Multi Higgs Measurements and Projections for the European Strategy Update

Agni Bethani on behalf of CMS and ATLAS

SM@LHC 2025

The Higgs potential

Higgs complex doublet $\varphi = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix}$

$\mu^2 < 0, \lambda > 0$

- Higgs potential (real part): $V(\varphi) = -\frac{1}{2}\mu^2\varphi^2 + \frac{1}{4}\lambda\varphi^4$
- Expand around the vacuum expectation value: $V(\varphi) \rightarrow V(\upsilon + h)$
- $V(h) = V_0 + \lambda\upsilon^2 h^2 + \lambda\upsilon h^3 + \frac{1}{4}\lambda h^4 + \cdots$
- $V(h) = V_0 + \frac{1}{2}{m_h}^2 h^2 + \lambda\upsilon h^3 + \frac{1}{4}\lambda h^4 + \cdots$

$\upsilon = \frac{\mu}{\sqrt{\lambda}}$ and $\mu = \frac{{m_h}^2}{2}$

Mass term

Higgs trilinear self-coupling

Higgs quadratic self-coupling

Double Higgs production

Triple Higgs production

In the SM υ=246 GeV

$$\lambda = \frac{{m_h}^2}{2\upsilon^2} \approx 0.13$$

The Higgs potential

Higgs complex doublet $\varphi = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix}$

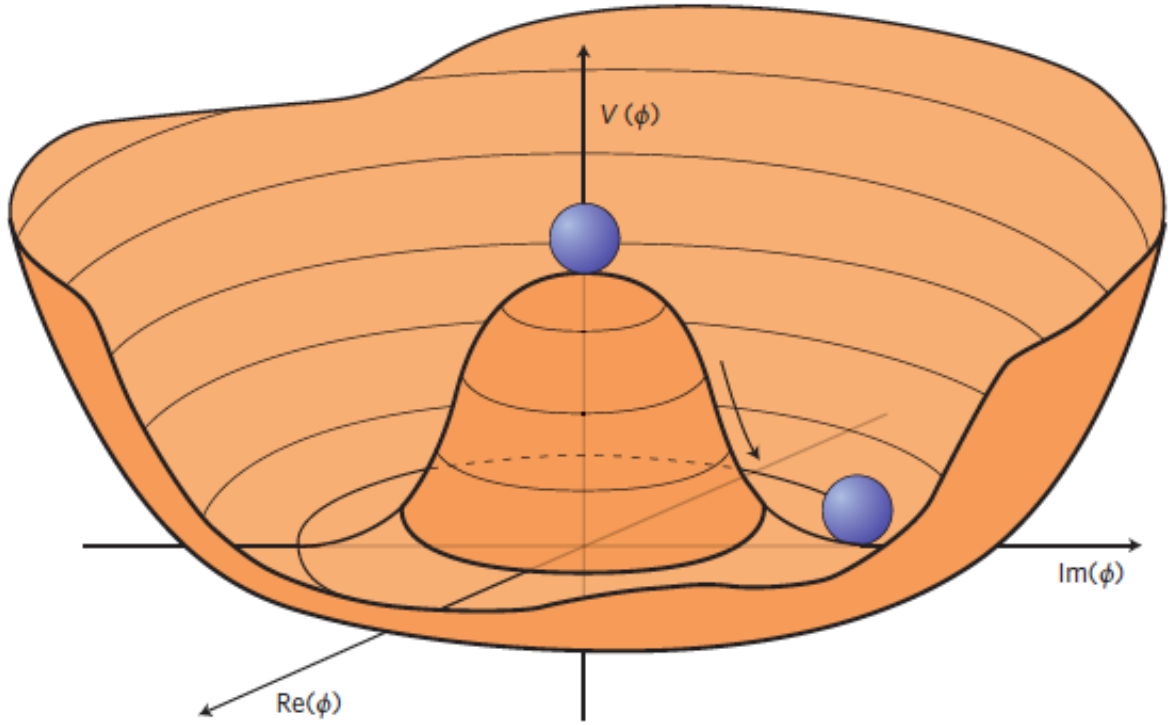
$\mu^2 < 0, \lambda > 0$

- Higgs potential (real part): $V(\varphi) = -\frac{1}{2}\mu^2\varphi^2 + \frac{1}{4}\lambda\varphi^4$
- Expand around the vacuum exp
- $V(h) = V_0 + \lambda v^2 h^2 + \lambda v h^3 +$
- $V(h) = V_0 + \frac{1}{2}m_h{}^2 h^2 + \lambda v h^3$ -

Mass term

Higg trilinear coupli

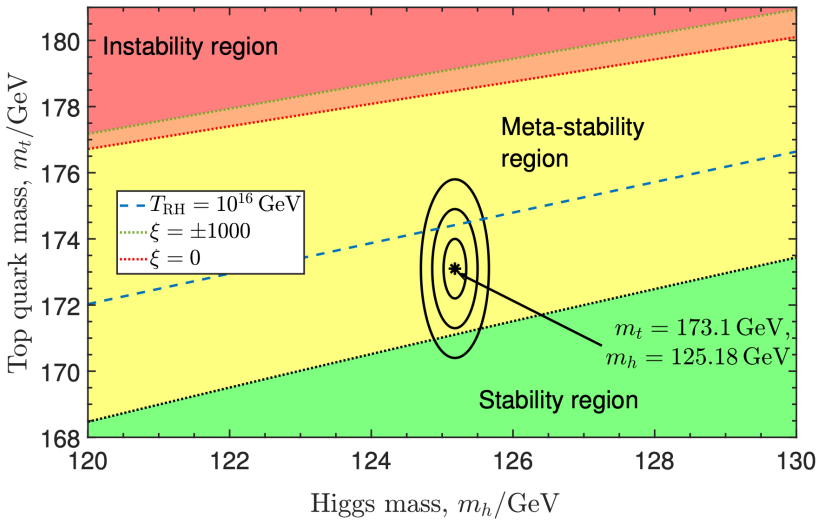
Double Higgs production
This is what this talk is about

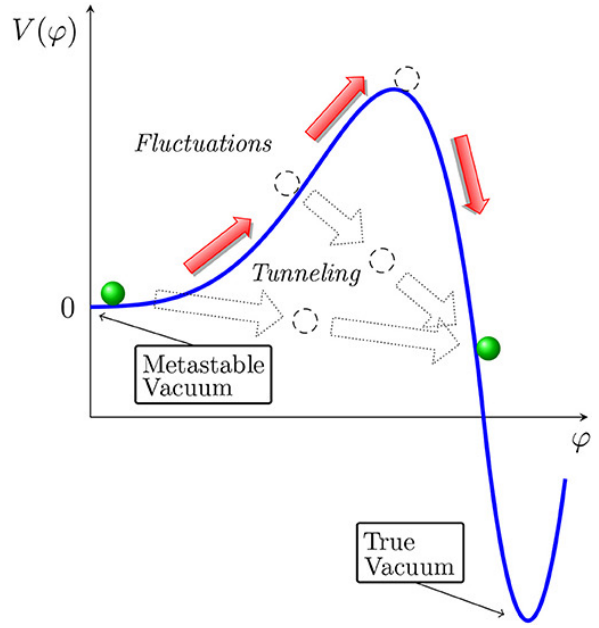


Triple Higgs production

The Higgs potential

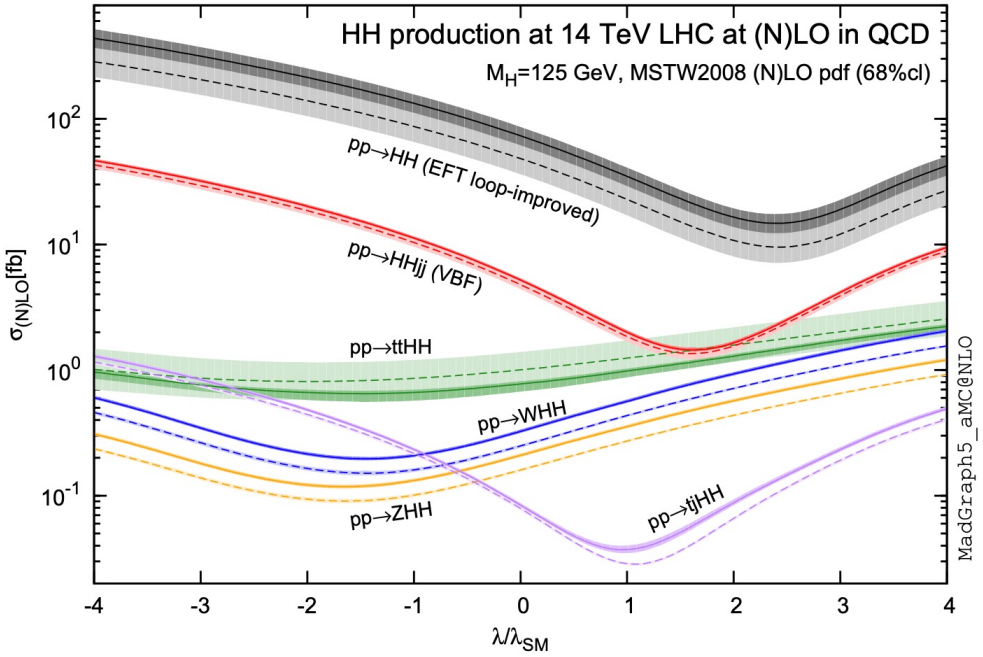
- The least explored part of the Standard Model!
- The Higgs sector is sensitive to new physics BSM
- Cosmological consequences:
  - Inflation
  - Vacuum stability
  - Baryogenesis
  - …?

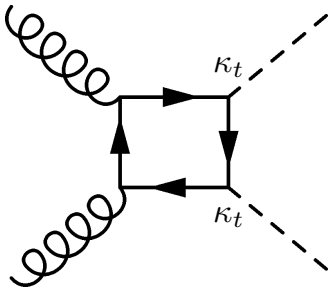


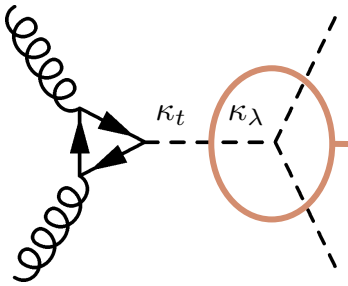


Double Higgs production at the LHC (SM)

- At the LHC dominant production mechanism for SM double Higgs production is gluon fusion (ggf)
- Other productions such as VBF and VHH also possible; σ is much smaller
- The "box" and "triangle" diagrams interact destructively
- SM cross-section very small !!
  (~1000 times smaller than single Higgs production)







Higgs trilinear coupling

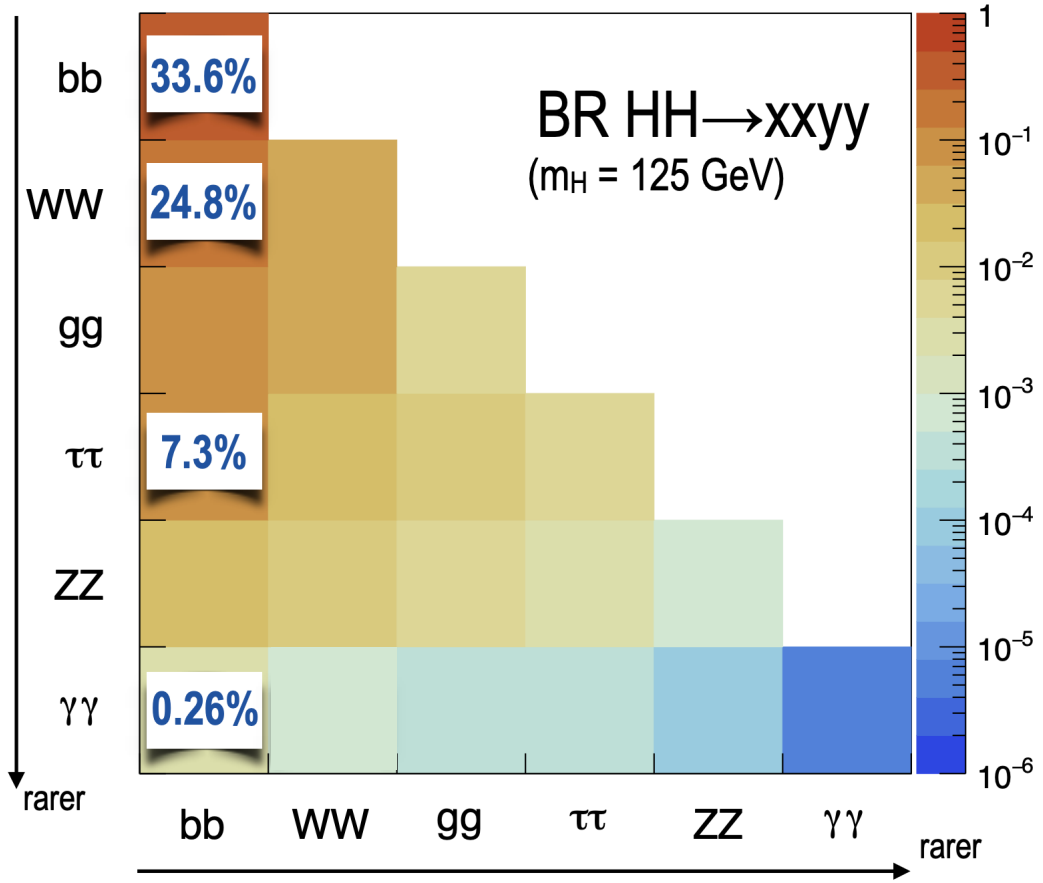
HH decays:

Most sensitive

bbbb:
the highest branching fraction, large multijet background

bbWW(bbVV):
Second largest branching fraction
Large background. Final states with at least one lepton cleaner.

Multilepton(WW*WW*, WW*ττ, and ττττ):
Many different signatures, clean leptonic final states, no b-tagging needed



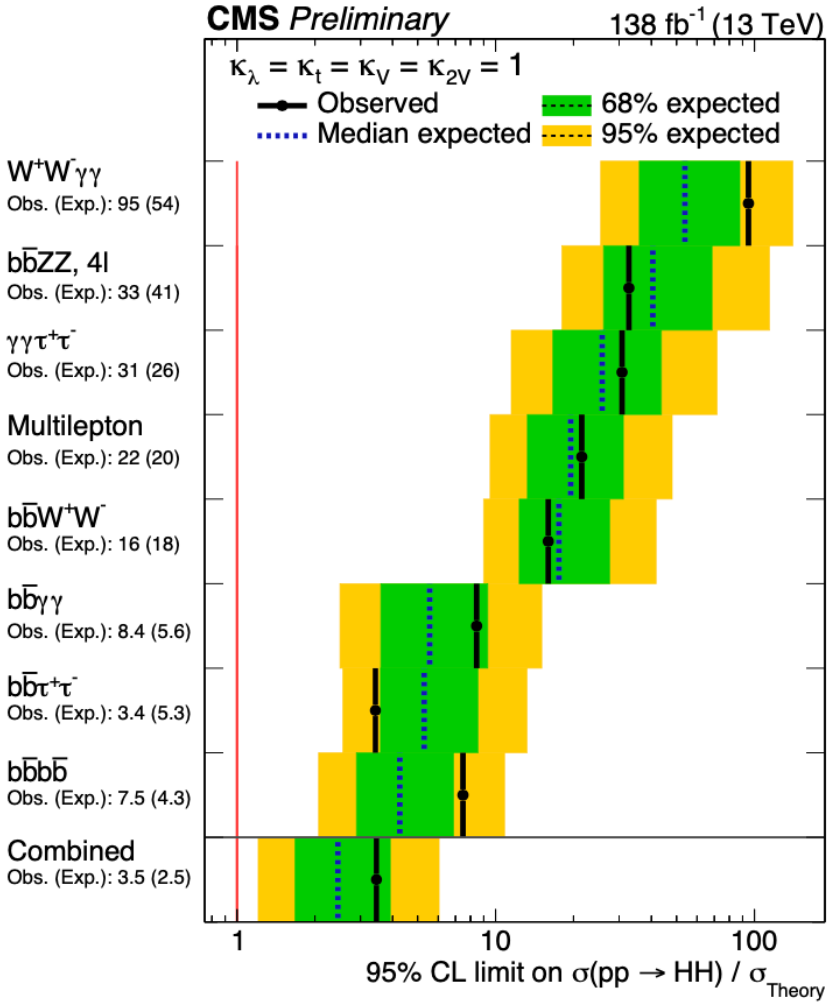
bbττ:
relatively large branching fraction, cleaner final state

