Higgs self-coupling measurements in CMS

Agni Bethani
on behalf of the the CMS collaboration

23rd September

Higgs Hunting 2024

UCLouvain

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
This is what this talk is about

In the SM υ=246 GeV

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

The Higgs potential

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- 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

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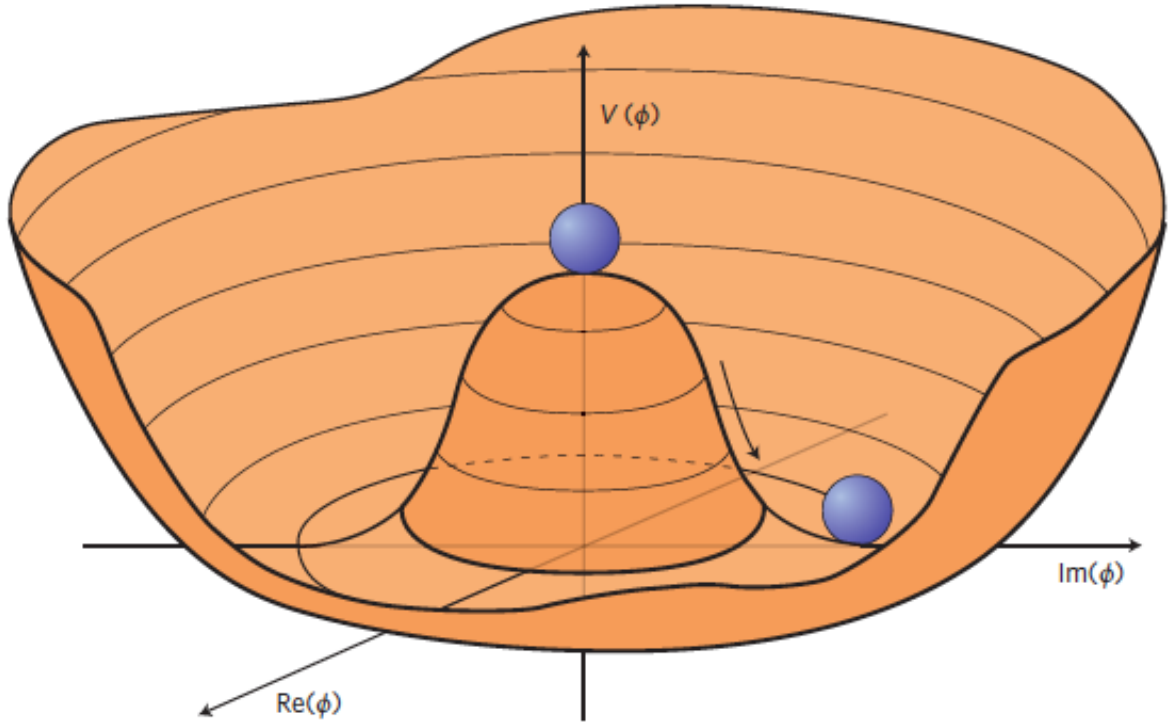
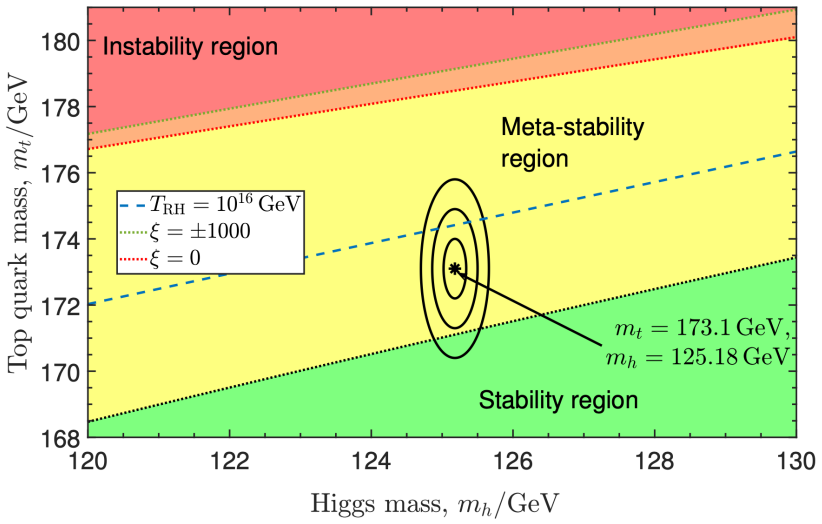
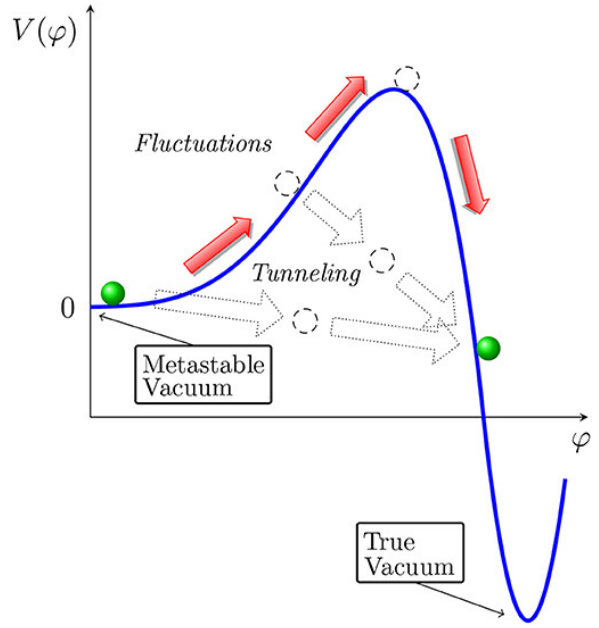


The Higgs potential

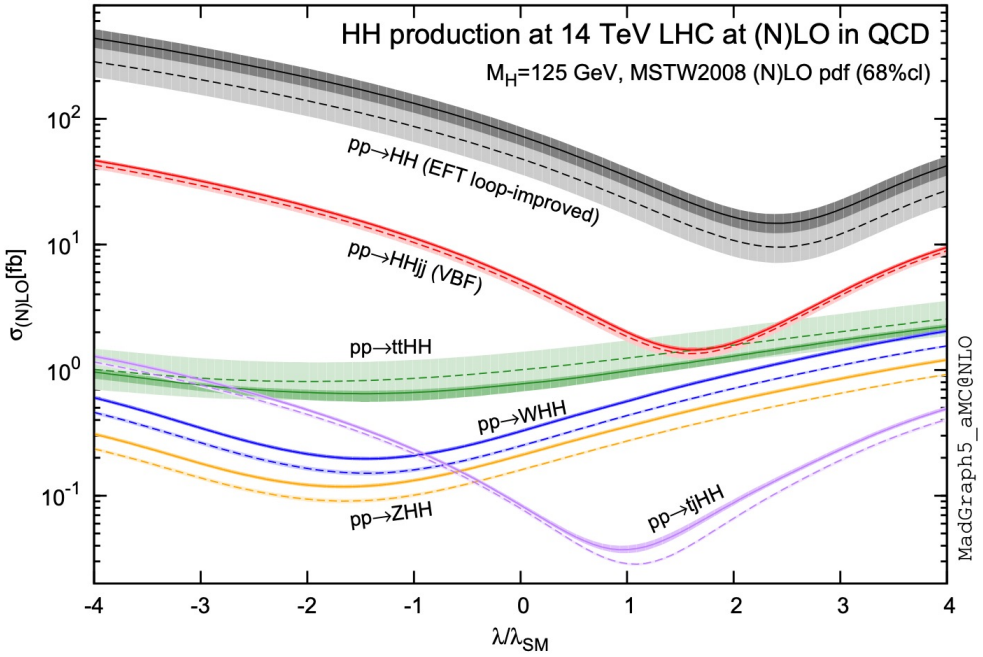
- The least explored part of the Standard Model!
- The Higgs sector is sensitive to new physics BSM
- Cosmological consequences:
  - Inflation
  - Vacuum stability
  - Baryogenesis
  - …?

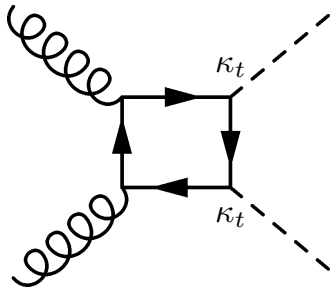


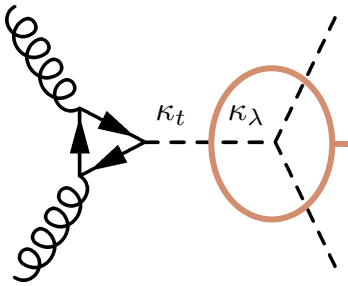


Double Higgs production at the LHC (SM)

- 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)

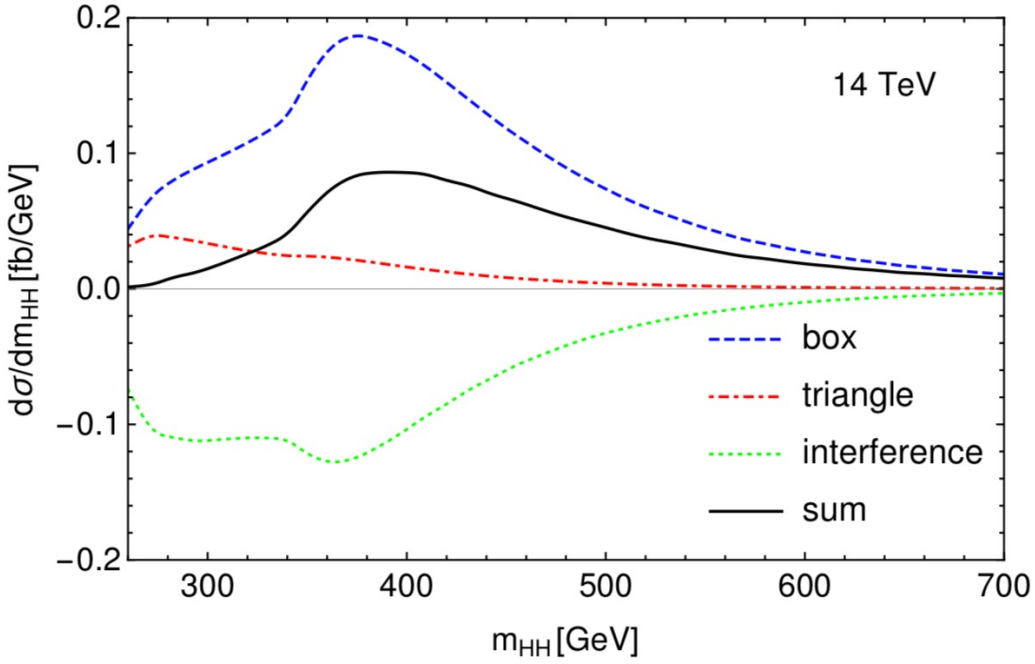


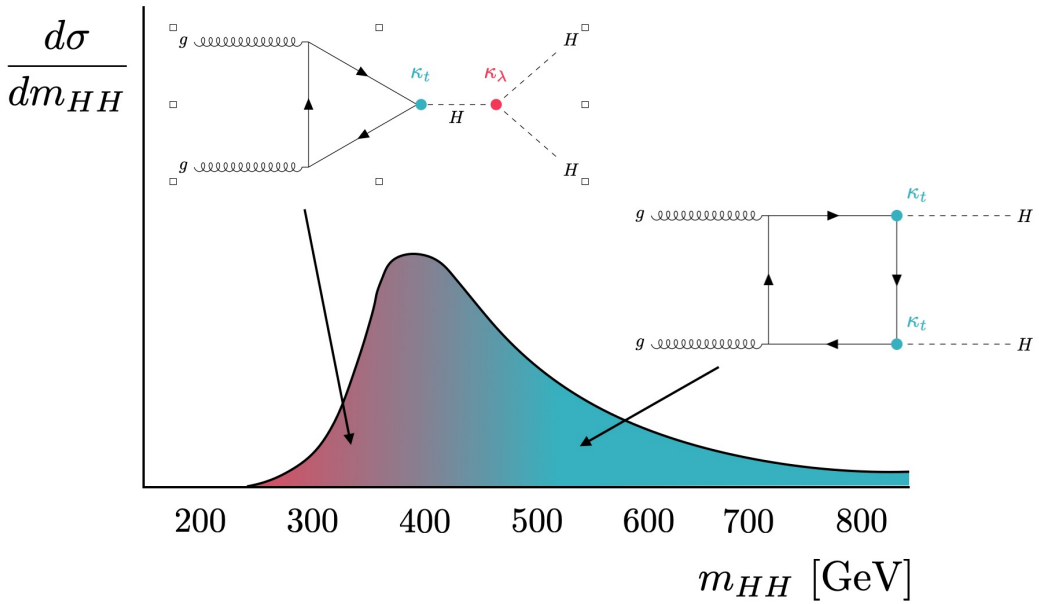




Higgs trilinear coupling

Double Higgs production at the LHC (SM)



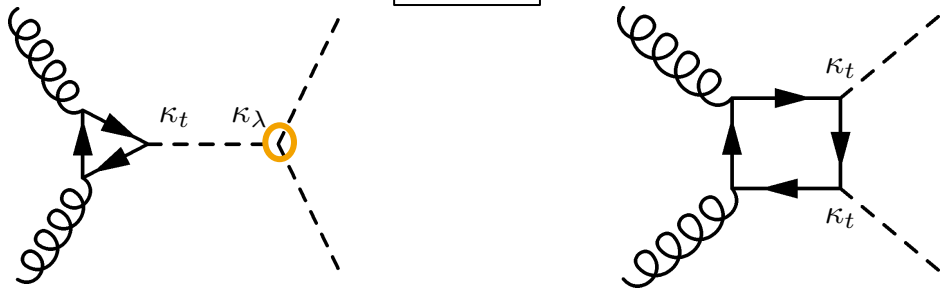


Graphic by Katherine Leney

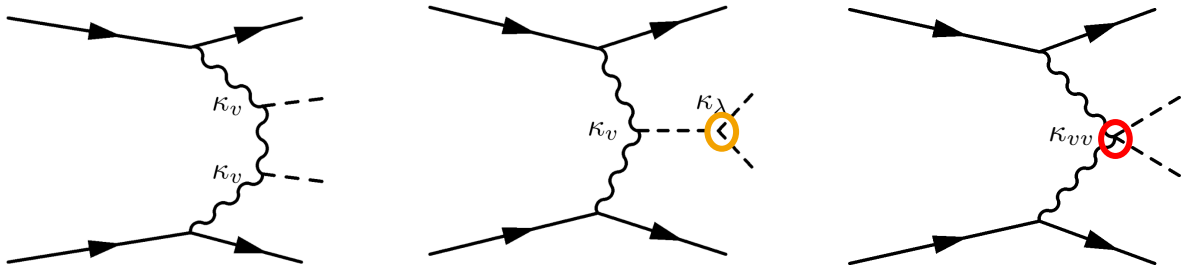
Higgs trilinear coupling

Higgs pair production

ggF

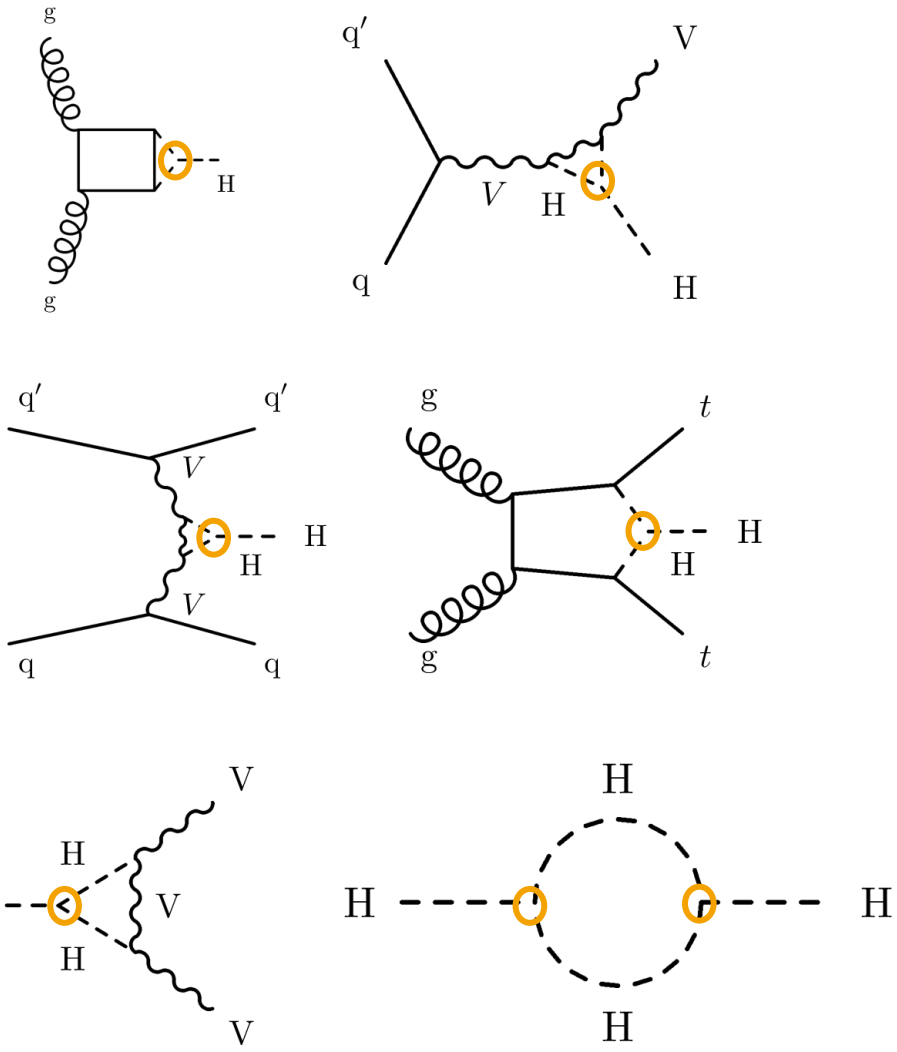


VBF



Sensitivity to κ_λ via single Higgs production

NLO corrections in H->VV decay and Higgs boson propagator

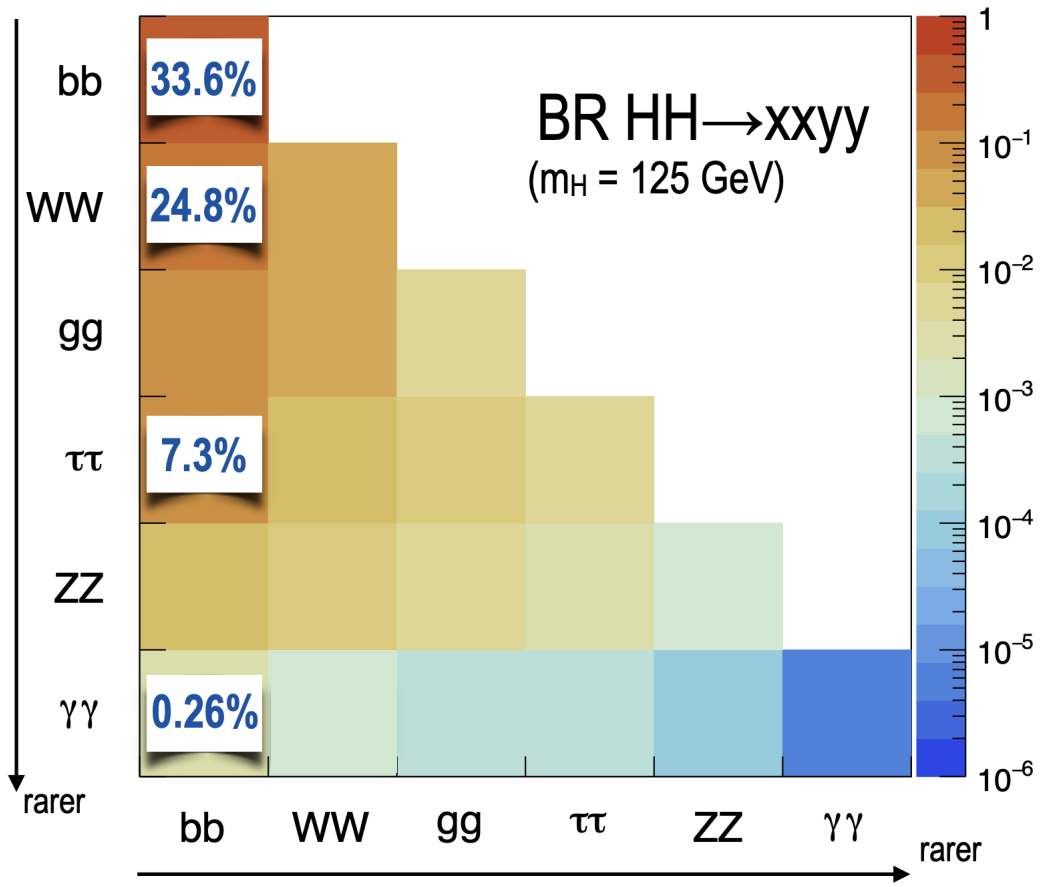


HH decays:

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

HH decays:

