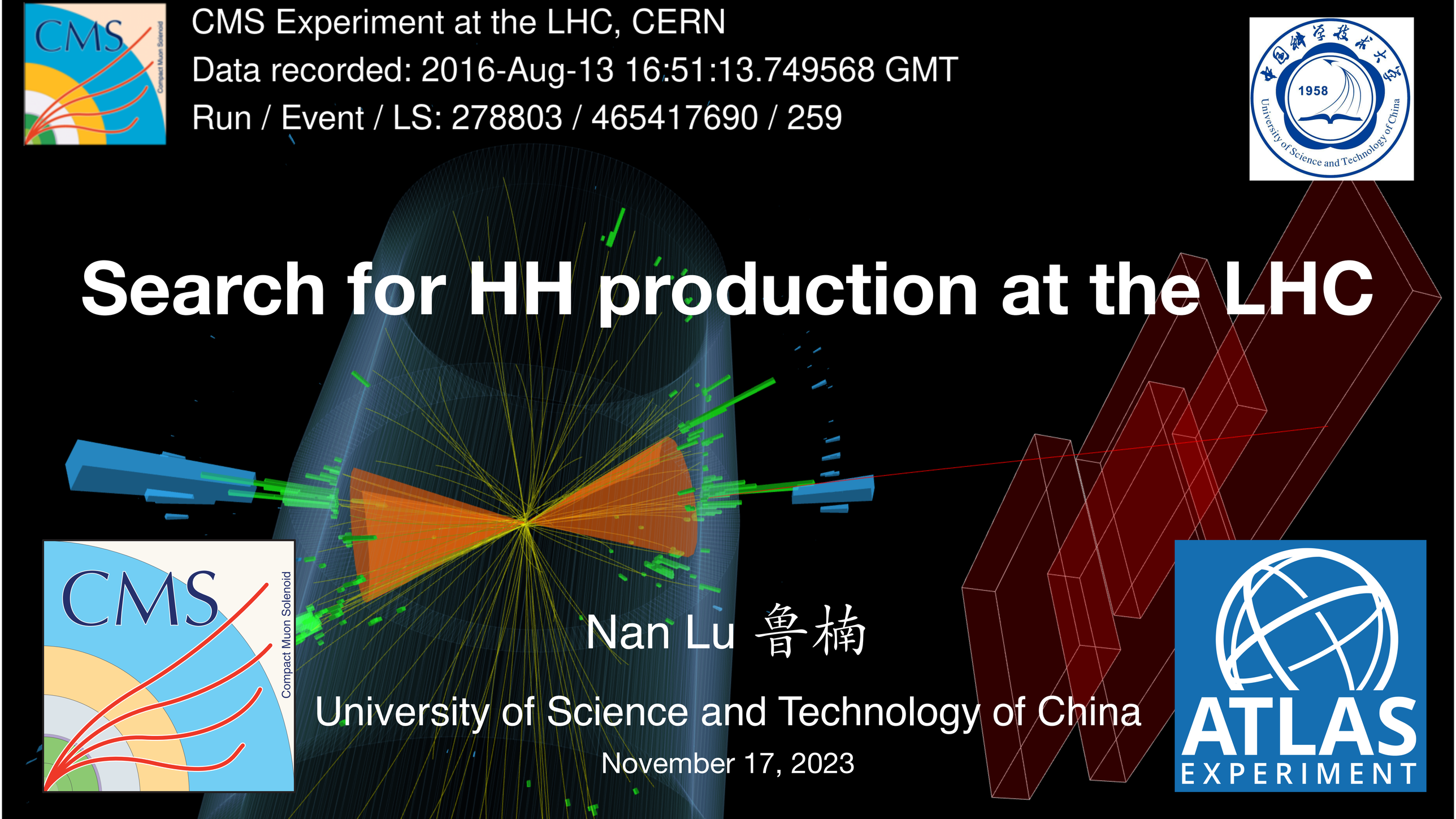


Search for HH production at the LHC

Nan Lu 鲁楠

University of Science and Technology of China

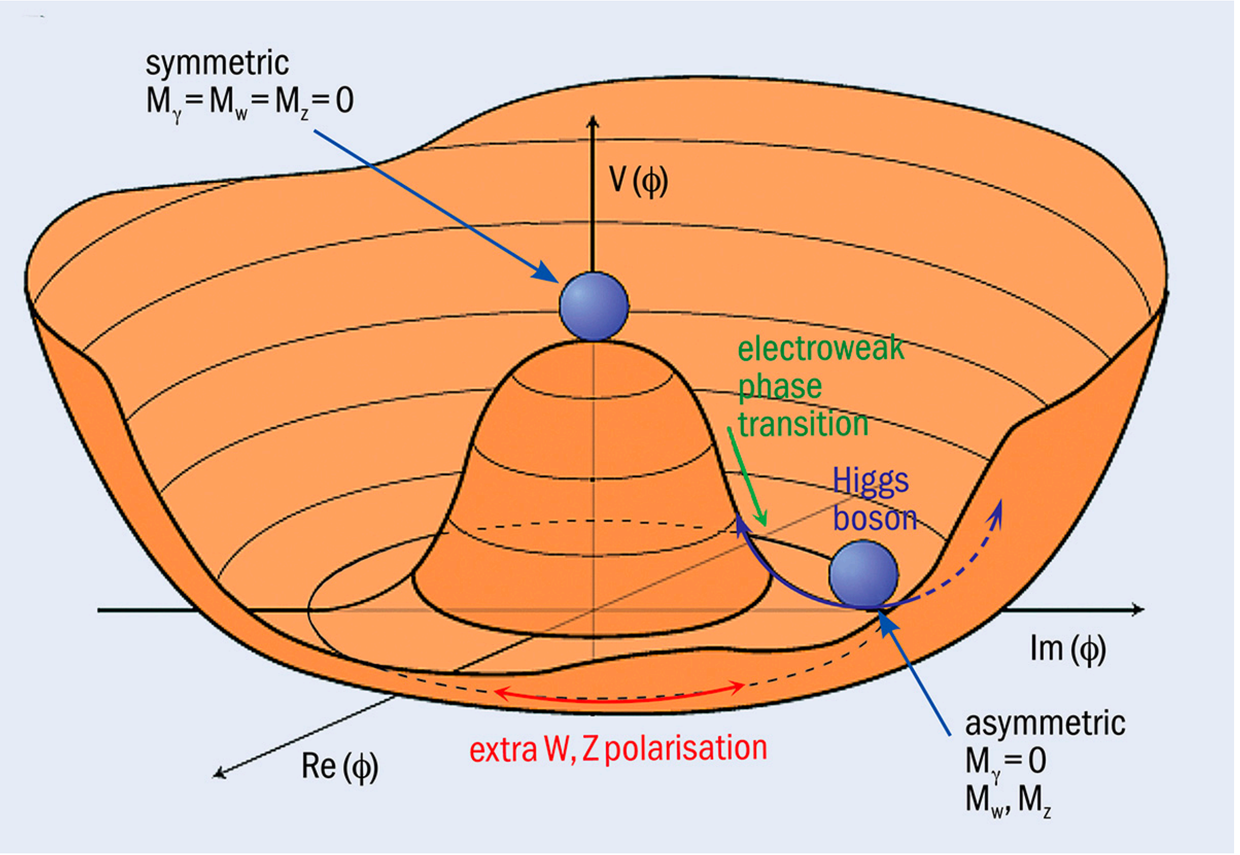
November 17, 2023

DiHiggs production in the Standard Model

- The shape of the Higgs potential determined by the H self-coupling λ

$$V(\phi) = \frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4$$

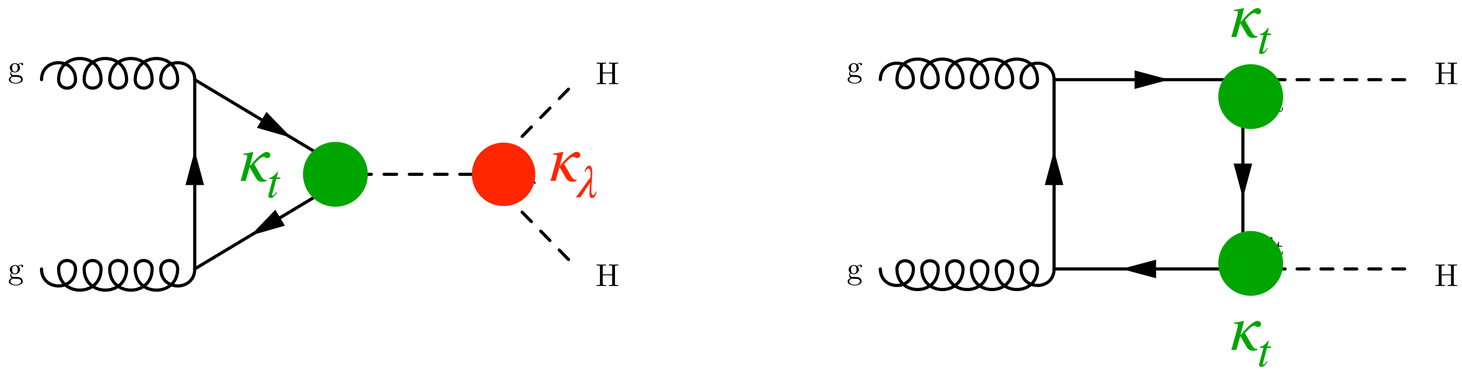
- Trilinear self-coupling (λ_3) can be probed directly via HH production, extremely challenging to measure at LHC



diHiggs production in the Standard Model - gluon fusion HH

- Dominant gluon-gluon fusion (ggF) production mode: best access to (λ_3)
- σ_{ggF} = 31.05 ± 3.0% (PDF+α_S unc.) $^{+2.2\%}_{-5.0\%}$ (Scale unc.) $^{+4\%}_{-18\%}$ (m_{top} scheme unc.) fb NNLO FTapprox, for m_H = 125 GeV at 13 TeV