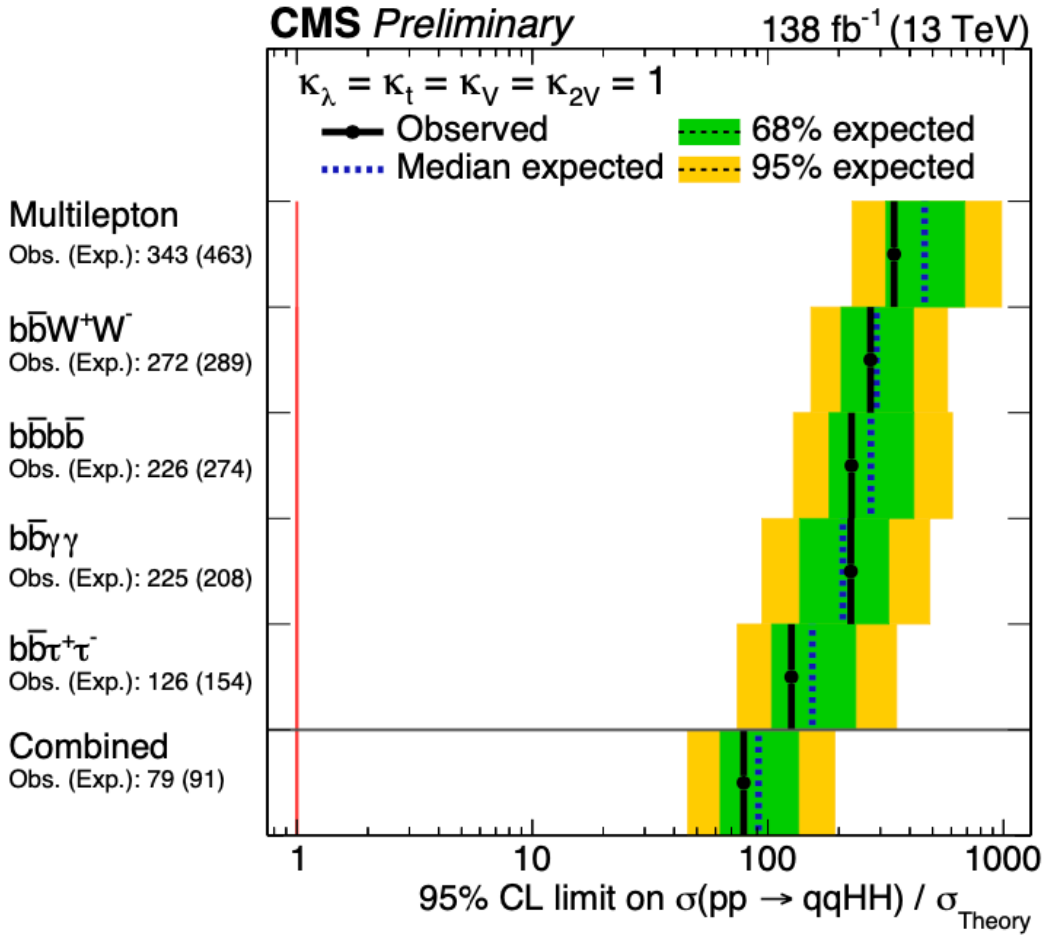
bbγγ:
very small branching fraction, clean signal extraction due to the narrow h → γγ mass peak

WWγγ:
Clean γγ peak, leptonic final states or jets

ττγγ:
best of ττ and γγ. Small BR

Higgs pair production cross-section





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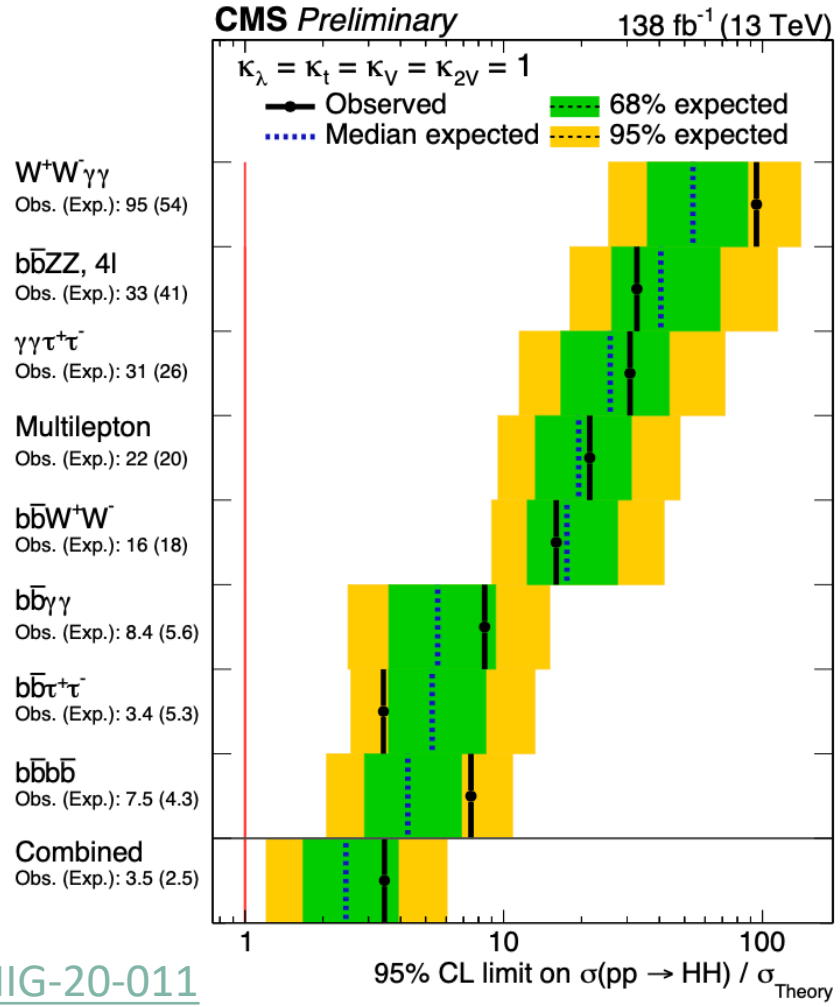
Higgs pair production cross-section



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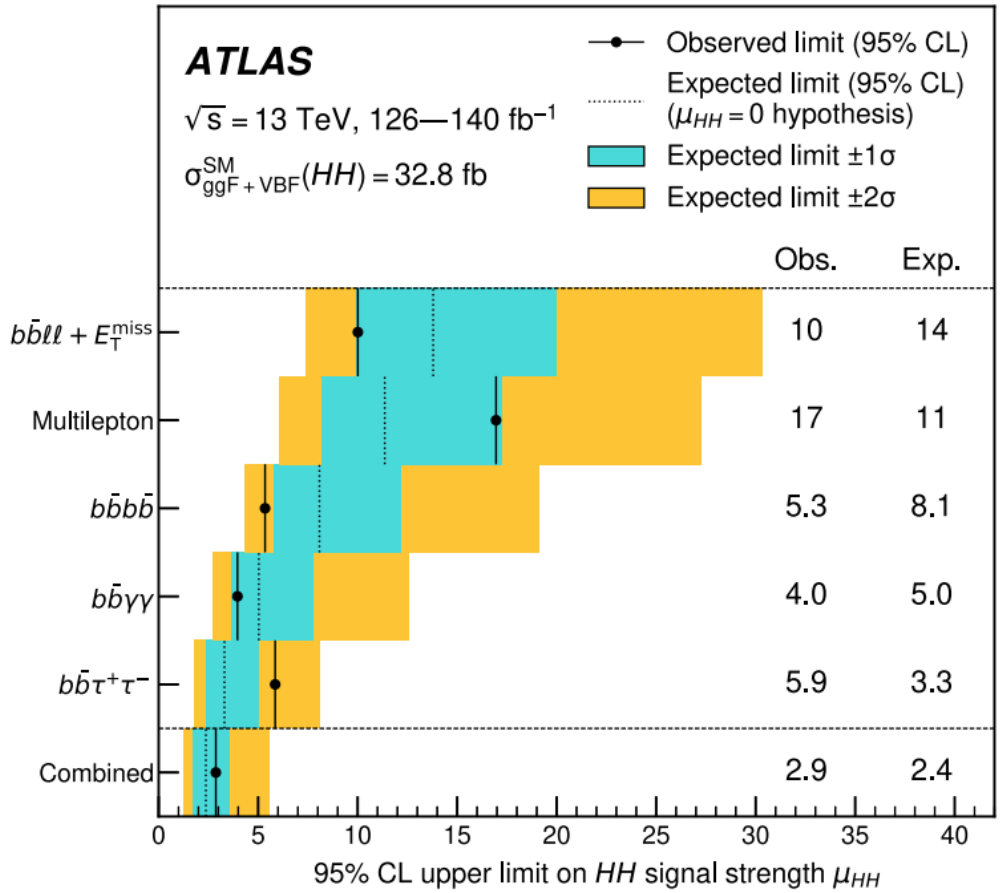
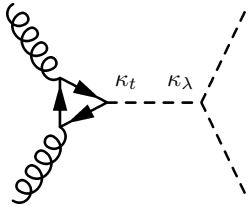
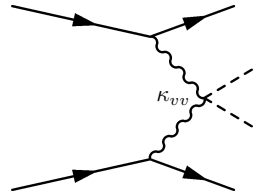
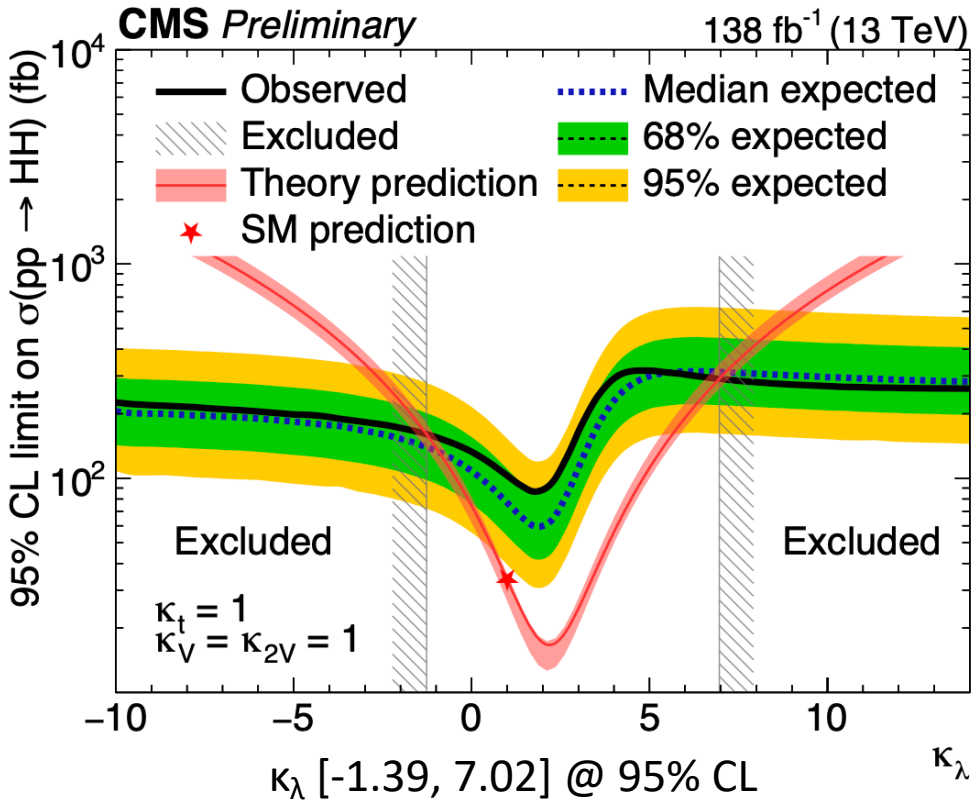