Most sensitive

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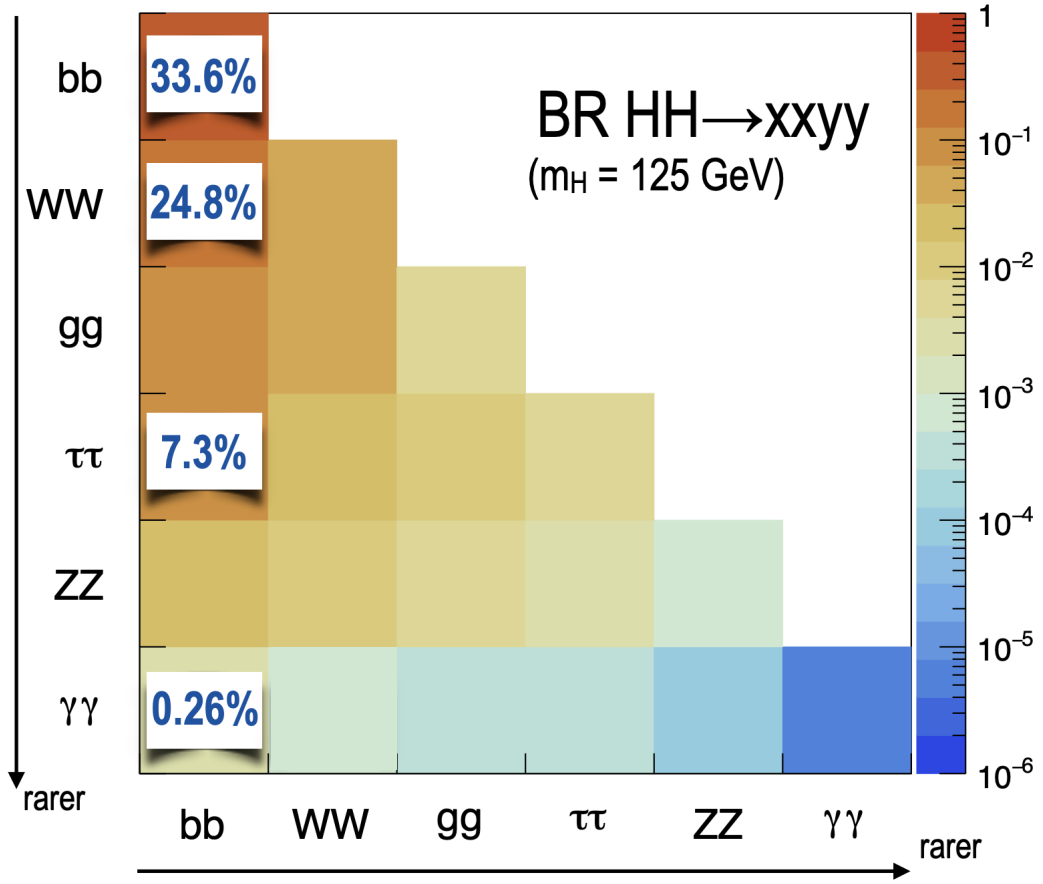

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HH decays:

Most recent
Will be discussed in this talk

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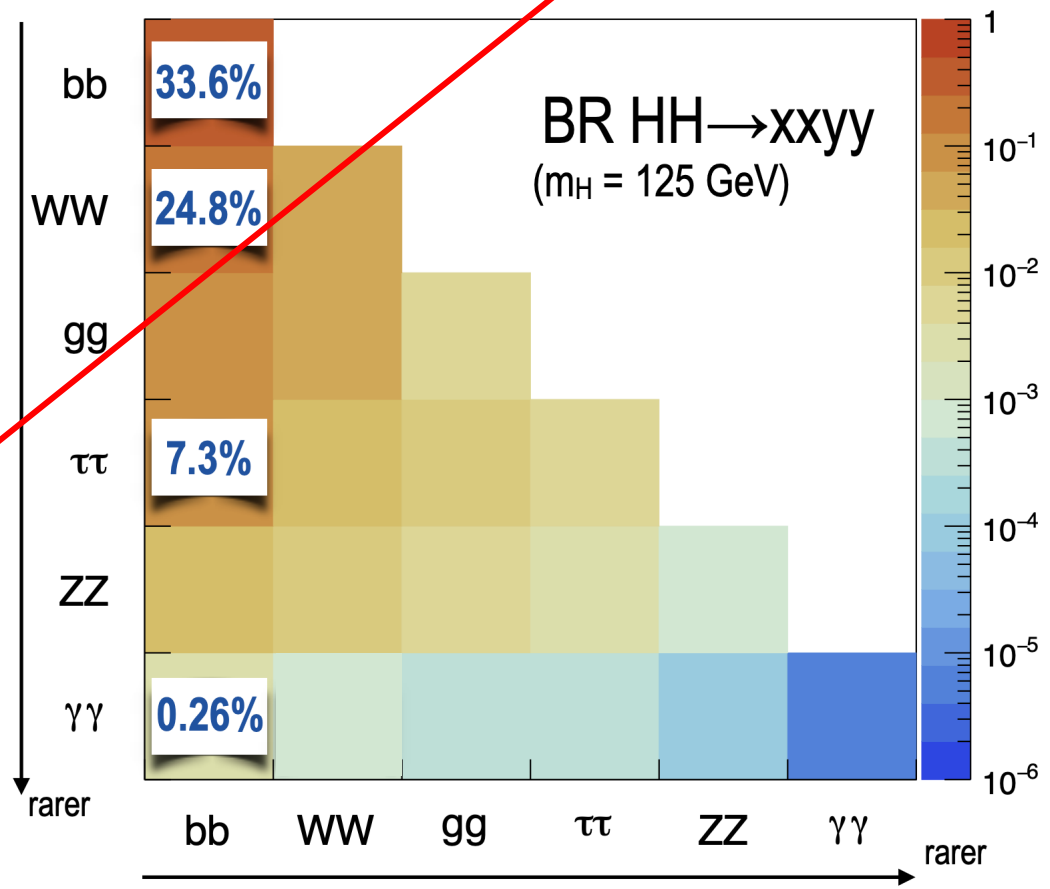

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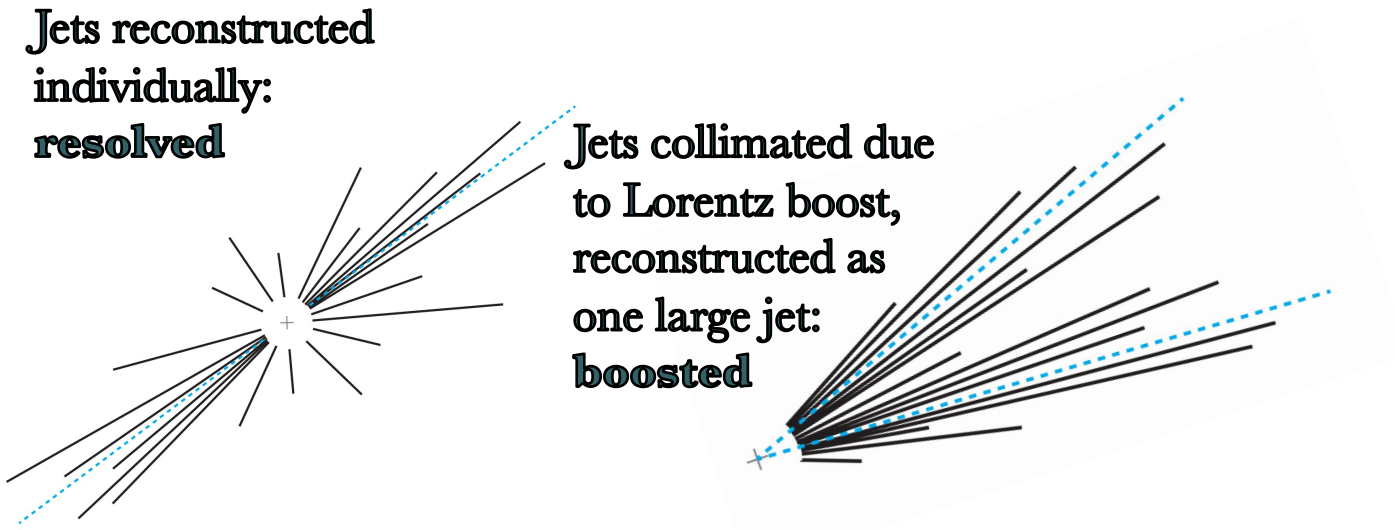
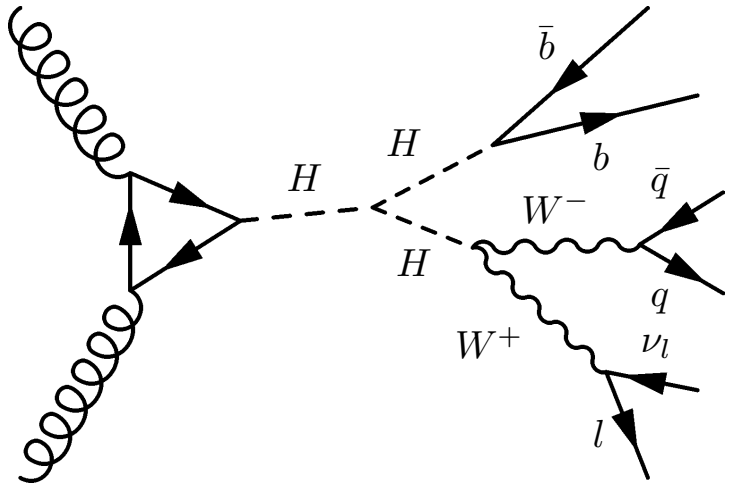
HH→bbWW

- Single lepton and di-lepton
  - Mainly from WW decays, ZZ and ττ are included well
- Gluon fusion and VBF
- Boosted and resolved topology
- Multiclass Deep Neural Network (DNN)
- Additional Lorentz Boost Network (LBN)
- Event categories according H → bb topology and b-jet multiplicity
  - boosted/resolved
  - 1 or 2 b-tagged jets
- Simultaneous fit in all categories on DNN score





https://link.springer.com/article/10.1007/JHEP07(2024)293

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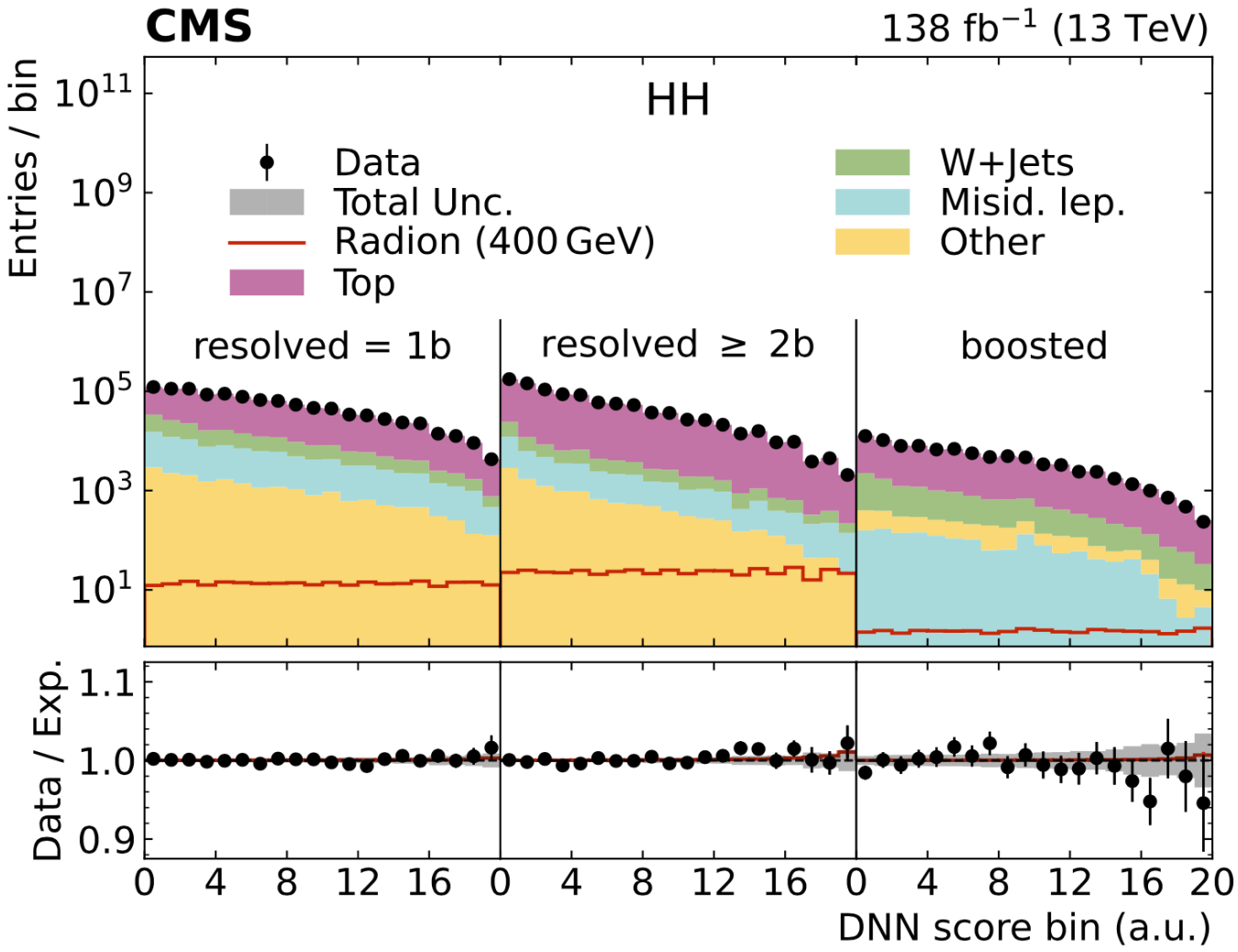

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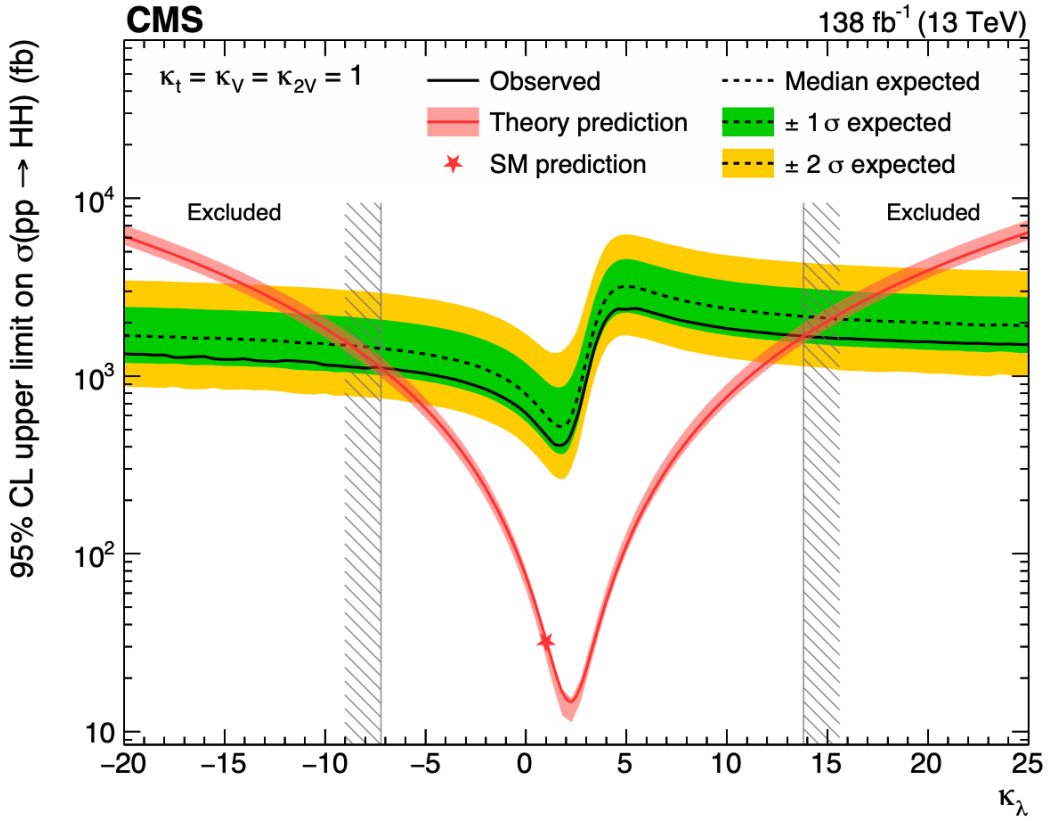


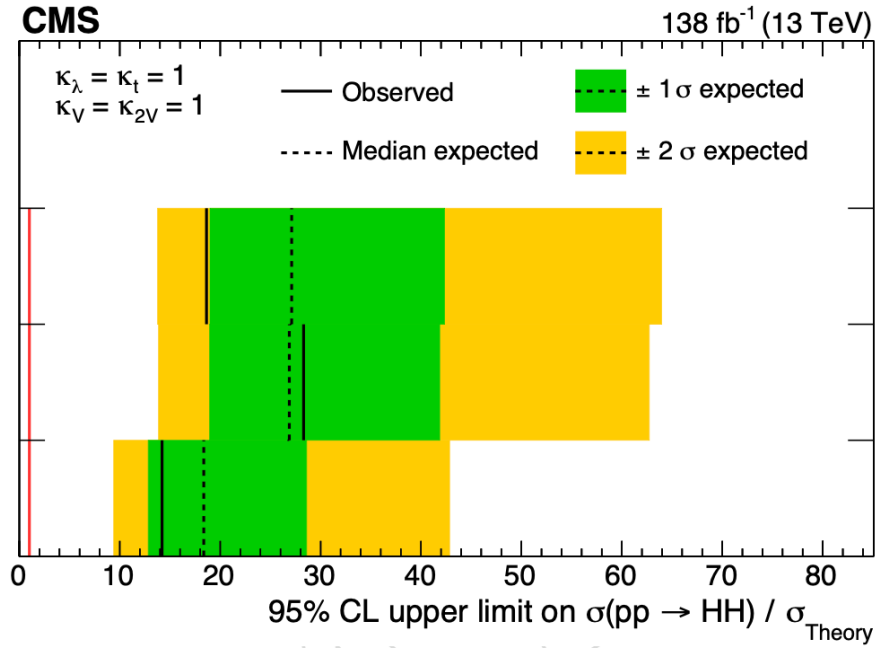
κλ [−7.2, 13.8] (expected [−8.7, 15.2])

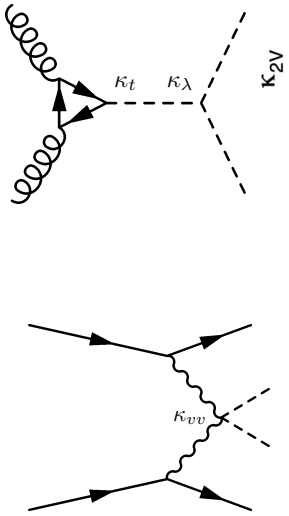
bbWW

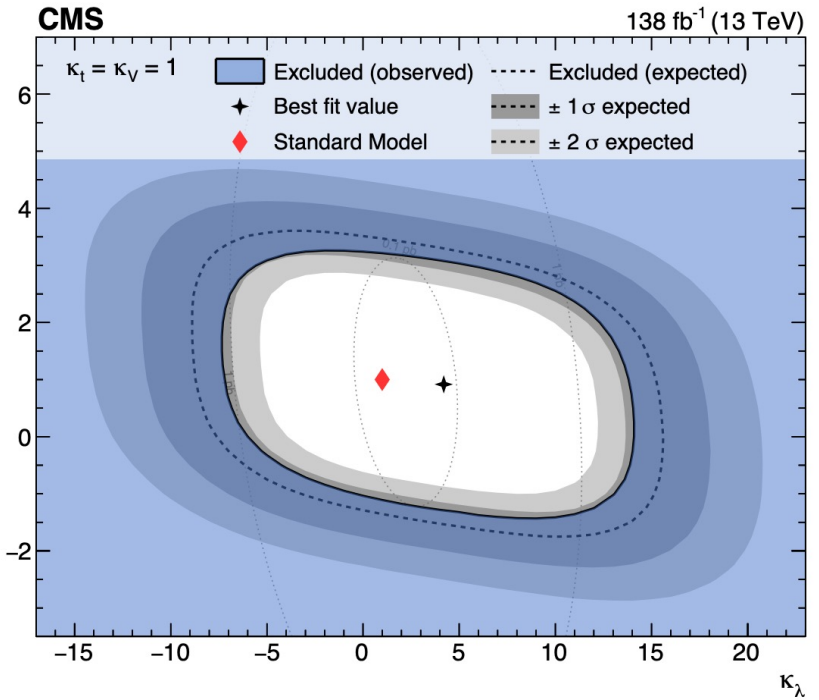
dilepton
Expected: 27
Observed: 19

single-lepton
Expected: 27
Observed: 28

Combined
Expected: 18
Observed: 14



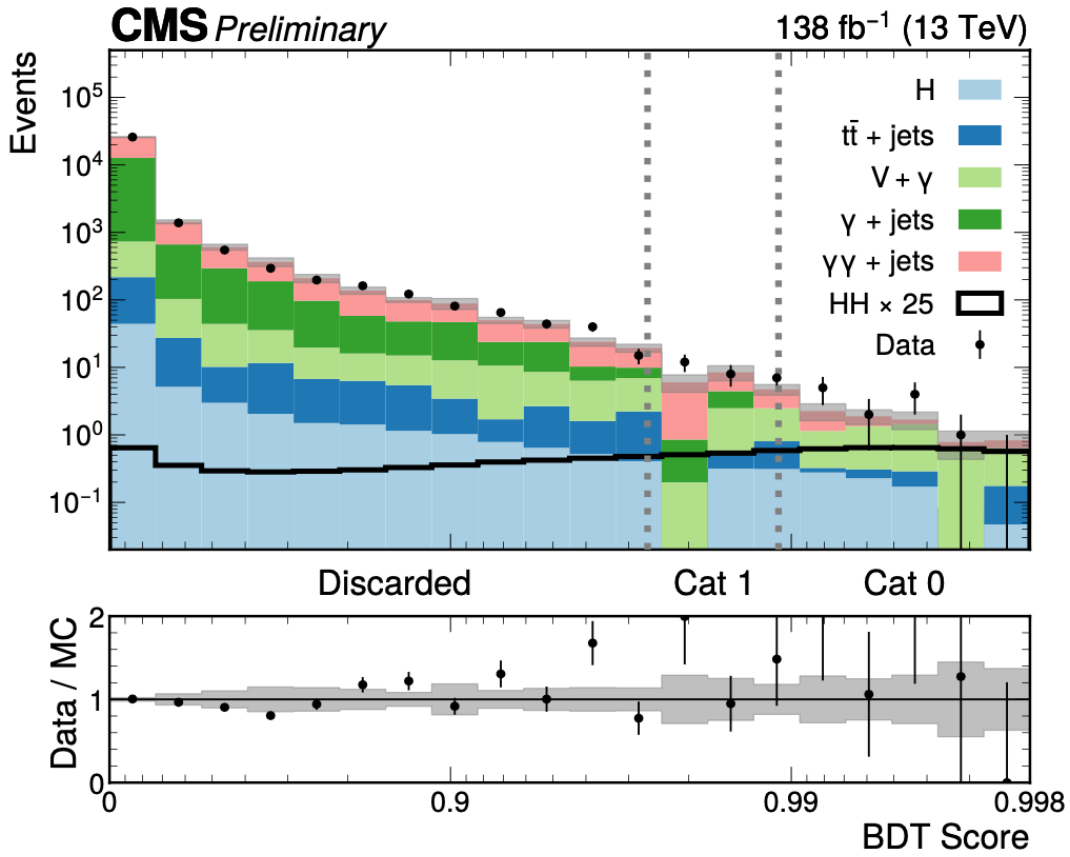




HH→ττγγ

https://inspirehep.net/literature/2784595

- 5 channels based on τ decay signature:
  - 2 τ+0 l, 1τ+1l, 0τ+2l, 1τ+Isolated track, 1τ+0l
- Categorized based on the output of a BDT classifier.
- Two categories based on signal purity, maximizing the expected upper limit
- mγγ spectrum
  - Signal: Double Crystal Ball functions
  - Background: data driven smooth function chosen through a discrete profiling method