JHEP05(2018)059



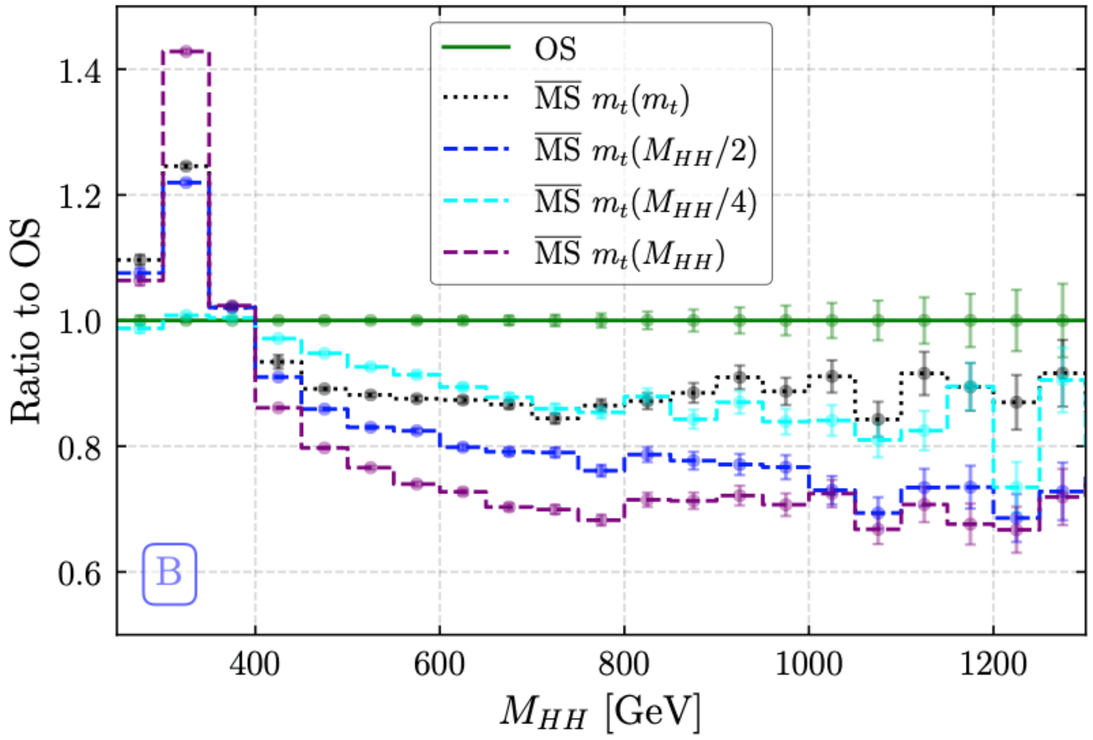
- Powheg NLO + PS MC event generator (ggHH and ggHH SMEFT)

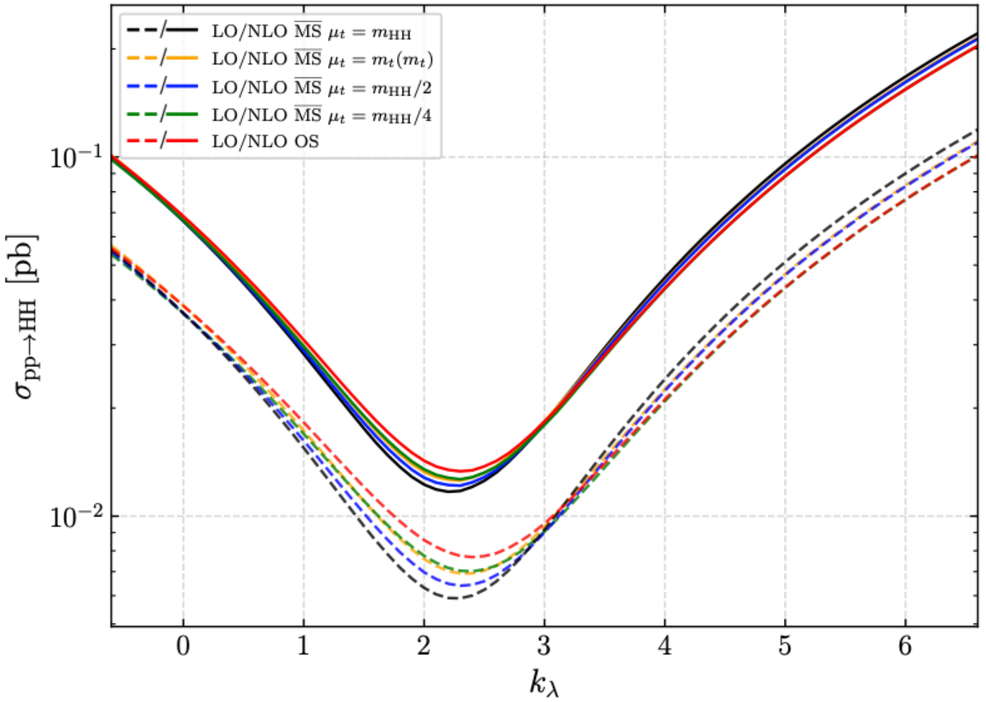
G. Heinrich et al JHEP 08 (2017) 088, JHEP 06 (2019), 066 JHEP 10 (2020) 021

WG4 in LHCHWG https://twikiai.cern.ch/twiki/bin/view/LHCPhysics/LHCHWGHH

diHiggs production in the Standard Model - gluon fusion HH

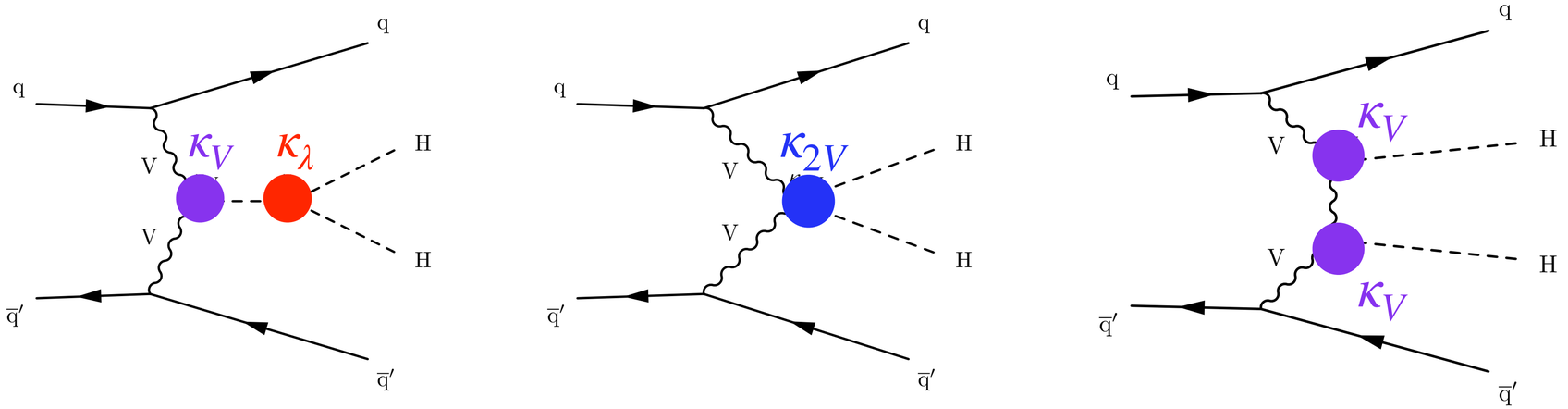
- ggHH: a new Powheg NLO + PS MC event generator Bagnaschi et al., 2309.10525
  - varying the trilinear self-coupling and input parameters (e.g. m_H, m_{Top} scheme)
  - offer the possibility to study uncertainty from top mass scheme at analysis level