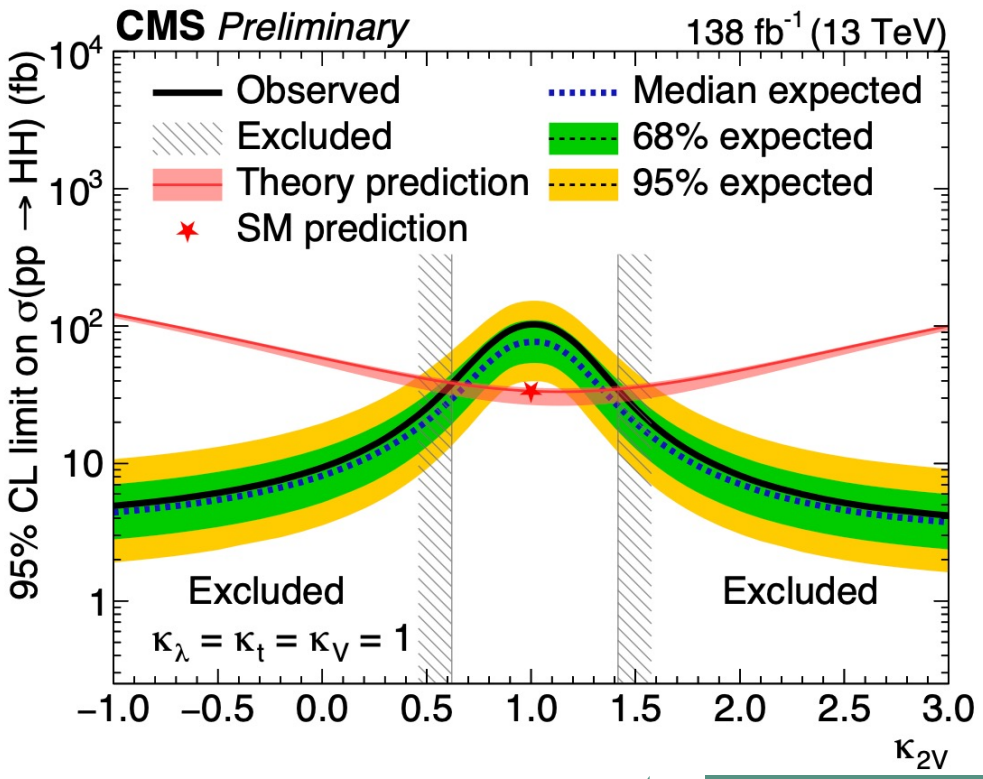
PhysRevLett.133.101801

Constraints of Higgs couplings from HH





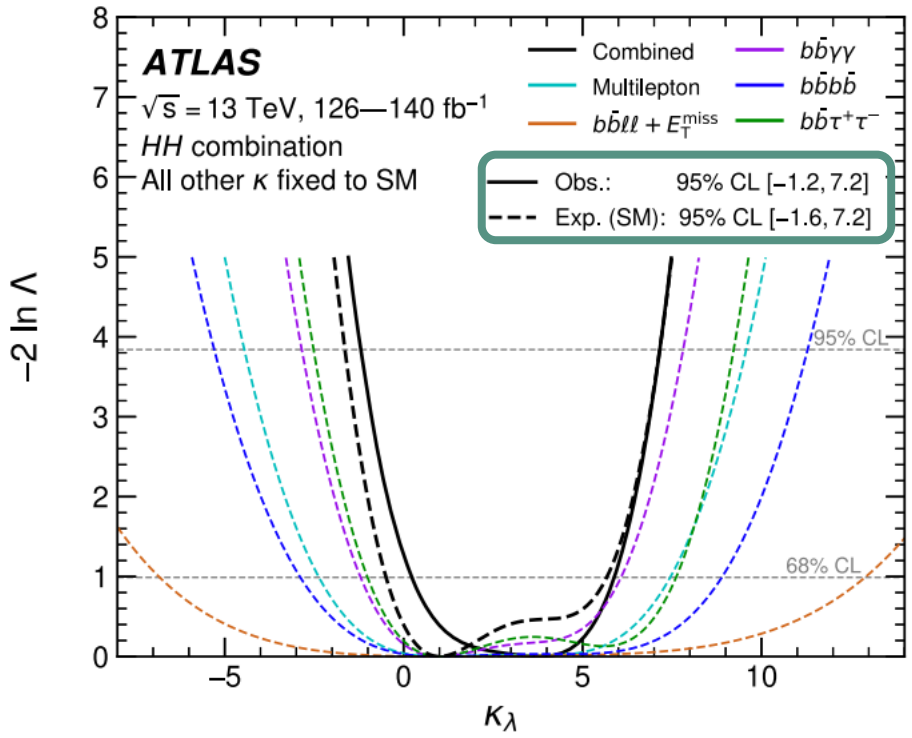


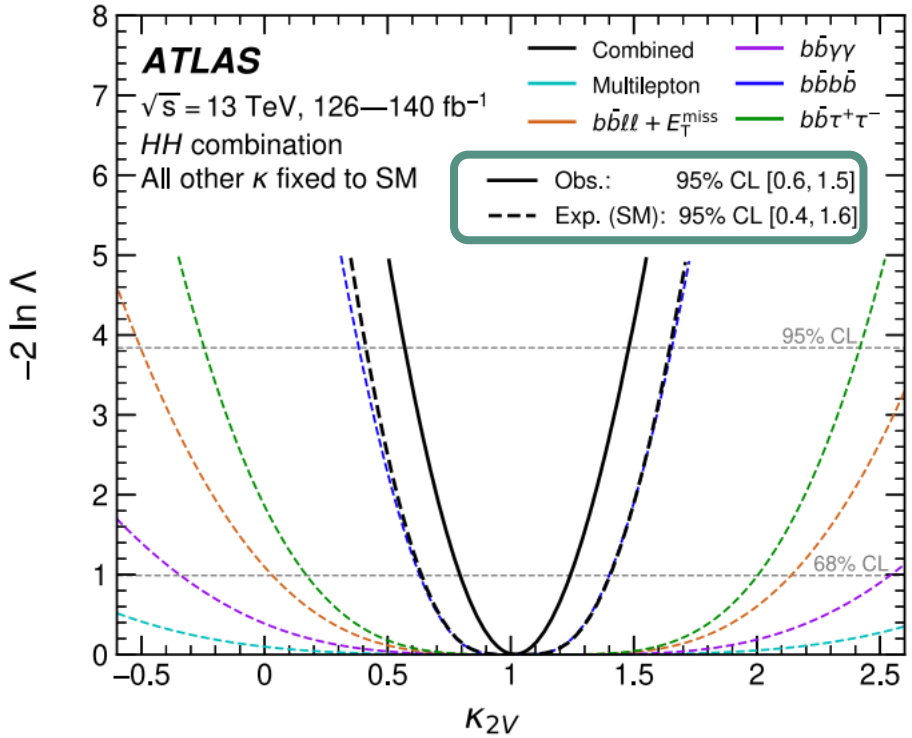


Assuming κt=κv=1, κvv=0 is excluded at a CL higher than 99.99%.

HIG-20-011

Constraints of Higgs couplings from HH





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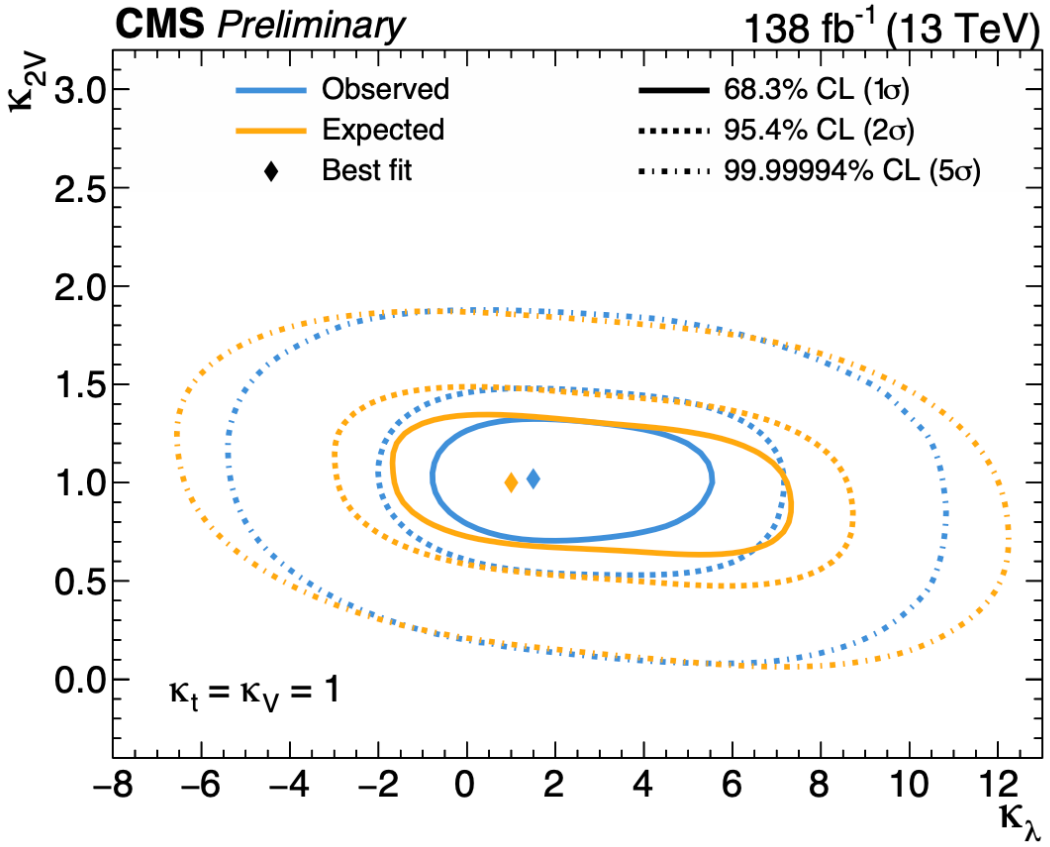
Higgs trilinear coupling

κ_{2V}=0 exluded for all values of κ_λ



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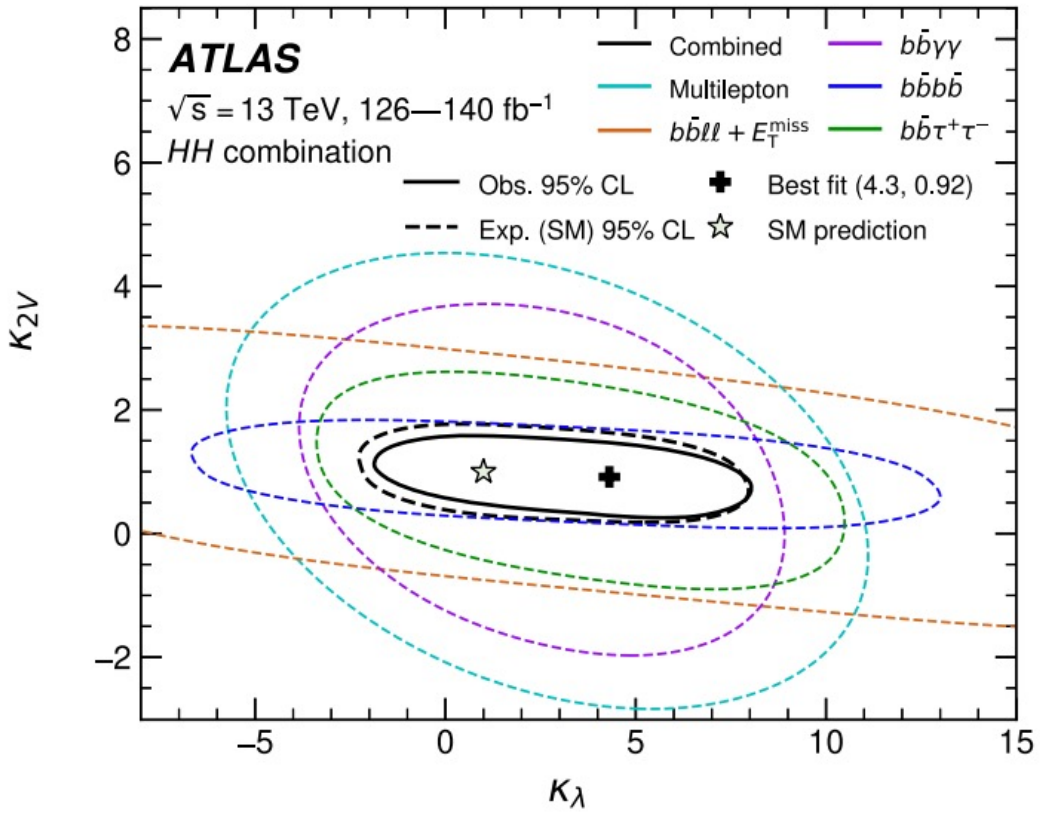

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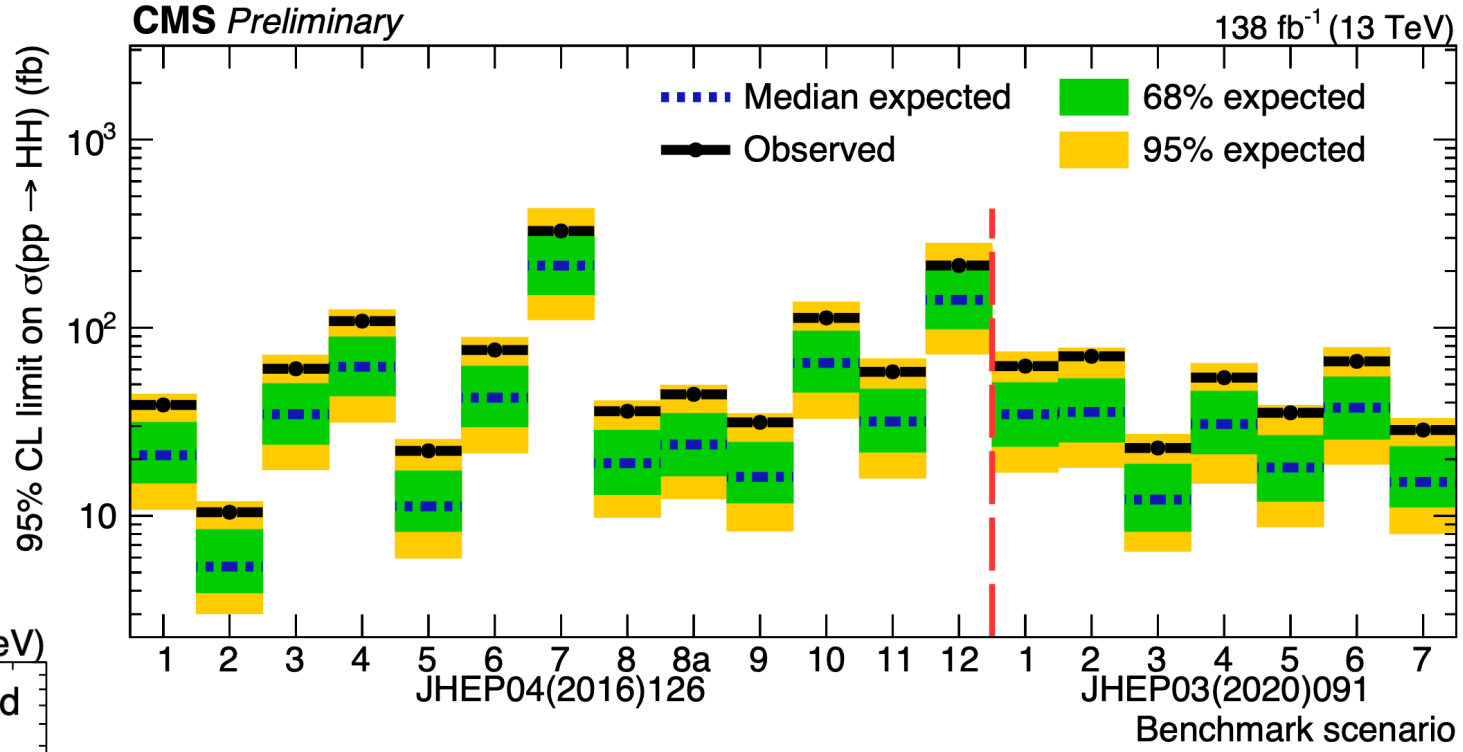
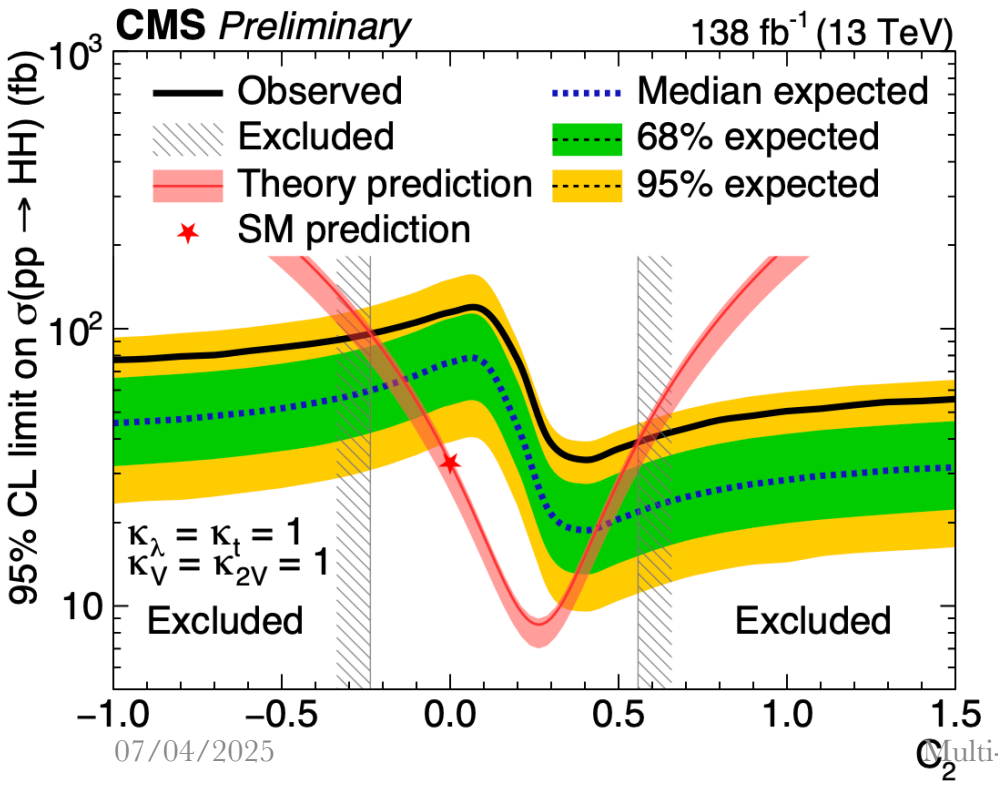
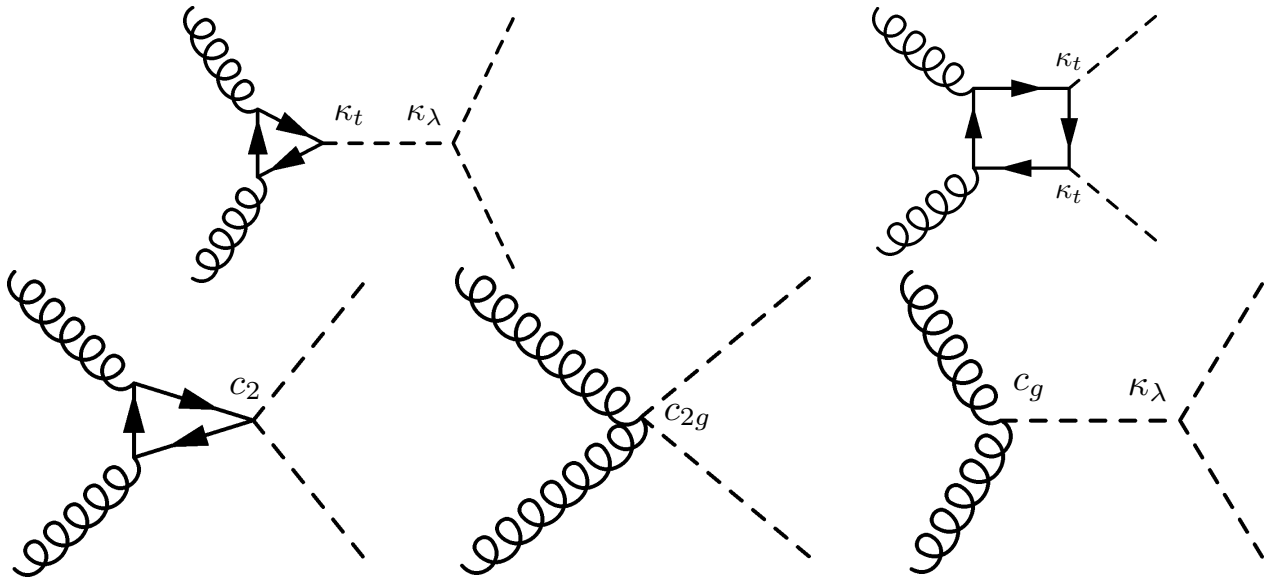
HH anomalous couplings

