 6.5]$	$[-2.1, 5.9]$
Expected	$[-4.35, 10.56]$	$[-1.71, 7.18]$	$[-1.55, 6.80]$	$[-1.62, 6.88]$

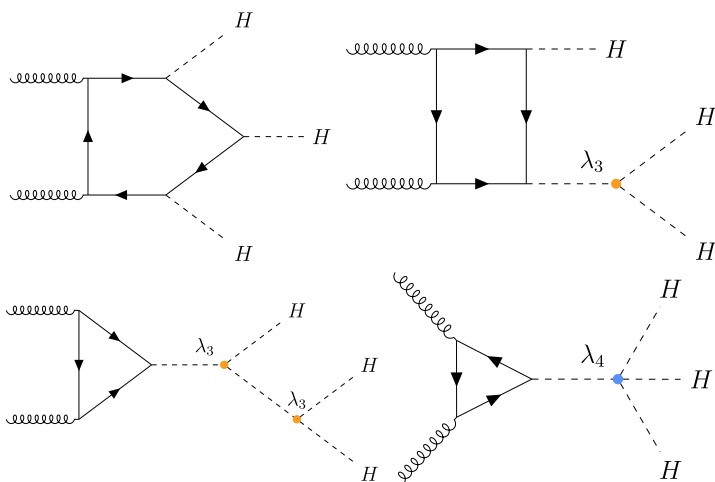
Expected 95% CL interval width: -6% vs HH (κ_3 only); $+2\%$ with coupling profiling.

HH provides direct κ_3 sensitivity; single H adds loop information and constrains other Higgs couplings. H+HH enables coupling profiling with little loss in κ_3 sensitivity and reduced model dependence.

HHH $\rightarrow$ 6b: direct access to the quartic vertex

HHH probes κ_4 directly, while its dependence on κ_3 and the HH component also matters.

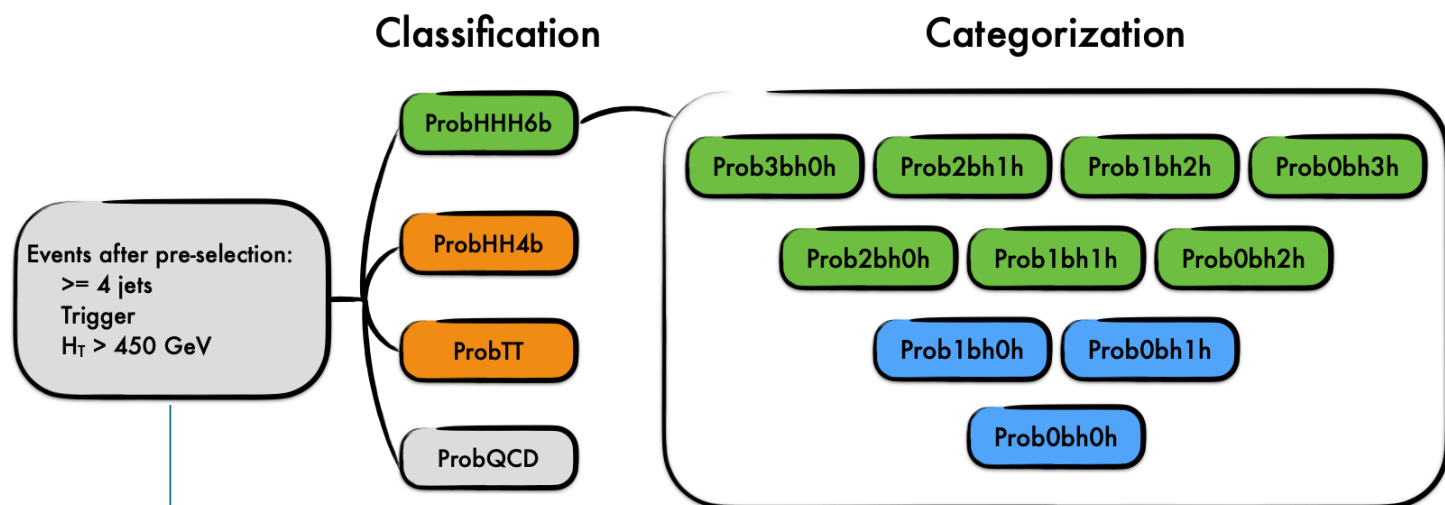
ggF HHH



Why 6b?

Three $H \rightarrow b\bar{b}$ decays give a sizeable branching fraction; multijet backgrounds and jet assignment remain challenging.

CMS analysis strategy

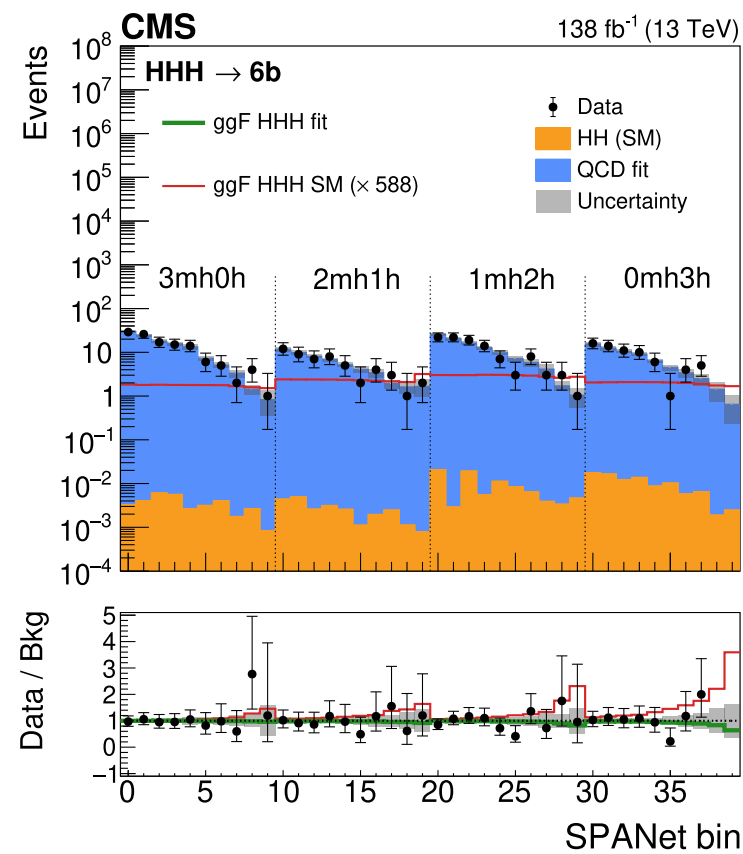


ParticleNet identifies b jets and merged $H \rightarrow b\bar{b}$ candidates.

SPANet (symmetry-preserving attention) assigns jets to H candidates and classifies event topologies.