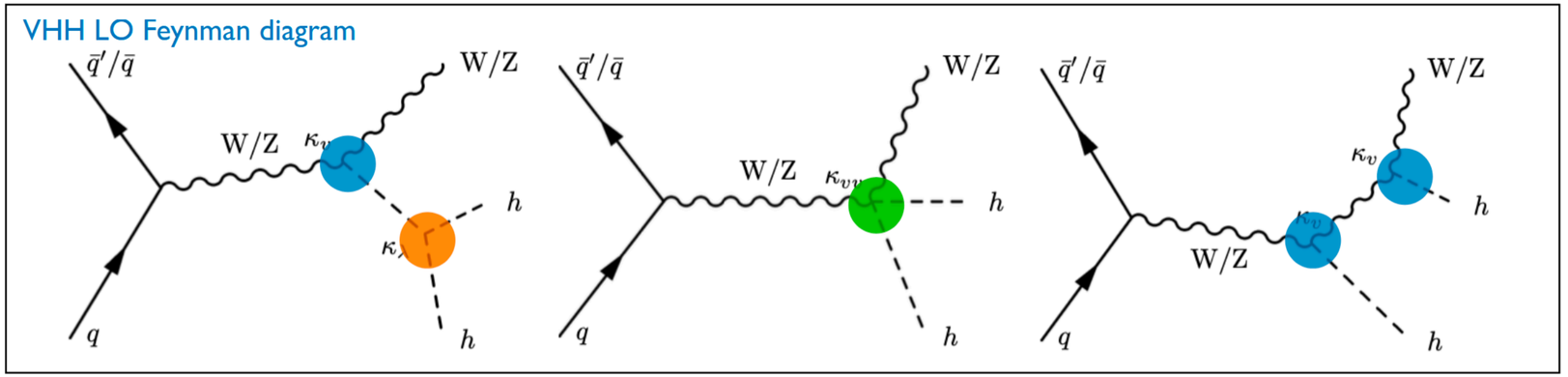


diHiggs production in the Standard Model

- Vector boson fusion (VBF) (σ_{VBF} = 1.73 fb) sensitive to HHVV coupling

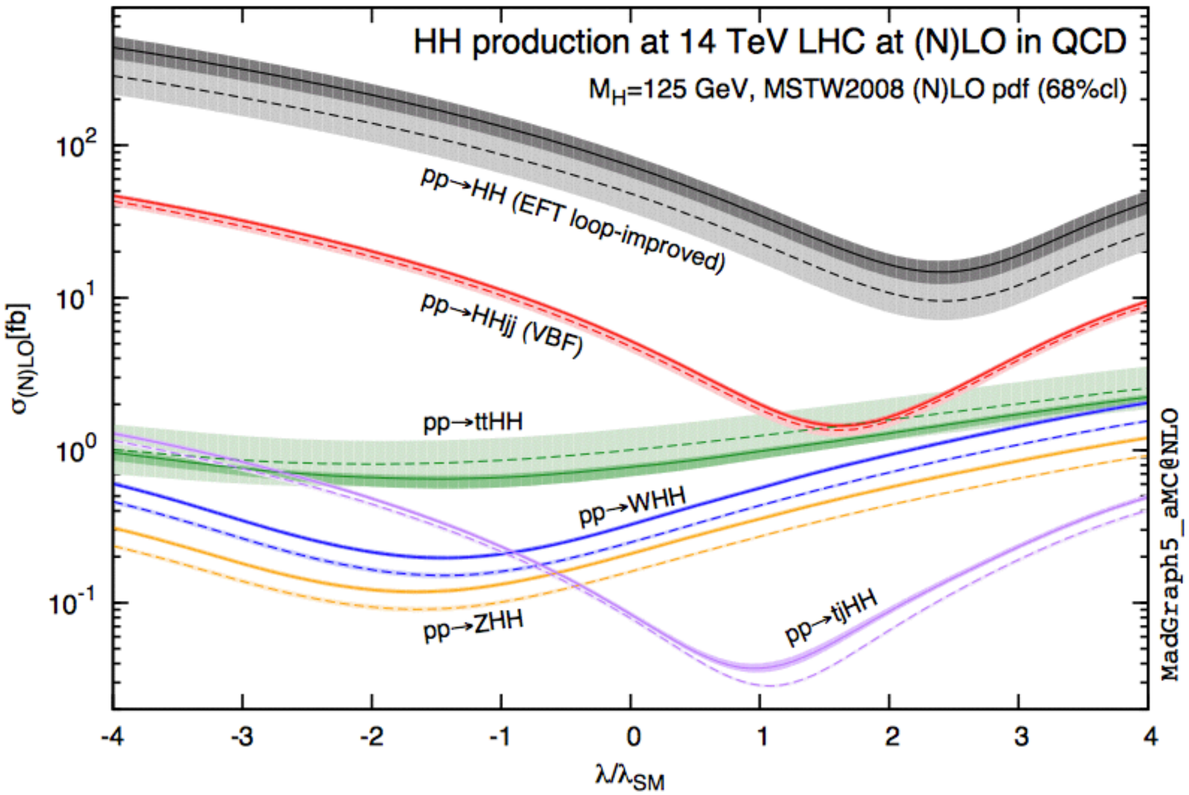


- Associated production (VHH) (σ_{VHH} = 0.86 fb) probe HHWW HHZZ couplings separately



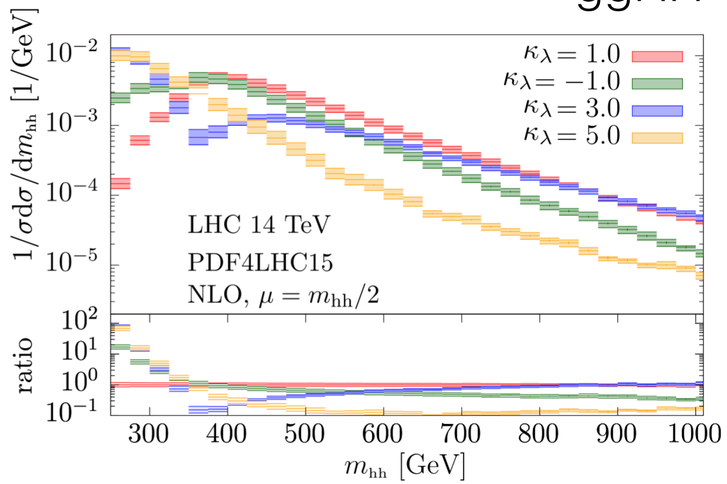
non-resonant diHiggs production in BSM

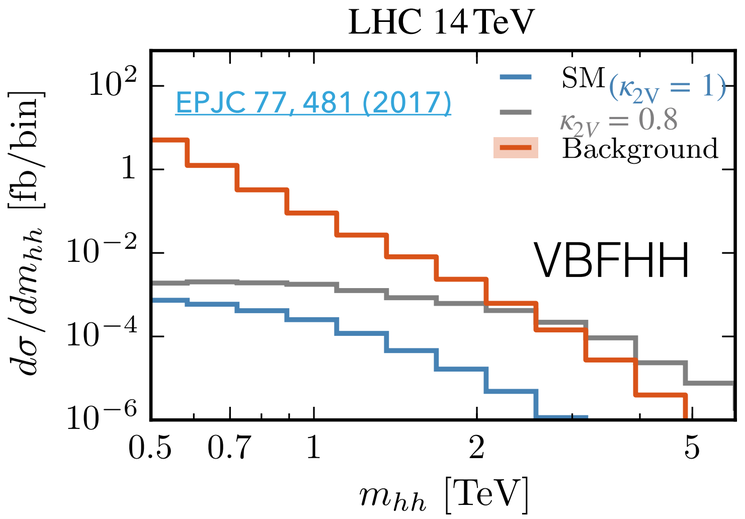
- Enhancement of the non-resonant di-Higgs production via modified Higgs boson self-coupling and top Yukawa coupling, new vertices…



R.Frederix et al: Phys.Lett. B732 (2014) 142-149

ggHH





Di-Higgs decay channels

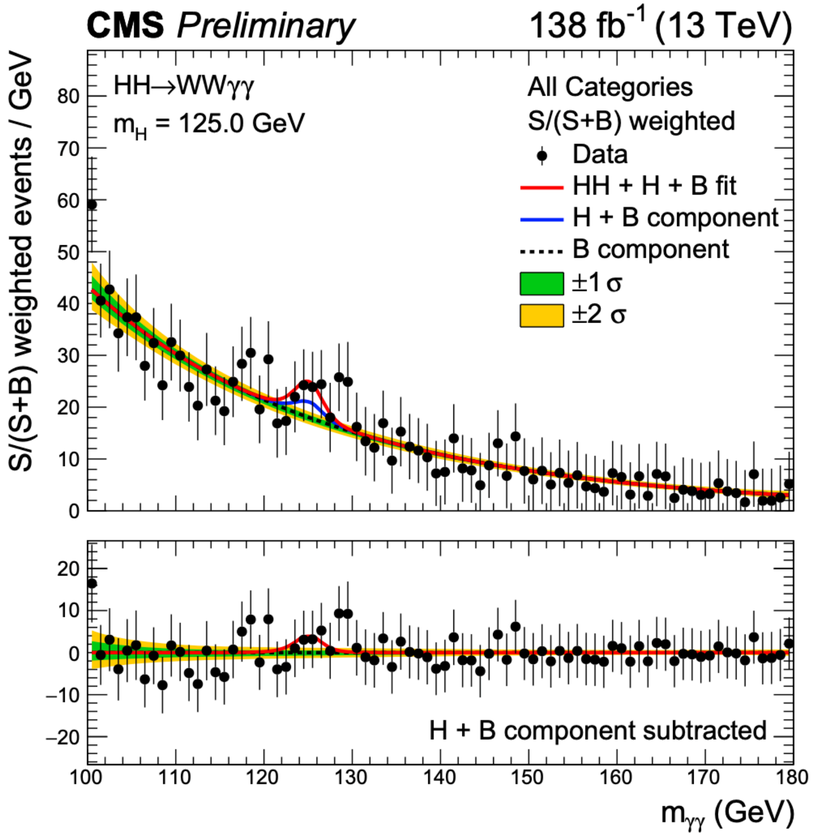
channel	production mechanism		μ=σ(HH)/σ(SM HH) obs(exp)	reference	talks in CLHCP2023
bbγγ	ggF+VBF	ATLAS	4.0(5.0)	arxiv:2310.12301	Talk by Zihang Jia
	ggF+VBF	CMS	7.7(5.2)	JHEP 03 (2021) 257	
bbττ	ggF+VBF	ATLAS	4.7(3.9)	JHEP 07 (2023) 040	Talk by Liangliang Han
	ggF+VBF	CMS	3.3(5.2)	Phys. Lett. B 842.137531	
bbbb	ggF+VBF	ATLAS	8.1	Phys. Rev. D 108 (2023) 052003	
	VHH		183(87)	Eur. Phys. J. C 83 (2023) 519	
	ggF+VBF	CMS	3.9(7.9) 9.9(5.1)	resolved： Phys. Rev. Lett. 129.081802 boosted： Phys. Rev. Lett. 131.041803	
	VHH		294(124)	CMS-PAS-HIG-22-006	Talk by Licheng Zhang

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

- H→bb: large BR, background rejection from heavy-flavour jet ID
- H final states with leptons, γ, τ(h): efficient background rejection