HIG-20-011

- HEFT parametrisation
- Benchmarks combinations of the coupling modifiers
  (κ_λ , κ_t , c_2 , c_g , c_{2g})

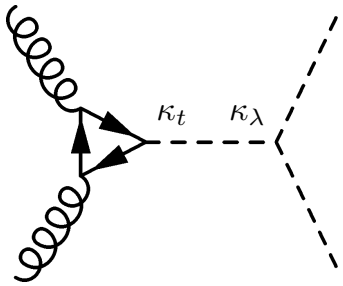


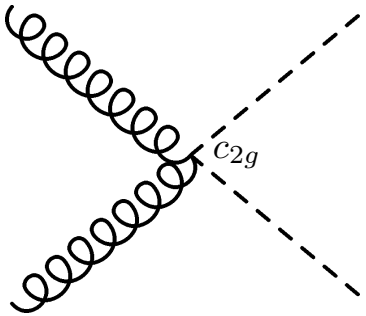


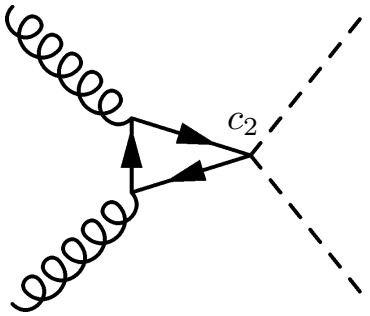


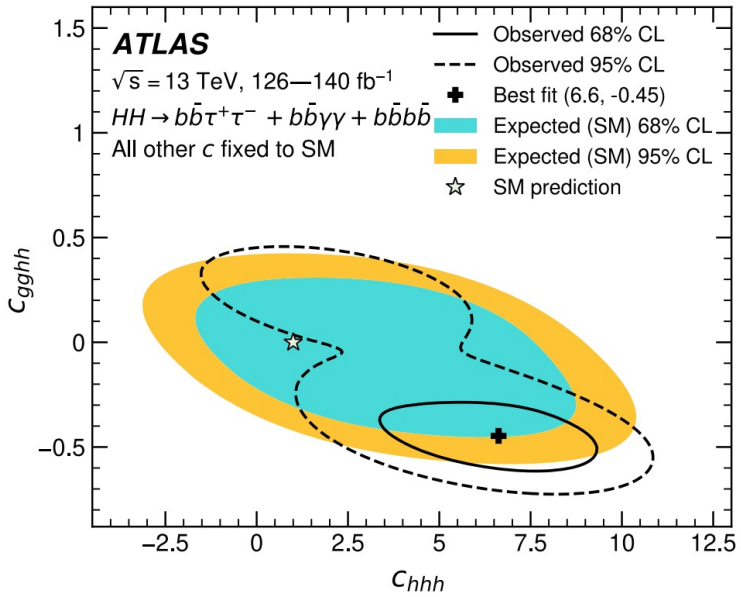
HH anomalous couplings

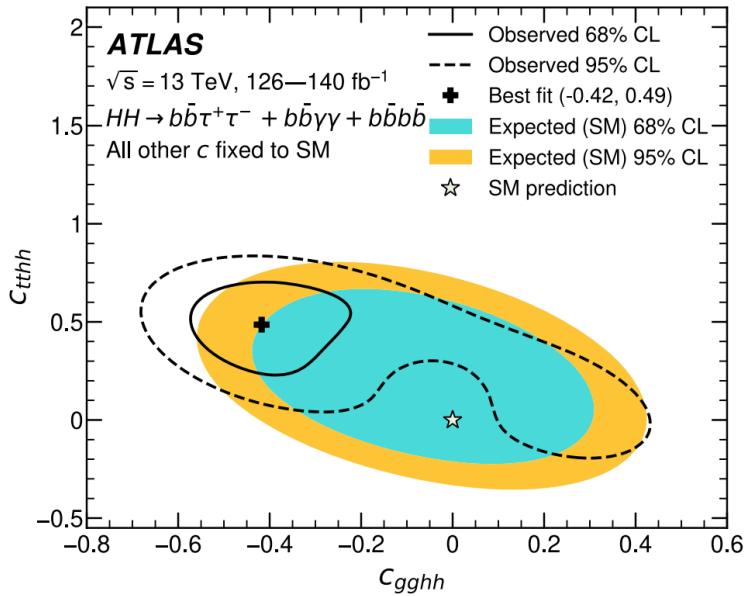
- HEFT parametrisation, parameters considered κ_λ, c_2, c_{2g}

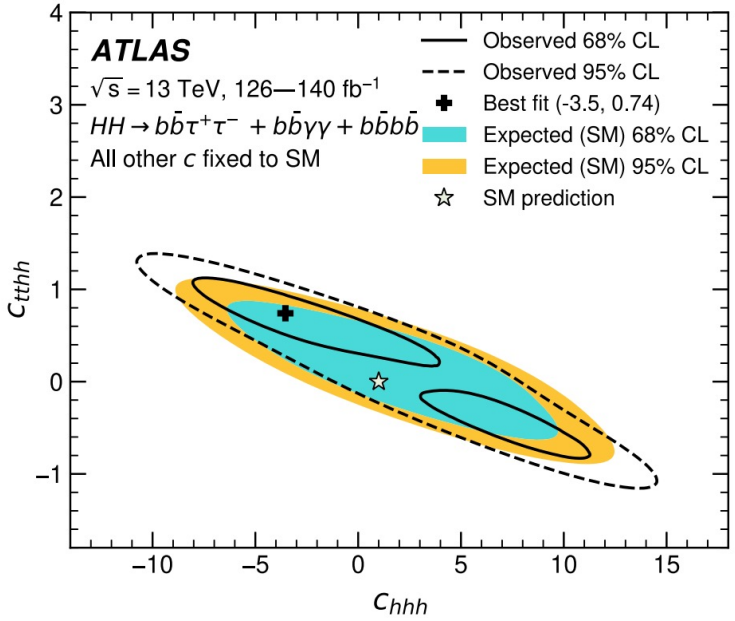












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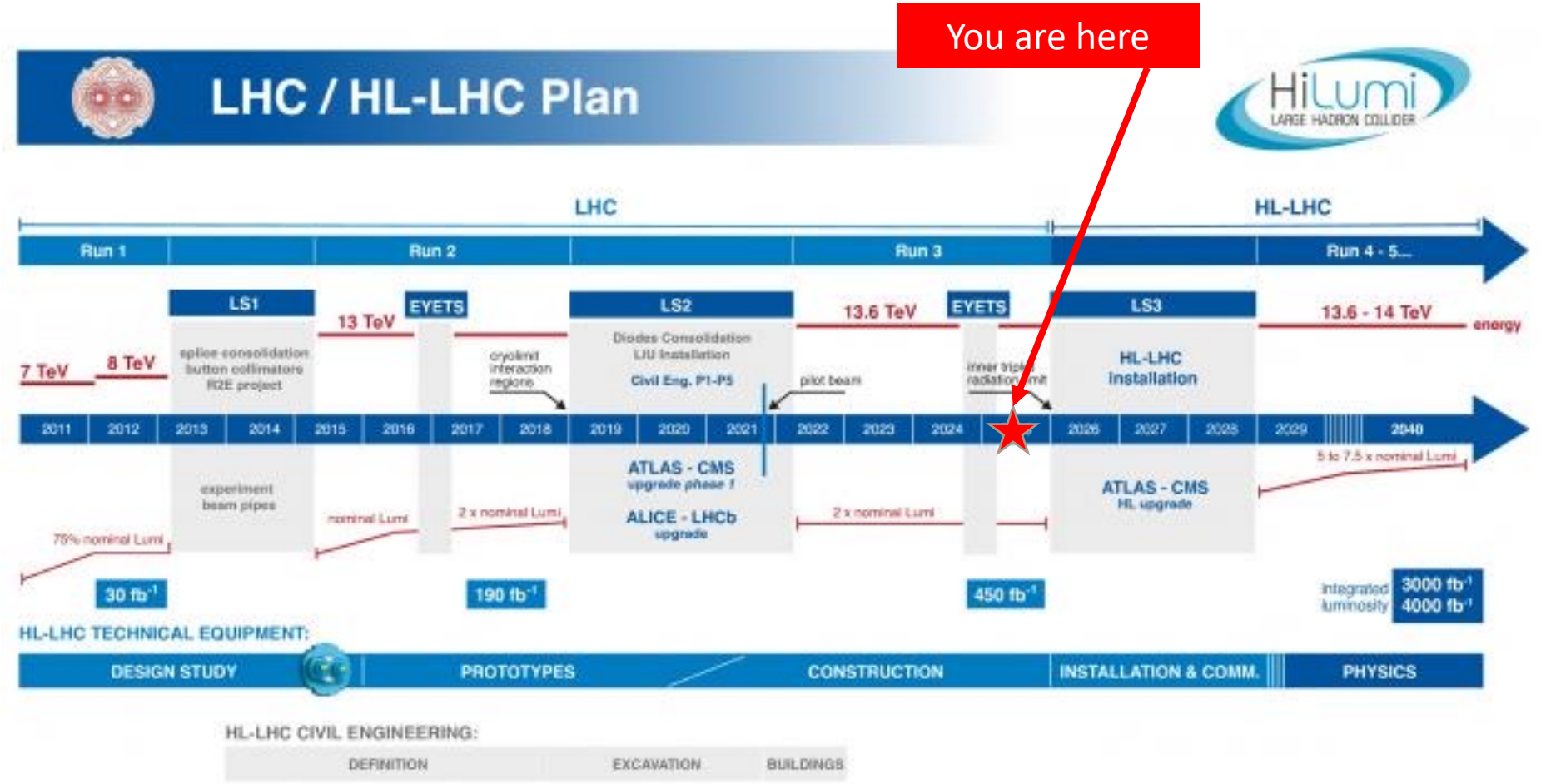
(HL-)LHC timeline

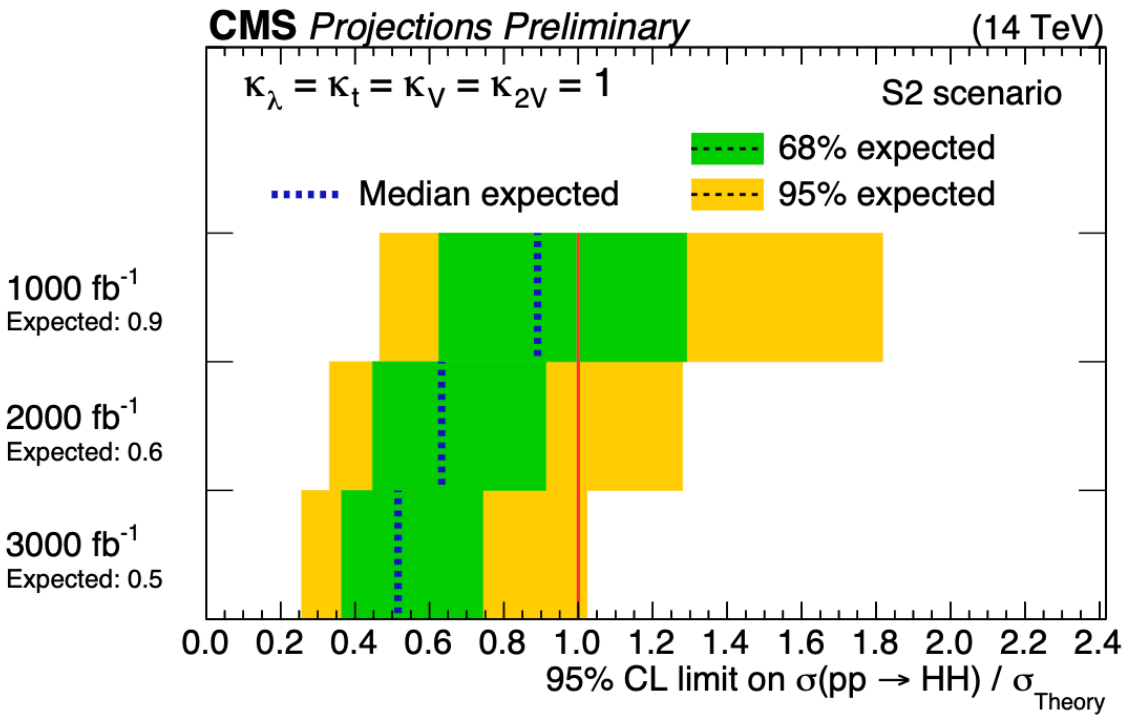


HL-LHC projections CMS

- HL-LHC is planned to start in 2029
- 3000 fb^{-1} (maybe even 4000 fb^{-1})
- center-of-mass energy of 14 TeV
- 140 (200) PU baseline (ultimate) scenario.

- S1
  - systematics same as Run2
  - conservative
- S2
  - Systematic uncertainties halved
  - Datadriven/statistical uncertainties scaled with lumi
  - no MC statistical uncertainties
- S3
  - S2
  - Improvements from upgraded detector and reconstruction performance taken into account

HL-LHC projections CMS



	2000 fb^{-1}		3000 fb^{-1}	
	S2	S3	S2	S3
$b\bar{b}b\bar{b}$ resolved-jets	0.96	1.0	1.2	1.3
$b\bar{b}b\bar{b}$ merged-jets	1.8	1.8	2.2	2.2
$\tau\tau b\bar{b}$	1.9	2.2	2.4	2.7
$\gamma\gamma b\bar{b}$	2.0	2.1	2.4	2.6
Combination	3.5	3.7	4.2	4.5

- We can have discovery at the end of HL-LHC!
- Historically projections are always conservative