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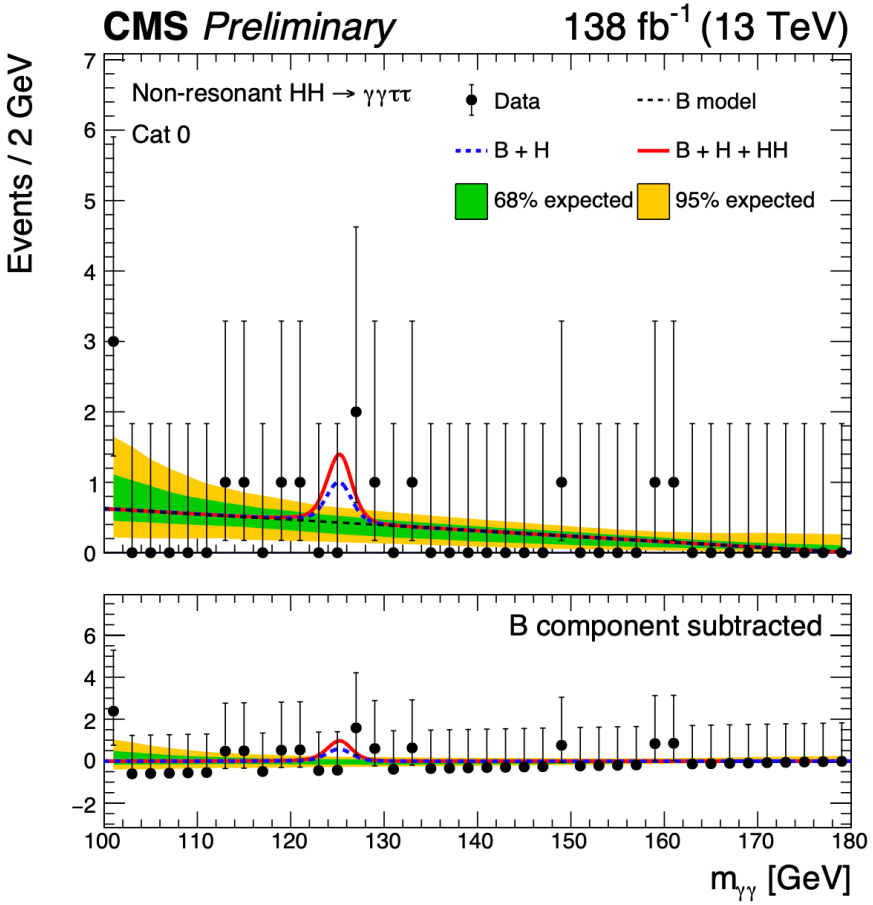
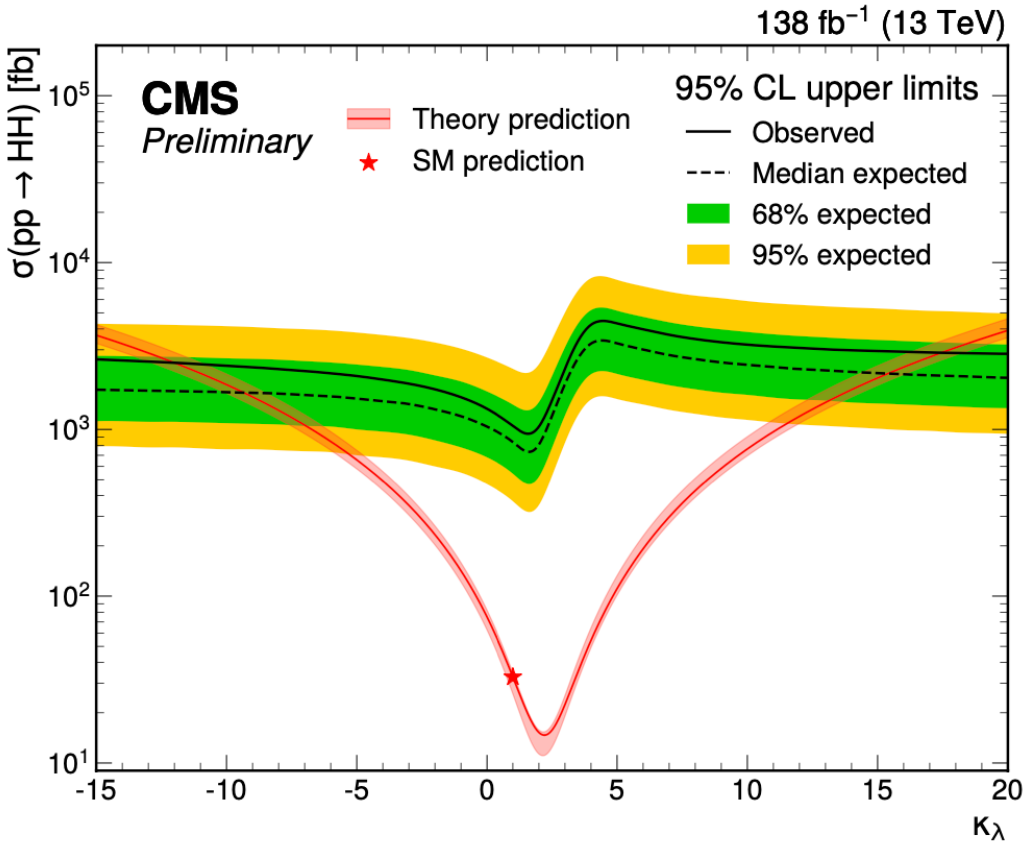


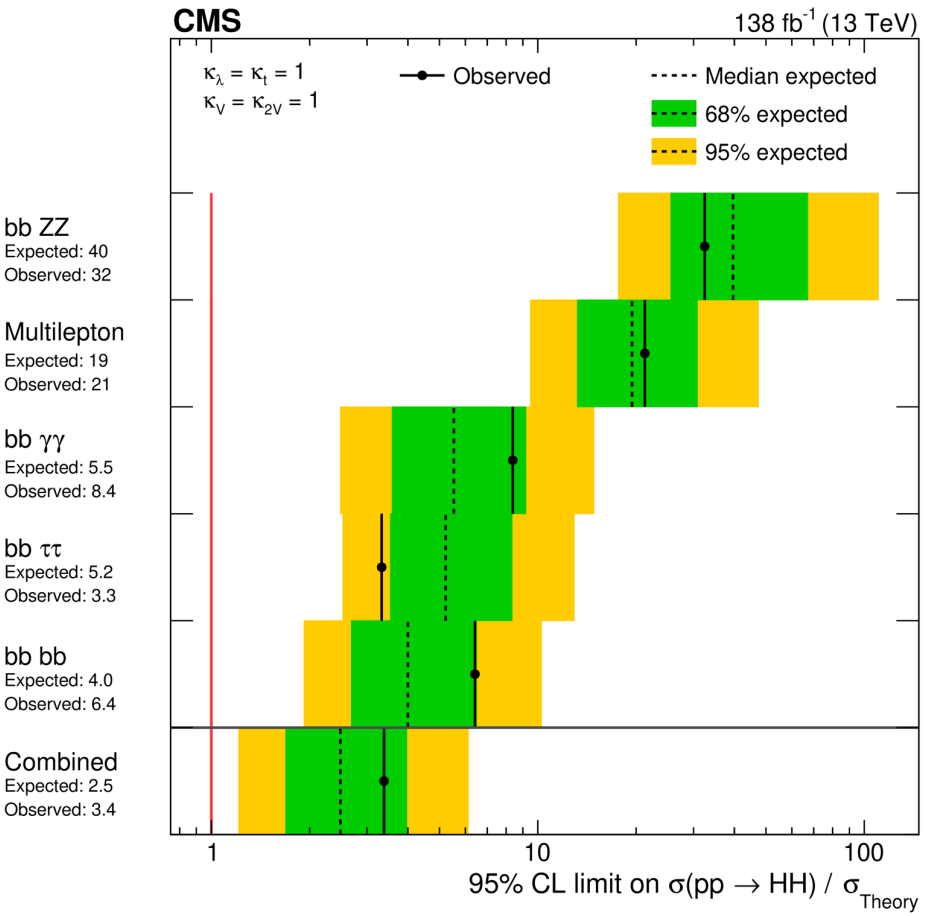
HH→ττγγ

https://inspirehep.net/literature/2784595

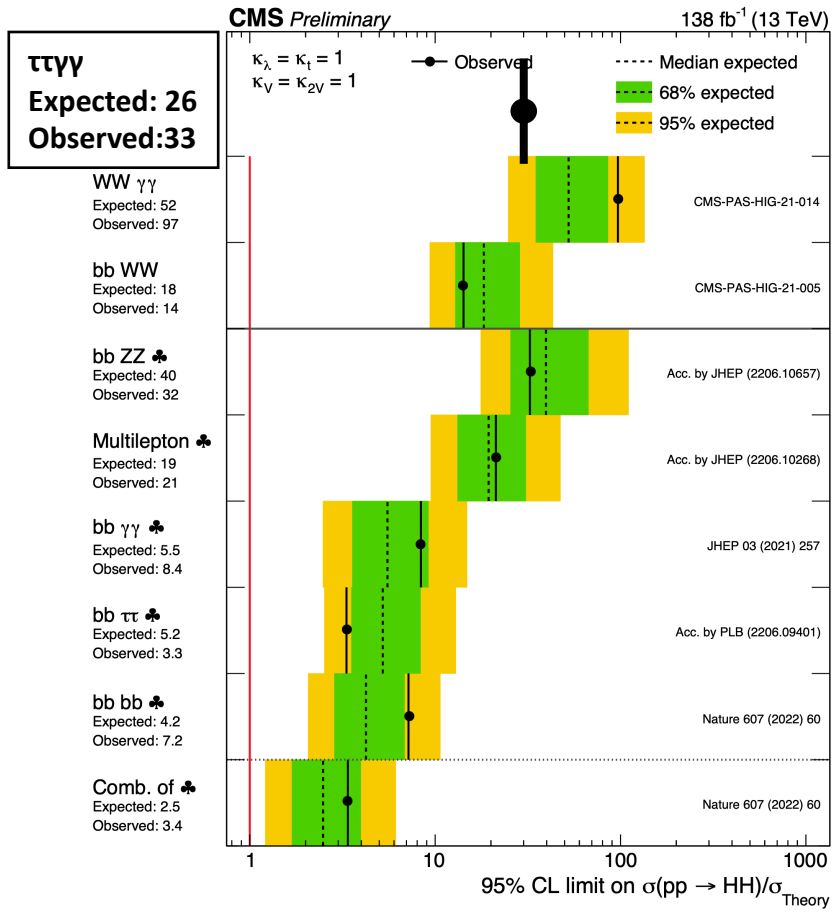
- Limits on cross secrion:
  33 x σ_{SM} (expected 26 x σ_{SM})
- Constraints on κλ:
  κλ [−13, 18] (expected [−11, 16])



Higgs pair production cross-section

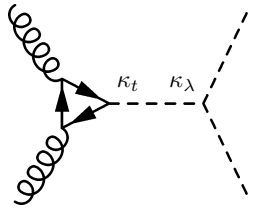


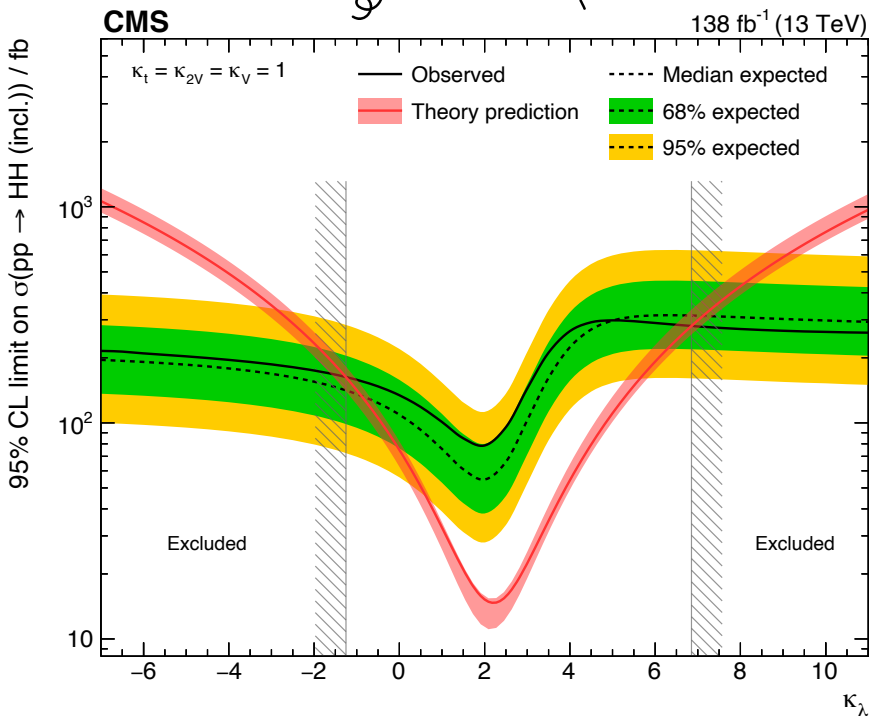
Nature volume 607, pages60–68 (2022)



CMSPublic twiki

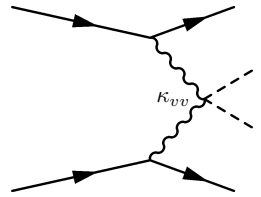
Constraints of Higgs couplings from HH

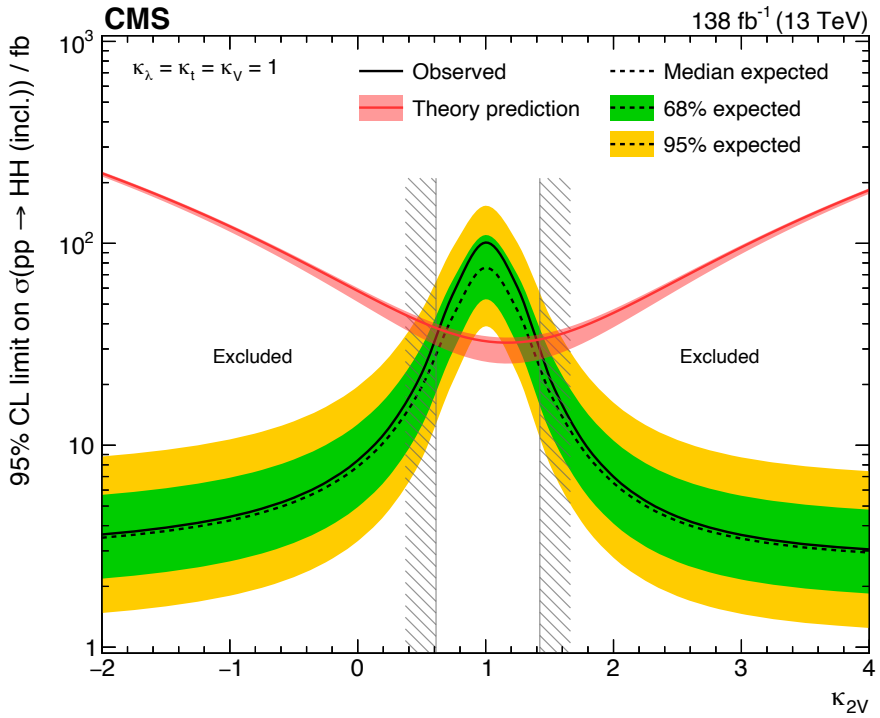




κ_λ [-1.25, 6.85] @ 95% CL

Nature volume 607, pages60–68 (2022)

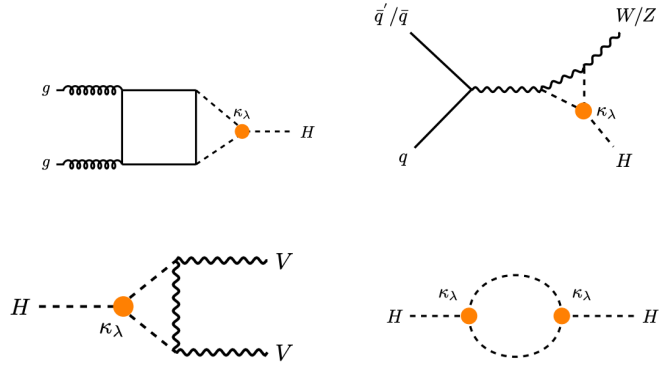


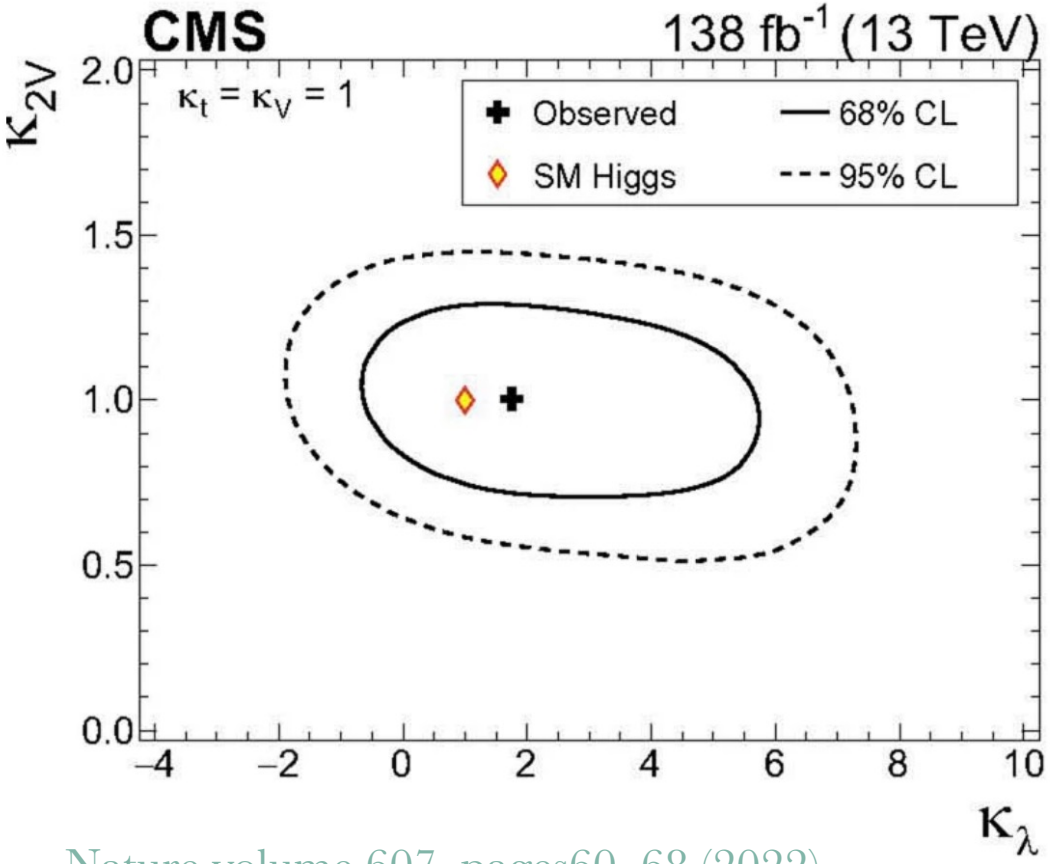


κ_{2V} [0.67, 1.38] @95% CL

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

Higgs trilinear coupling





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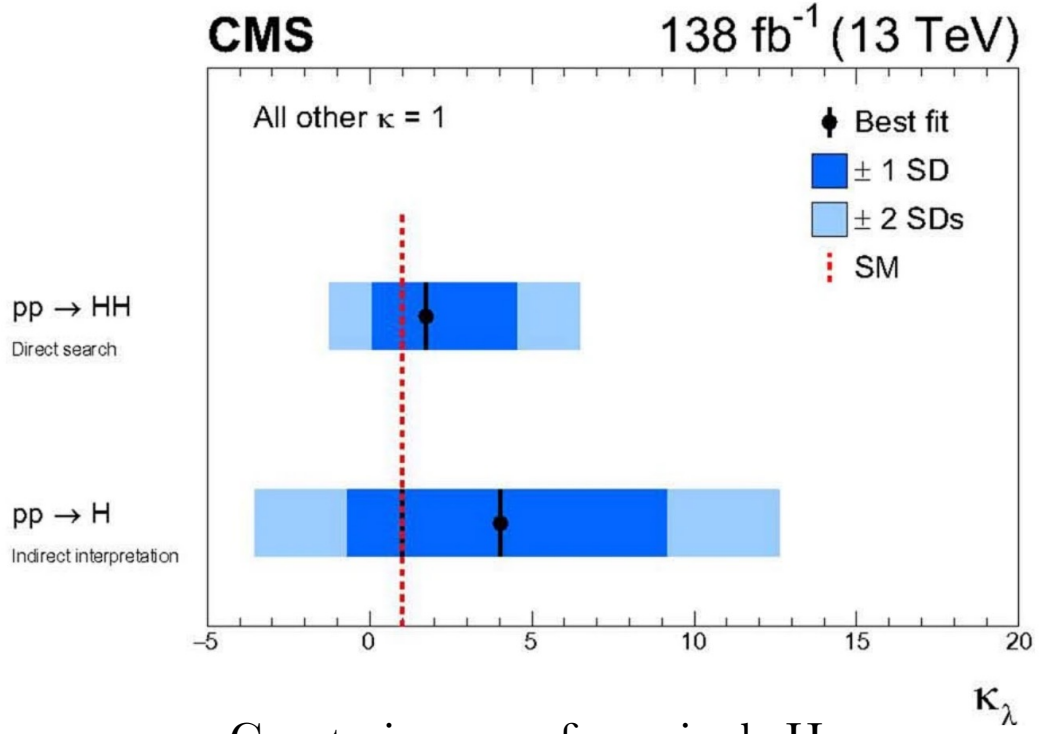


Constrains on κ_λ from single H production, not negligible!