CMS 6b: rate limits and coupling slices

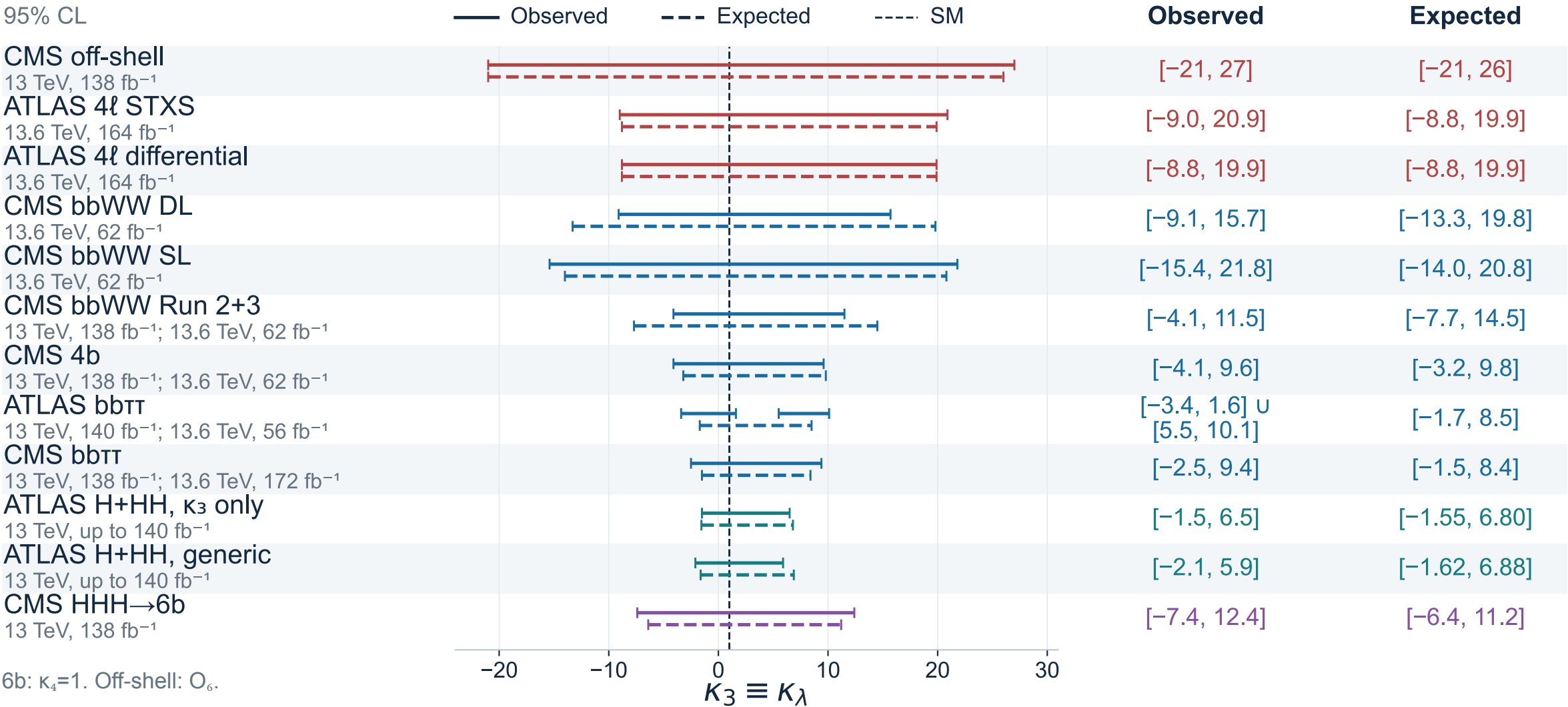
138 fb⁻¹ at 13 TeV



95% CL	Observed	Expected
μ_{HHH} upper limit	588	572
$\kappa_3, \kappa_4=1$	$[-7.4, 12.4]$	$[-6.4, 11.2]$
$\kappa_4, \kappa_3=1$	$[-177, 185]$	$[-180, 190]$

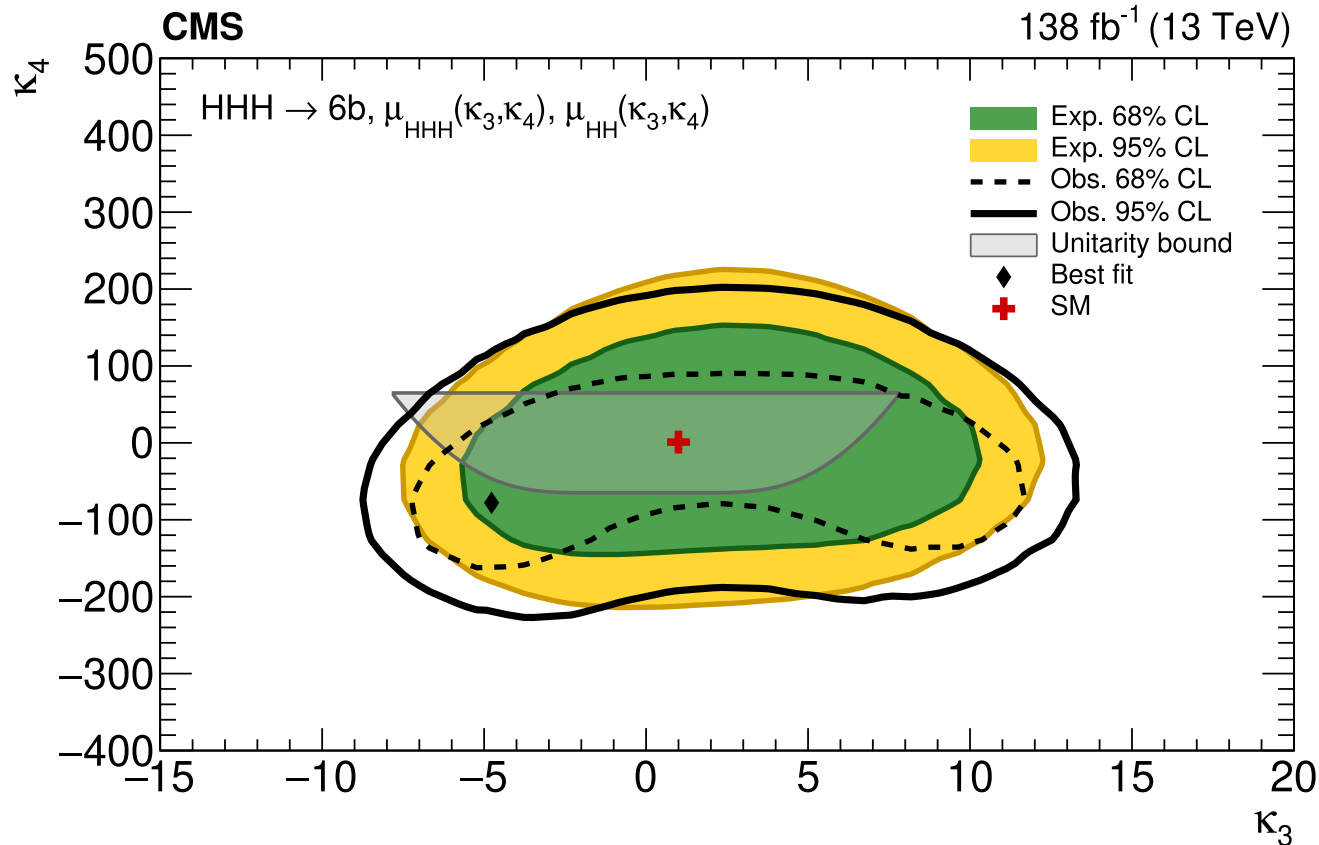
6b adds direct quartic information to the experimental test of the Higgs potential.

Trilinear constraints from H, HH and HHH



Complementary H, HH and HHH measurements provide a broad study of κ_3 across different processes and kinematic regimes.