After 1000 fb-1 of data we will be sensitive to μ=1

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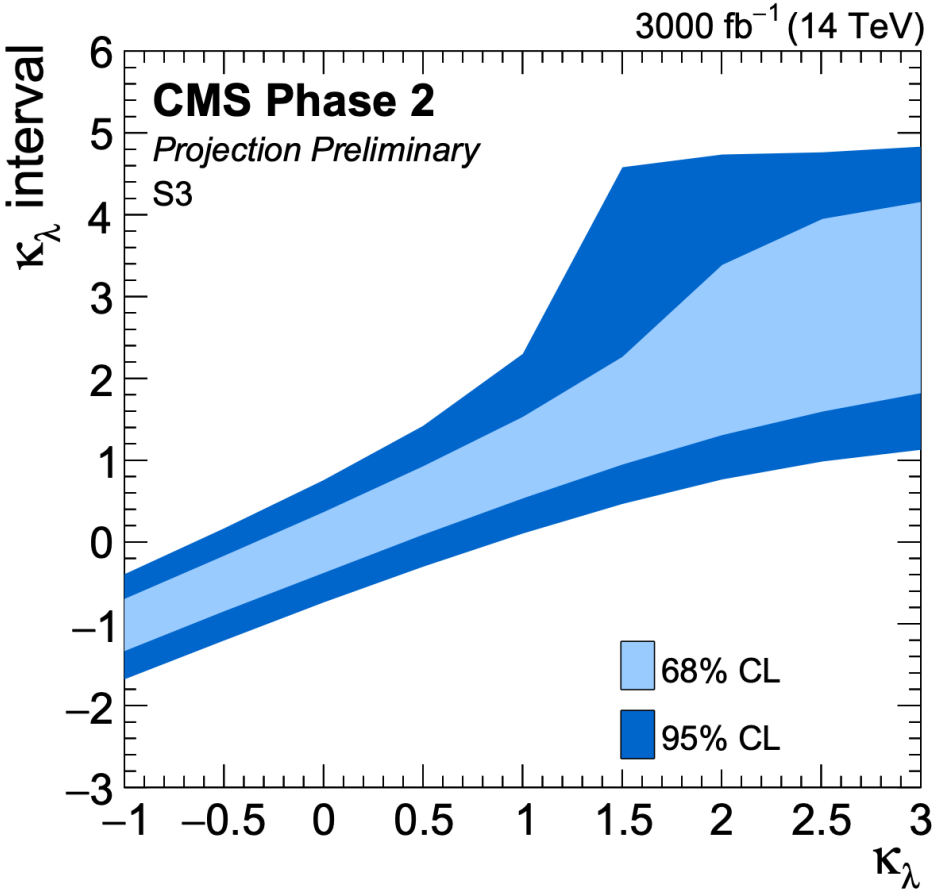
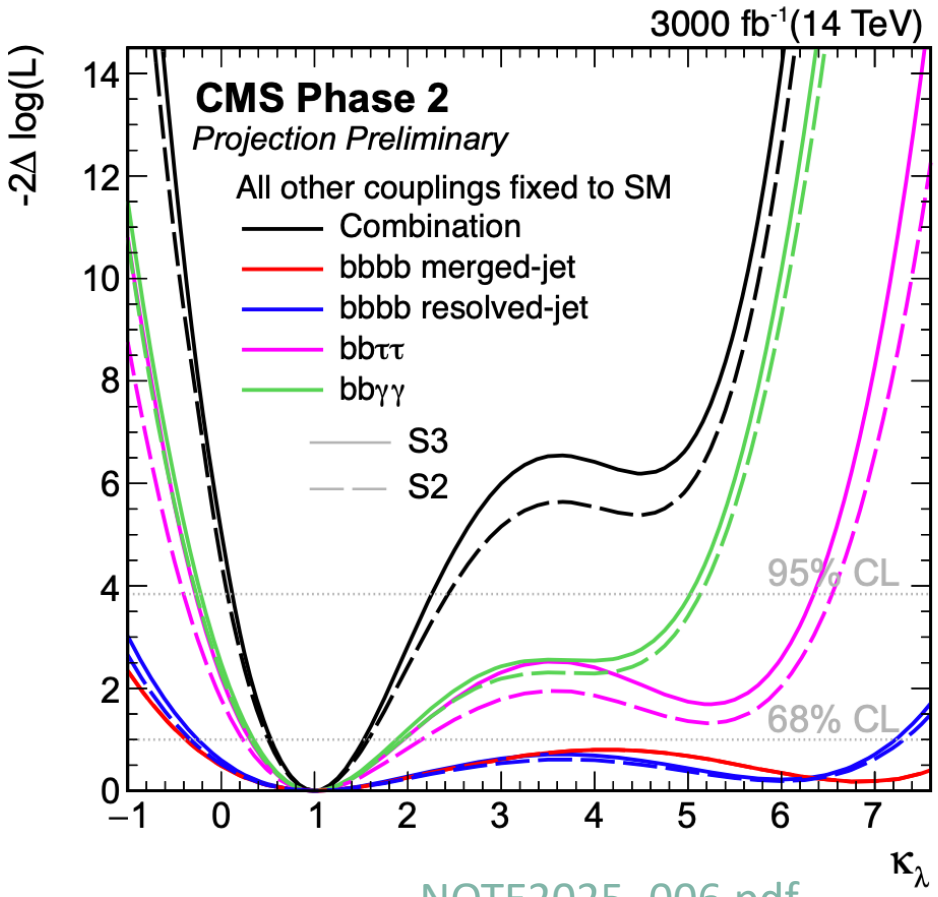
NOTE2025_006.pdf

HL-LHC projections CMS



- κλ [+0.53, +1.5] (S3 scenario, 3000 fb^{-1})