Di-Higgs decay channels

channel	production modes		μ=σ(HH)/ σ(SM HH) obs(exp)	reference
bbZZ(4l)	ggF	CMS	32(40)	JHEP 06 (2023) 130
bbWW(single or dilepton of W decays)	ggF+VBF	CMS	18(14)	CMS-PAS-HIG-21-005
multilepton(WWW + WWττ + ττττ)	ggF+VBF	CMS	21.3(40)	JHEP 07 (2023) 095
bbll+MET (bb+WW,ZZ,ττ)	ggF+VBF	ATLAS	9.2(16.2)	arXiv:2310.11286
WWγγ	ggF	CMS	97(52)	CMS-PAS-HIG-21-014



"Preliminary Results on Higgs Pair Production in Multi-lepton Channel with the ATLAS Experiment" Yulei Zhang

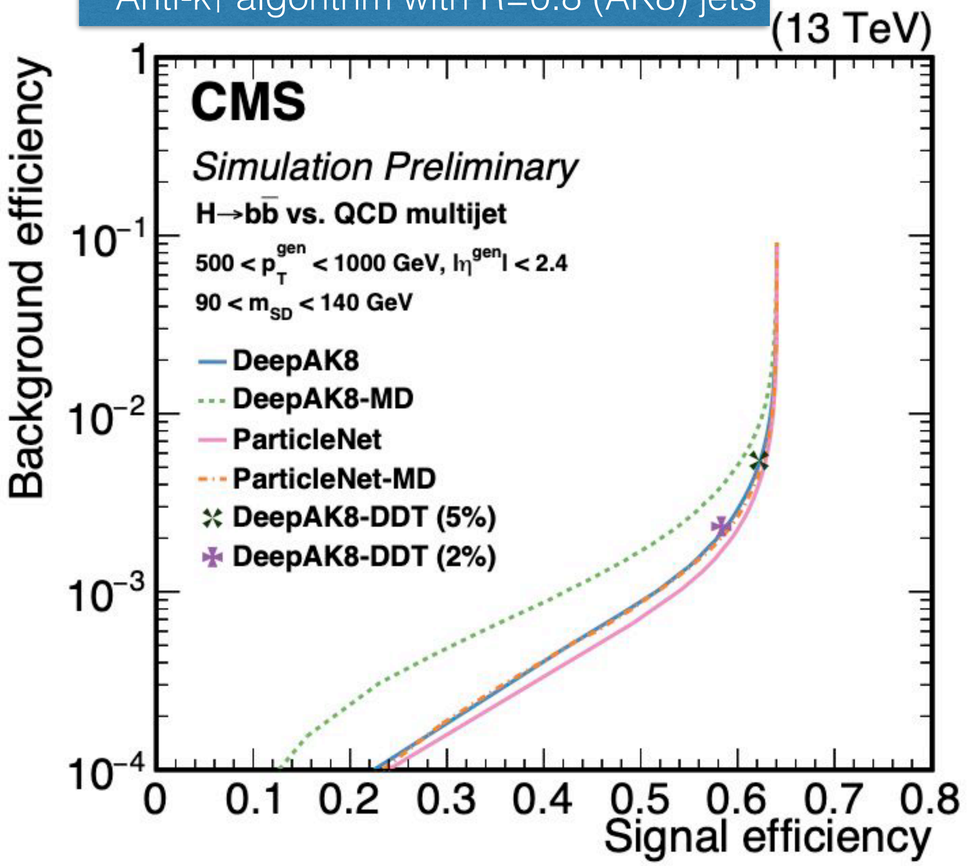
"Search for Higgs boson pair production in the bbμμ final state at the LHC" talk by Botao Guo

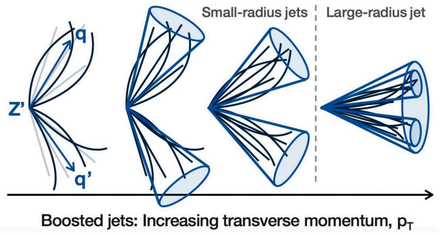
What's new in Run 2 analysis - boosted topologies

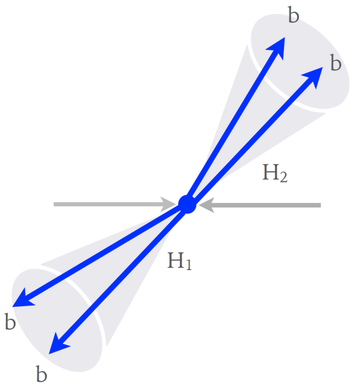
Phys. Rev. Lett. 131.041803

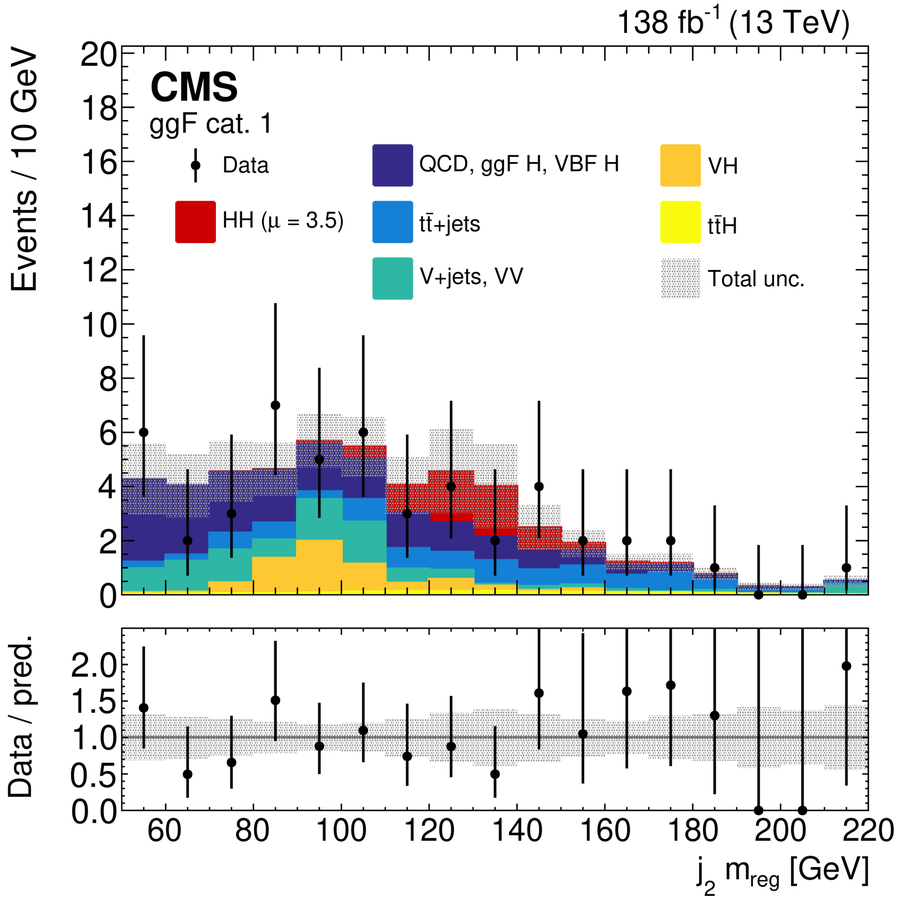
- σ(HH)/σ(SM HH) < 9.9 (5.1) × SM Observed (expected) upper limit at 95% CL
- most stringent expected limit from single channel analysis in CMS