Single and double Higgs searches

Simultaneously constrain

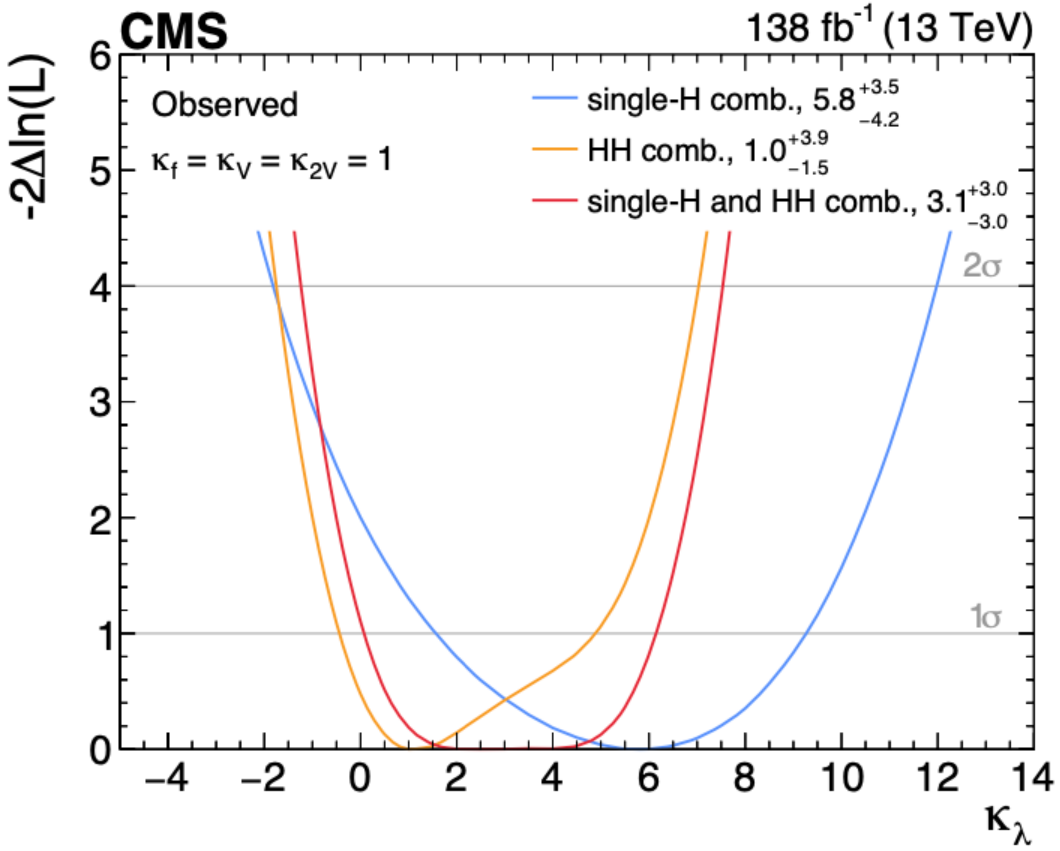
- Higgs boson trilinear self-coupling
- Higgs boson couplings to fermions and to vector bosons.

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



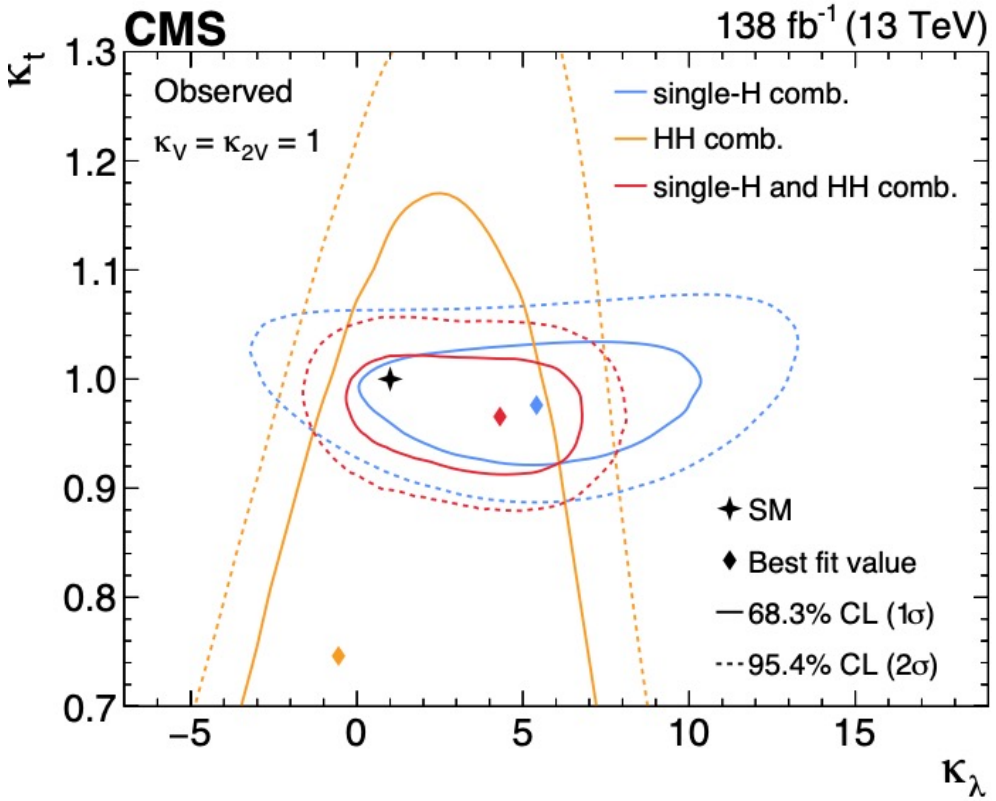
CMS

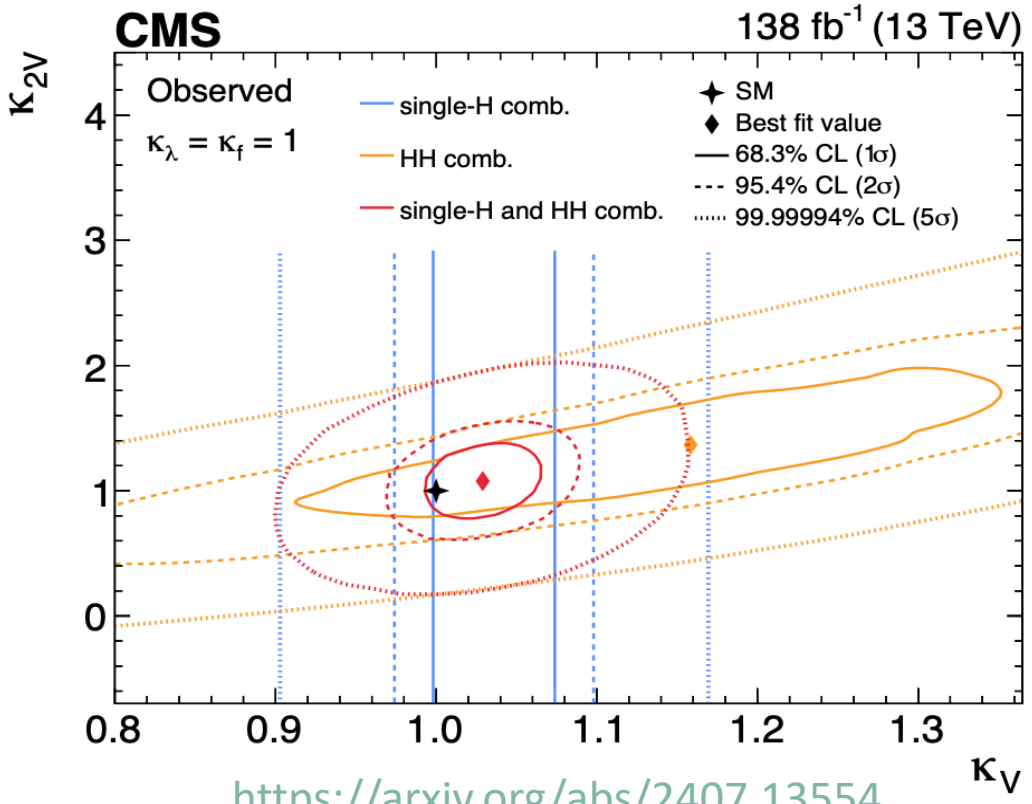
Hypothesis	Best fit $\pm1\sigma$ Expected	Best fit $\pm1\sigma$ Observed	95% CL interval Expected	95% CL interval Observed
Other couplings fixed to SM	$1.0^{+4.6}_{-1.7}$	$3.1^{+3.0}_{-3.0}$	$[-2.0, +7.7]$	$[-1.2, +7.5]$
Floating (κ_V, κ_{2V}, κ_f)	$1.0^{+4.7}_{-1.8}$	$4.5^{+1.8}_{-4.7}$	$[-2.2, +7.8]$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





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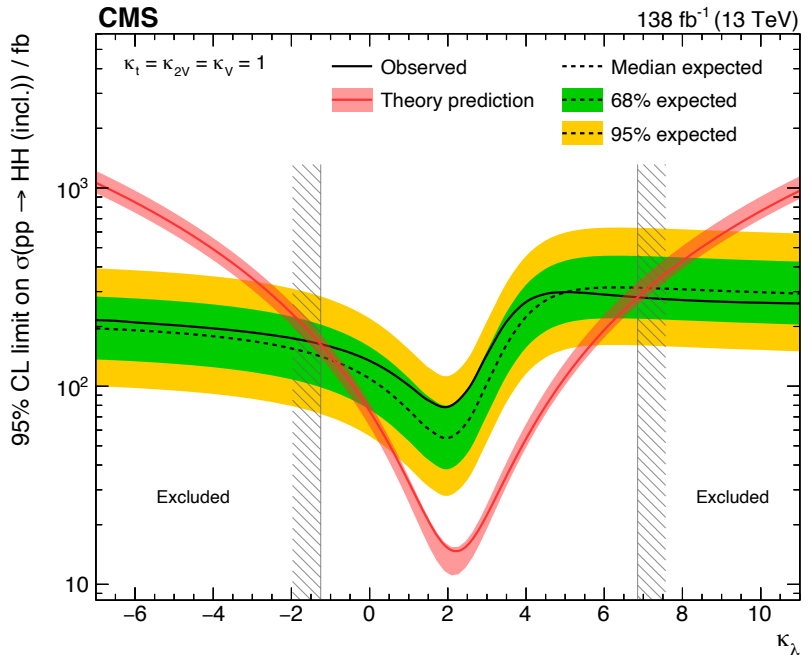
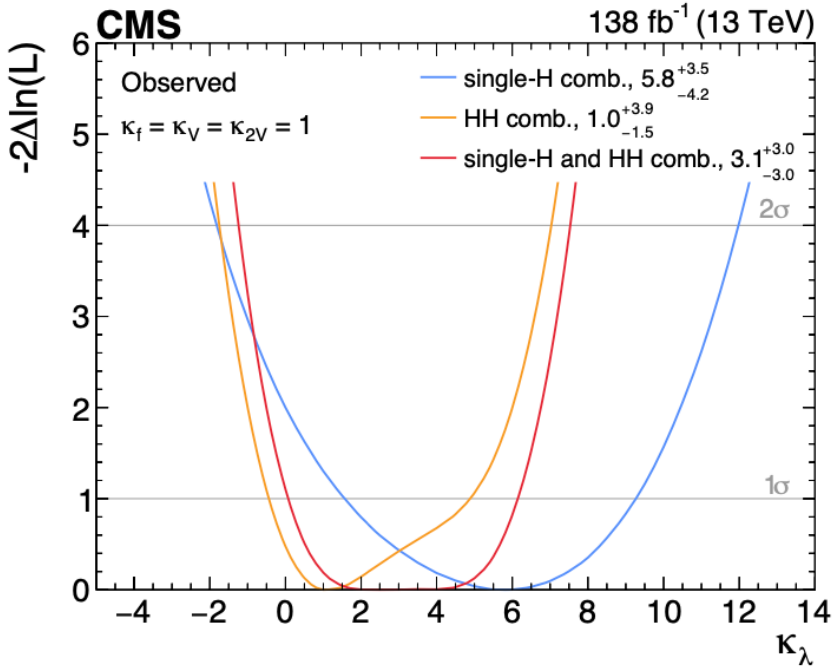
- Adding the H constraints on κt and κv bring enormous improvement to 2D countours!

Summary

- Best constraints by CMS:
  κλ [-1.25, +6.85]
- Many Higgs decay channels
- Single H and HH production studied
- A diverse set of parameter scans and BSM interpretentions is possible when studying HH events. Not addressed in this talk.
- Looking forward to more data!

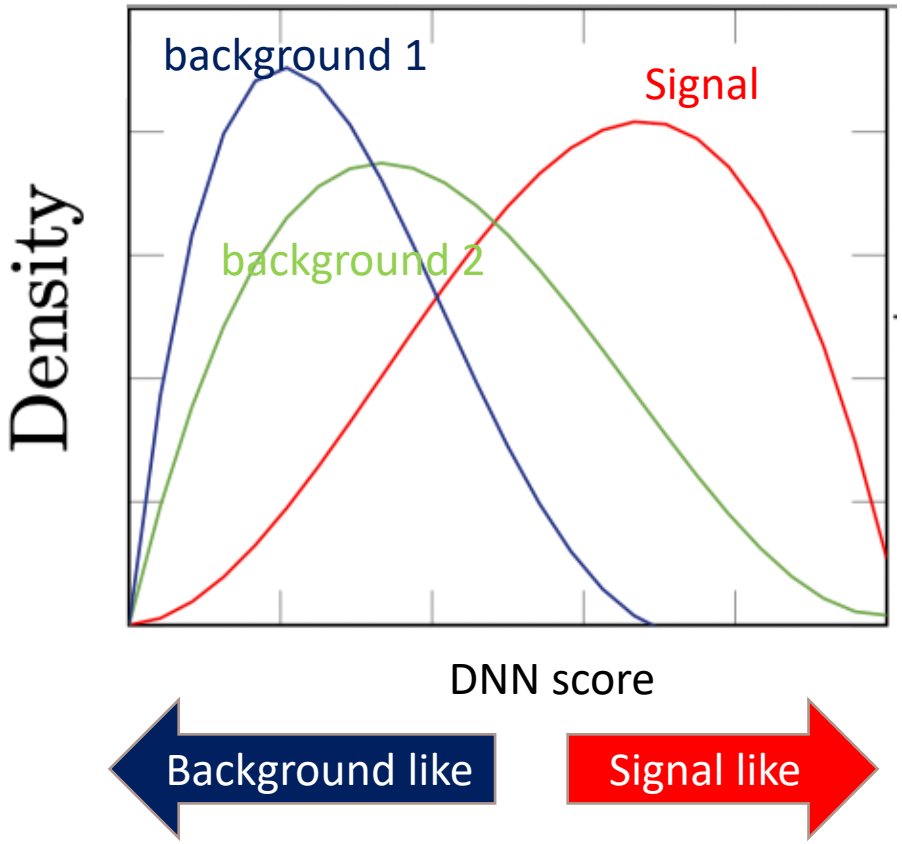




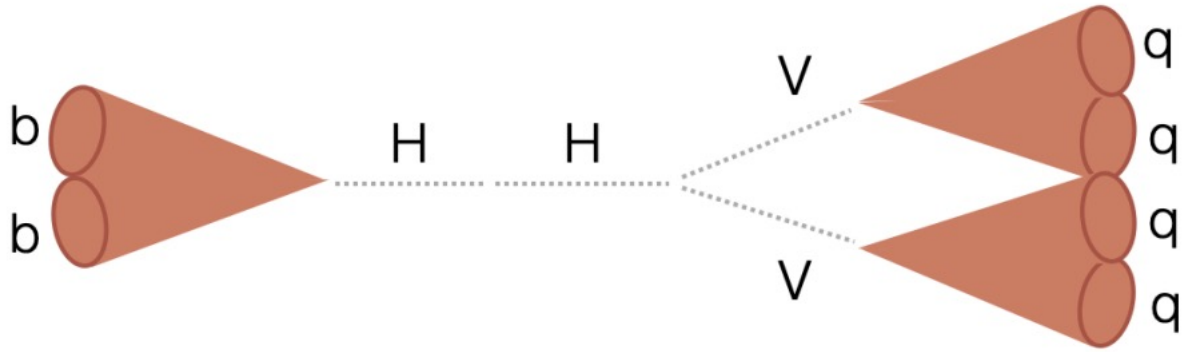
Bonus material

HH→ bbWW: Analysis strategy

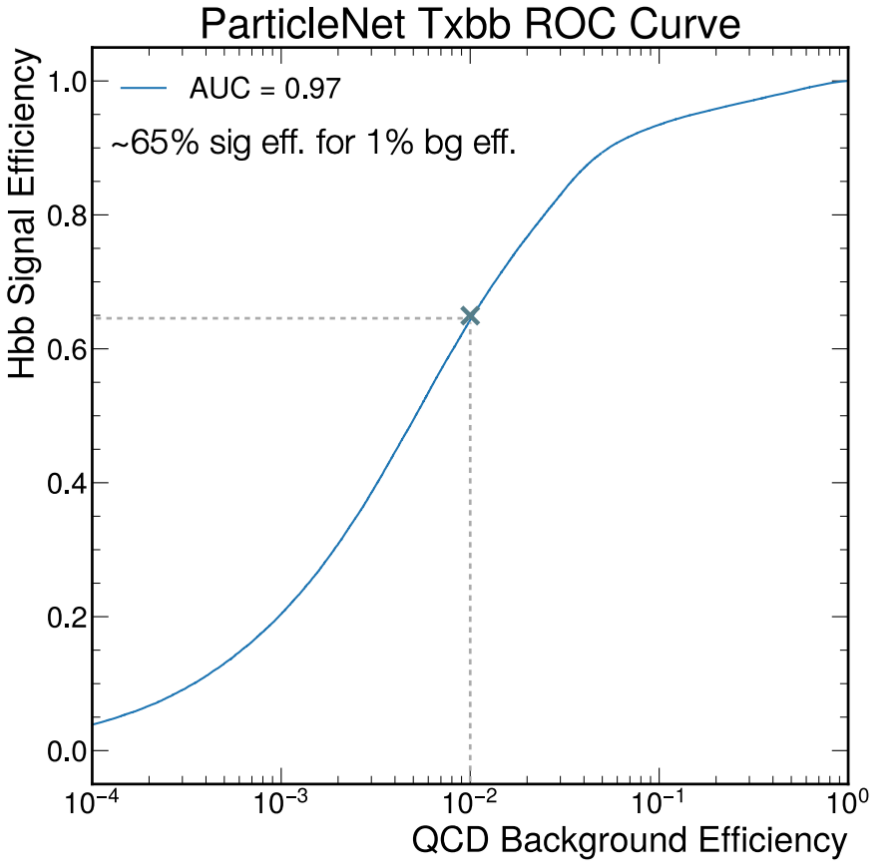
- Multiclass Deep Neural Network (DNN)
  - Signal vs background discrimination
  - Categorisation into signal and background enriched regions
- additional Lorentz Boost Network (LBN)
  - Acts like a pre-processor
  - Creates additional observables
  - 10% gain in the sensitivity
- Event categories according H → bb topology and b-jet multiplicity
  - boosted/resolved
  - 1 or 2 b-tagged jets
- Simultaneous fit in all categories



bbVV hadronic

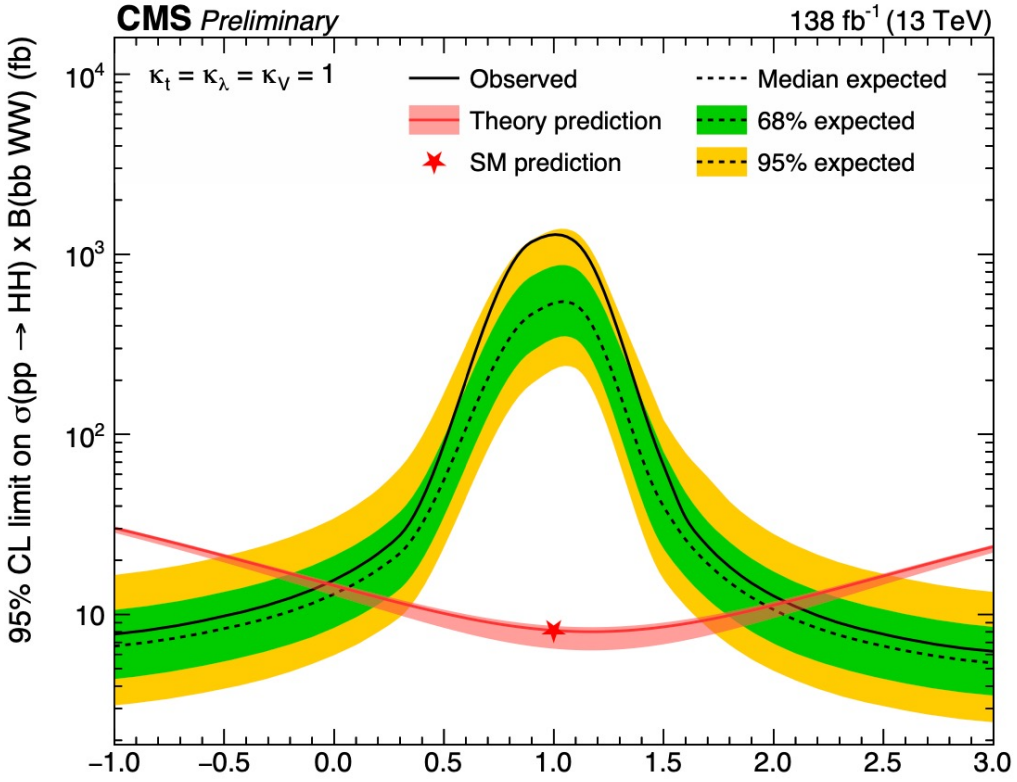


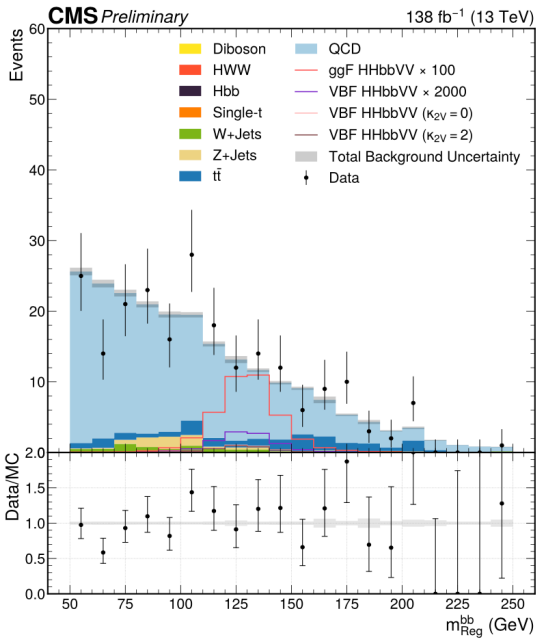
- HH->(bb)(VV → 4q)
- gluon-gluon fusion (ggF) and vector boson fusion (VBF)
- Lorentz-boosted HH candidates ->large-radius jets
- new global particle transformer (GloParT) classifier to identify VV → 4q
- ParticleNet algorithm is used for H → bb tagging.