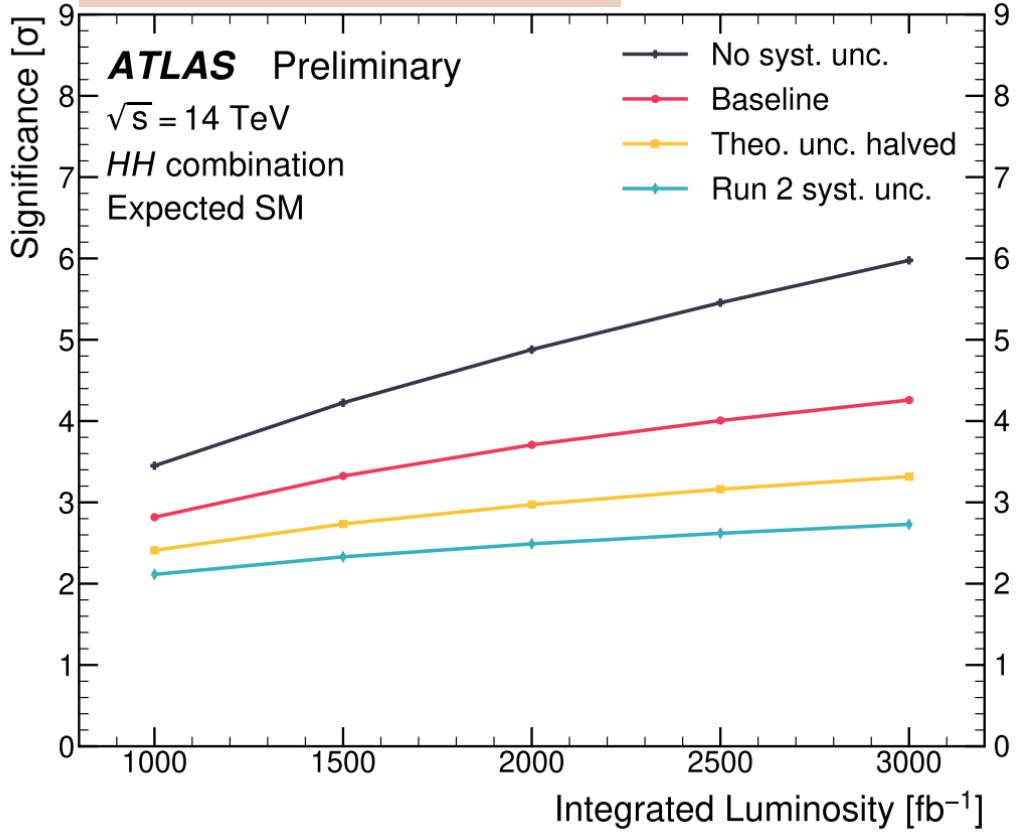


NOTE2025_006.pdf

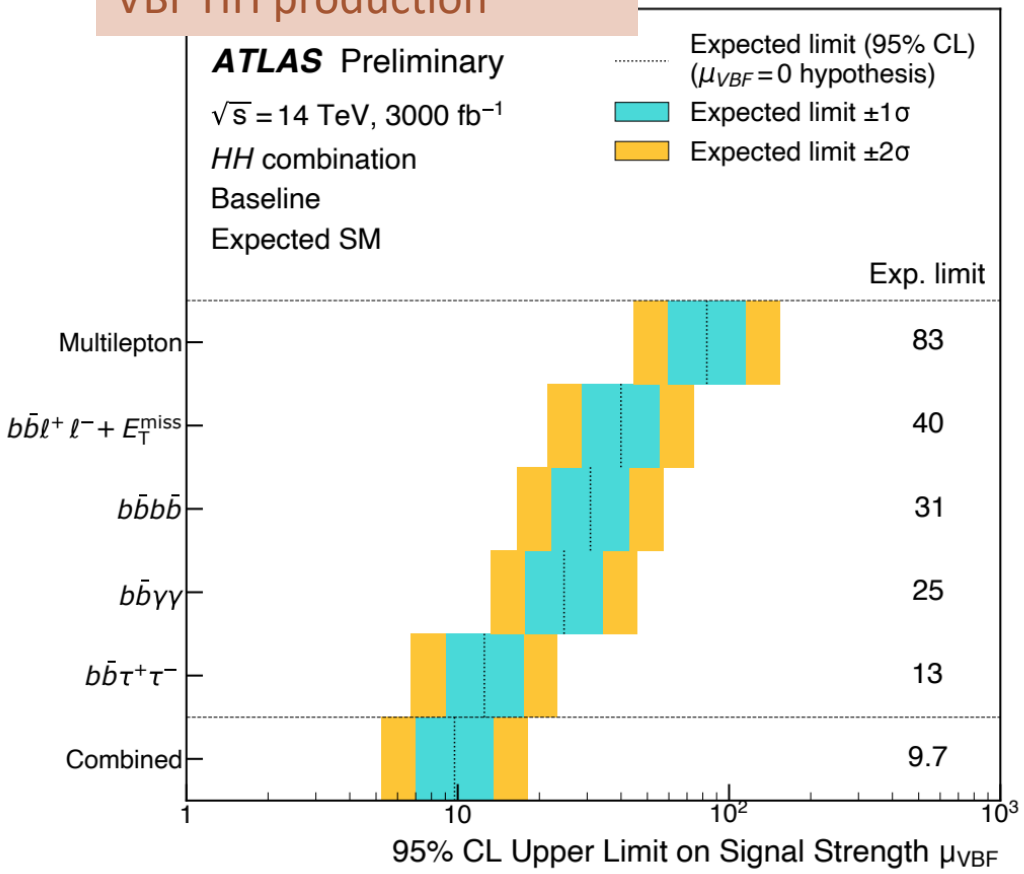
HL-LHC projections ATLAS

ATL-PHYS-PUB-2025-006

Inclusive HH production

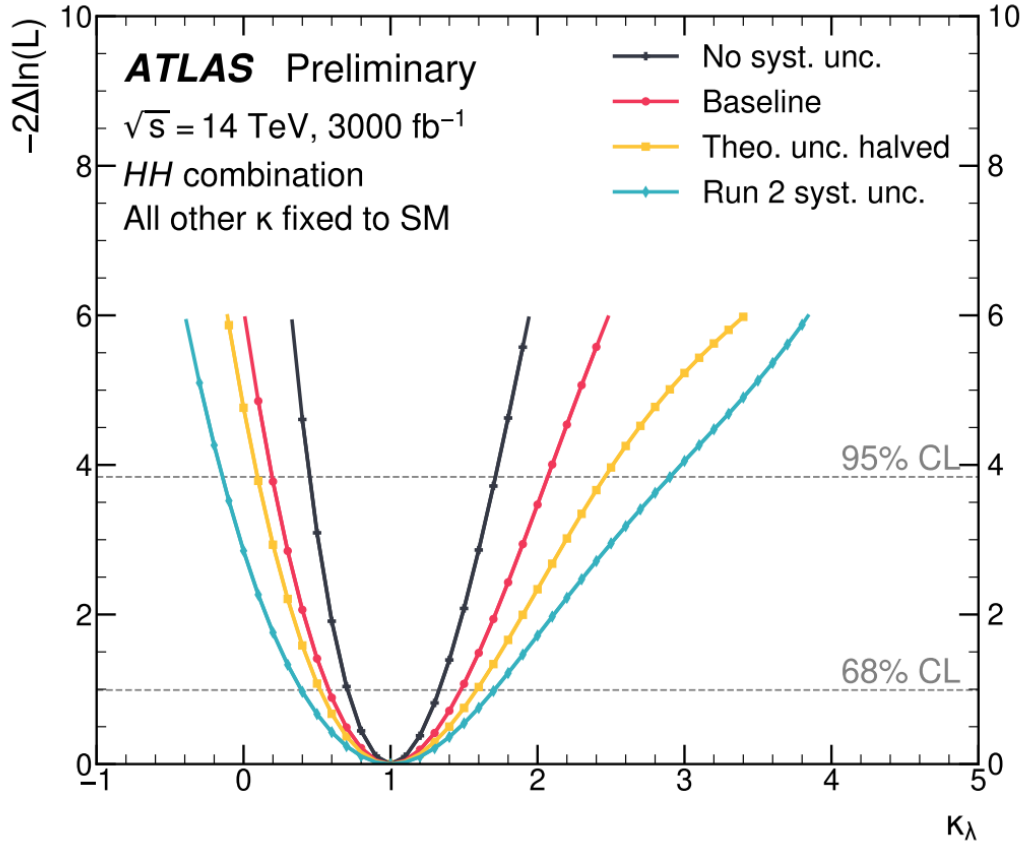


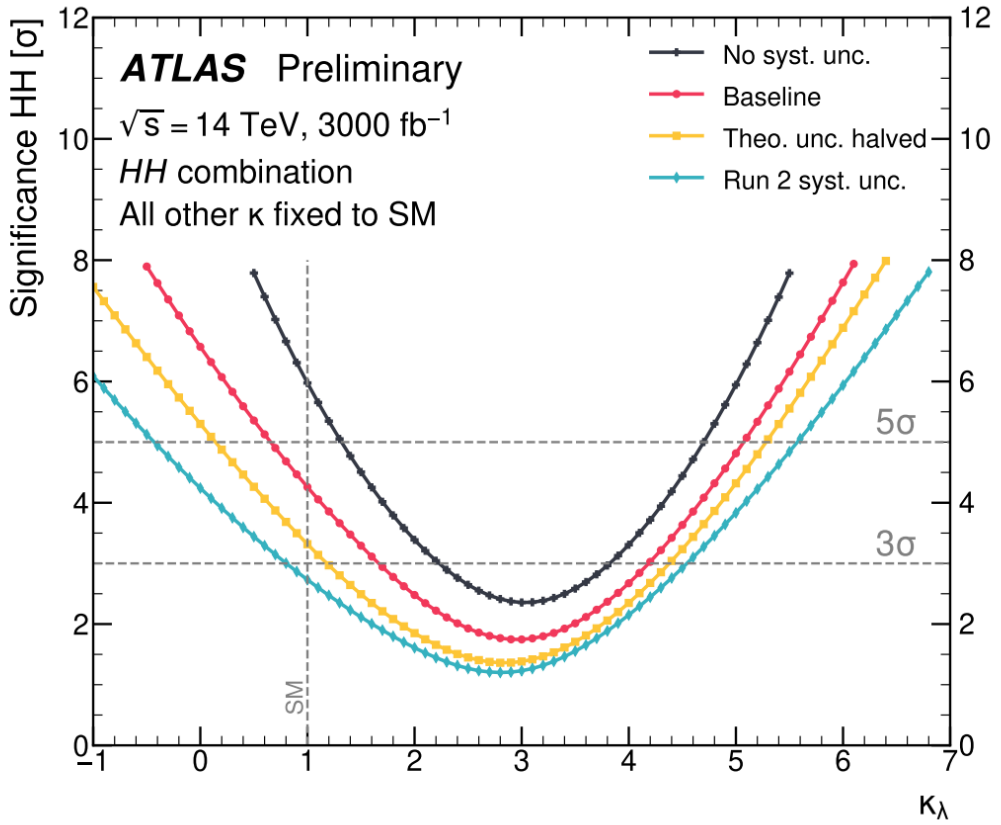
VBF HH production



HL-LHC projections ATLAS

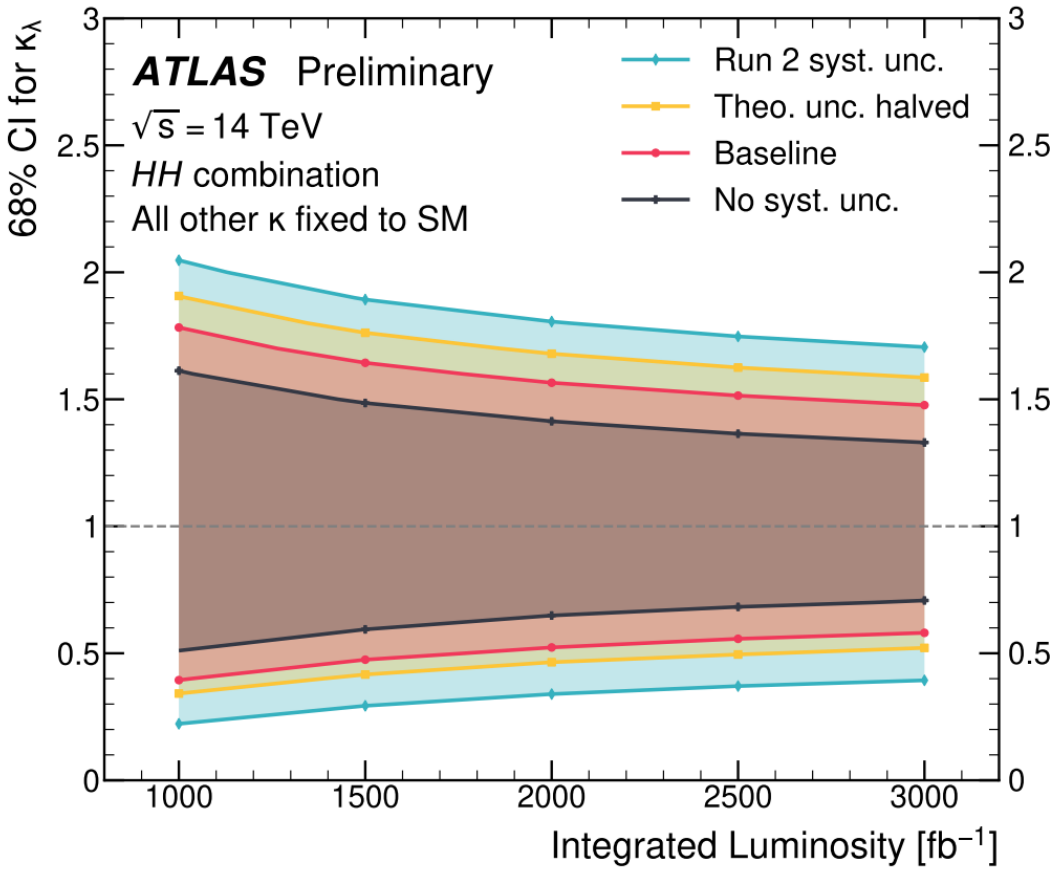
ATL-PHYS-PUB-2025-006





HL-LHC projections ATLAS

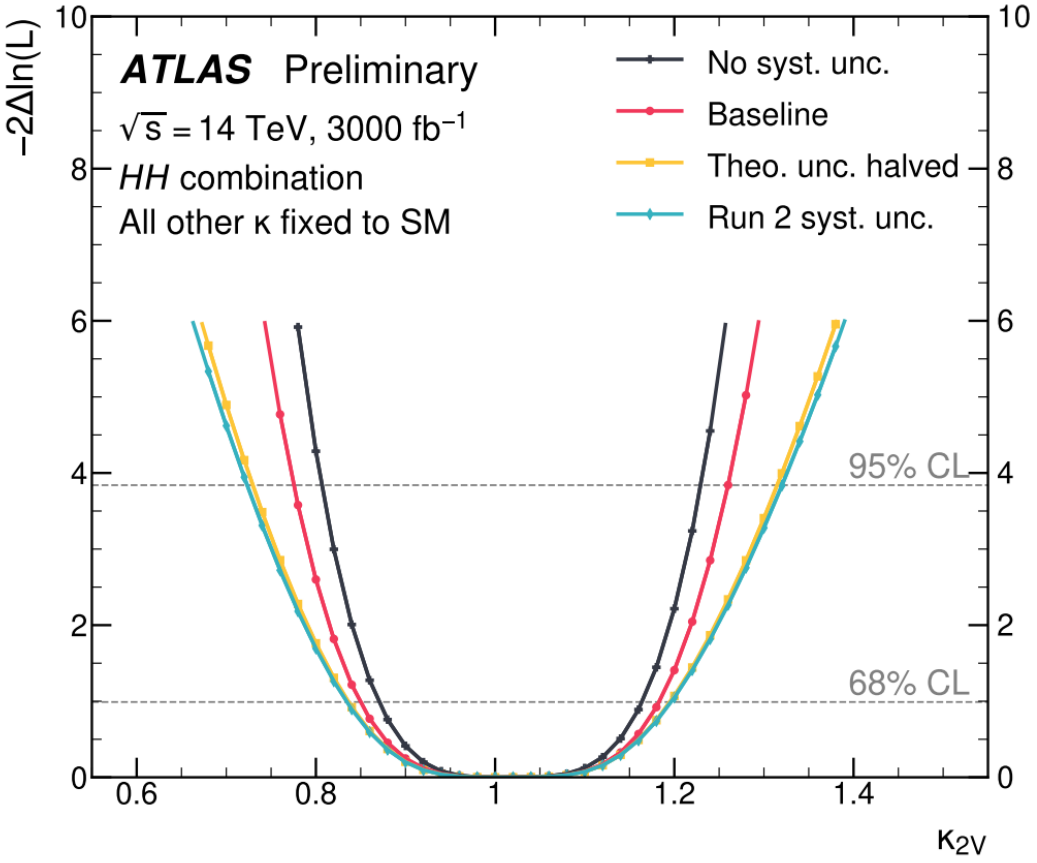
ATL-PHYS-PUB-2025-006



Uncertainty scenario	68% κ_λ Combination
Run 2 syst. unc.	[0.39, 1.71]
Theory unc. halved	[0.52, 1.59]
Baseline	[0.58, 1.48]
No syst. unc.	[0.71, 1.33]

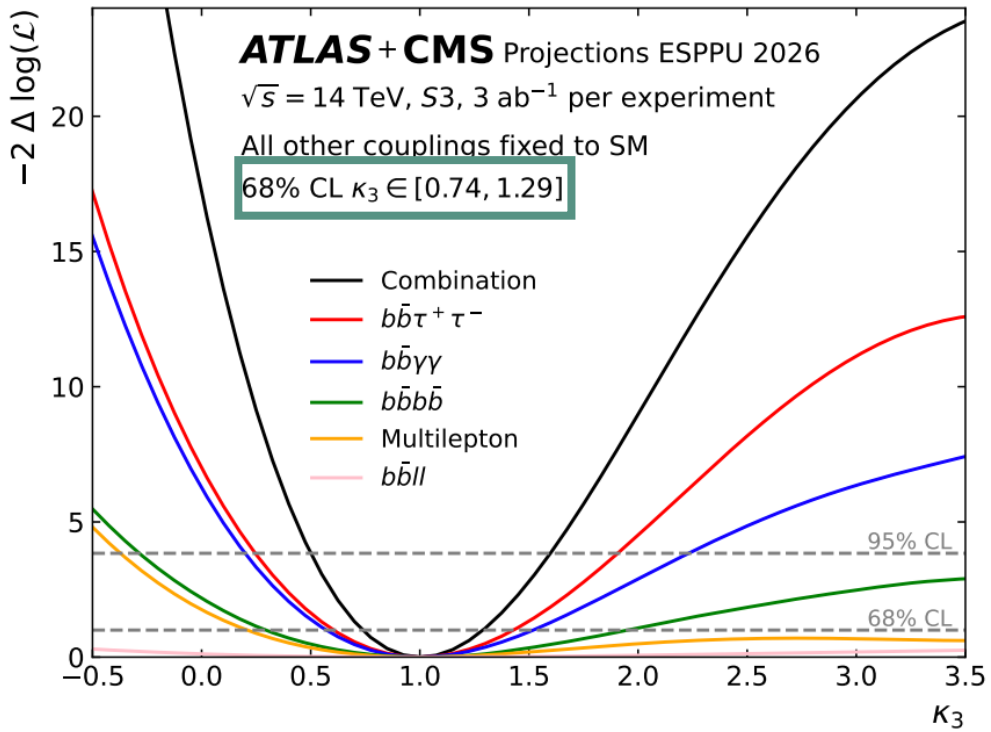
HL-LHC projections ATLAS

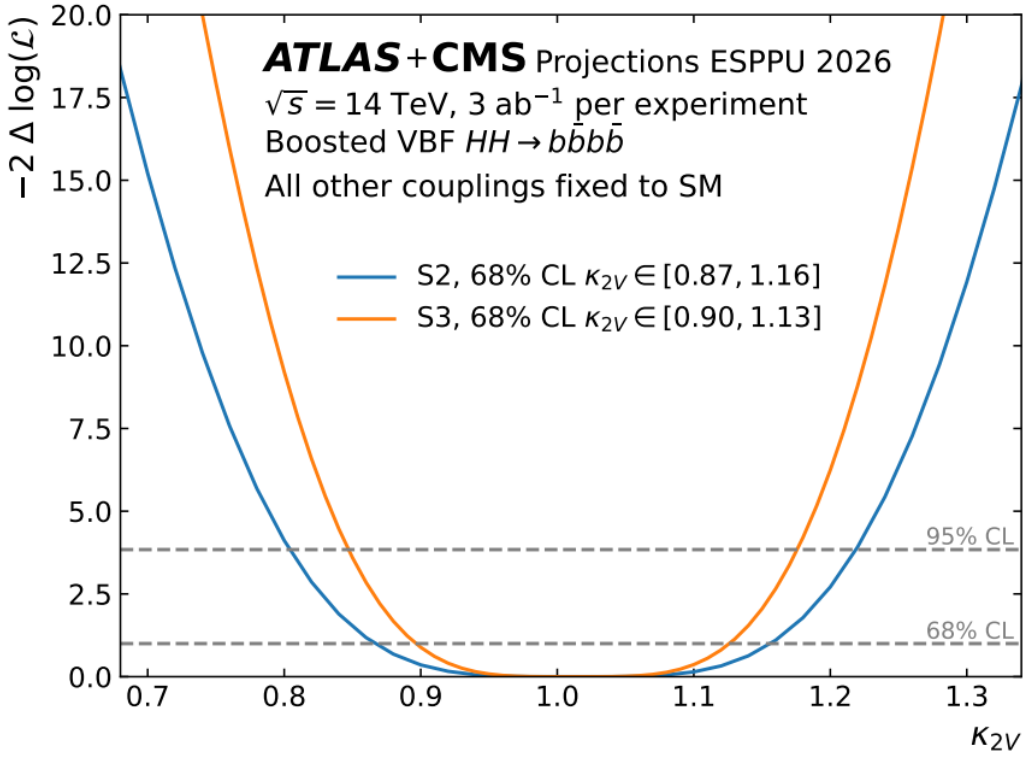
ATL-PHYS-PUB-2025-006



Uncertainty scenario	68% κ_{2V} Combination
Run 2 syst. unc.	[0.84, 1.20]
Theory unc. halved	[0.84, 1.20]
Baseline	[0.85, 1.18]
No syst. unc.	[0.87, 1.16]

ATLAS and CMS combined performance





Submision for European Strategy Update 2026: https://arxiv.org/pdf/2504.00672

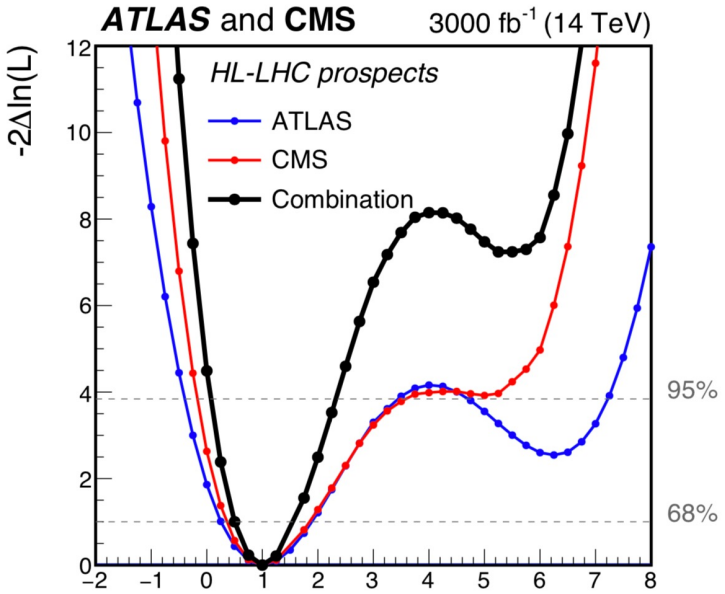
ATLAS and CMS combined performance

	$2\ \text{ab}^{-1}$ (*S2*)		$3\ \text{ab}^{-1}$ (*S2*)		$3\ \text{ab}^{-1}$ (*S3*)	
	ATLAS	CMS	ATLAS	CMS	ATLAS	CMS
	HH statistical significance					
$b\bar{b}\tau^+\tau^-$	$3.0^\dagger$	1.9	$3.5^\dagger$	2.4	**3.8**†	**2.7**
$b\bar{b}\gamma\gamma$	$2.1^\dagger$	$2.0^\dagger$	$2.4^\dagger$	$2.4^\dagger$	**2.6**†	**2.6**†
$b\bar{b}b\bar{b}$ resolved	0.9	$1.0^\dagger$	1.0	$1.2^\dagger$	**1.0**	**1.3**†
$b\bar{b}b\bar{b}$ boosted	–	$1.8^\dagger$	–	$2.2^\dagger$	–	**2.2**†
Multilepton	$0.8^\dagger$	–	$1.0^\dagger$	–	**1.0**†	–
$b\bar{b}\ell^+\ell^-$	$0.4^\dagger$	–	$0.5^\dagger$	–	**0.5**†	–
Combination	3.7	3.5	4.3	4.2	**4.5**	**4.5**
ATLAS+CMS	6.0		7.2		**7.6**	