Anti-k_T algorithm with R=0.8 (AK8) jets





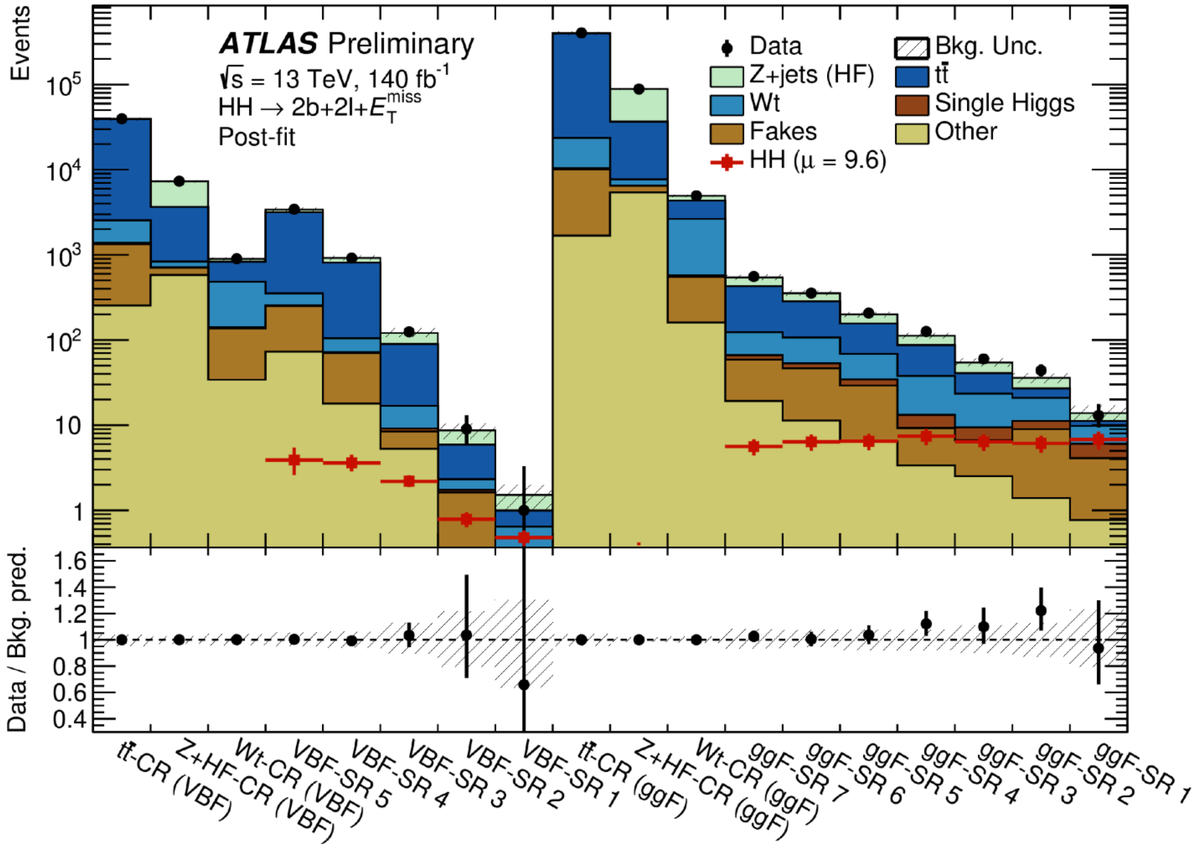




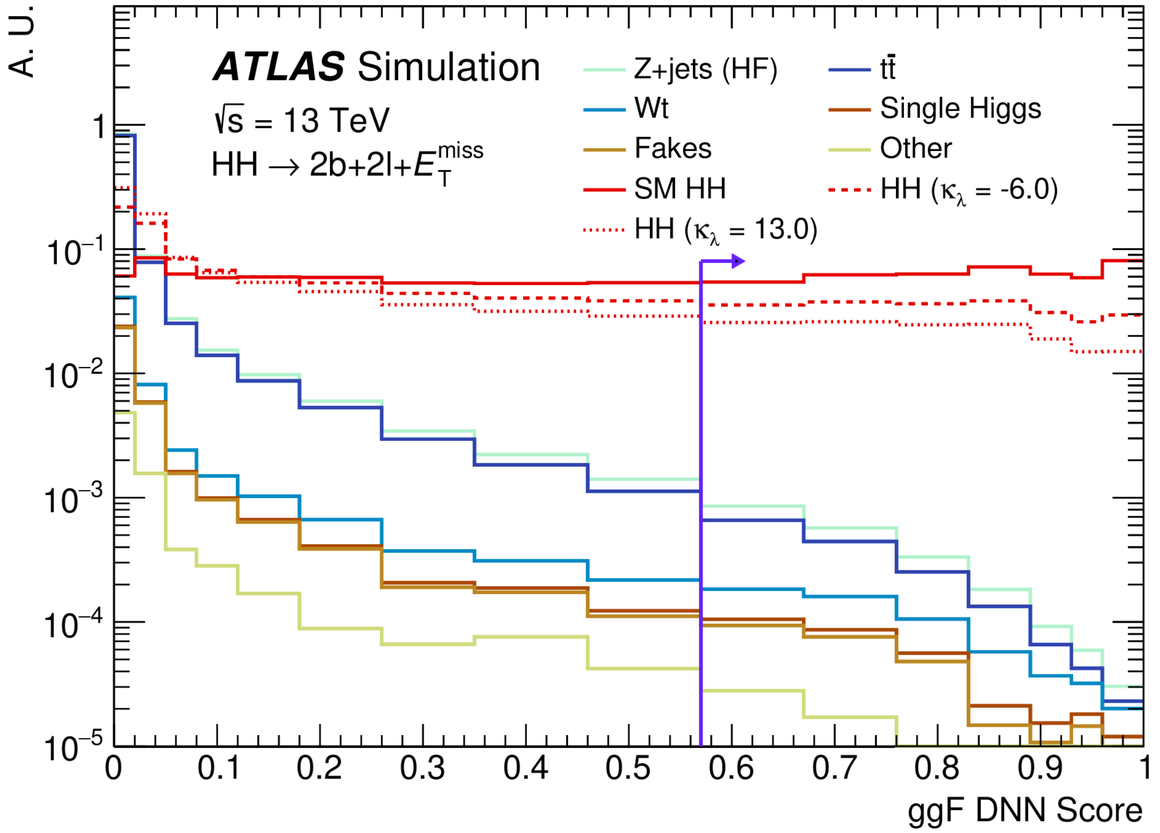
What's new in Run 2 analysis - machine learning

arXiv:2310.11286

- σ(HH)/σ(SM HH) < 9.6 (16.2) × SM Observed (expected) upper limit at 95% CL
- significant improvement (previous 40(29))



DNN for ggF



What's new in Run 2 analysis - EFT interpretation

Probe effects at lower energy scales from resonances with very large masses

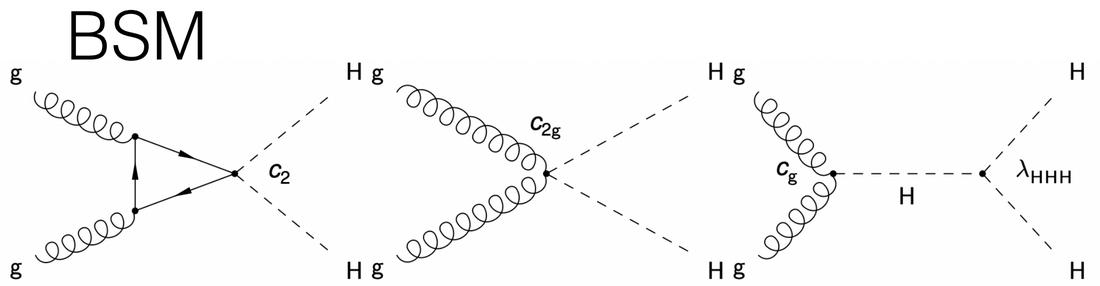
- Constraint BSM EFT couplings
- Probe EFT benchmark points

- SMEF: Talk by Zihang Jia

- HEFT: operators up to dimension 6, tree-level interactions of the Higgs boson are modeled by five parameters κ_λ, κ_t, c_2, c_g, c_{2g}

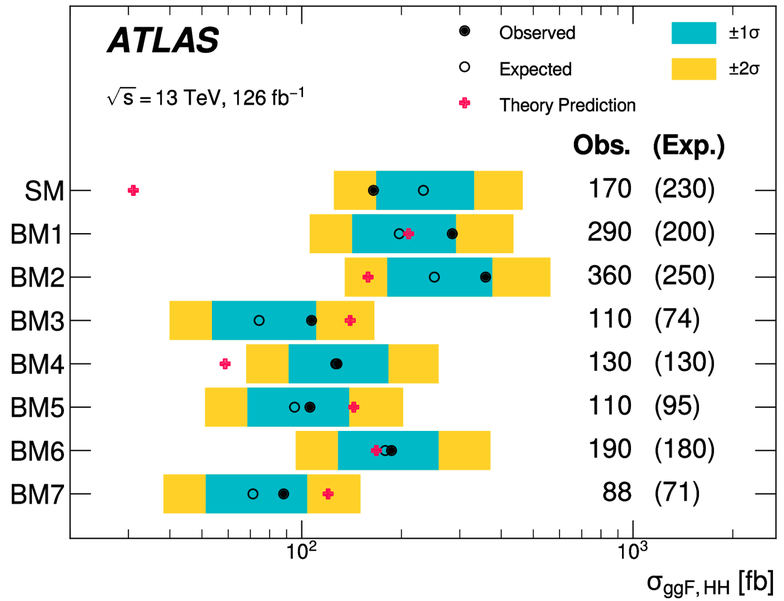
JHEP09(2018)057, JHEP03(2020)091

Benchmark	c_{hhh}	c_{tth}	c_{ggh}	c_{gghh}	c_{tthh}
SM	1	1	0	0	0
1	5.11	1.10	0	0	0
2	6.84	1.03	-1/3	0	1/6
3	2.21	1.05	1/2	1/2	-1/3
4	2.79	0.90	-1/3	-1/2	-1/6
5	3.95	1.17	1/6	-1/2	-1/3
6	-0.68	0.90	1/2	0.25	-1/6
7	-0.10	0.94	1/6	-1/6	1