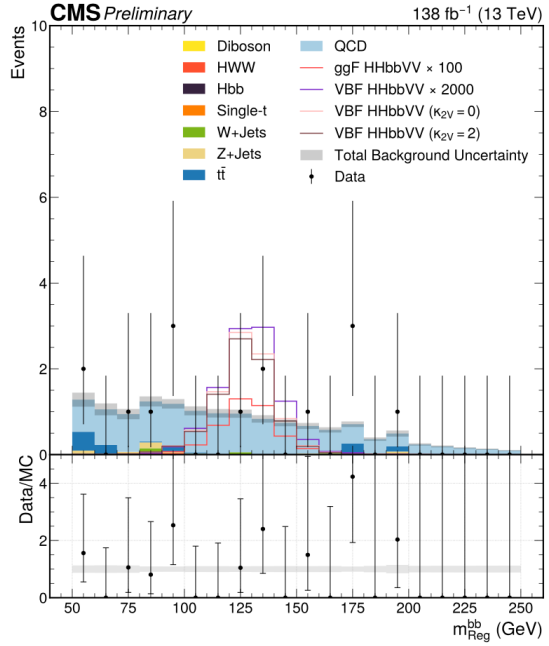


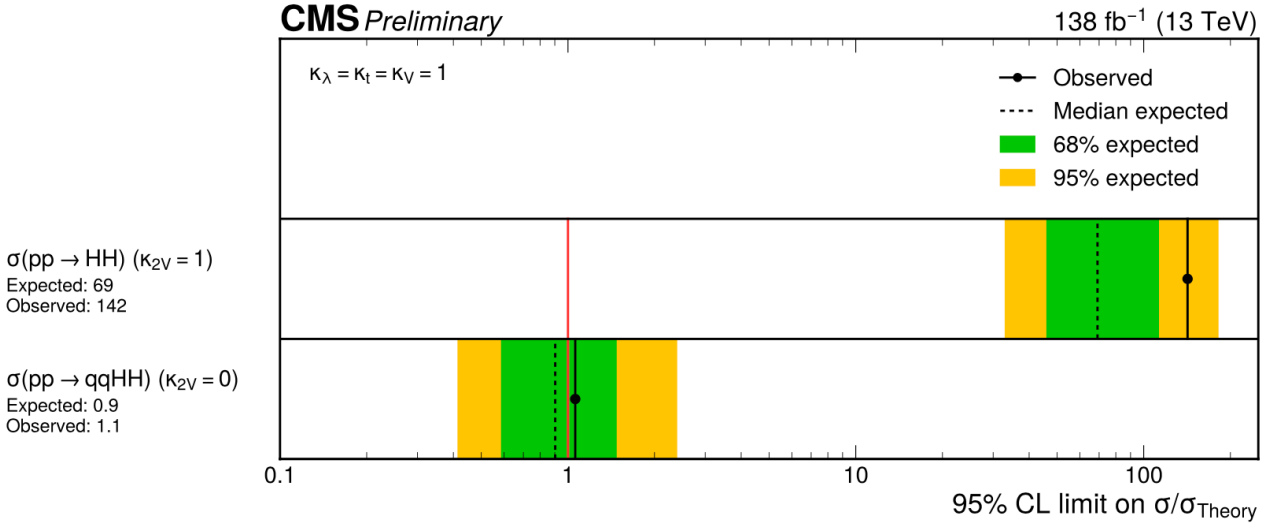
bbVV hadronic

- $\kappa_2 V$ −0.04, 2.05 (0.05, 1.98)





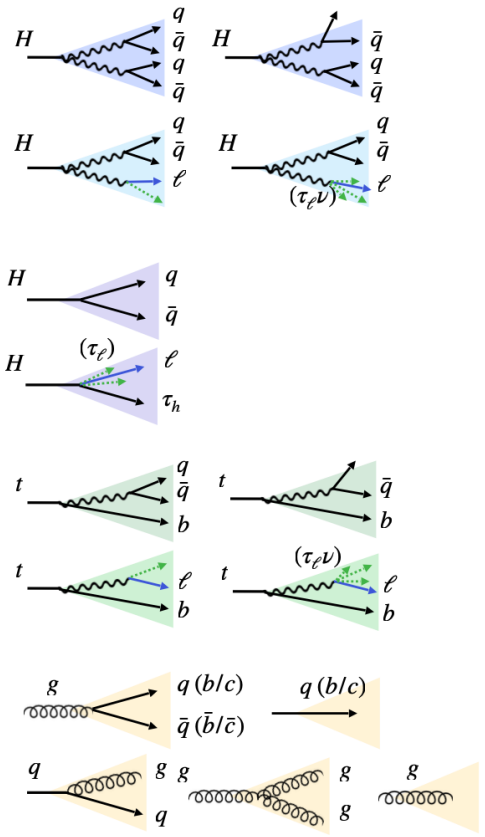


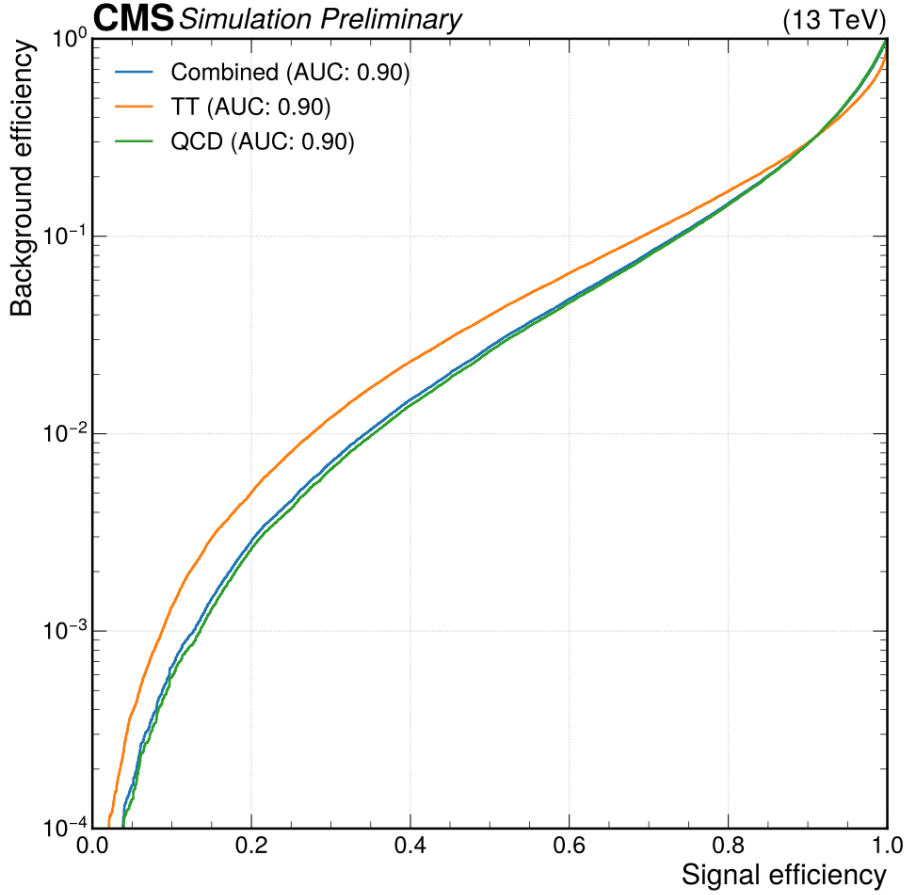


GloParT

$$T_{\mathrm{HVV}} = \frac{P_{\mathrm{HVV4q}} + P_{\mathrm{HVV3q}}}{P_{\mathrm{QCD}} + P_{\mathrm{Top}} + P_{\mathrm{HVV4q}} + P_{\mathrm{HVV3q}}},$$

Process	Final state/ prongness	heavy flavour	# of classes
H→VV (full-hadronic)	qqqq	0c/1c/2c	3
	qqq		3
H→WW (semi-leptonic)	evqq	0c/1c	2
	μvqq		2
	$\tau_e$vqq		2
	$\tau_\mu$vqq		2
	$\tau_h$vqq		2
H→qq		bb	1
		cc	1
		ss	1
		qq (q=u/d)	1
H→ττ	$\tau_e\tau_h$		1
	$\tau_\mu\tau_h$		1
	$\tau_h\tau_h$		1
t→bW (hadronic)	bqq	1b + 0c/1c	2
	bq		2
t→bW (leptonic)	bev	1b	1
	bμv		1
	bτ_ev		1
	bτ_μv		1
	bτ_hv		1
QCD		b	1
		bb	1
		c	1
		cc	1
		others (light)	1

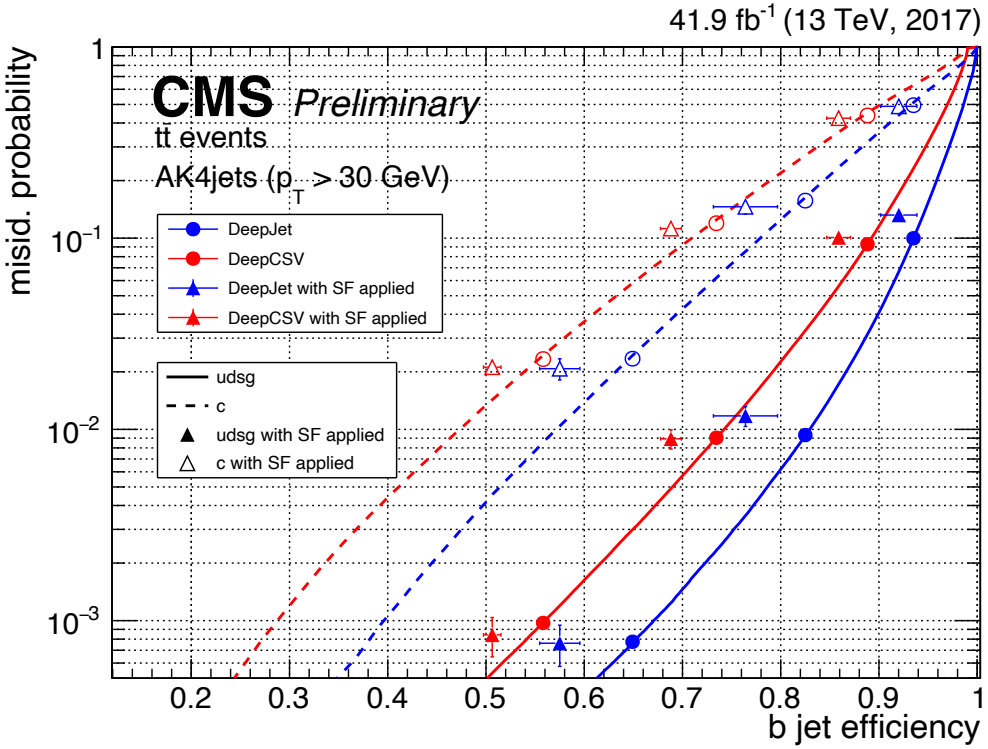




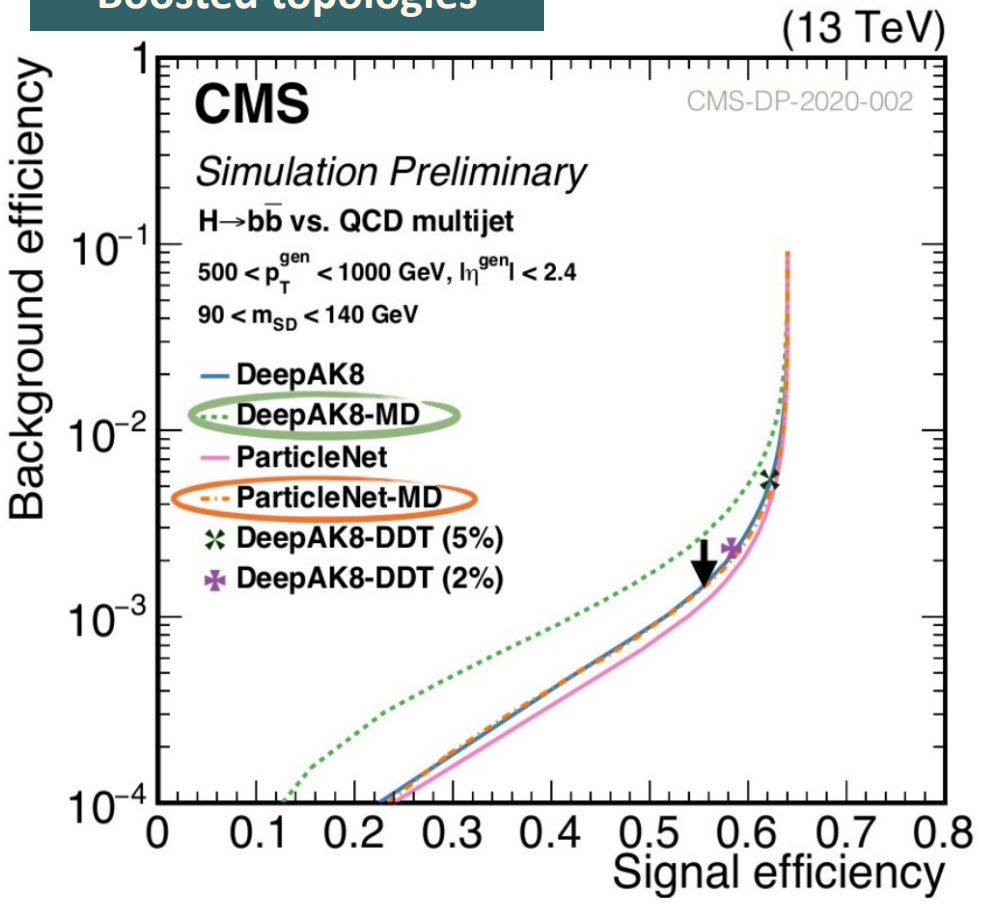
b-jet tagging performance

ParticleNet:
Cutting edge b-tagging algorithm for boosted topologies.
Outperforms DeepAK8 x 2

Resolved topologies



Boosted topologies

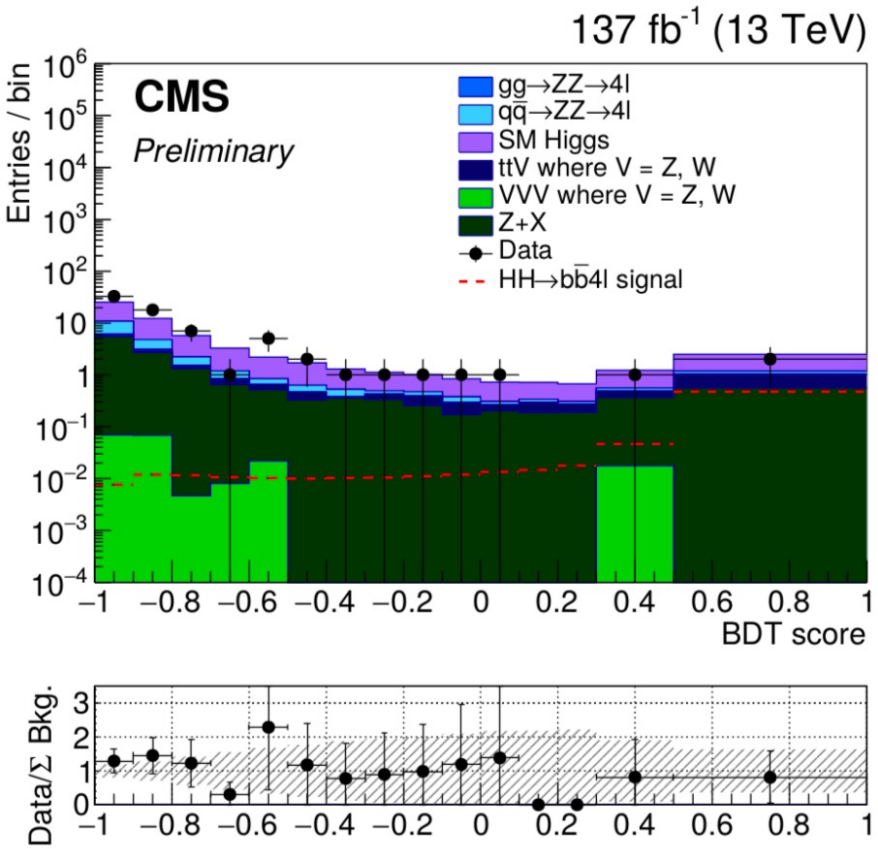


Machine learning abundantly applied here!
All algorithms on this slide are based neural networks (NN)

bbZZ(4l)

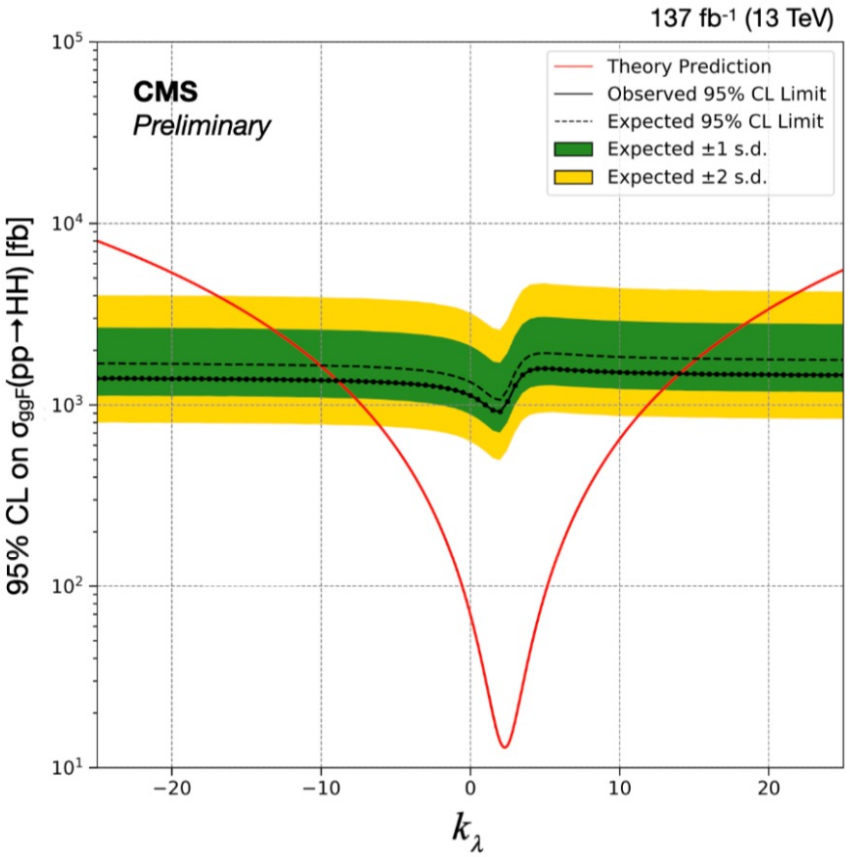
HIG-20-004

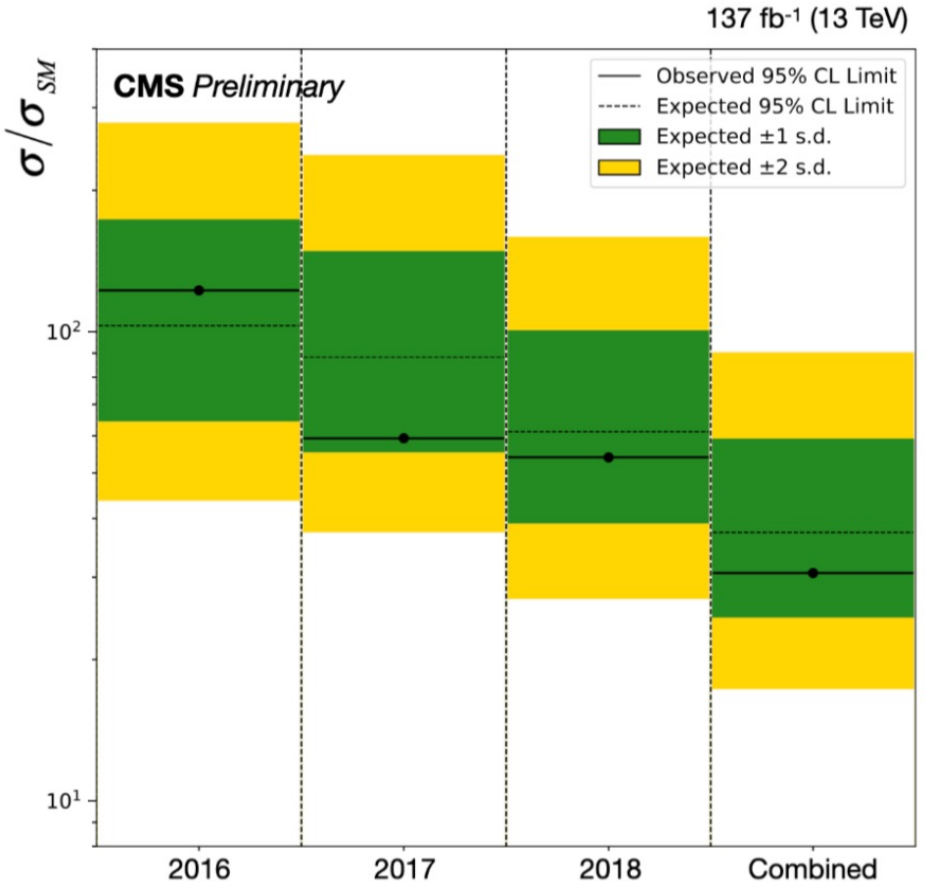
- Final state: 2 pairs of opposite-charge leptons (4μ, 4e, 2e2μ) and 2 b-jets
- Main background: Single Higgs production
- Signal region $|m_{4l} - 125| < 10$ GeV + number of jets >=2
- BDT trained discriminate between signal and background
- BDT score used in the maximum likelihood fit



bbZZ(4l)