https://arxiv.org/pdf/2504.00672

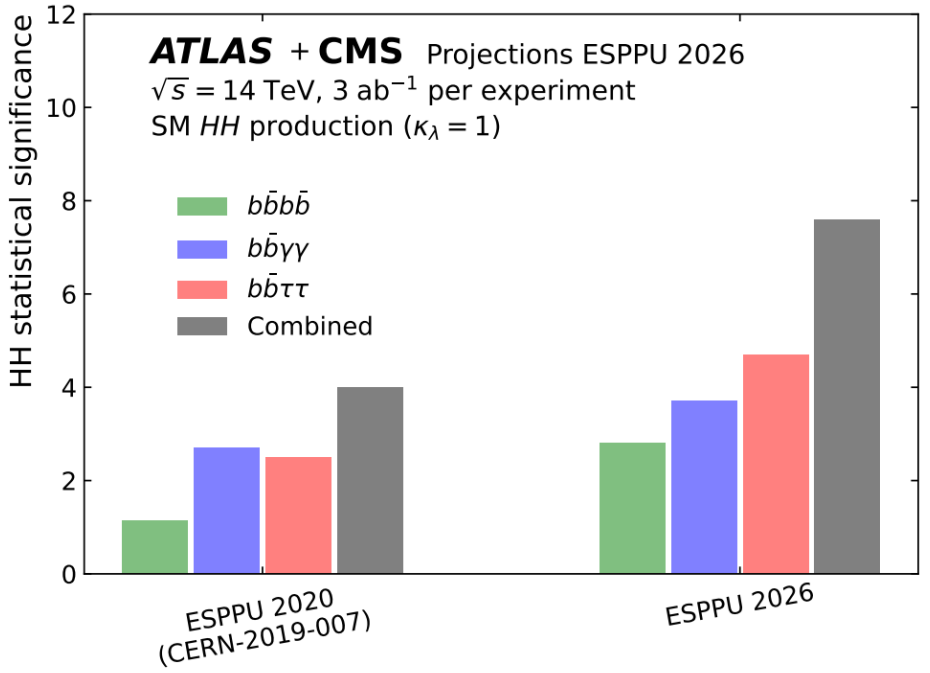
HL-LHC prospect studies from 2019

https://doi.org/10.1016/j.revip.2020.100045



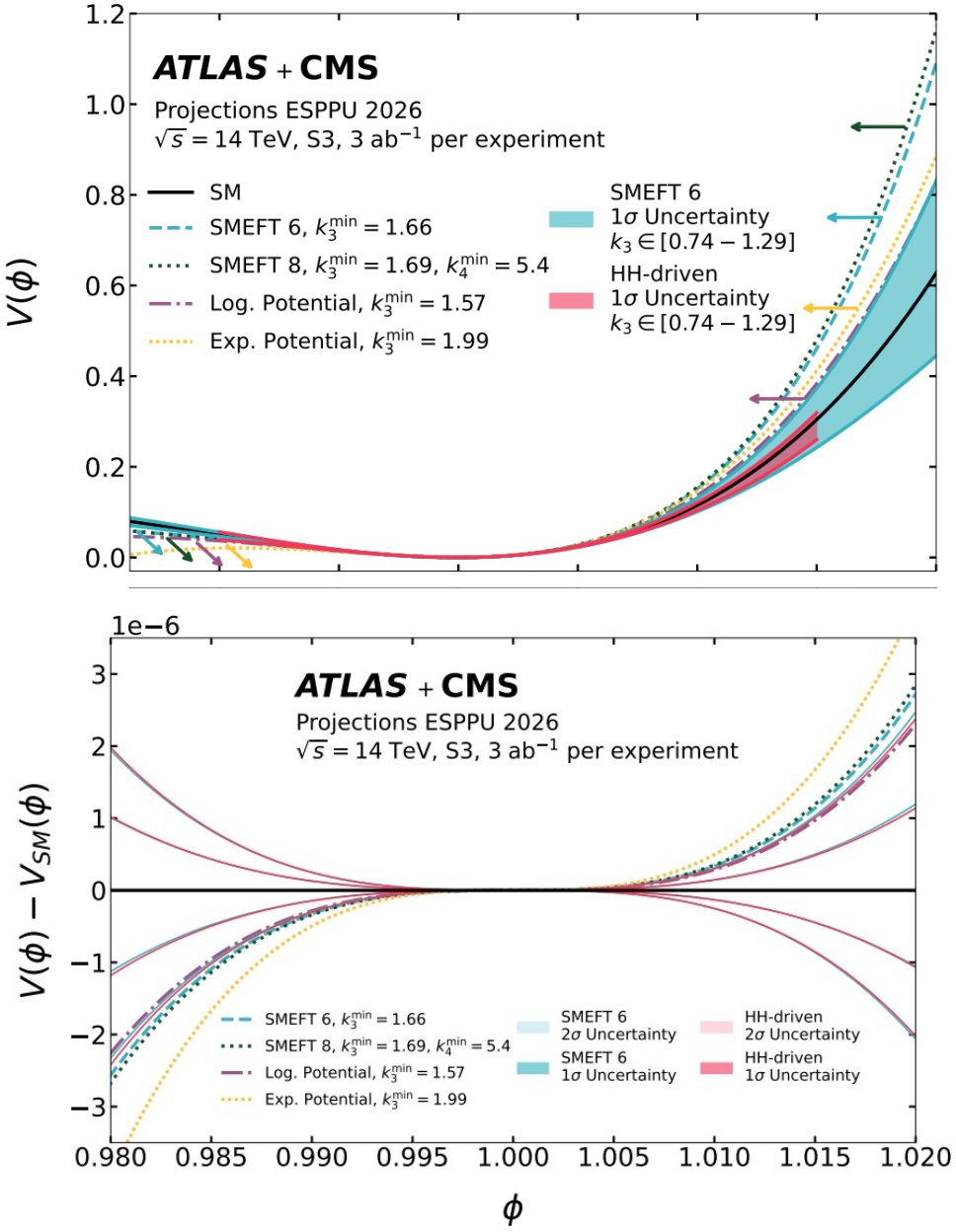
- These projections based on first Run2 analyses published in ~2018
- $0.52 \leq \kappa\lambda \leq 1.5$ (with systematics)
- $0.57 \leq \kappa\lambda \leq 1.5$ (stat only)

	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau^+\tau^-$	2.5	1.6	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \to b\bar{b}VV^*$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ(4\ell)$	-	0.37	-	0.37
Combination	3.5	2.8	3.0	2.6
	4.5		4.0	



ATLAS and CMS combined performance

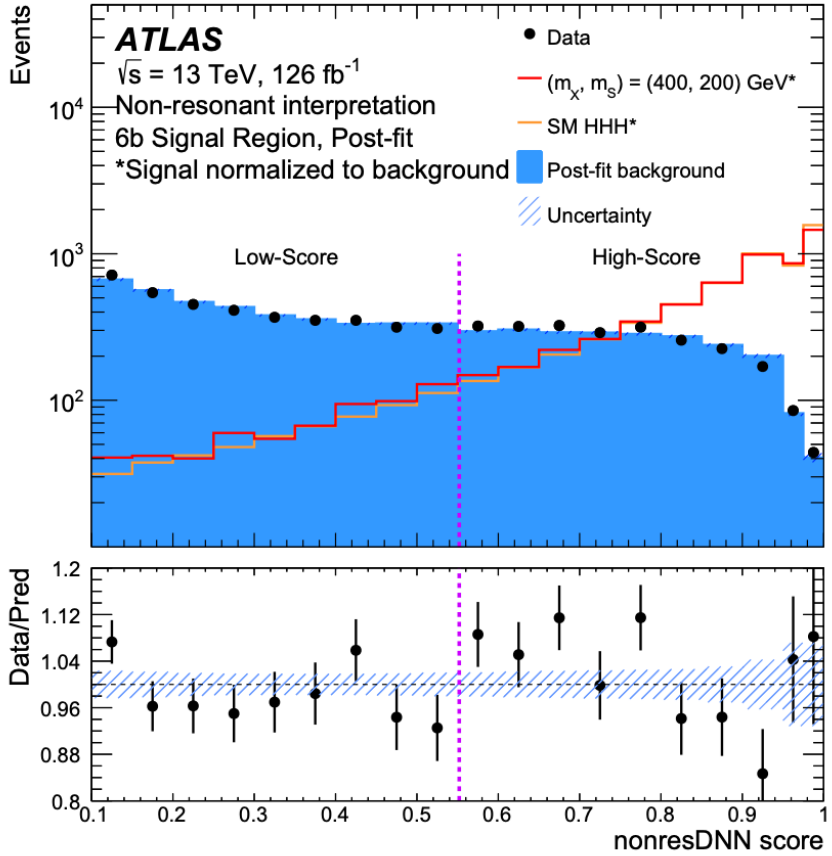
- Constrain 4 BSM scenarios with modified EWSB potential
- Strong first-order phase transition
- At 3000 fb-1 all models predicting first order phase transition excluded!

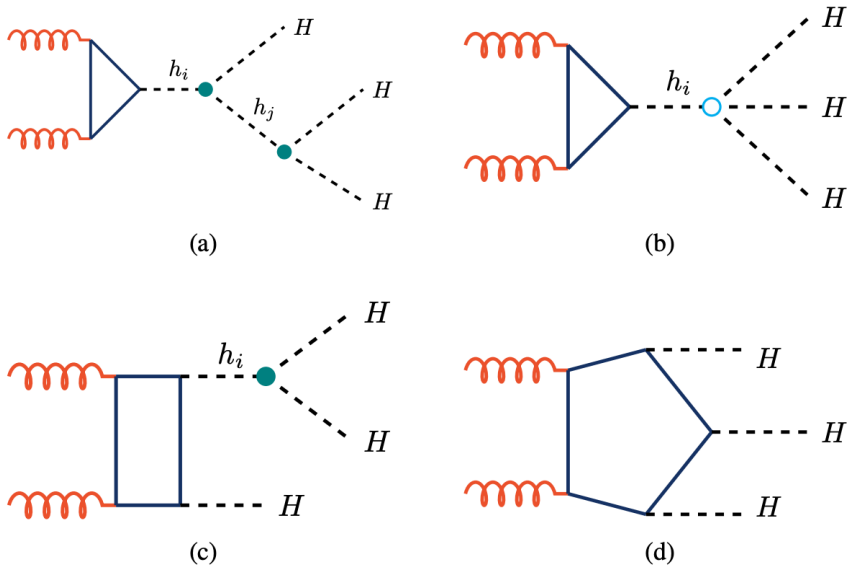


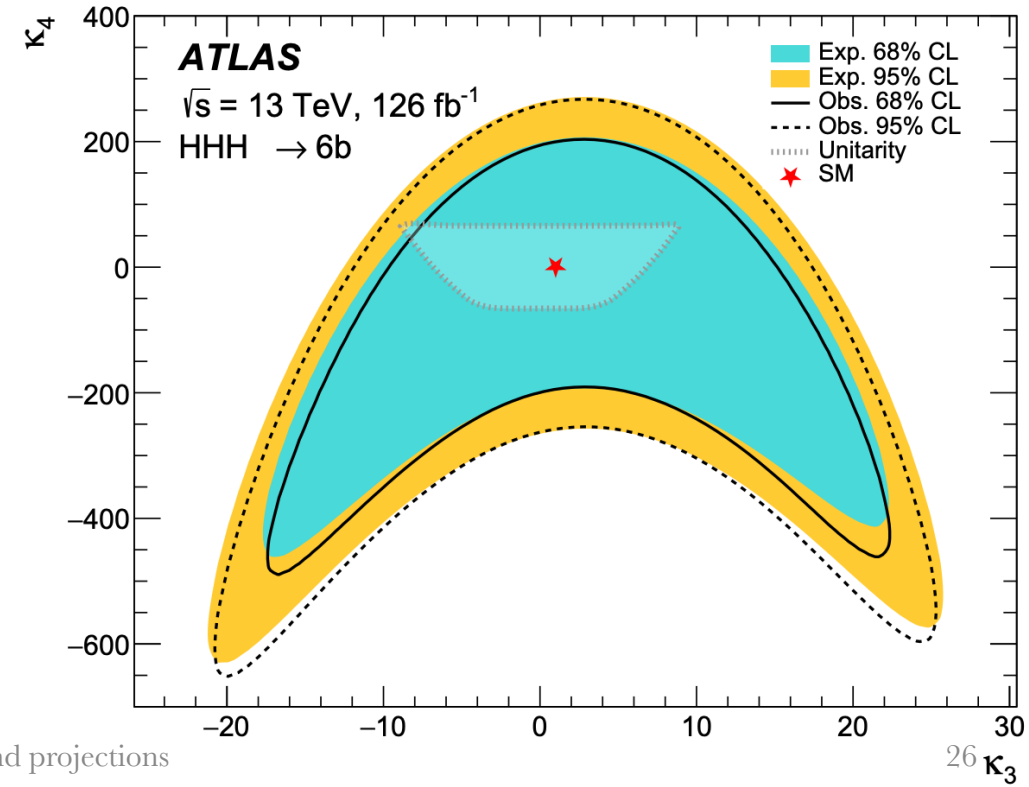
https://arxiv.org/pdf/2504.00672

Search for HHH->6b jets

http://dx.doi.org/10.1103/PhysRevD.111.032006



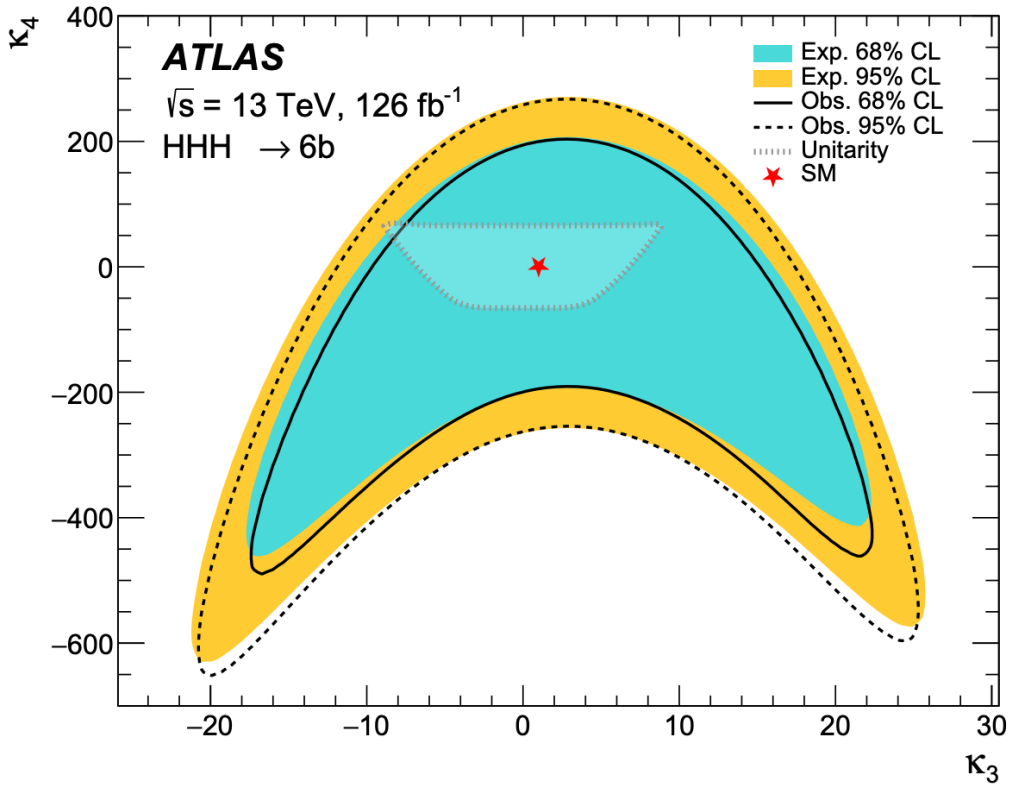


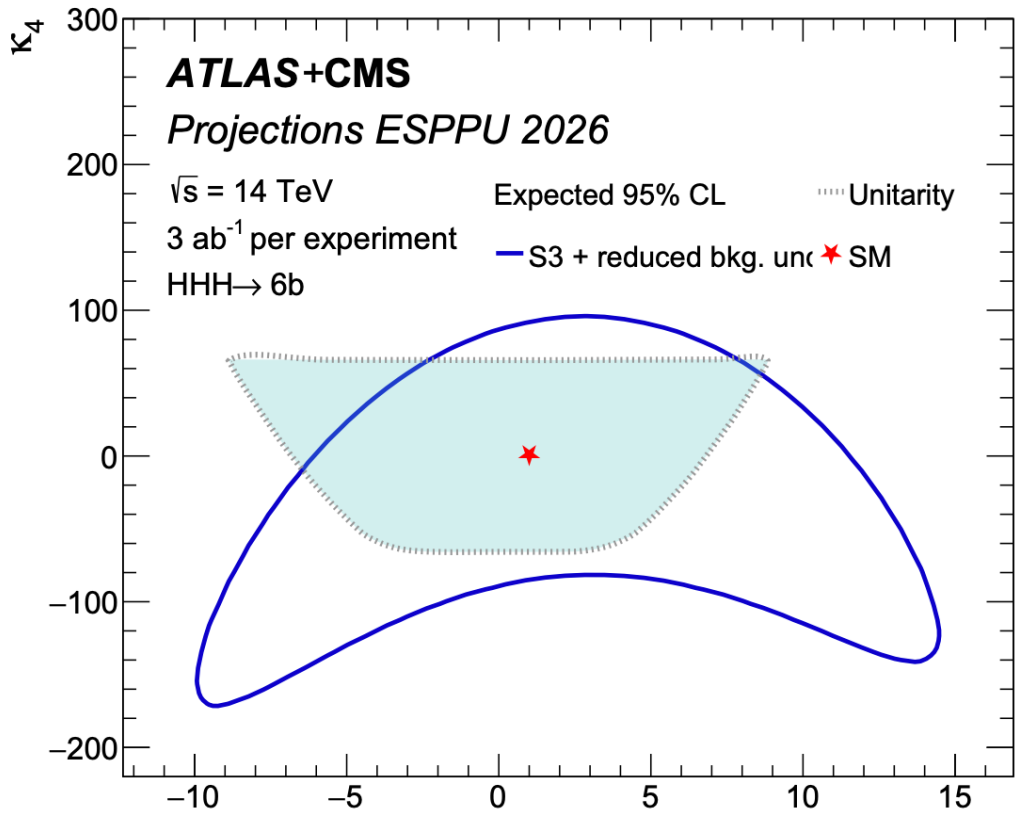


HHHH coupling κ4

HL-LHC we can exclude a significant fraction of the parameter phase space within the perturbative unitarity bounds!