The self-coupling picture is two-dimensional

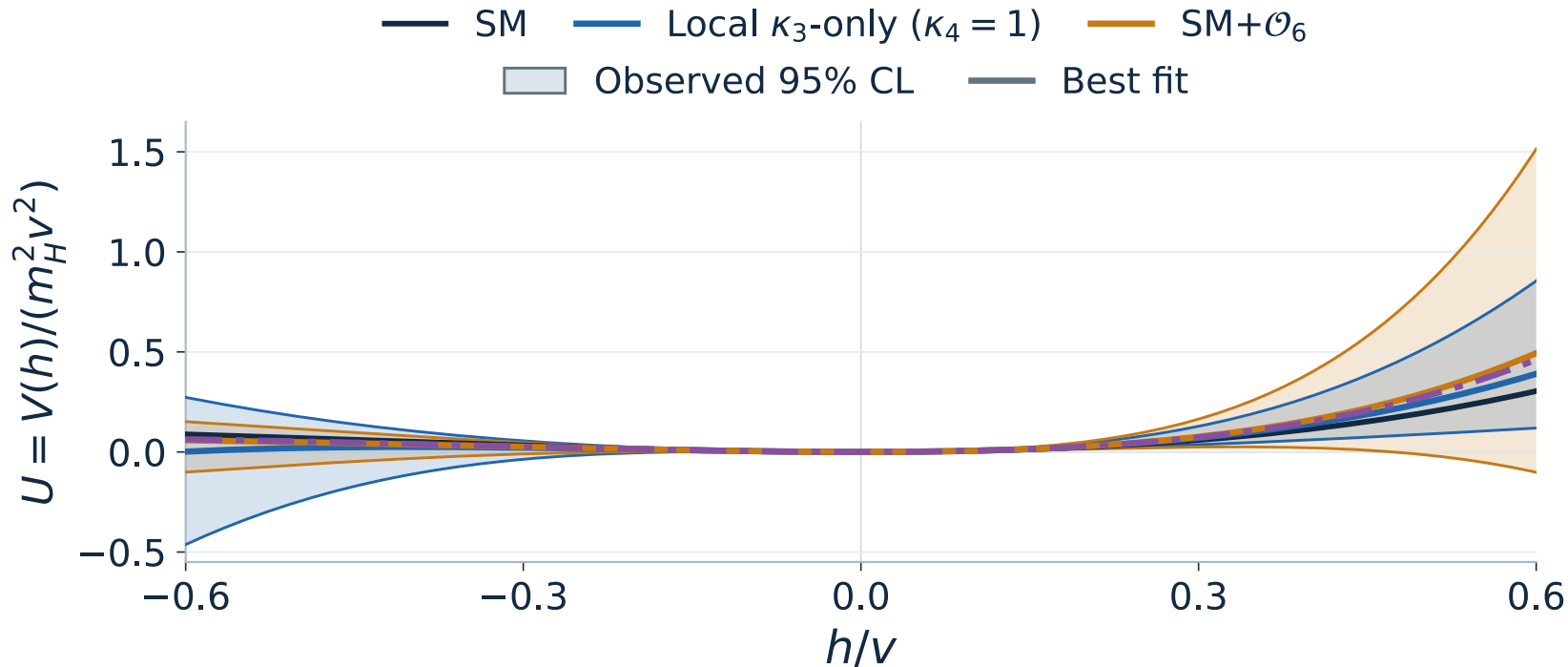


- The 6b likelihood constrains κ_3 and κ_4 simultaneously.
- HH also depends on κ_4 through electroweak loop corrections.
- Perturbative unitarity limits the strength of HH→HH scattering. CMS excludes part of the allowed region.

Probing both trilinear and quartic self-couplings gives a more complete test of the Higgs potential.

HH constraints and the Higgs potential

$$U_{\text{local}} = \frac{V(h)}{m_H^2 v^2} = \frac{x^2}{2} + \frac{\kappa_3 x^3}{2} + \frac{x^4}{8}, \quad x = \frac{h}{v}.$$



Observed κ_3 , 95% CL: $[-0.71, 6.1]$

Best fit $\kappa_3 = 1.8$

**The transition prediction comes from the model's finite-temperature potential.
 Current HH constraints still allow this SMEFT6 strong-transition benchmark.**

Interpreting the electroweak transition requires a specified model.

SM+ $\mathcal{O}_6$ is a minimal gauge-invariant extension of the potential: one parameter correlates its higher self-interactions.

$$U_{\mathcal{O}_6} = U_{\text{SM}} + \frac{(\kappa_3 - 1)x^3(x+2)^3}{16}$$

$$\kappa_4 - 1 = 6(\kappa_3 - 1)$$

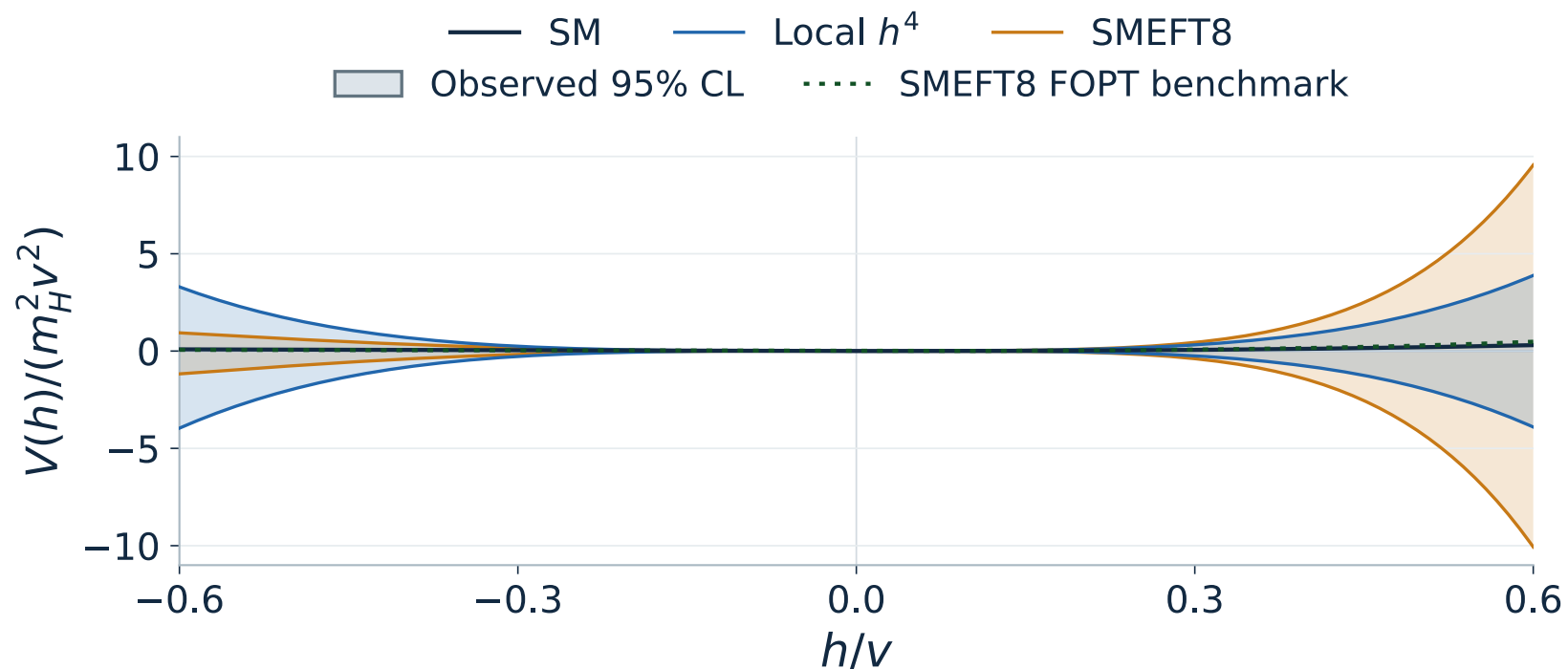
SMEFT6 FOPT boundary

$$(\kappa_3, \kappa_4) \approx (1.66, 4.96)$$

Joint self-couplings and the Higgs potential

Together, trilinear and quartic self-couplings provide a fuller test of the Higgs potential.

$$U_8(x) = U_{\text{SM}}(x) + \frac{(\kappa_3 - 1)x^3(x+2)^3}{16} + \frac{(\kappa_4 - 6\kappa_3 + 5)x^4(x+2)^4}{128}.$$



SMEFT8

Independent κ_3 and κ_4 , with higher self-interactions correlated through h^8 .