- Observed (expected) $\sigma/\sigma_{SM} < 30(37)$ at 95% CL





bbγγ

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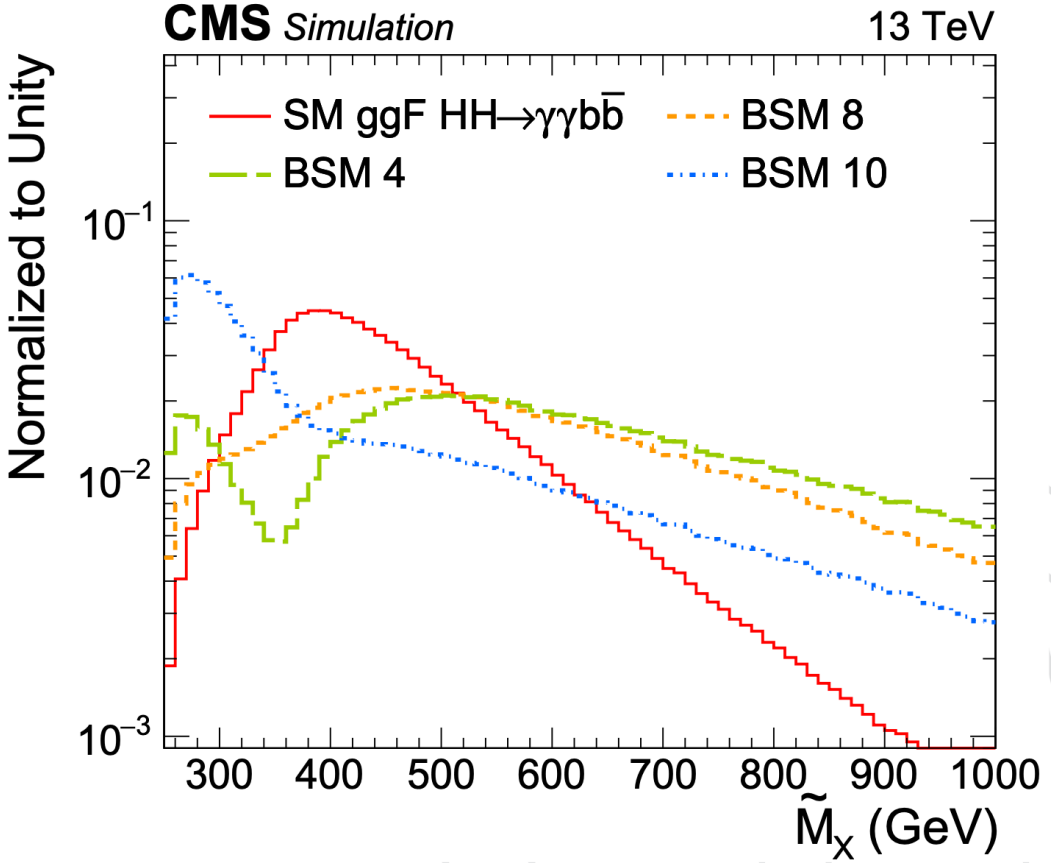
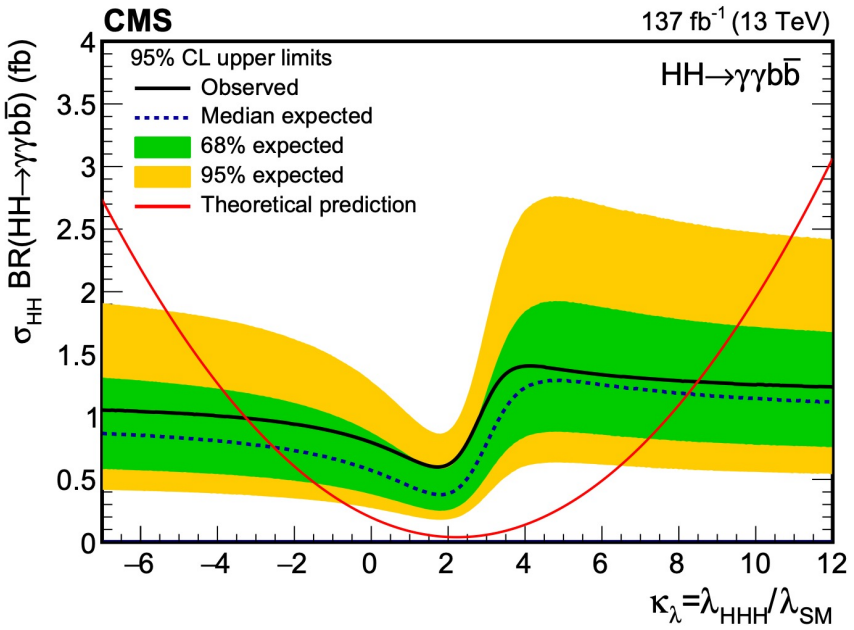
- Final state: 2 γ and 2 b-jets
- Both gluon fusion (ggf) and VBF production studied
- Dedicated DNN (ttHScore) against ttH
- 1 BDT for ggf and 1 for VBF against
  γγ + jets and γ + jets backgrounds
- Several categories depending on the BDT output and $\tilde{M}_X$
- Simultaneous 2D fit ($m_{\gamma\gamma}$, m_{bb}) in all categories.



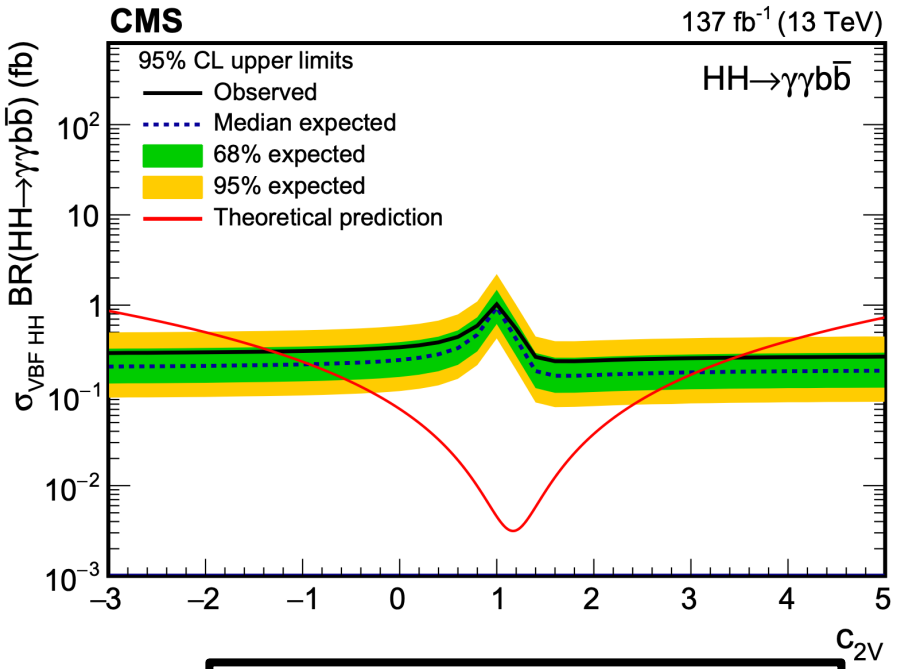
$$\tilde{M}_X = m_{\gamma\gamma jj} - (m_{jj} - m_H) - (m_{\gamma\gamma} - m_H)$$

bbγγ

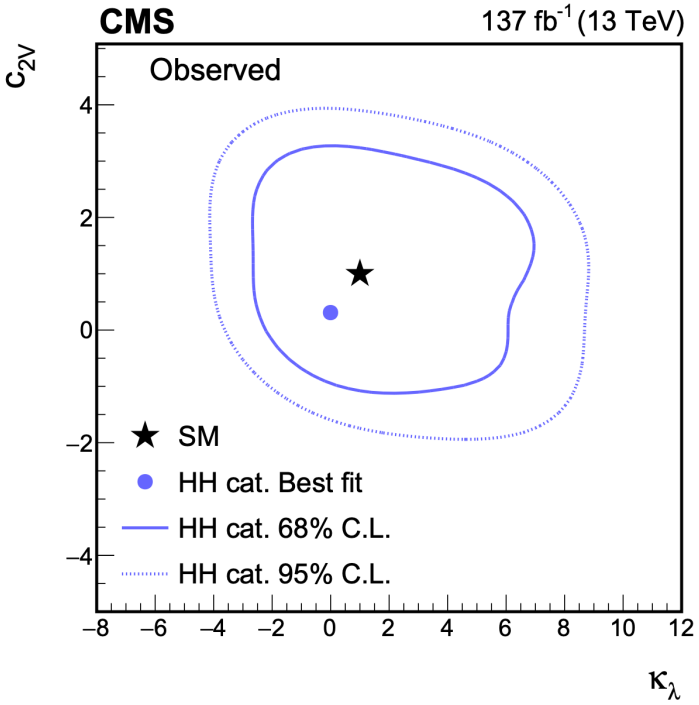
Observed (expected) σ/σ_{SM} <7.7(5.2) at 95% CL



Observed: -3.3 < κ_λ < 8.5
Expected: -2.5 < κ_λ < 8.2

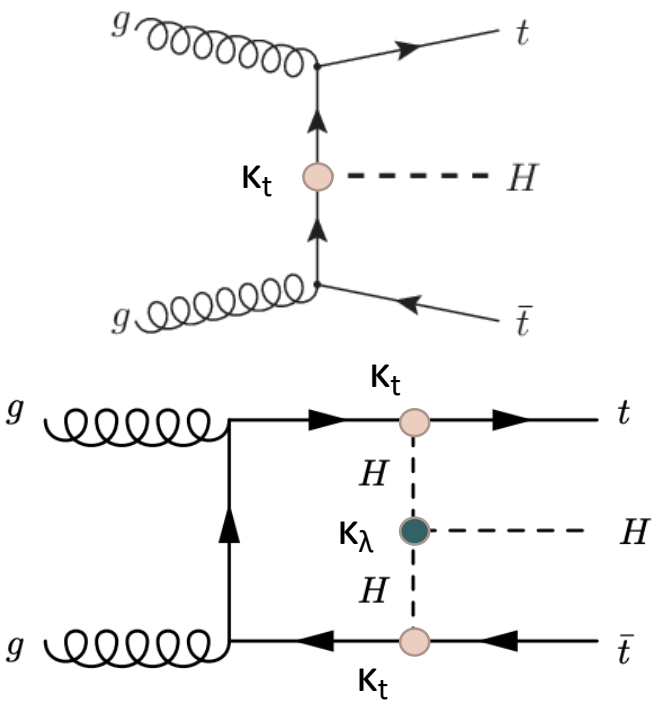


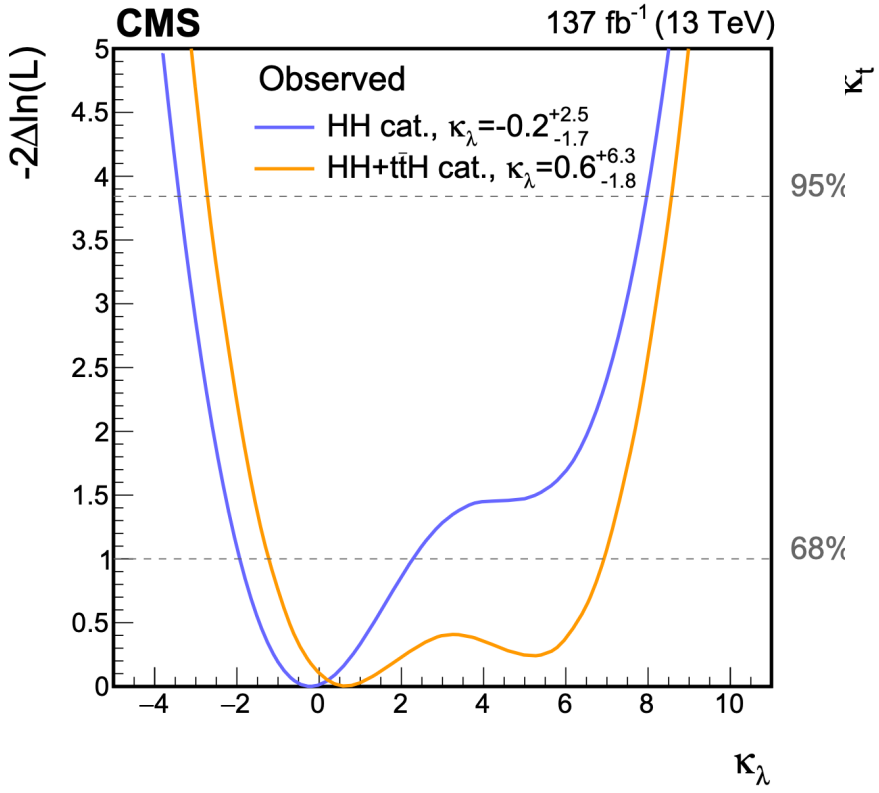
Observed: -1.3 < κ_{2V} < 3.5
Expected: -0.9 < κ_{2V} < 3.0

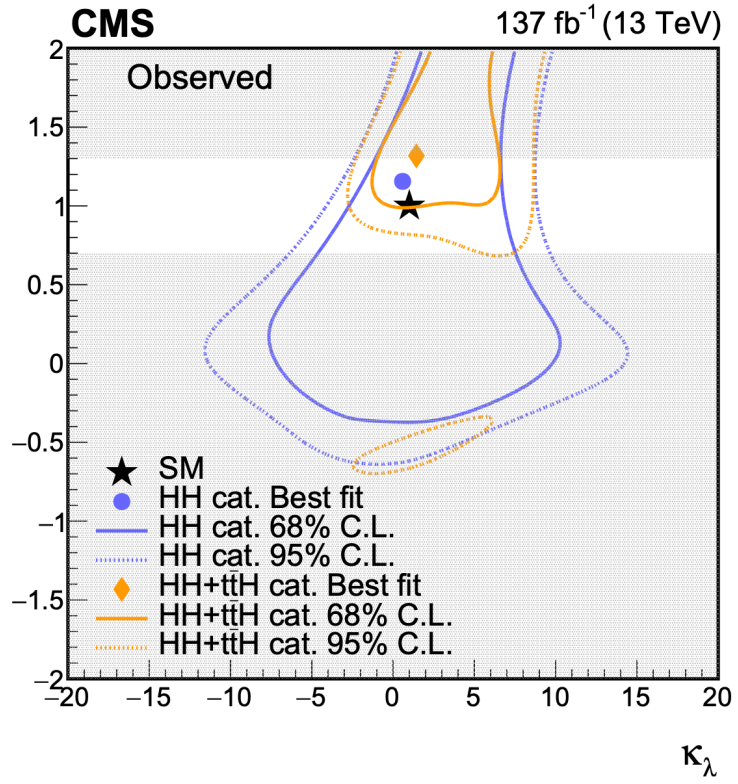


bbγγ

- HH → bbγγ signal was combined with the ttH

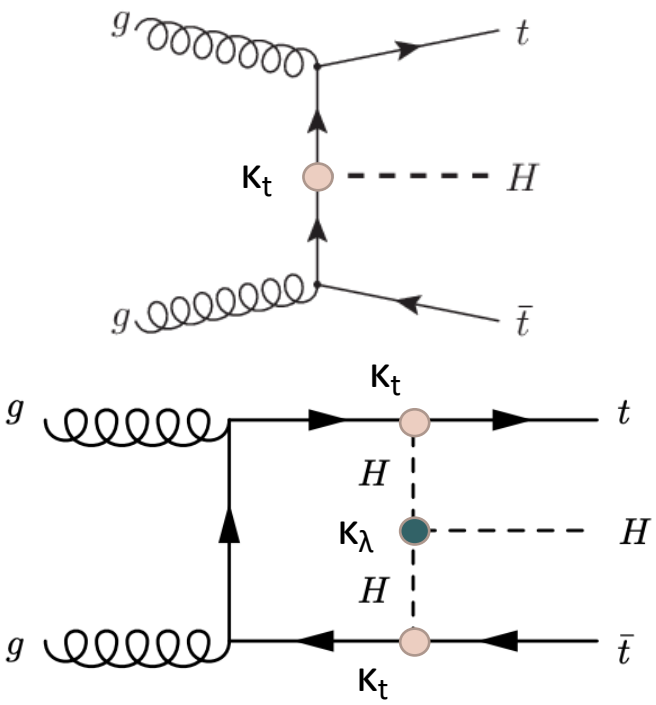


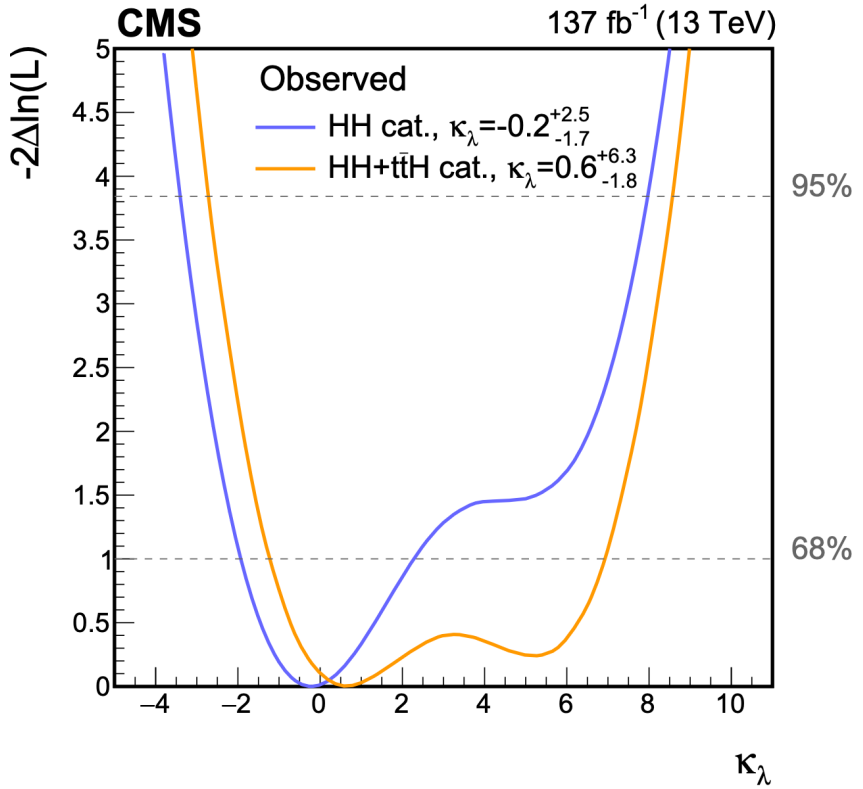


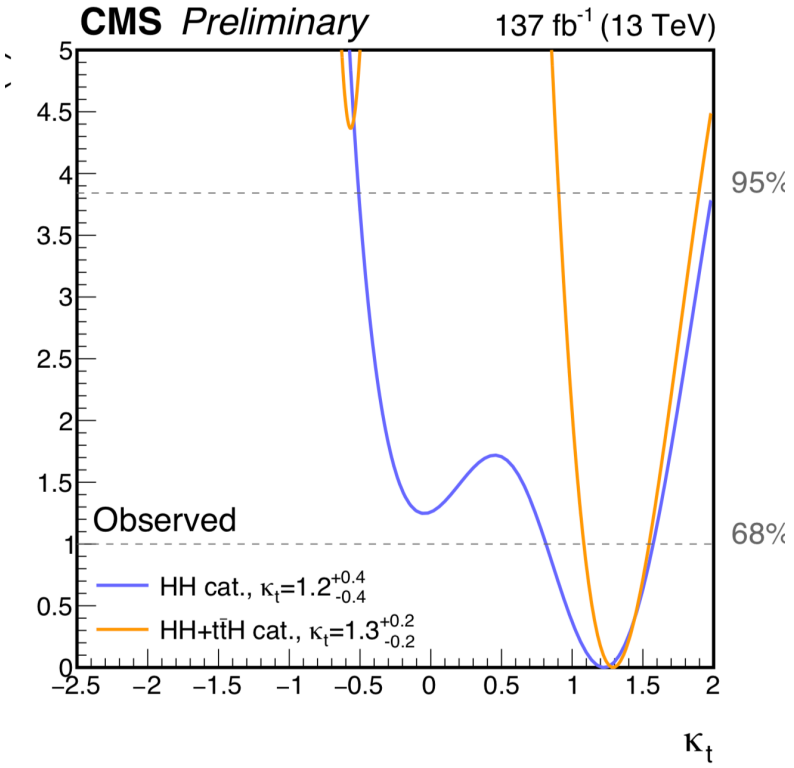


bbγγ

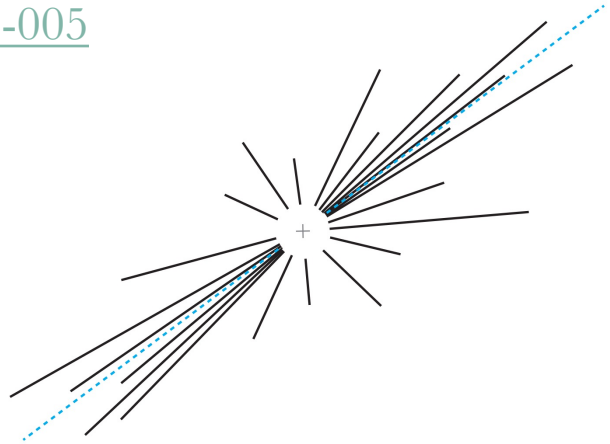
- HH → bbγγ signal was combined with the ttH