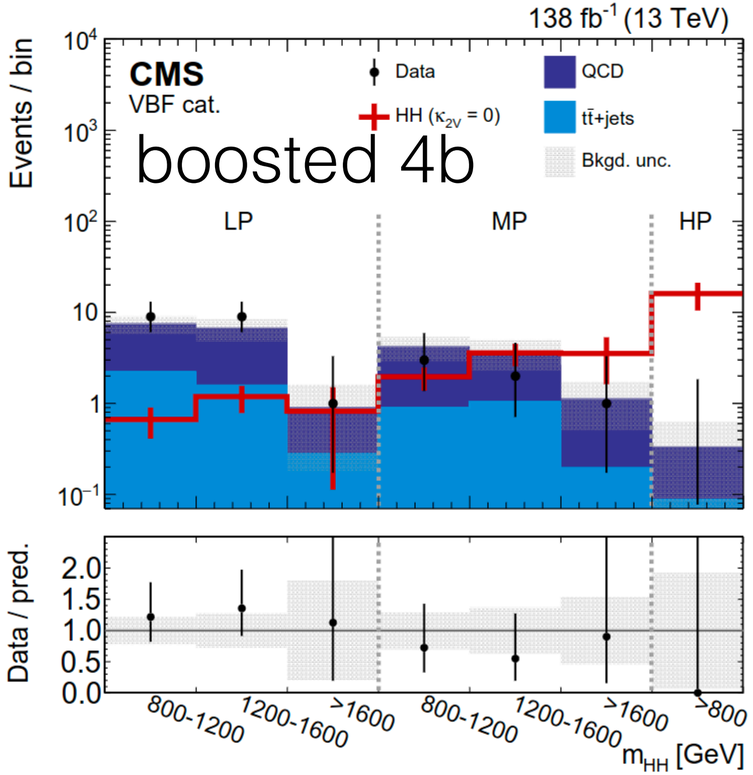
Phys. Rev. D 108 (2023) 052003

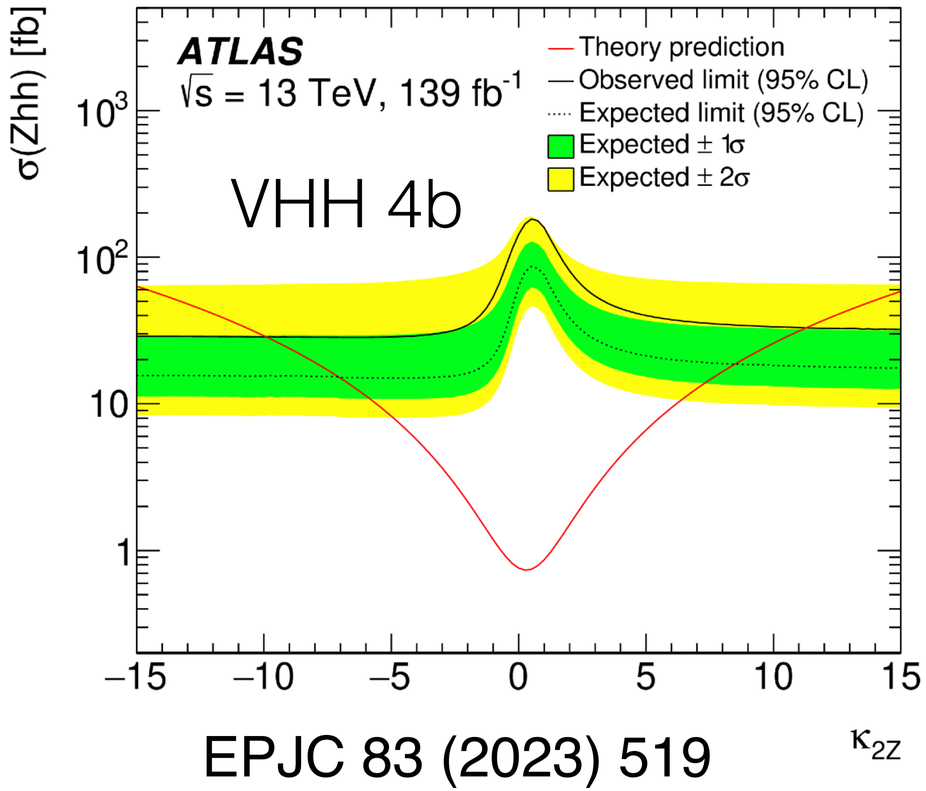
HH → bbbb



What's new in Run 2 analysis - VBFHH and VHH

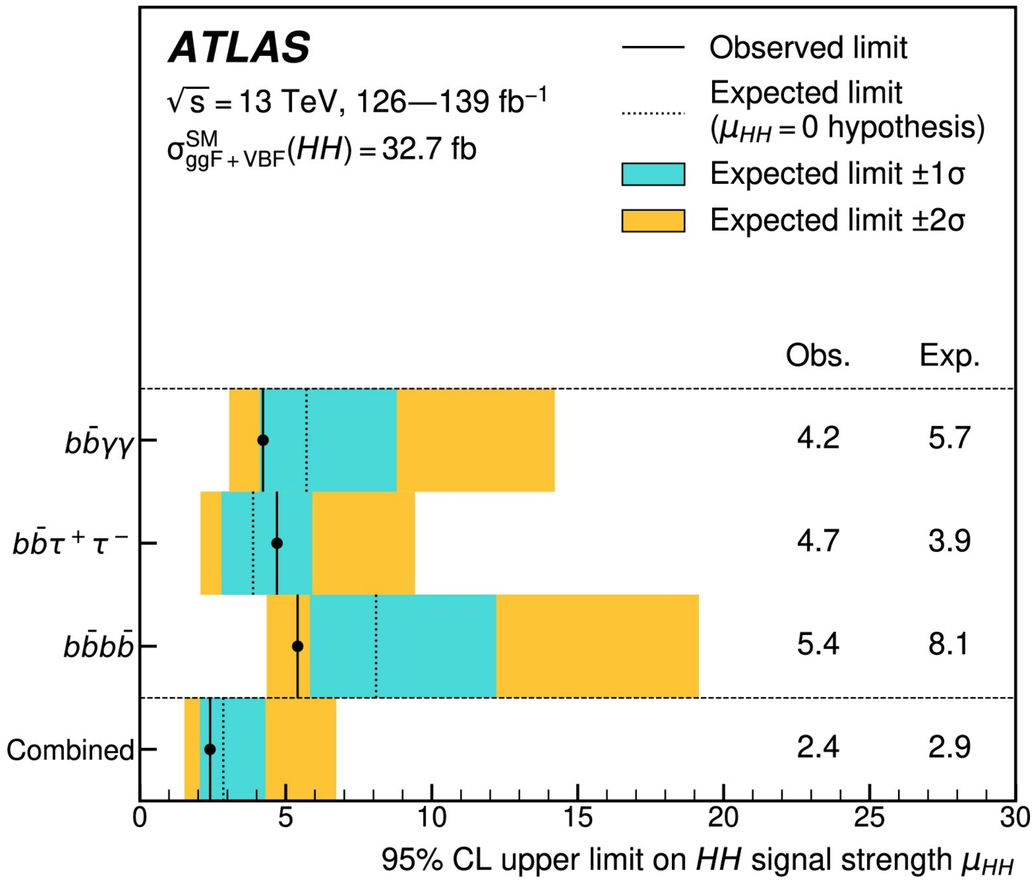
- VBFHH and VHH both probe VVHH interaction
  - VHH can probe separately WWHH and ZZHH interactions
- provide complementary constrain to Higgs self-coupling
- CMS VHH 4b talk by Licheng ZHANG



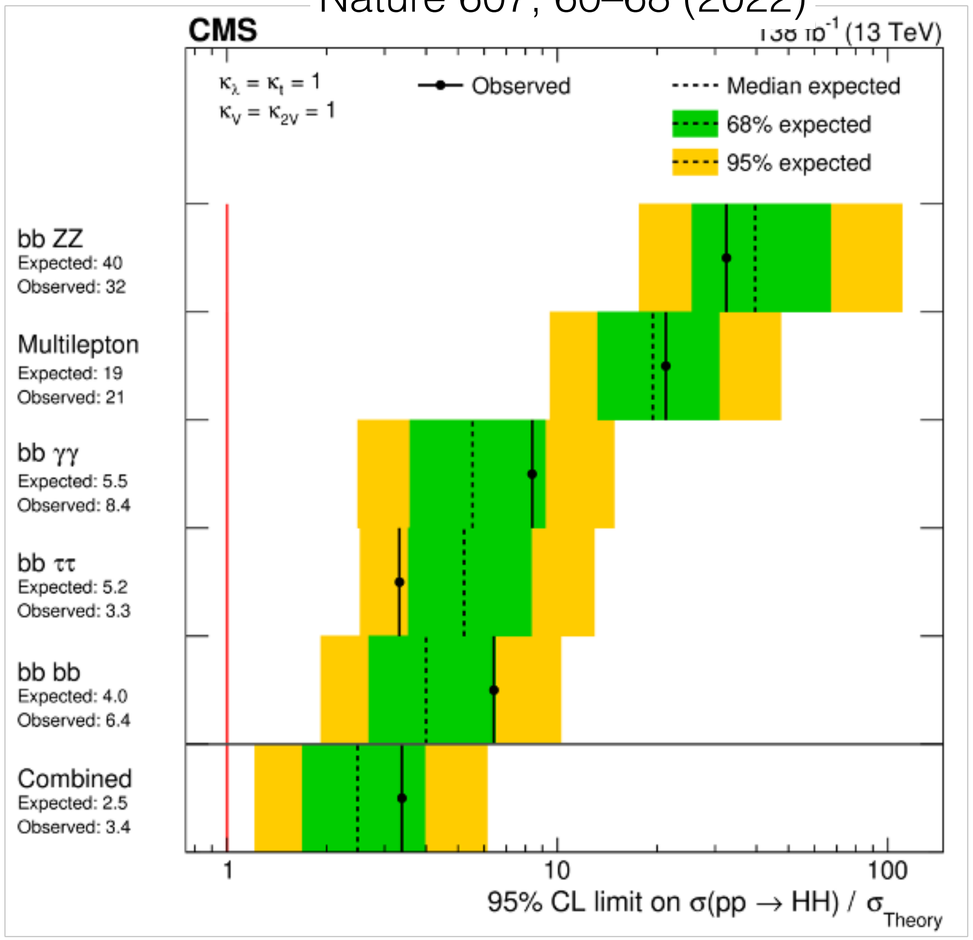


HH combination

Phys. Lett. B 843 (2023) 137745



Nature 607, 60–68 (2022)