Strong-FOPT boundary benchmark

$$(\kappa_3, \kappa_4) \approx (1.69, 5.4)$$

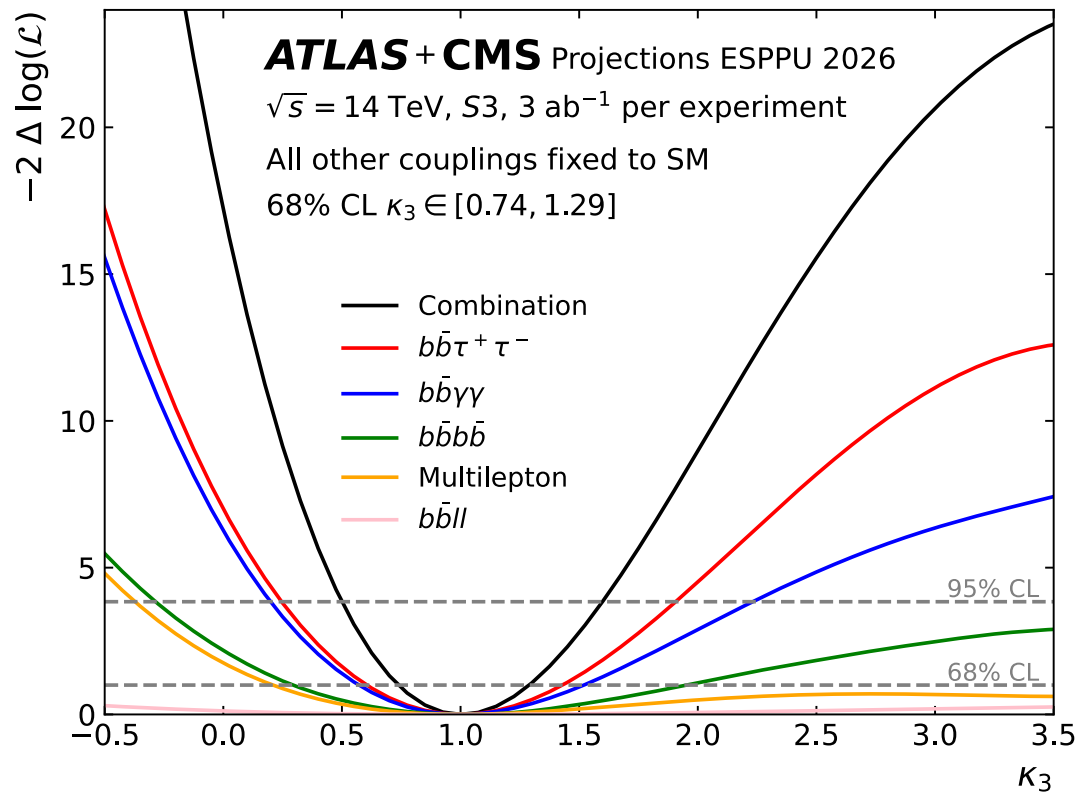
Within the observed CMS 2D region.

Current joint constraints still allow this SMEFT8 strong-transition benchmark.

HL-LHC: HH observation and a precise κ_3 measurement

Projections set quantitative targets for HH observation and a precise self-coupling measurement.

ATLAS+CMS · 14 TeV · 3 ab⁻¹ per experiment



Expected joint limit

HH significance

7.6 σ

κ_3 , 68% CL

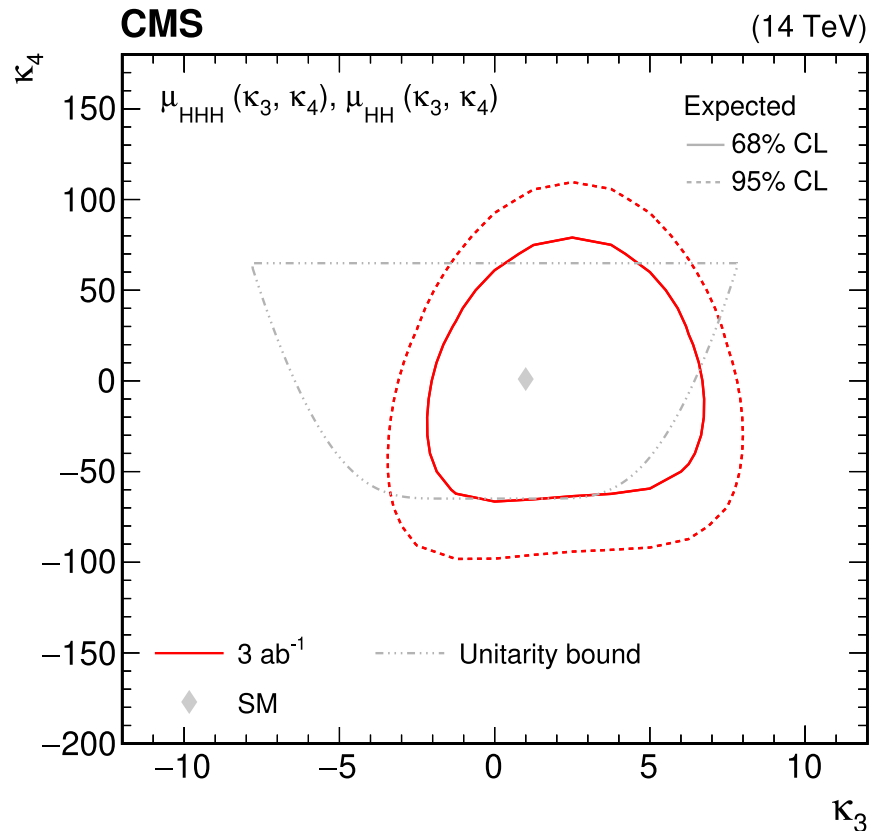
[0.74, 1.29]

What sets the results?

The projected results depend on detector and reconstruction performance, background control and systematic uncertainties.

HL-LHC: extend the test to κ_4

The trilinear target is much closer; the quartic programme remains essential and challenging.



CMS HHH projection

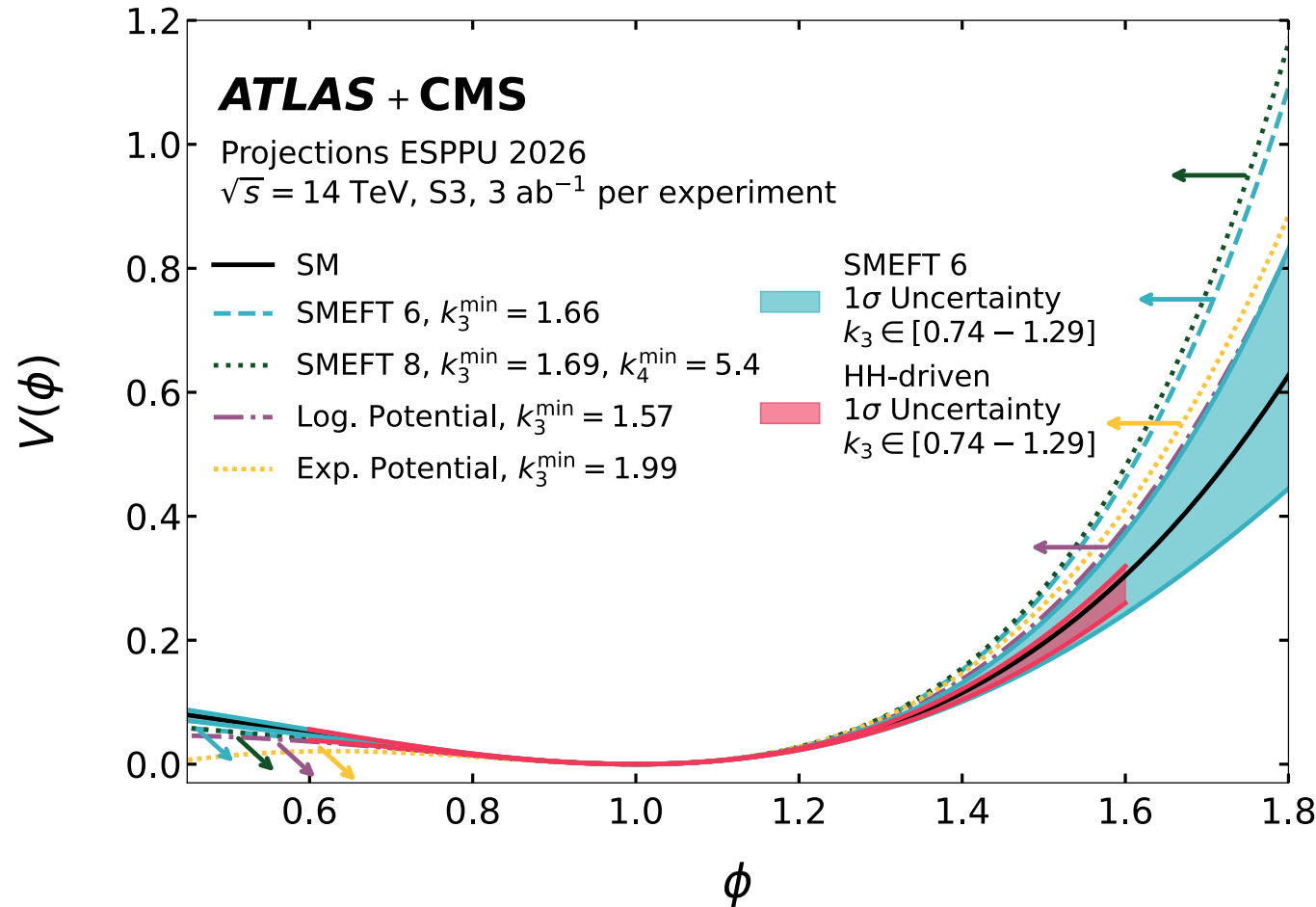
14 TeV · 3 ab^{-1}

Expected 95% CL

$$\mu_{HHH} < 151$$

Further channels, improved reconstruction and controlled coupling-dependent modelling are needed for a more complete κ_4 programme.