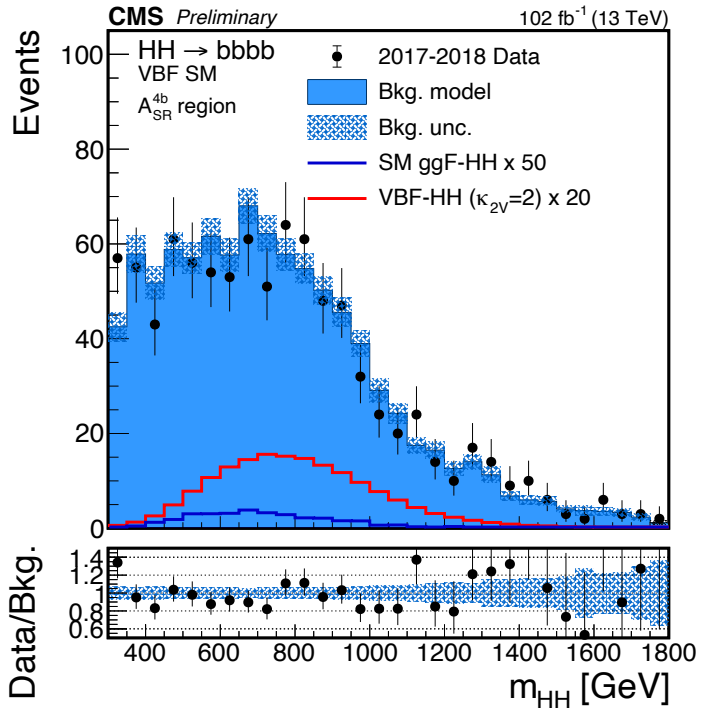


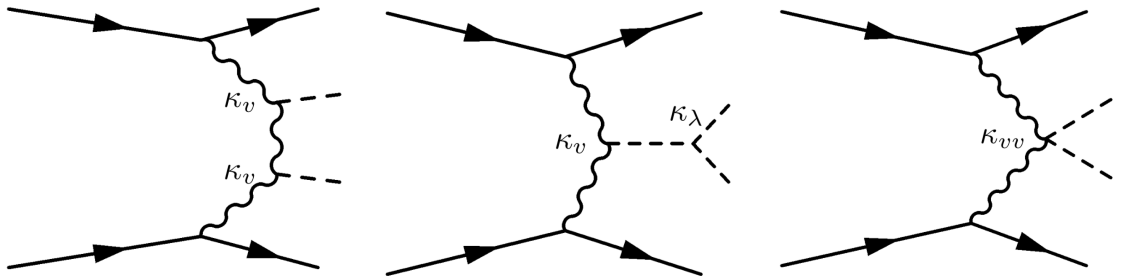


bbbb (resolved) HIG-20-005



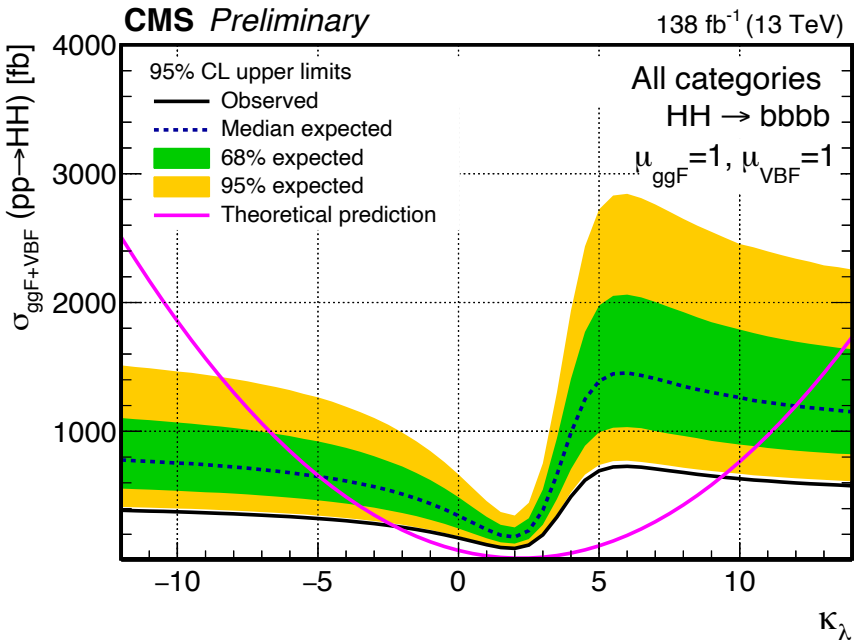
- 4 dinstict b-jets in the final state
  - large combinatoric background
- Large QCD multijets background
  - datadriven!
- Study both GGF and VBF
- GGF strategy
  - BDT to discriminate GGF HH vs background
    - GGF high mass
    - GGF low mass
  - Fit on BDT discriminator
- VBF strategy (requiring 2 extra jets)
  - BDT to discriminate GGF and VBF (GGFKiller)
  - Categories based on GGF killer
    - VBF SM
    - VBF anomalous couplings
  - Fit on mHH



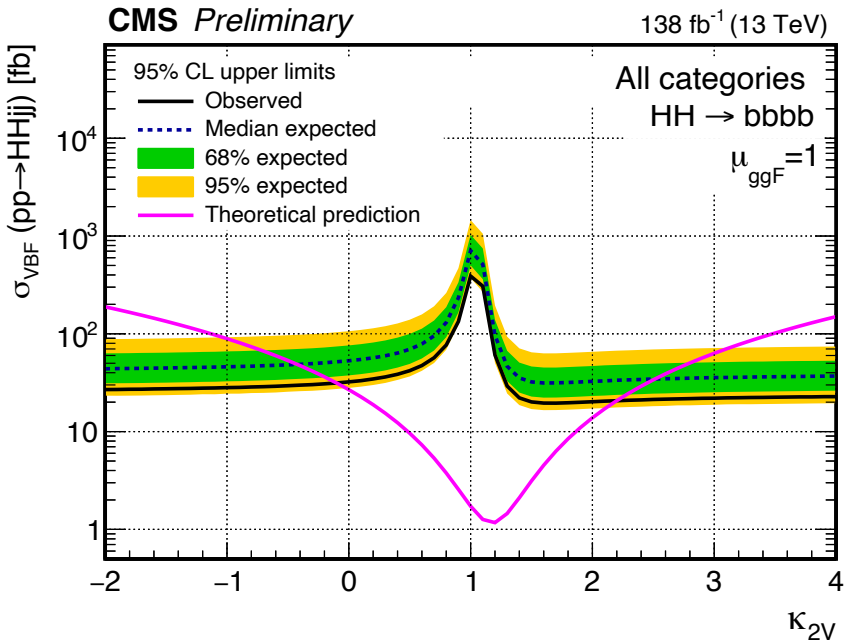


bbbb (resolved)

Observed (expected) $\sigma/\sigma_{SM} < 3.7(7.3)$ at 95% CL



Observed: $-2.5 < \kappa_\lambda < 9.5$
Expected: $-5.0 < \kappa_\lambda < 12.0$

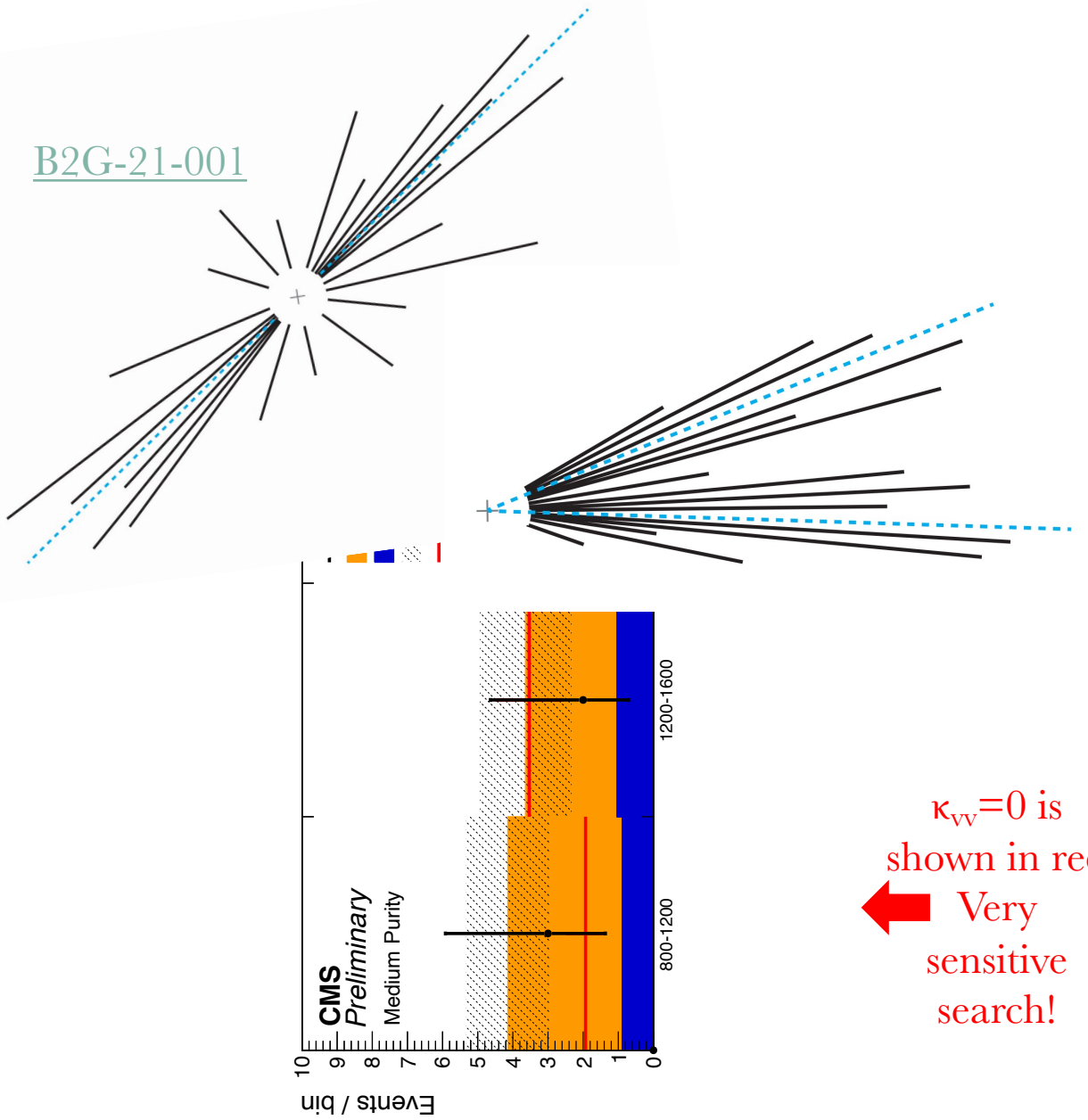


Observed: $-0.1 < \kappa_{2v} < 2.2$
Expected: $-0.4 < \kappa_{2v} < 2.5$

bbbb(VBF boosted)

- Modified couplings can lead to boosted topologies!
- Less combinatorics than resolved search
  - 2 defined large R jets, 1 per Higgs decay.
- H->bb identified using novel neural network (NN) algorithm, ParticleNet
  - graph convolutional NNs, multi-classifier
  - 3 event categories according the ParticleNet score (high, medium and low purity)
- ParticleNet also used for jet mass regression
- QCD multijet background estimated using sidebands in data
- Fit is performed on m_{HH}

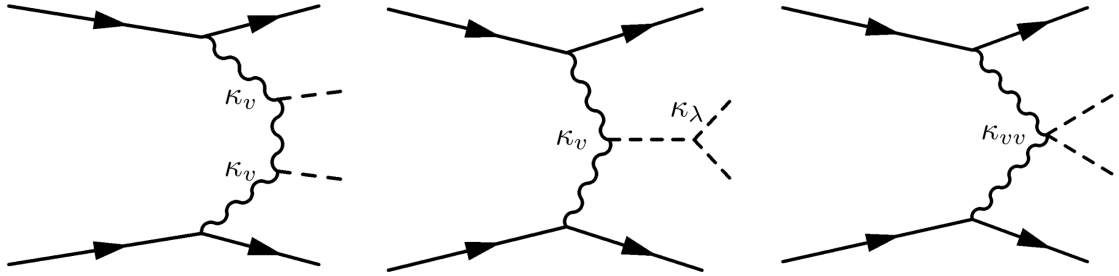
B2G-21-001

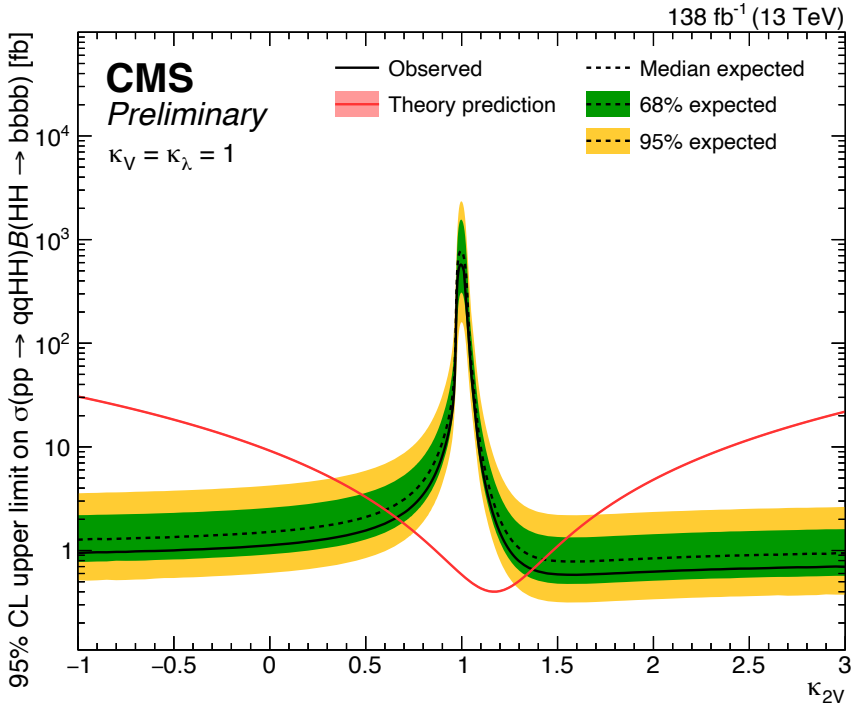


$\kappa_{VV}=0$ is shown in red

Very sensitive search!

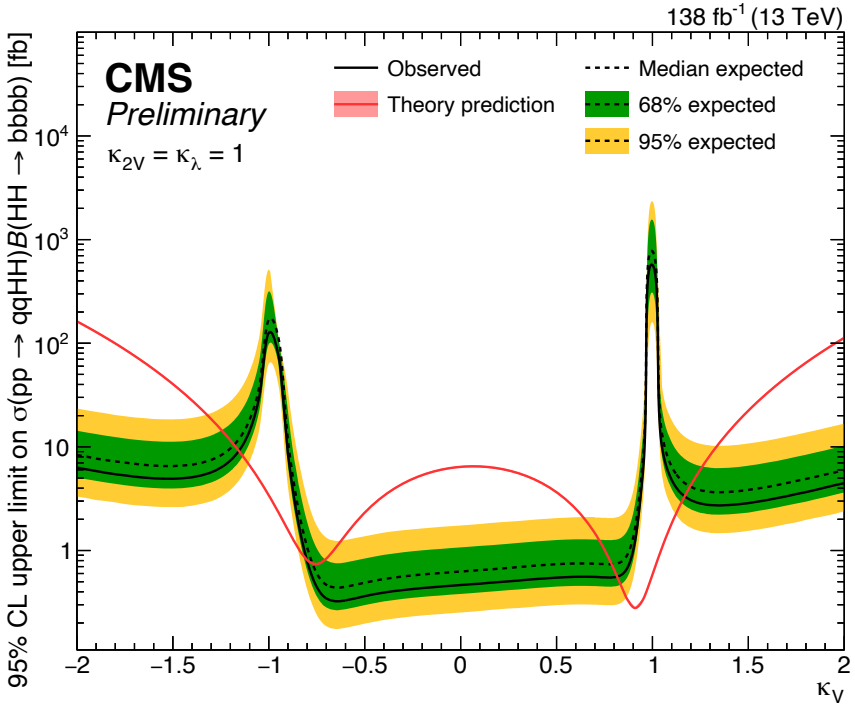
bbbb(VBF boosted)





Observed: 0.6< κ_{vv} < 1.4
Expected: 0.6 < κ_{vv} < 1.4

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

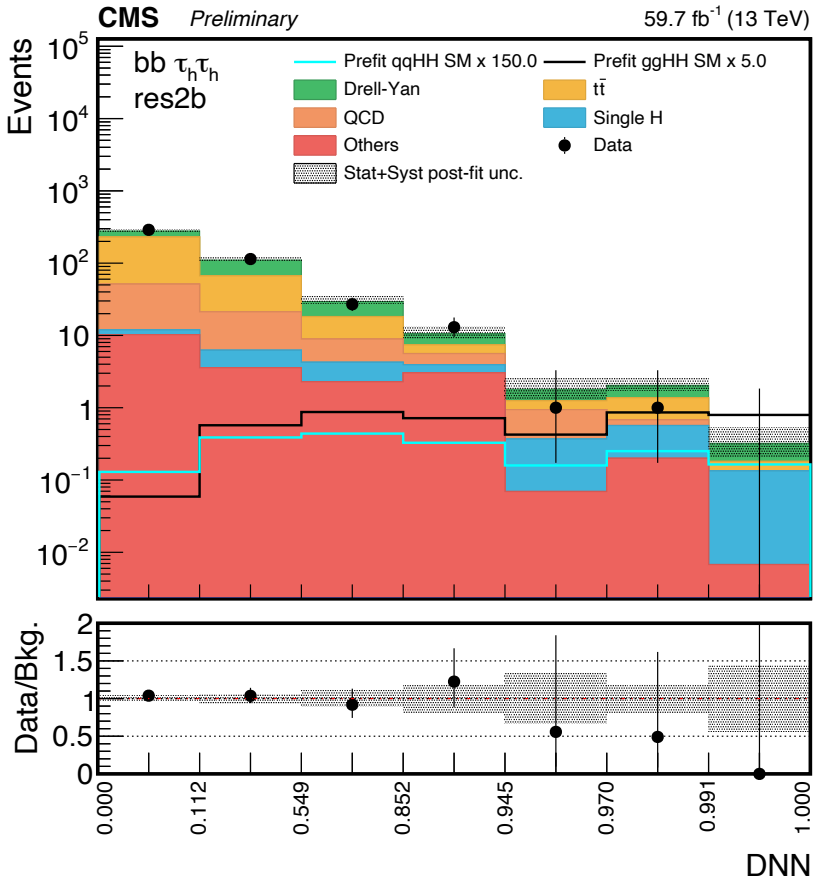


κ_v compatible with SM

bbττ

CMS-PAS-HIG-20-010

- H->ττ candidate
  - $\tau_h\tau_\mu$, $\tau_h\tau_e$,$\tau_h\tau_h$
  - isolated with opposite charge e,μ or τ_h
  - τ_h identified using DeepTau algorithm
- H->bb candidate
  - b-jets identified using DeepJet algorithm
  - neural network HH-btag
- Study both GGF and VBF
- Fake lepton and τ hadronic backgrounds in data driven way
- HH-selection and event categorisation
  - Elliptical mass cut on m(ττ) and m(bb)
  - Split events in 8 categories: 2 resolved, 1 boosted, and 5 VBF
  - VBF categories using multiclass DNN
- Signal extraction using DNN
  - binary signal vs background classification



bbττ

CMS-PAS-HIG-20-010

- H->ττ candidate
  - $\tau_h\tau_\mu$, $\tau_h\tau_e$,$\tau_h\tau_h$
  - isolated with opposite charge e,μ or τ_h
  - τ_h identified using DeepTau algorithm
- H->bb candidate
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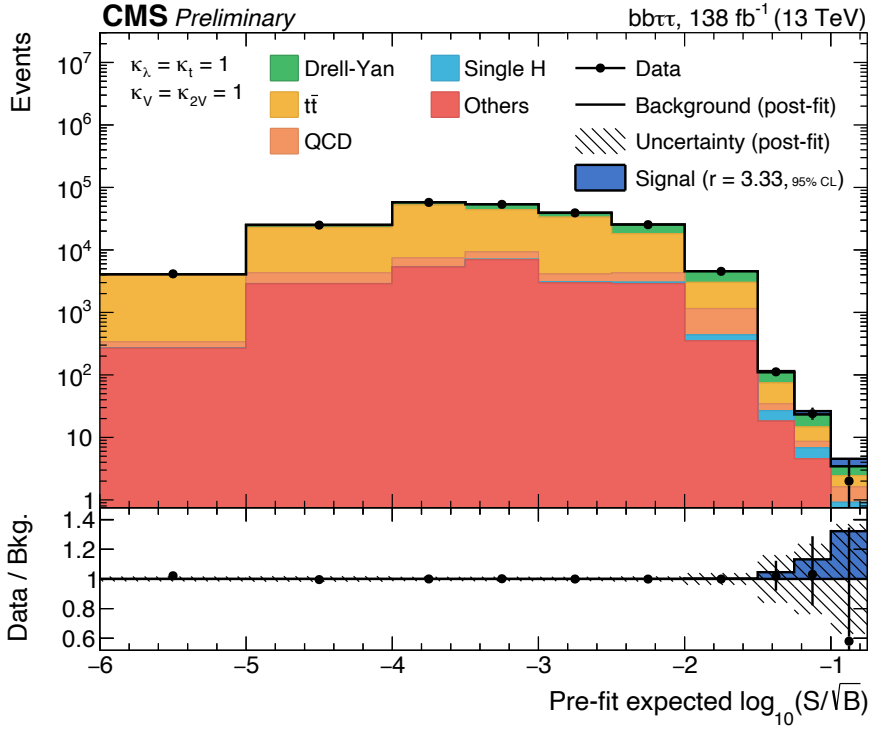
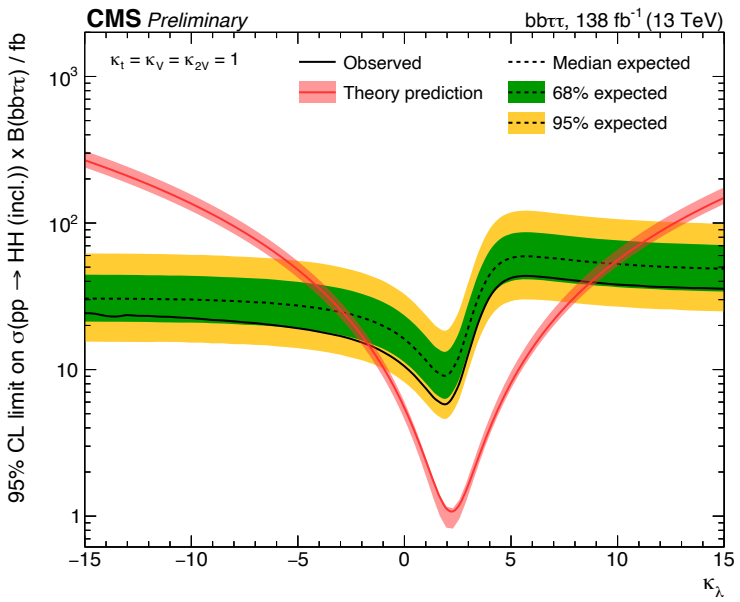


bbττ

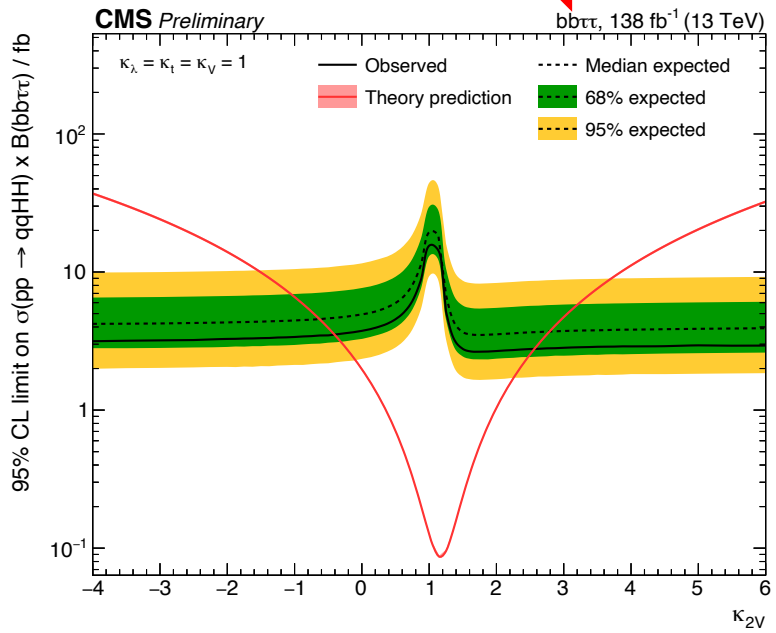
CMS-PAS-HIG-20-010

Observed (expected) inclusive $\sigma/\sigma_{SM} < 3.3(5.2)$ at 95% CL
Observed (expected) VBF$\sigma/\sigma_{SM} < 124(154)$ at 95% CL

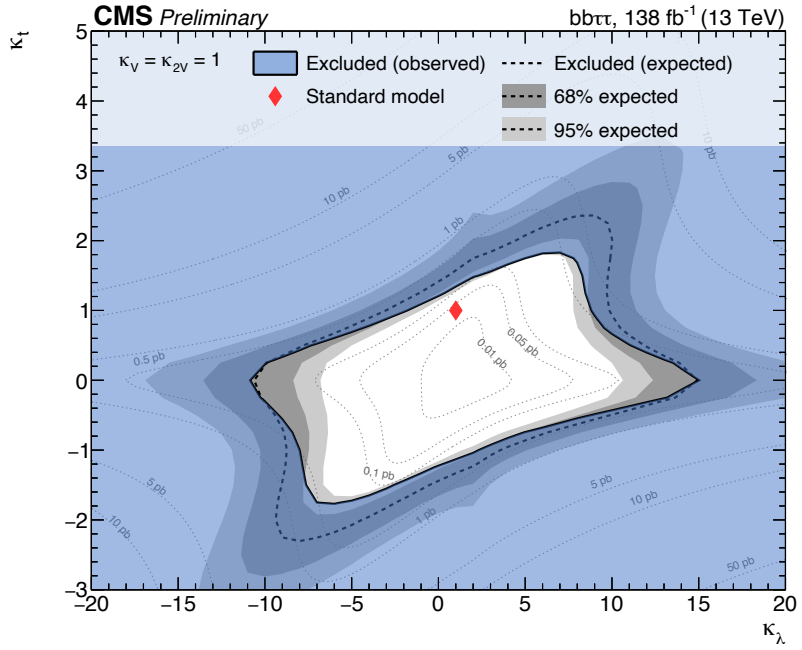
Best limit on VBF cross-section!