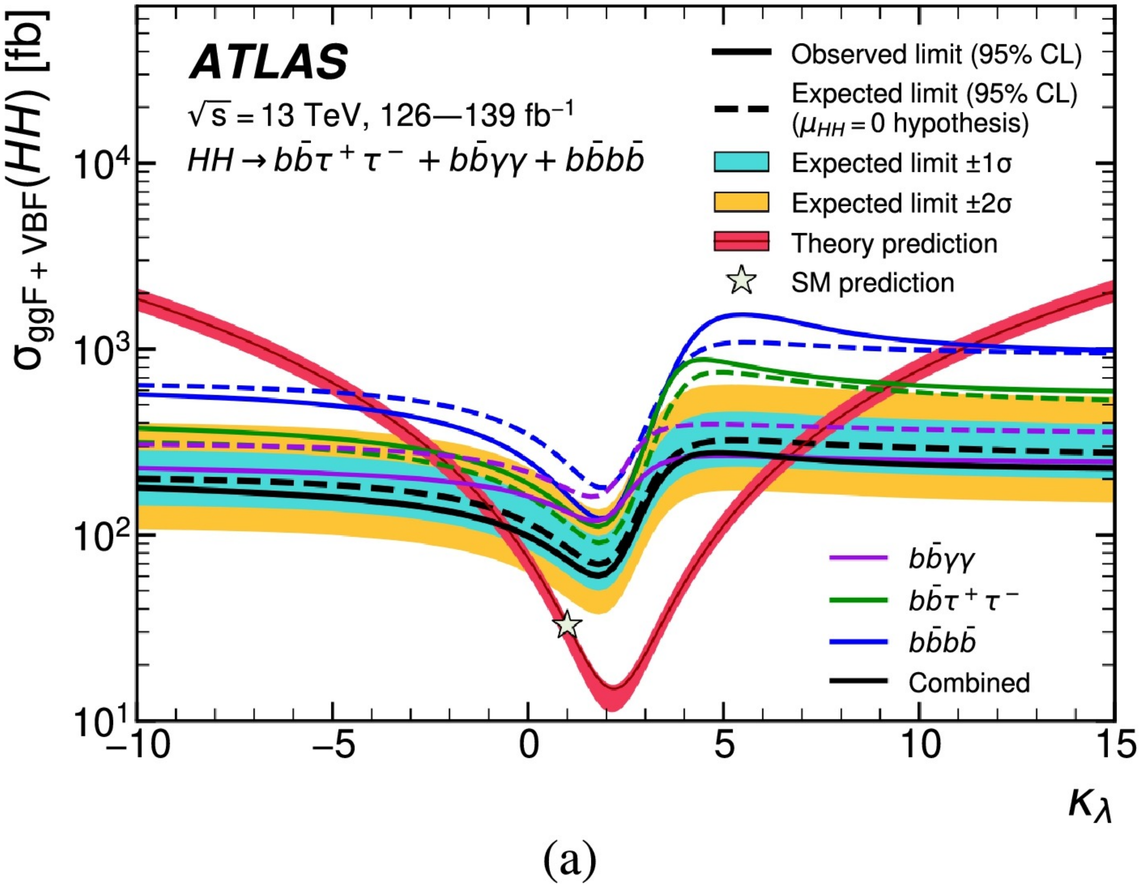
"CMS Higgs and double Higgs combinations" Talk by Jialin Guo

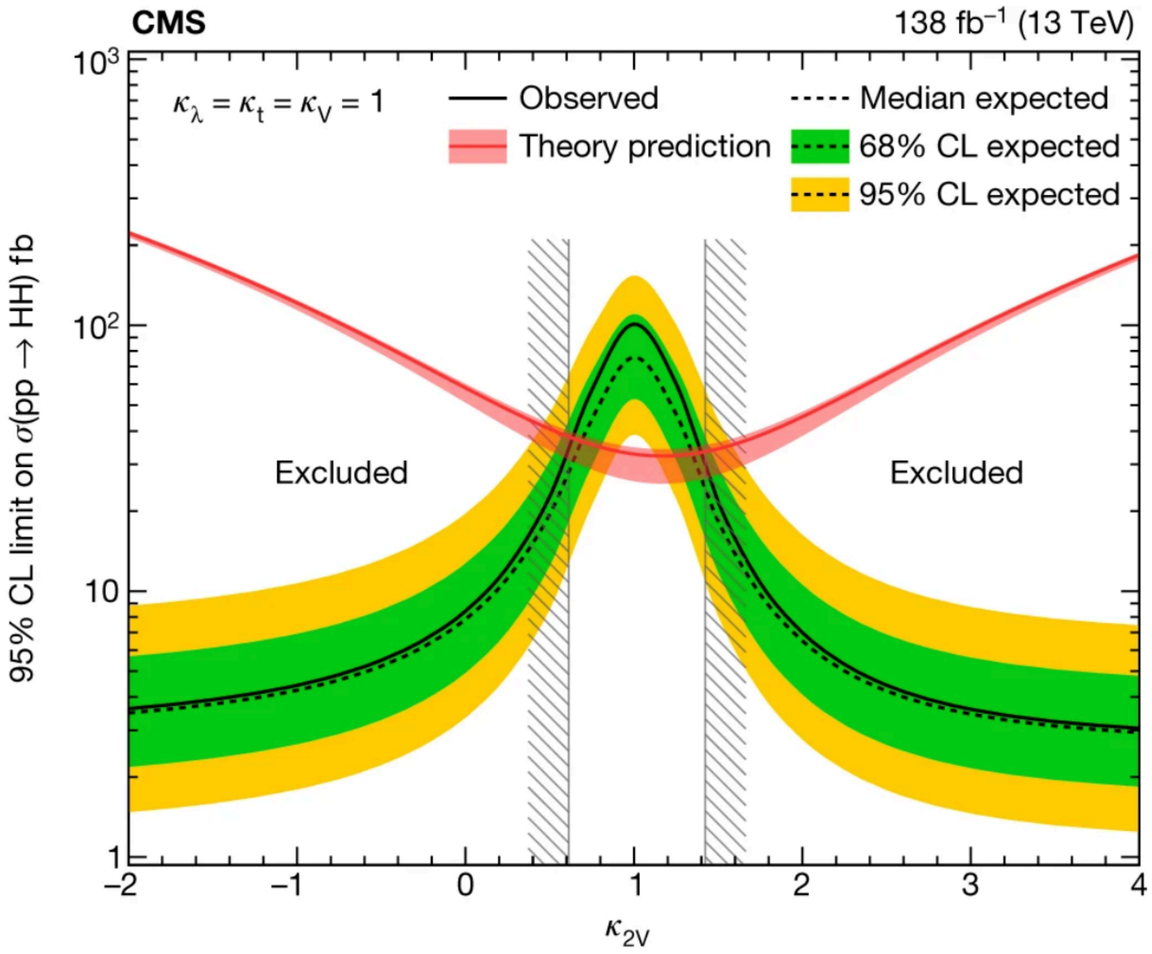
HH combination

CMS: Nature 607 (2022) 60

ATLAS: Phys. Lett. B 843 (2023) 137745

- upper limits of different couplings values, compared to theory prediction

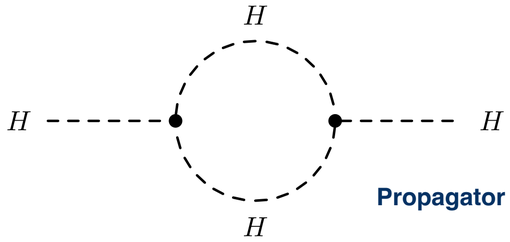




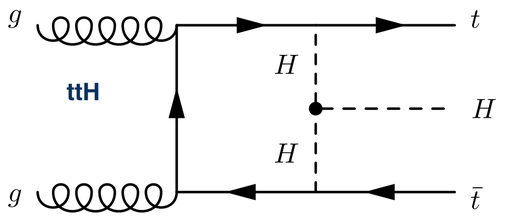
Self coupling from single H

- H production and decay sensitive to **self-coupling** κ_λ through NLO EW corrections

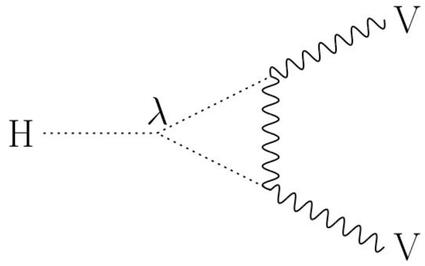
One universal correction for H wave-function renormalization