http://dx.doi.org/10.1103/PhysRevD.111.032006





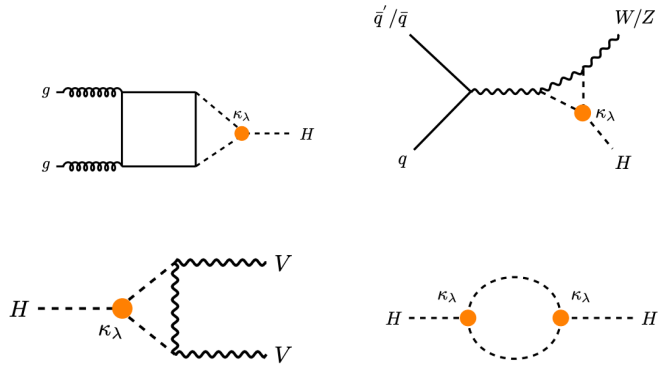
https://arxiv.org/pdf/2504.00672

Summary

- HH production
  - Currently upper limits on inclusive cross-section ~ 2.5 x SM
  - Projections for HL-LHC:
    - 1000 fb-1 ~1 x SM
    - 3000 fb-1 significance ~4.5 σ for CMS and ATLAS respectively
      3000 fb-1 CMS+ATLAS combined significance >7σ
- κ_λ coupling
  - Current constraints ~(1.4, 7)
  - 3000 fb-1 ~(0.5, 1.5) for CMS and ATLAS respectively
  - 3000 fb-1~(0.7, 1.3) CMS+ATLAS combined
- At HL-LHC we will be able to exclude BSM scenarios regarding the Higgs field and EWSB

Additional material

Single and double Higgs searches



Simultaneously constrain

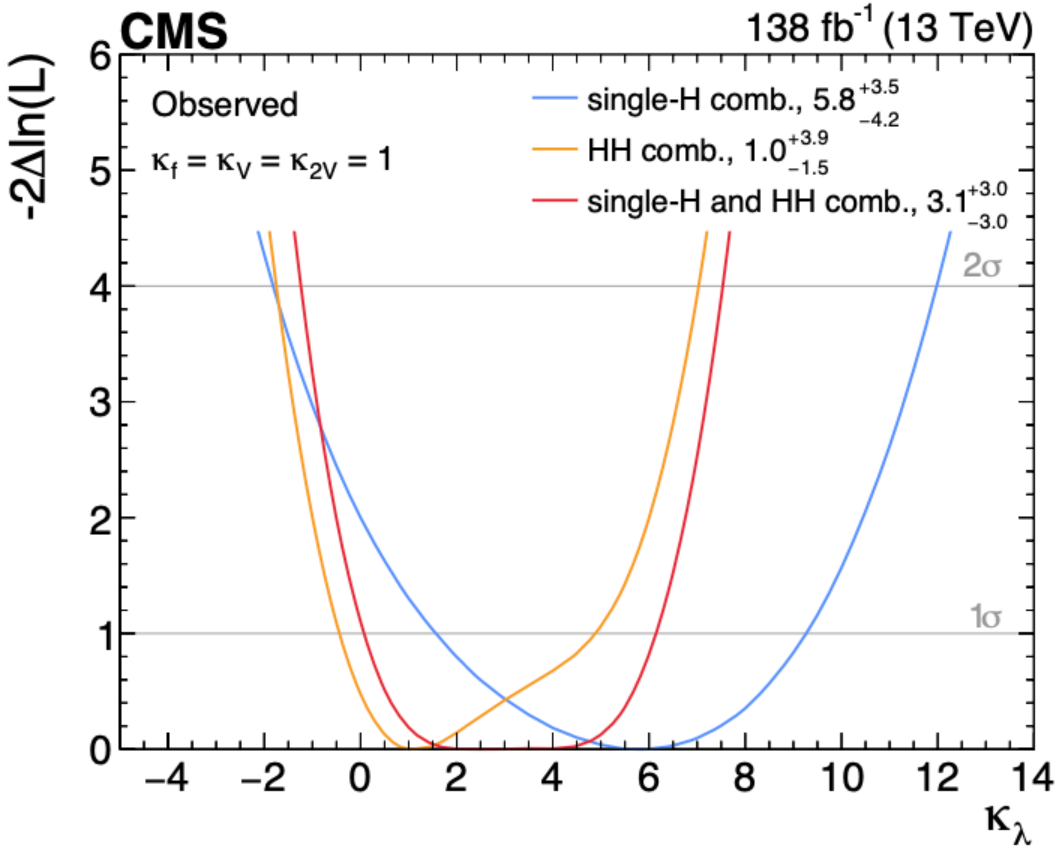
- Higgs boson trilinear self-coupling
- Higgs boson couplings to fermions and to vector bosons.

Analysis	Integrated luminosity (fb^{-1})	Maximum granularity	References
$H \to 4l$	138	STXS 1.2	[34]
$H \to \gamma\gamma$	138	STXS 1.2	[35,none]
$H \to WW$	138	STXS 1.2	[37]
$H \to$ leptons ($t\bar{t}H$)	138	Inclusive	[38]
$H \to b\bar{b}$ (ggH)	138	Inclusive	[39]
$H \to b\bar{b}$ (VH)	77	Inclusive	[40,41]
$H \to b\bar{b}$ ($t\bar{t}H$)	36	Inclusive	[42]
$H \to \tau\tau$	138	STXS 1.2	[43]
$H \to \mu\mu$	138	Inclusive	[44]

Analysis	Int. luminosity (fb^{-1})	Targeted production modes
$HH \to \gamma\gamma b\bar{b}$	138	ggHH and qqHH
$HH \to \tau\tau b\bar{b}$	138	ggHH and qqHH
$HH \to 4b$	138	ggHH, qqHH and VHH
$HH \to$ leptons	138	ggHH
$HH \to WWb\bar{b}$	138	ggHH and qqHH

https://arxiv.org/abs/2407.13554

Single and double Higgs searches



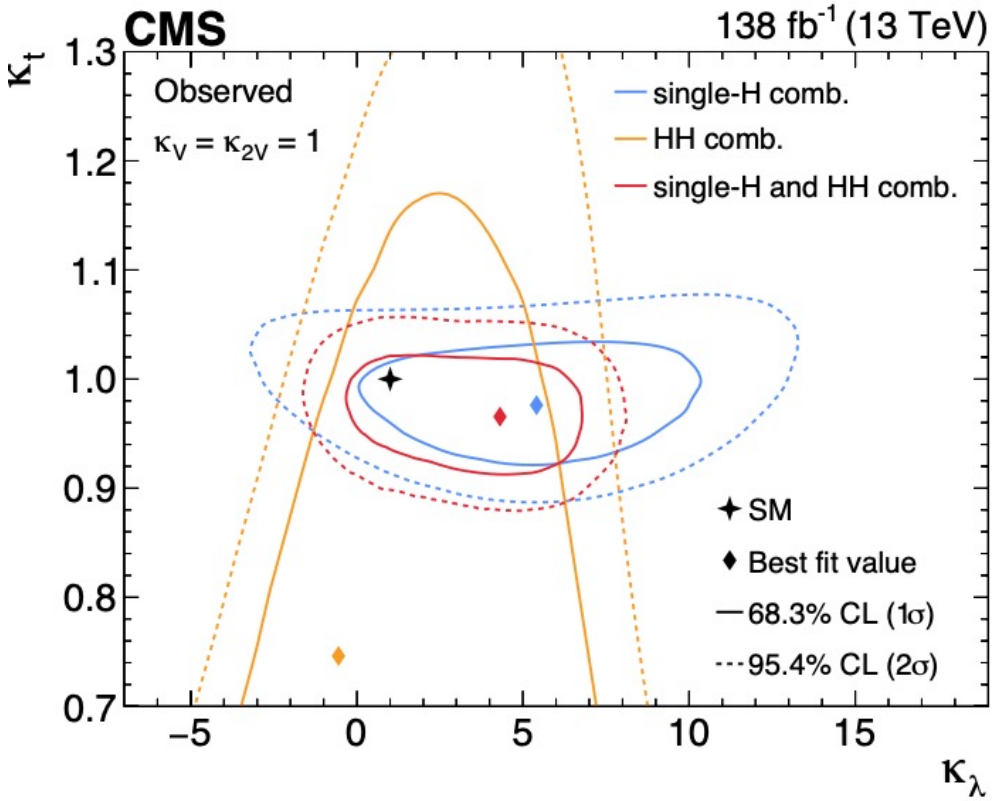
CMS

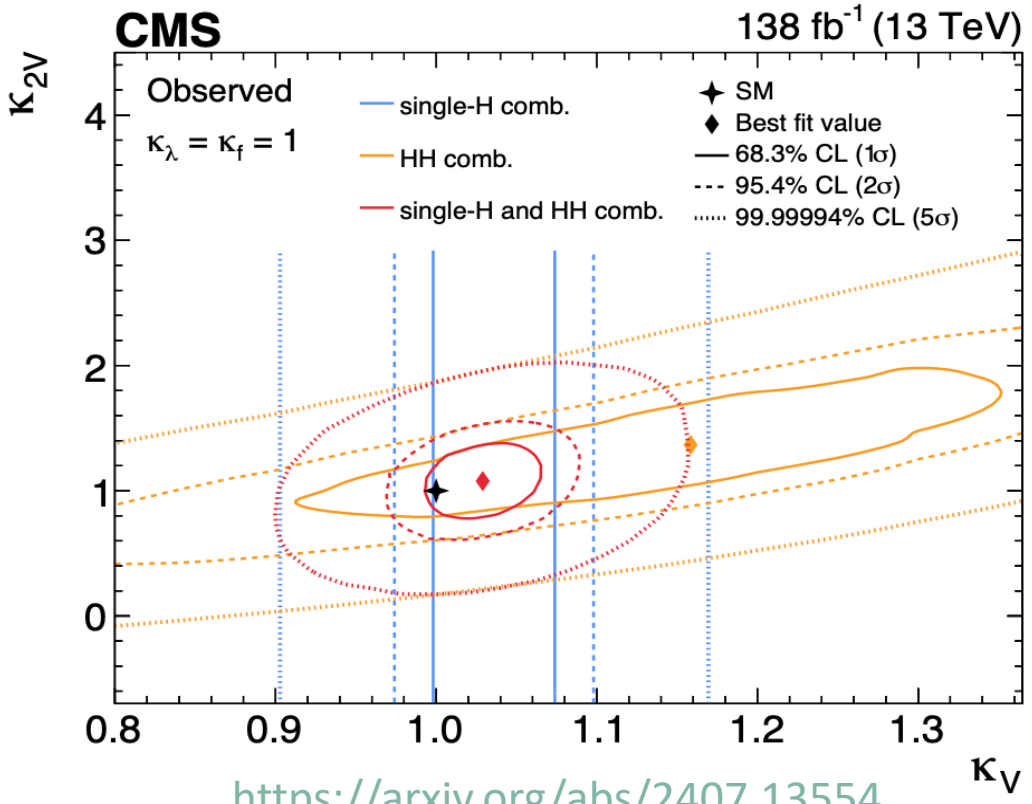
Hypothesis	Best fit $\pm1\sigma$ Expected	Best fit $\pm1\sigma$ Observed	95% CL interval Expected	95% CL interval Observed
Other couplings fixed to SM	$1.0^{+4.6}_{-1.7}$	$3.1^{+3.0}_{-3.0}$	$[-2.0, +7.7]$	$[-1.2, +7.5]$
Floating (κ_V, κ_{2V}, κ_f)	$1.0^{+4.7}_{-1.8}$	$4.5^{+1.8}_{-4.7}$	$[-2.2, +7.8]$	$[-1.7, +7.7]$
Floating (κ_V, κ_t, κ_b, κ_τ)	$1.0^{+4.8}_{-1.8}$	$4.7^{+1.7}_{-4.1}$	$[-2.3, +7.7]$	$[-1.4, +7.8]$
Floating (κ_V, κ_{2V}, κ_t, κ_b, κ_τ, κ_μ)	$1.0^{+4.8}_{-1.8}$	$4.7^{+1.7}_{-4.2}$	$[-2.3, +7.8]$	$[-1.4, +7.8]$

- Single H prefers positive κλ
- Allowing other coupling to float doesn't affect the constraints a lot. We can measure κλ without assumptions!

https://arxiv.org/abs/2407.13554

Single and double Higgs searches

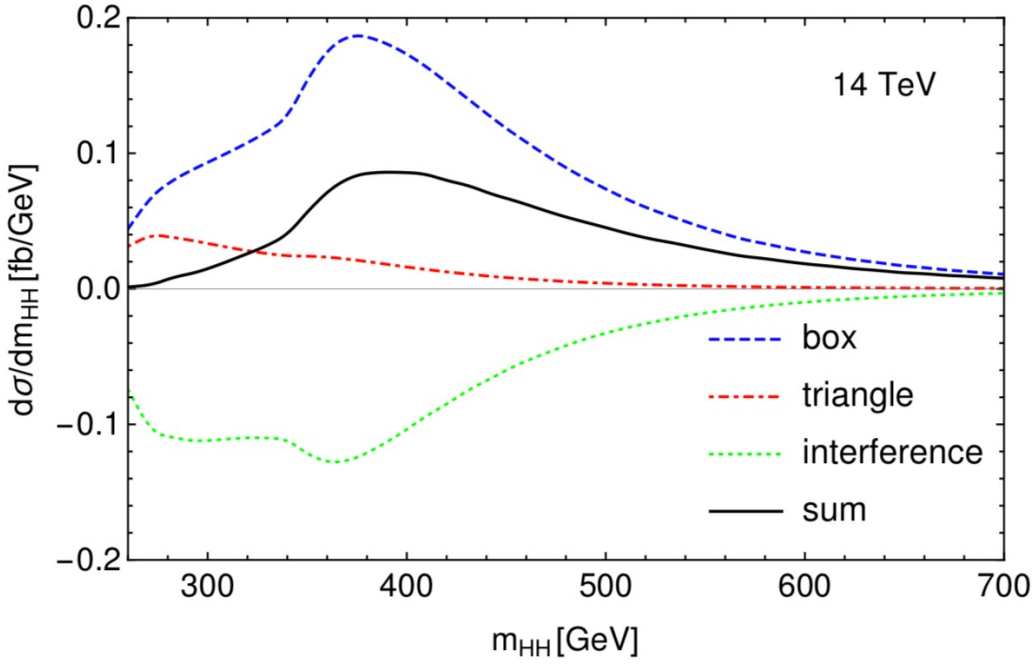


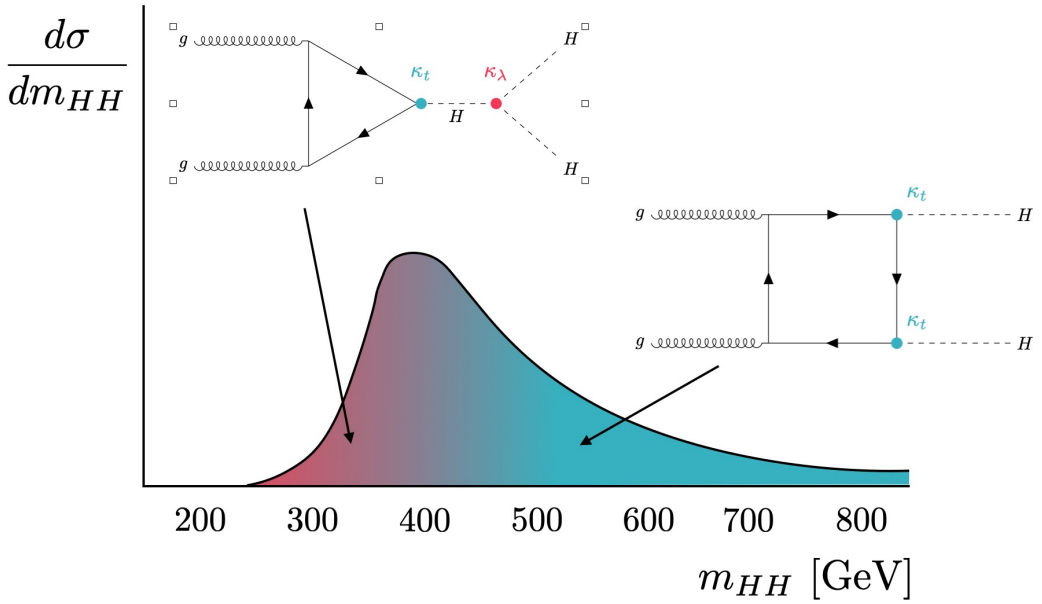


https://arxiv.org/abs/2407.13554

- Adding the H constraints on κt and κv bring enormous improvement to 2D countours!

Double Higgs production at the LHC (SM)





Graphic by Katherine Leney