Observed: $-1.8 < \kappa_\lambda < 8.8$
Expected: $-3 < \kappa_\lambda < 9.9$



Observed: $-0.4 < \kappa_{2V} < 2.6$
Expected: $-0.6 < \kappa_{2V} < 2.8$

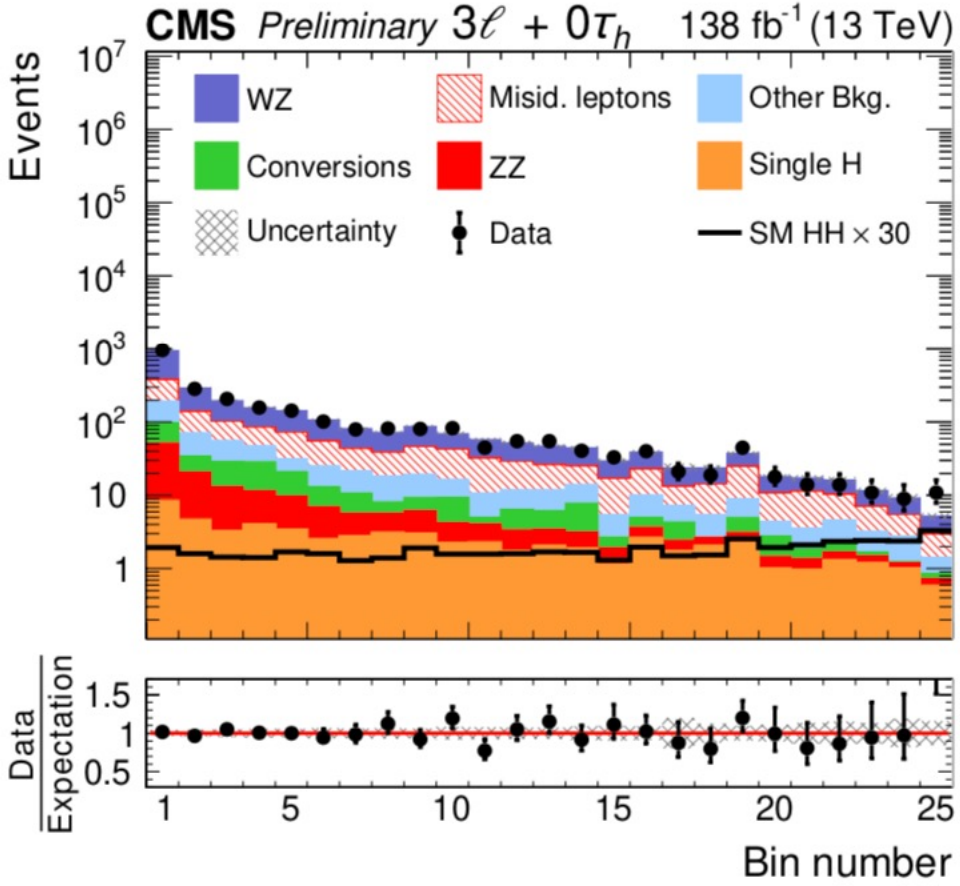


Multilepton*

CMS-PAS-HIG-21-002

*WWWW, WWττ, and ττττ

- Higgs bosons decays to either WW, ZZ, or $\tau\tau$.
- First search for WWττ and ττττ.
- 2, 3, or 4 leptons
  - including hadronically decaying τ
  - 7 channels
- b-jet veto!
- BDT classifiers
- control regions WZ and ZZ also included in each of these fits
- Fake lepton and τ hadronic backgrounds in data driven way (fake factor method)



Multilepton*

CMS-PAS-HIG-21-002

*WWWW, WWττ, and ττττ

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  - 7 channels
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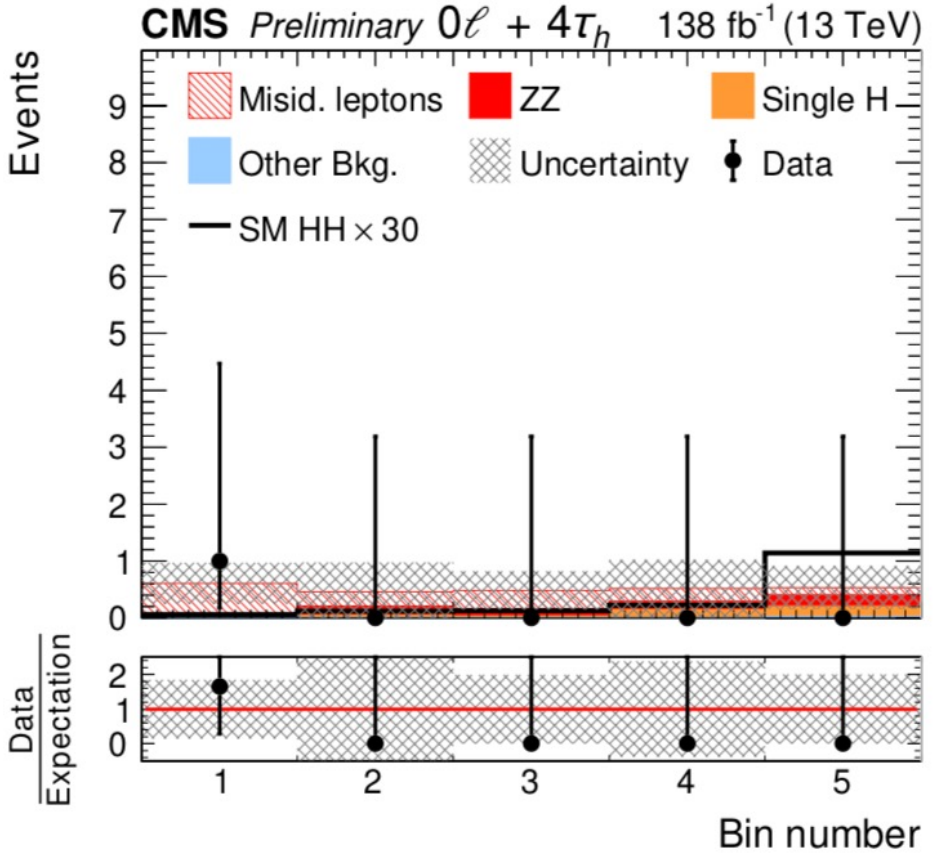
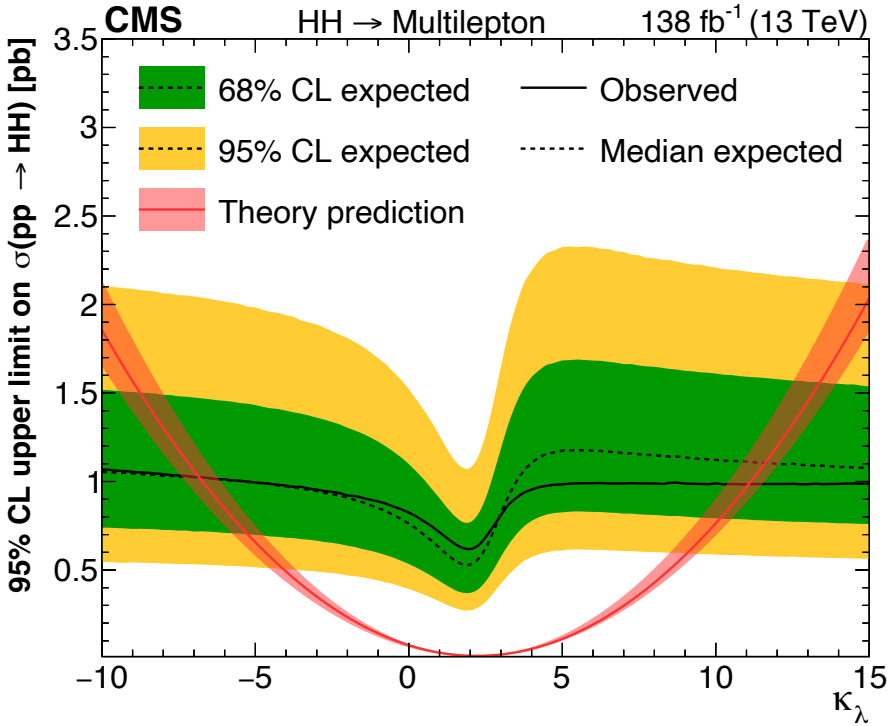


Multilepton*

*WWWW, WWττ, and ττττ

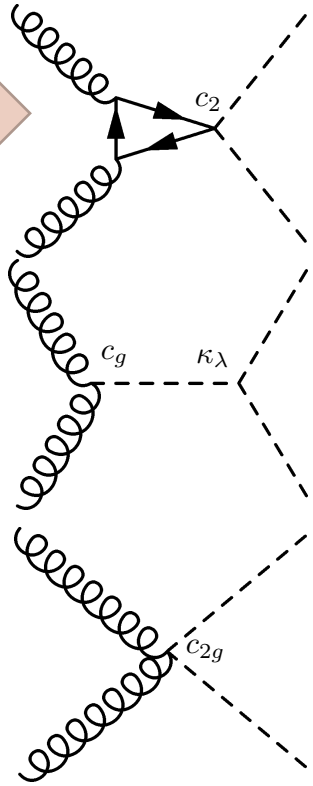
CMS-PAS-HIG-21-002

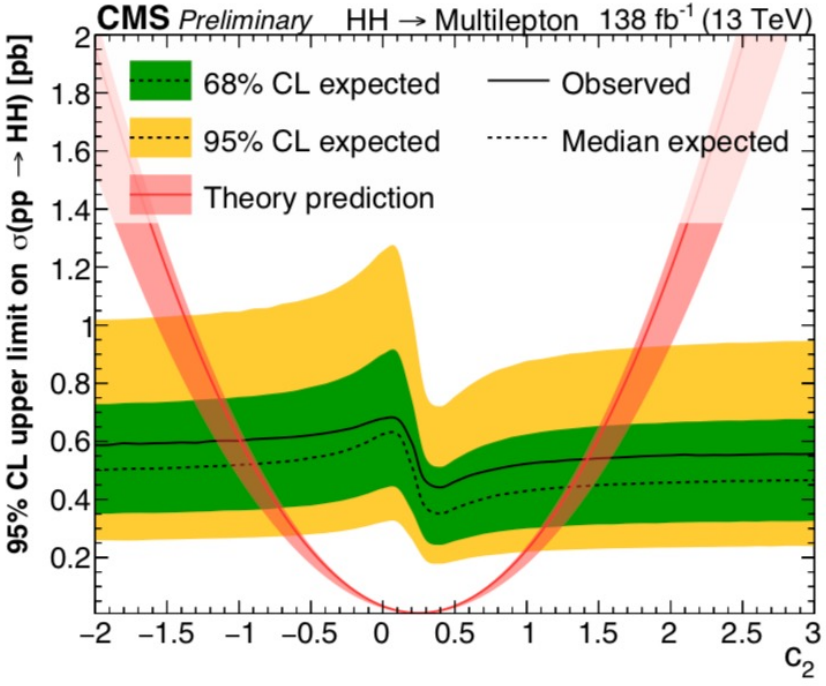
Observed (expected) σ/σ_{SM} < 21.8 (19.6) at 95% CL

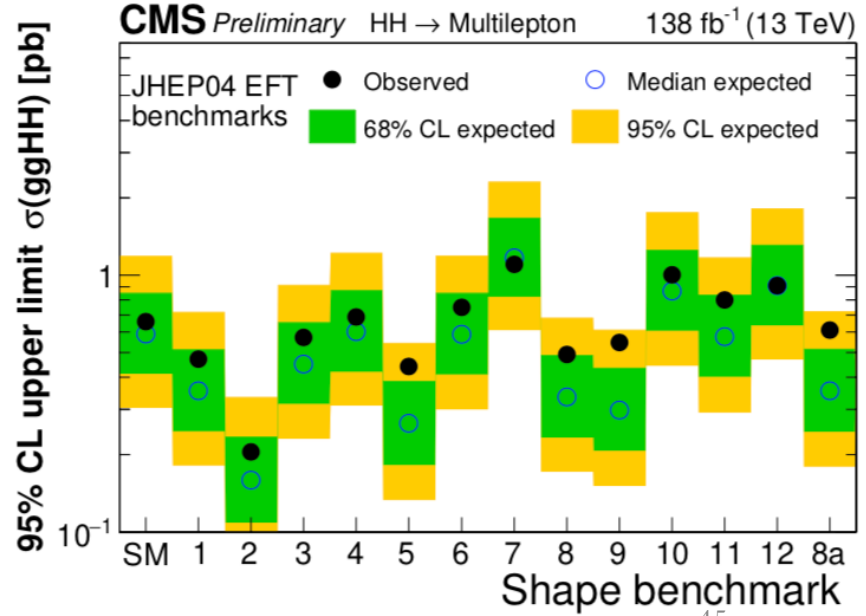


Observed: -7.0 < κ_λ < 11.2
Expected: -7.0 < κ_λ < 11.7

BSM couplings





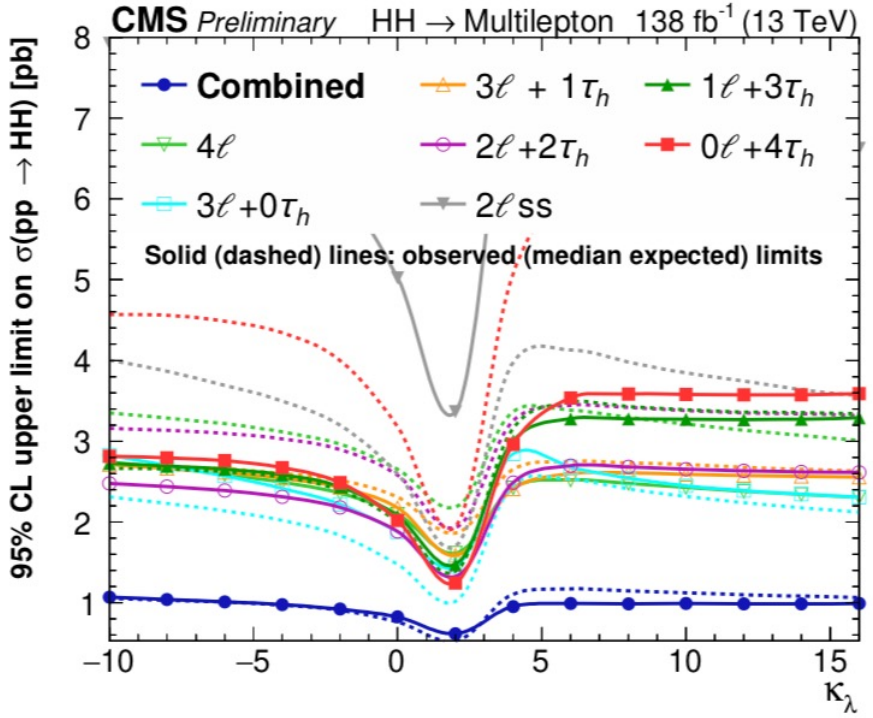


Multilepton*

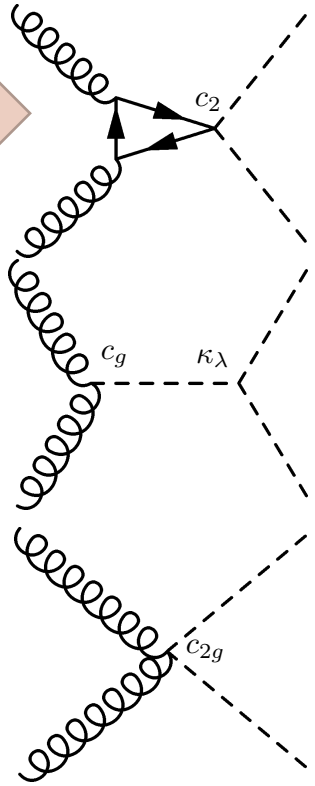
*WWWW, WWττ, and ττττ

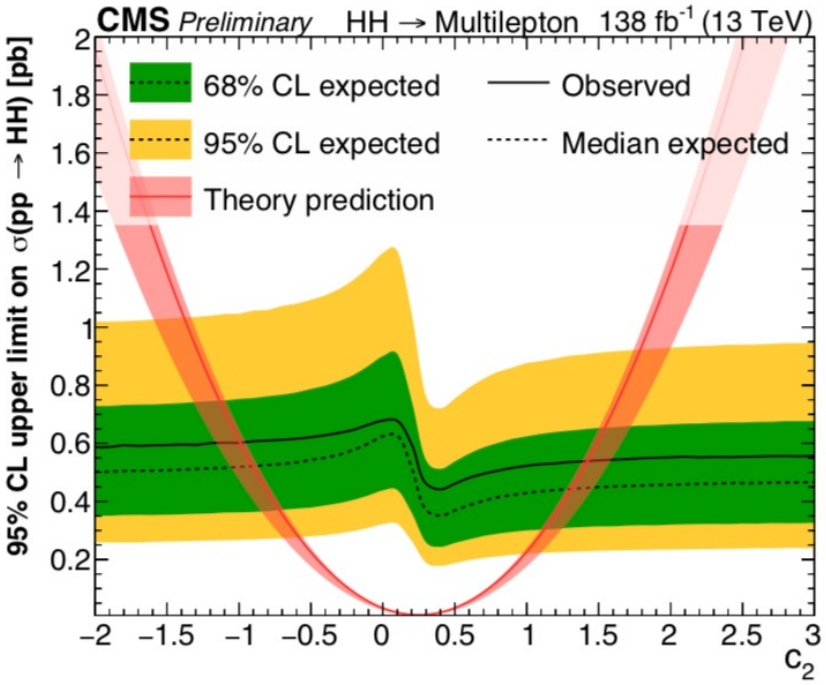
CMS-PAS-HIG-21-002

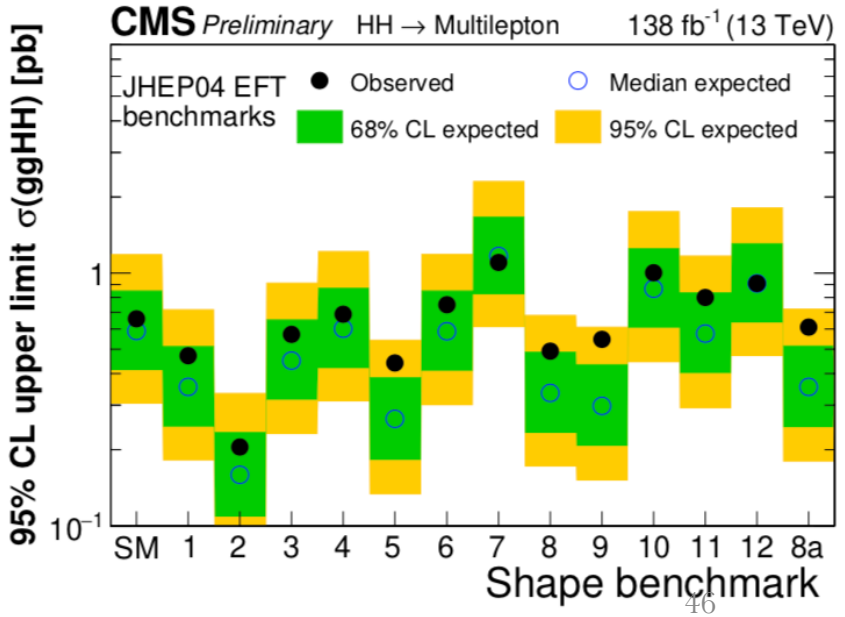
Observed (expected) σ/σ_{SM} < 21.8 (19.6) at 95% CL



BSM couplings







Observed: -7.0 < κ_λ < 11.2
Expected: -7.0 < κ_λ < 11.7