HL-LHC: the Higgs potential and electroweak transition



$$\varphi = 1 + x = 1 + \frac{h}{v}$$

$$V_{\text{figure}}(\varphi) = U(\varphi - 1) \\ = \frac{V(h)}{m_H^2 v^2}$$

Potential/phase-transition interpretations must combine complementary probes within a specified model.

Conclusions

1 Recent self-coupling progress relies on complementary H, HH and HHH measurements.

Run 3 HH gains come from data, triggering, reconstruction and analysis strategies. Precision H adds loop information; HHH→6b adds direct κ_4 sensitivity.

2 Current data still allow a wide range of self-couplings.

Observed, 95% CL:

ATLAS H+HH, κ_3 only: $\kappa_3 \in [-1.5, 6.5]$.

CMS HHH→6b, κ_4 only: $\kappa_4 \in [-177, 185]$.

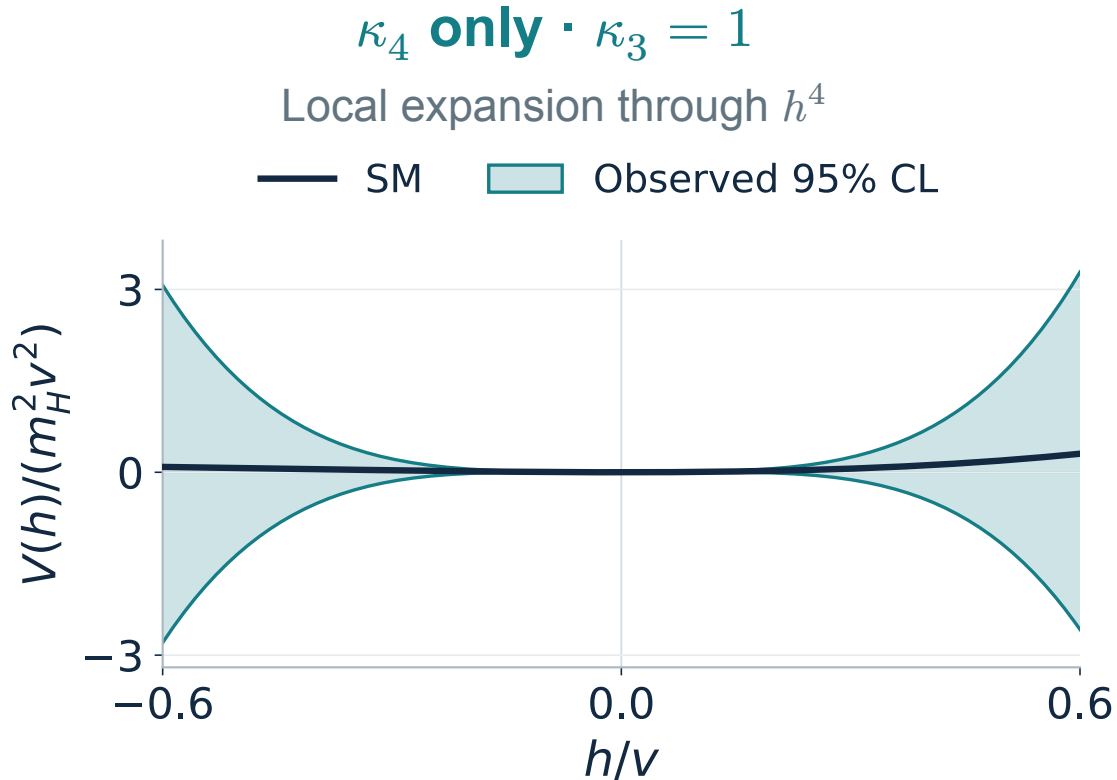
3 HL-LHC targets HH observation and a κ_3 measurement.

Joint projections reach roughly 30% trilinear precision. A fuller test of the potential also requires quartic information and a specified theoretical framework.

Thank you!



Backup: quartic potential and conventions



Observed, 95% CL: $[-177, 185]$

Expected, 95% CL: $[-180, 190]$

Coupling conventions

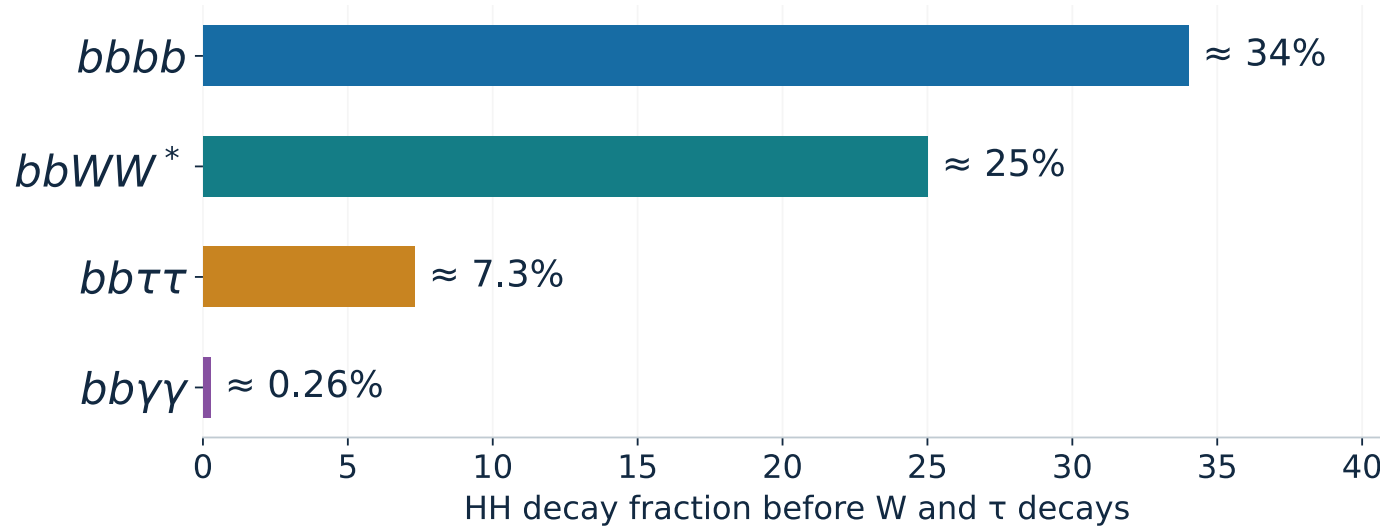
$$V(h) = \frac{1}{2}m_H^2 h^2 + \lambda_3 v h^3 + \frac{1}{4}\lambda_4 h^4 + \dots$$

$$\lambda_3^{\text{SM}} = \lambda_4^{\text{SM}} = \frac{m_H^2}{2v^2} \approx 0.13$$

$$\kappa_i = \frac{\lambda_i}{\lambda_i^{\text{SM}}}$$

- Vertex conventions with $\frac{g_{hhh}}{3!}$ and $\frac{g_{hhhh}}{4!}$ give the same modifiers after consistent normalisation.
- κ_{2V} modifies HHVV, not the four-Higgs vertex. A strong $\kappa_2 V$ result is not a κ_4 measurement.
- κ -only, SMEFT single-operator and more general EFT interpretations impose different correlations and validity assumptions.

Backup: complementary HH decay channels



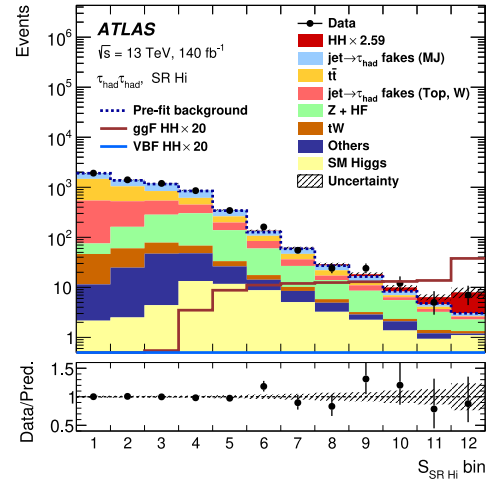
- 4b: highest decay fraction; difficult multijet background.
- $bb\tau\tau$: useful rate with distinctive τ signatures.
- $bbWW$: several lepton topologies; missing energy and top backgrounds.
- $bb\gamma\gamma$: small rate but a narrow diphoton mass peak.

Channel value depends on resolution, purity, acceptance and parameter dependence, not branching fraction alone.

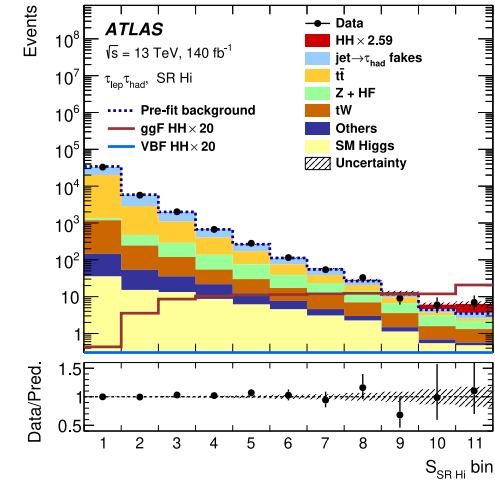
Backup: ATLAS bb $\tau\tau$ SR Hi distributions

Run 2

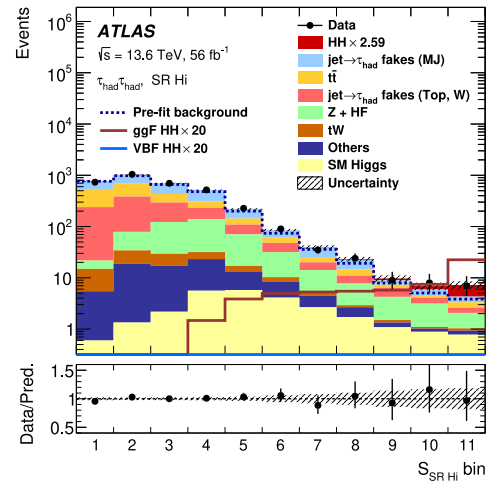
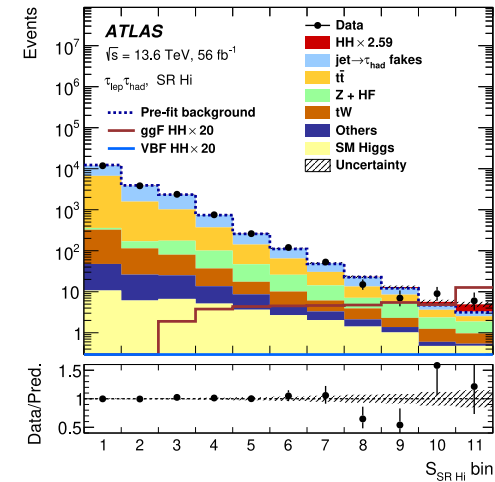
$\tau_{\text{had}}\tau_{\text{had}}$



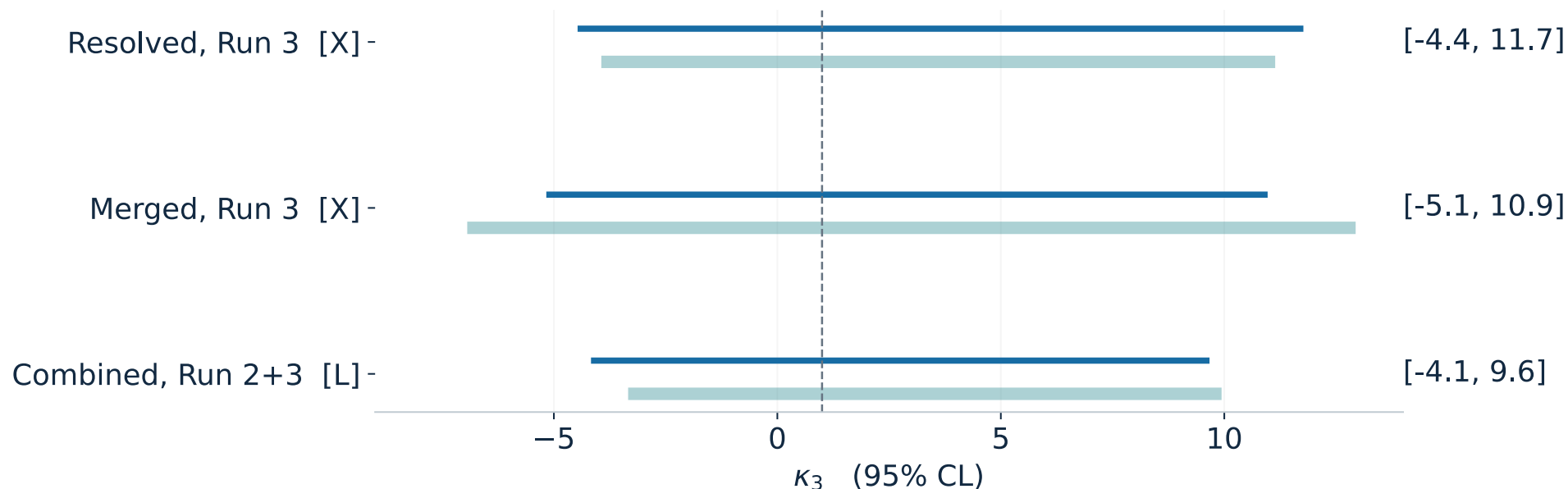
$\tau_{\text{lep}}\tau_{\text{had}}$



Run 3



Backup: why the 4b topologies differ



Resolved results retain the lower-boost acceptance useful for κ_3 . Merged reconstruction improves boosted reach and has a strong role in VBF/ κ_2 V sensitivity. The published best expected approach is used for each topology, with overlap removal before combination.

Observed intervals shown with expected intervals in pale teal. The combined Run 2+3 row also changes dataset and interval construction; it is not a topology-only comparison.

Backup: bbWW combinations and expected results

Configuration	μ_{HH} UL obs. (exp.)	κ_3 obs. 95% CL	κ_3 exp. 95% CL
Run 3 DL, public	12.0 (18.5)	−9.1 to 15.7	−13.3 to 19.8
Run 3 SL	35 (29)	−15.4 to 21.8	−14.0 to 20.8
Run 3 SL+DL	11 (16)	−7.3 to 14.3	−10.3 to 17.2
Run 2+3	7.8 (12)	−4.1 to 11.5	−7.7 to 14.5

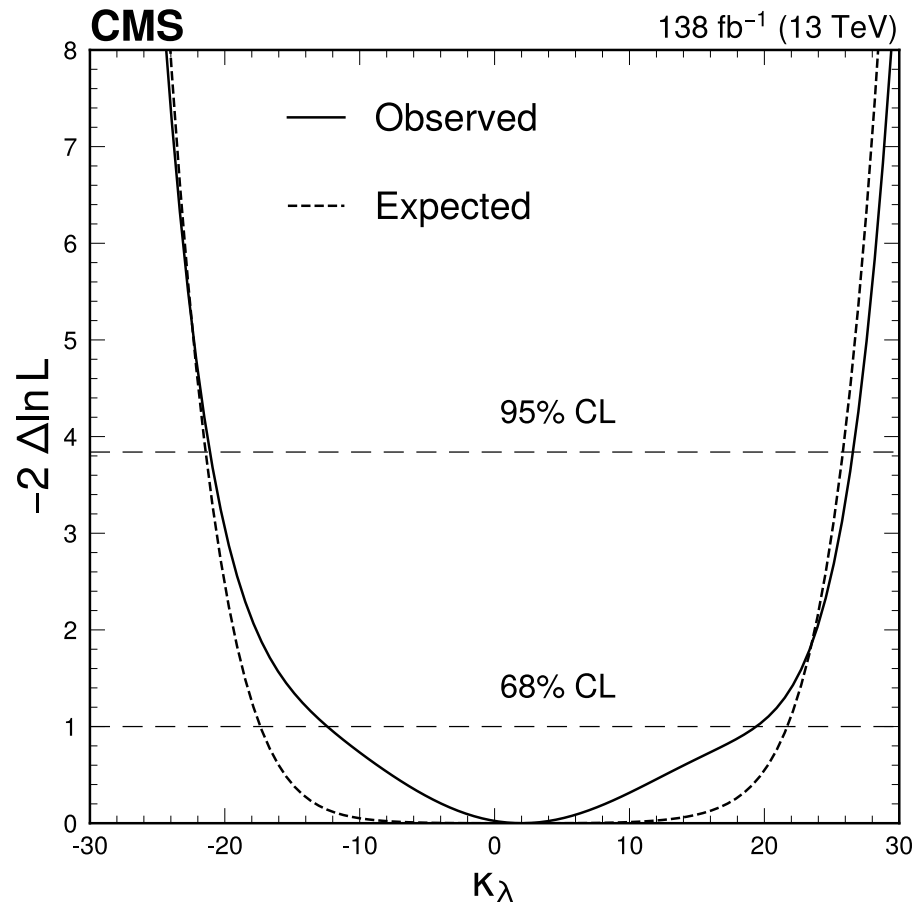
κ_3 intervals use profile likelihood with SM Asimov expected scans. HH upper limits use background-only expected results. The Run 2 input combines SL and DL.

Backup: ATLAS 4l interpretation

$$Z_H^{\text{BSM}} = \frac{1}{1 - (\kappa_3^2 - 1) \delta Z_H}$$

- The fiducial differential interpretation uses the unfolded four-lepton transverse-momentum spectrum. STXS uses production-mode and kinematic bins extracted with a categorised signal model.
- The paper attributes the slightly weaker observed STXS constraint to its fitted ggF signal strength being below the inclusive signal strength. Rate suppression at large $|\kappa_3|$ provides a qualitative explanation; the endpoints depend on the full likelihood.
- These results use the same underlying dataset. Their statistical and systematic correlations must be included before any combination.
- The paper states $|\kappa_3| < 20$ for the loop parameterisation. The quoted STXS upper limit 20.9 should be read with this validity caveat.

Backup: the off-shell likelihood



Observed versus expected

Best fit:

$$\kappa_3 = 2^{+17}_{-15}$$

68% CL

Observed 95% CL: [-21, 27]

Expected 95% CL: [-21, 26]

The interpretation isolates the effect of the potential operator O_6 . Rate and high-mass shape information probe its loop corrections.

The width and other BSM results in the same paper are separate interpretations; their significances are not a measurement of κ_3 .

Backup: H+HH with more couplings profiled

Fit	Observed 95% CL	Expected 95% CL
Single H	−5.3 to 8.8	−4.35 to 10.56
HH	−1.3 to 7.2	−1.71 to 7.18
H+HH, others fixed	−1.5 to 6.5	−1.55 to 6.80
H+HH, generic	−2.1 to 5.9	−1.62 to 6.88

The generic fit profiles κ_V , κ_t , κ_b and κ_τ alongside κ_3 . Its observed best fit shifts from 1.3 to 0.6. Expected intervals provide the cleaner comparison of the information retained when the assumptions are relaxed.

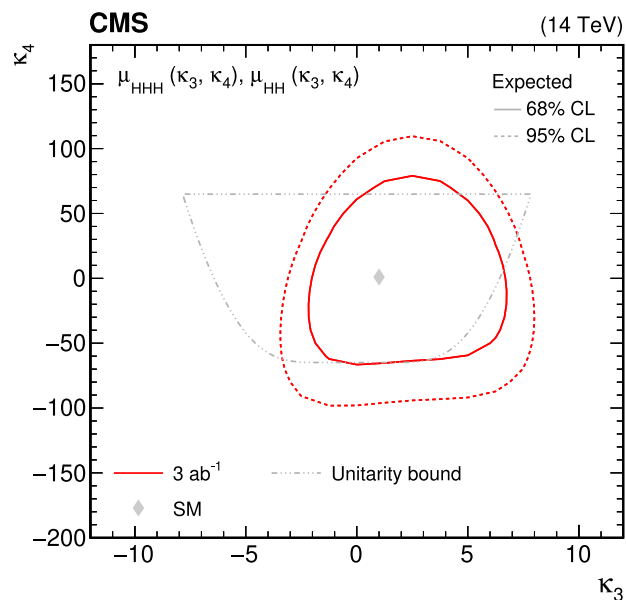
Backup: the trilinear comparisons in context

- All summary rows quote reported 95% CL intervals. An observed allowed interval is not an error bar around $\kappa_3=1$. Disconnected regions remain disconnected.
- Most rows fix other couplings to SM. The 6b slice additionally fixes $\kappa_4=1$ and uses rate-only signal scaling with an HH contribution. Off-shell bounds use the specified O_6 interpretation.
- Likelihood intervals, CLs cross-section intersections, Asimov signal assumptions and conditional nuisance treatments need not be identical. The native definitions are retained.
- Overlapping events, common uncertainties and different models prevent treating this summary as a new H+HH+HHH statistical combination.

Backup: HHH projections in context

CMS · 2026

14 TeV · 3 ab⁻¹ · one experiment

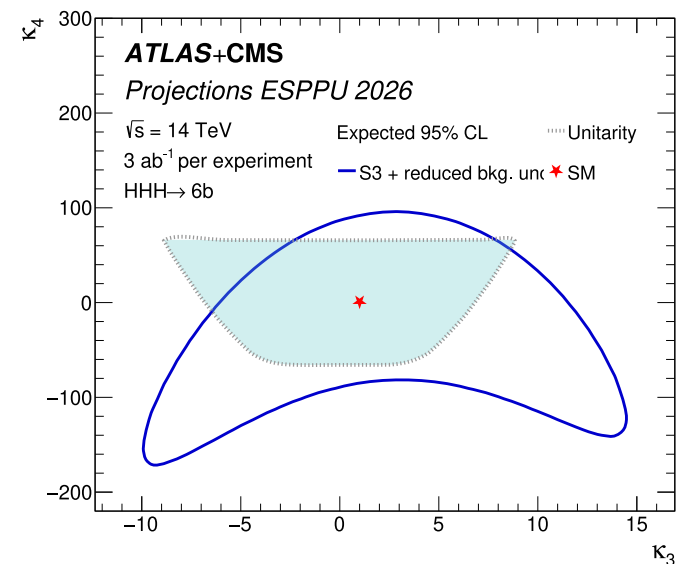


$\mu_{HHH} < 151$ Expected, 95% CL

CMS 6b analysis extrapolated to HL-LHC.

ATLAS+CMS · ESPPU 2026

14 TeV · 3 ab⁻¹ per experiment



$\mu_{HHH} < 86$ Expected, 95% CL

ATLAS-based sensitivity applied to both experiments;
reduced background uncertainty.

Different experiment counts and analysis assumptions prevent a direct improvement comparison.

Backup: projection inputs and potential benchmarks

Projection inputs

S2: reduced theory and experimental uncertainties.

Scenario	HH	$\delta\kappa_3$
2 ab ⁻¹ , S2	6.0 σ	-32/+37%
3 ab ⁻¹ , S2	7.2 σ	-27/+31%
3 ab ⁻¹ , S3	7.6 σ	-26/+29%

Existing signal, background and nuisance-parameter likelihood models are extrapolated.

ATLAS+CMS · 14 TeV

Luminosity per experiment; $\delta\kappa_3$ at 68% CL.

Assumes $\kappa_3^{\text{true}}=1$; other couplings fixed to SM.

SMEFT6: $\kappa_3^{\text{min}}=1.66 \Rightarrow \kappa_4 \approx 4.96$. SMEFT8: $\kappa_3^{\text{min}}=1.69$, $\kappa_4^{\text{min}}=5.4$.

Log potential: $\kappa_3^{\text{min}}=1.57$. Exponential potential: $\kappa_3^{\text{min}}=1.99$.

Potential benchmarks

SMEFT6: one O_6 coefficient fixes the higher derivatives.

$$\kappa_4 - 1 = 6(\kappa_3 - 1)$$

SMEFT8: adds an independent quartic direction.

HH-driven: local cubic variation around the vacuum.

Log / exp: nonpolynomial potential terms inspired by loop / instanton effects.

κ^{min} denotes a model-dependent strong-FOPT boundary, rather than an experimental limit.

Backup: rare modes add new coupling directions

ATLAS $t\bar{t}HH$ · Run 2+3 · 196 fb^{-1}



$$\mu_{t\bar{t}HH} < 20$$

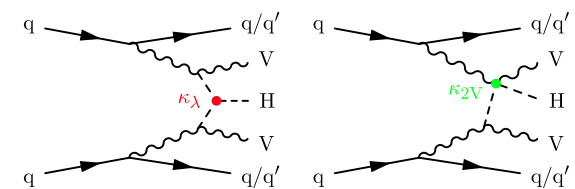
Expected 21; observed 95% CL

$$-3.9 < c_{t\bar{t}HH} < 3.3$$

HEFT contact interaction; SM value 0

CMS SL, 138 fb^{-1} : $\mu < 49$ (55 expected).
HEFT: $-6.6 < c_2 < 6.4$ (observed 95% CL).

CMS VBS VVH · Run 2 · 138 fb^{-1}



$$0.40 < \kappa_{2V} < 1.60$$

Expected [0.34, 1.66]; observed 95% CL

First search for VBS VVH.

All other couplings fixed to SM; $\kappa_3=1$.

First public July 2025; paper in 2026.

References and result status

ATLAS+CMS HH combination

arXiv:2602.23991 · PRL 137 (2026) 131803

Context: first public in October 2025

ATLAS HH→bbττ

arXiv:2607.26879 · July 2026

CMS HH→bbττ

CMS-PAS-HIG-25-008 · August 2026

CMS HH→4b

arXiv:2604.27044 · April 2026 paper

First public PAS: 29 October 2025

CMS HH→bbWW, dilepton

arXiv:2604.02127 · JHEP 08 (2026) 019

CMS bbWW SL and combinations

CMS-PAS-HIG-25-022

26 October 2026

ATLAS H→4l differential/STXS

arXiv:2605.19016 · JHEP 08 (2026) 052

CMS off-shell H→4l

arXiv:2607.23352 · July 2026

ATLAS single-H and H+HH combination

arXiv:2608.07332 · August 2026

CMS HHH→6b

arXiv:2607.05145v2 · September 2026 revision

First public PAS: 7 October 2025

ATLAS+CMS HL-LHC projections

arXiv:2504.00672

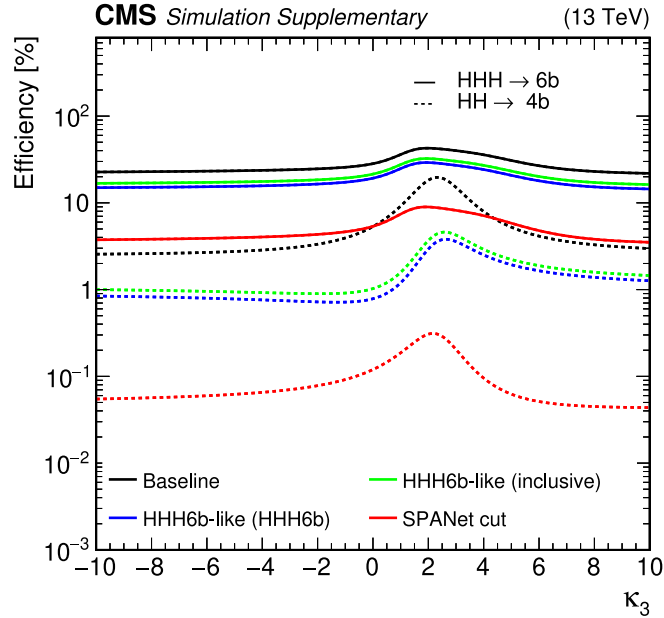
ATL-PHYS-PUB-2025-018 / CMS-HIG-25-002

Single-Higgs STXS κ_3 parameterisation

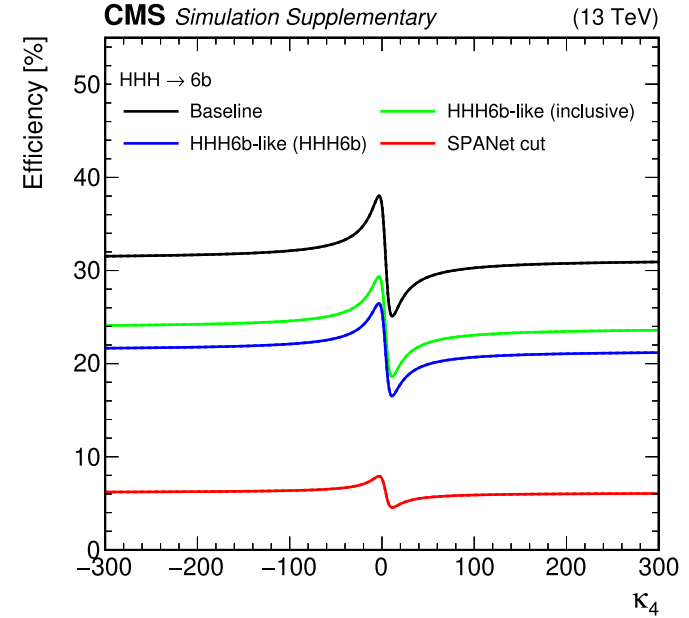
LHC Higgs Working Group · LHCHWG-2022-002

Backup: coupling-dependent selection efficiency

κ_3 : HHH and HH



κ_4 : HHH



$$N_b^P(\kappa_3, \kappa_4) = \frac{\sigma_P(\kappa_3, \kappa_4)}{\sigma_P^{\text{SM}}} N_b^{P, \text{SM}}, \quad P = \text{HH}, \text{HHH}$$

Nominal: SM selection efficiencies and template shapes; $\kappa_t = 1$.

Estimated weakening of expected boundaries: 12–15% for κ_3 ($\kappa_4=1$); 2–4% for κ_4 ($\kappa_3=1$).

Backup: HH loop dependence and perturbative unitarity

HH→HH: perturbative unitarity

$$\mathcal{A} = \kappa_4 \mathcal{A}_c + \kappa_3^2 (\mathcal{A}_s + \mathcal{A}_t + \mathcal{A}_u)$$

Tree-level contact and s/t/u Higgs-exchange amplitudes.

$$|\text{Re } a_0| \leq \frac{1}{2}$$

a_0 : the $J = 0$ partial wave, bounded by probability conservation.

Gray region on p26: satisfies this tree-level perturbative unitarity condition.

Outside the boundary, the perturbative description breaks down. This is not an experimental exclusion.

Why μ_{HH} depends on κ_4

$$\mu_{HH}(\kappa_3, \kappa_4) = \frac{\sigma_{HH}(\kappa_3, \kappa_4)}{\sigma_{HH}^{\text{SM}}}$$

At leading order, κ_3 enters the ggF HH triangle amplitude. Neither box nor triangle contains κ_4 .

Electroweak two-loop corrections contain the four-Higgs vertex, introducing κ_4 dependence.

CMS 6b coupling scans retain both HH and HHH contributions.