κ_λ-dependent diagrams for H production mechanisms

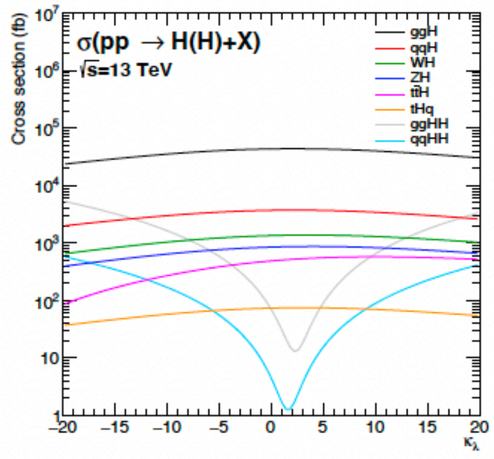


κ_λ-dependent diagrams for H→VV decay

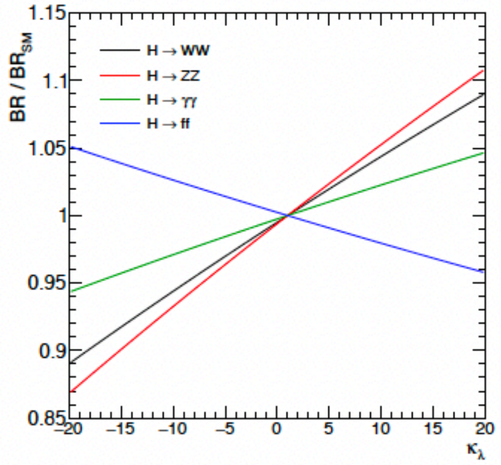


- CMS&ATLAS joint effort for modeling STXS 1.2 vs k_λ: LHCHWG-2022-002

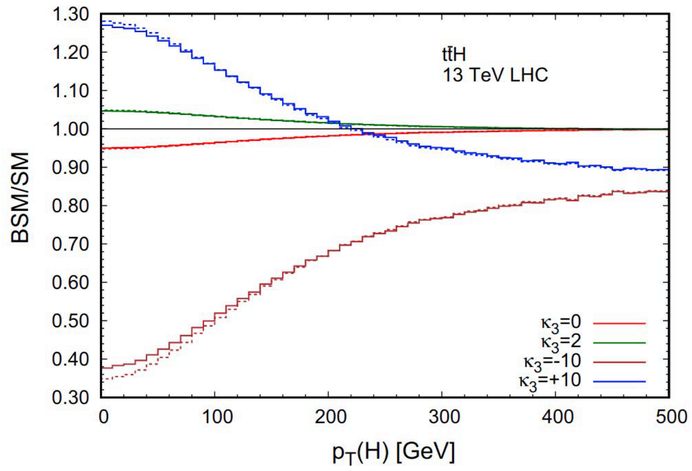
total cross section vs k_λ



H BR vs k_λ



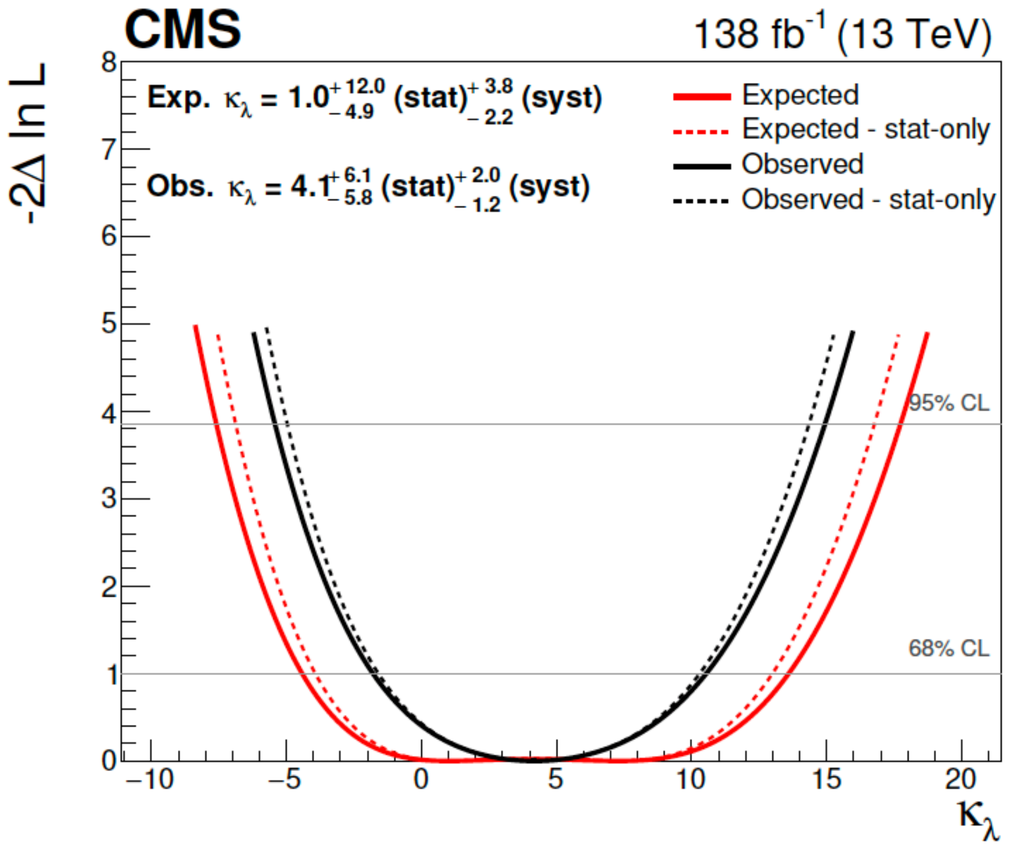
differential pT(H) and k_λ : larger variations for VH and ttH



Self-coupling from single H

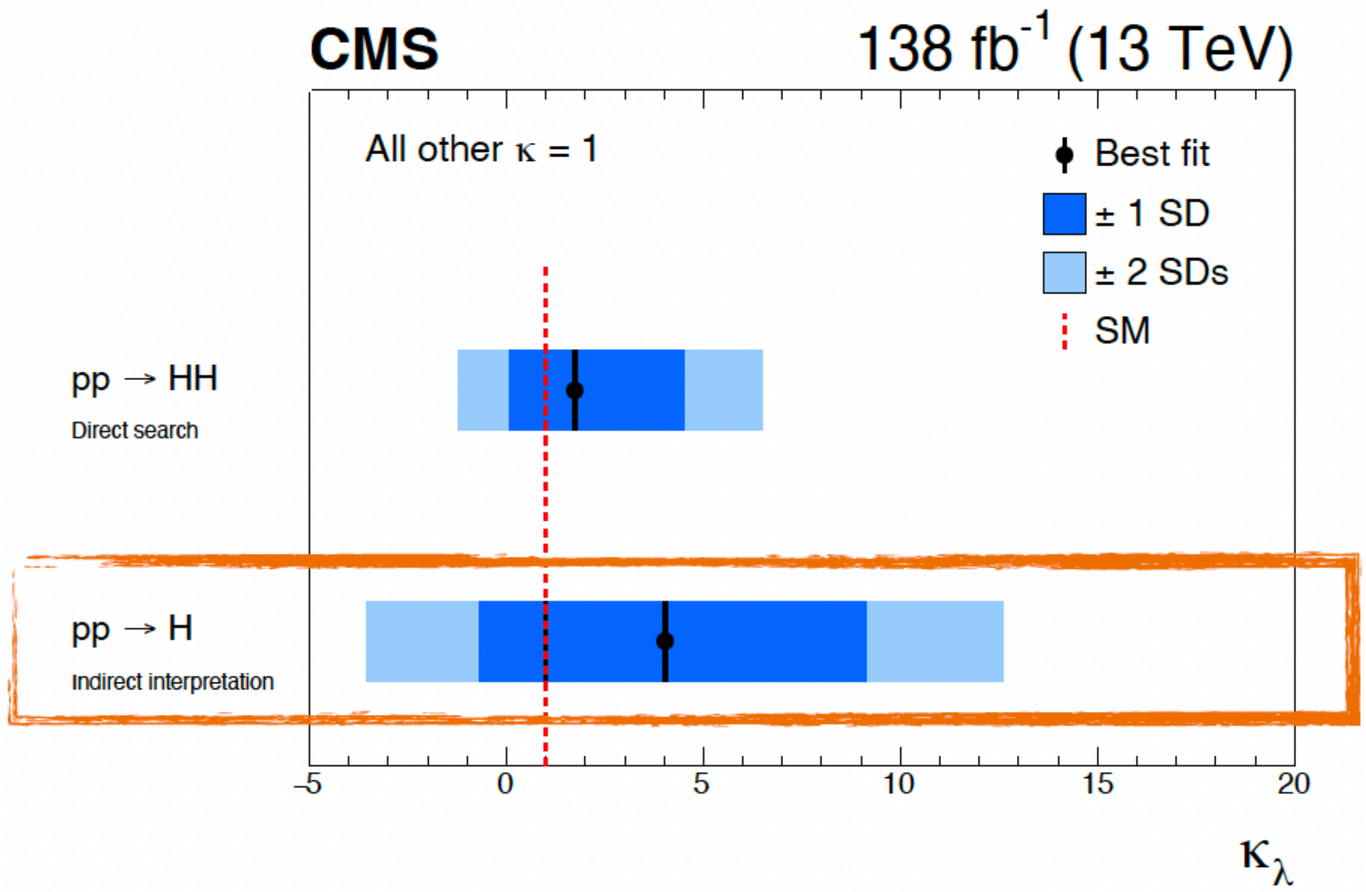
Differential H→ZZ→4l

JHEP 08 (2023) 040



H combination

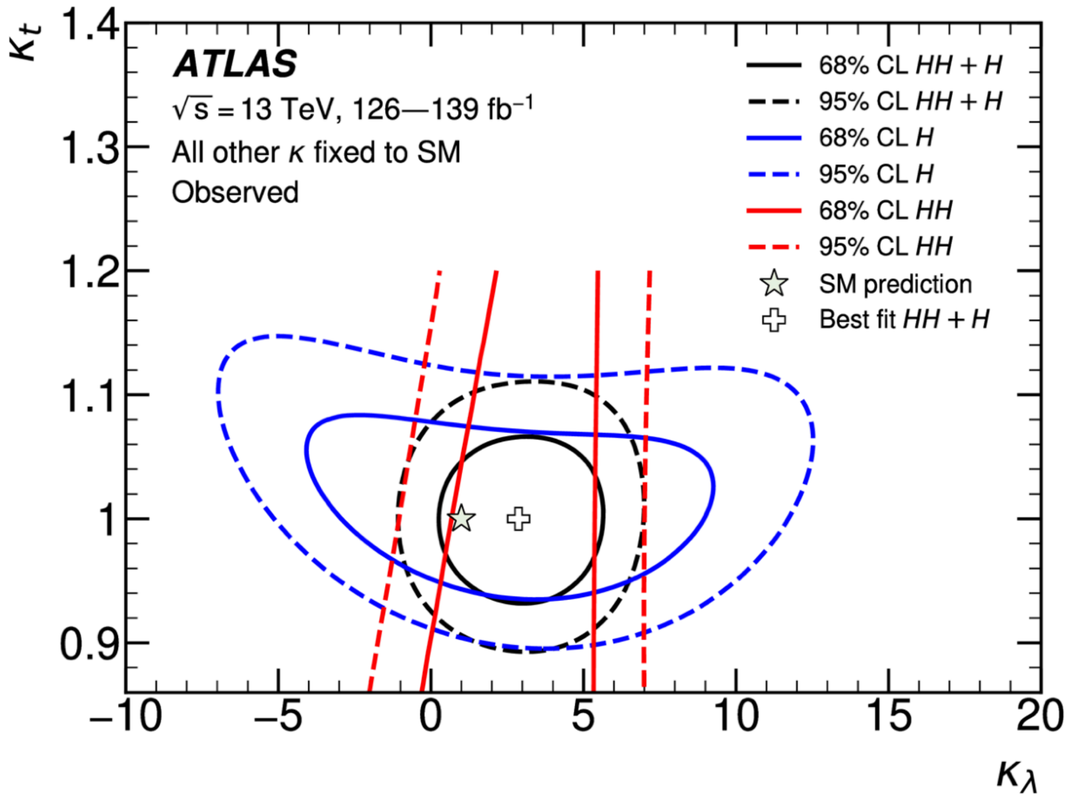
Nature 607 (2022) 60

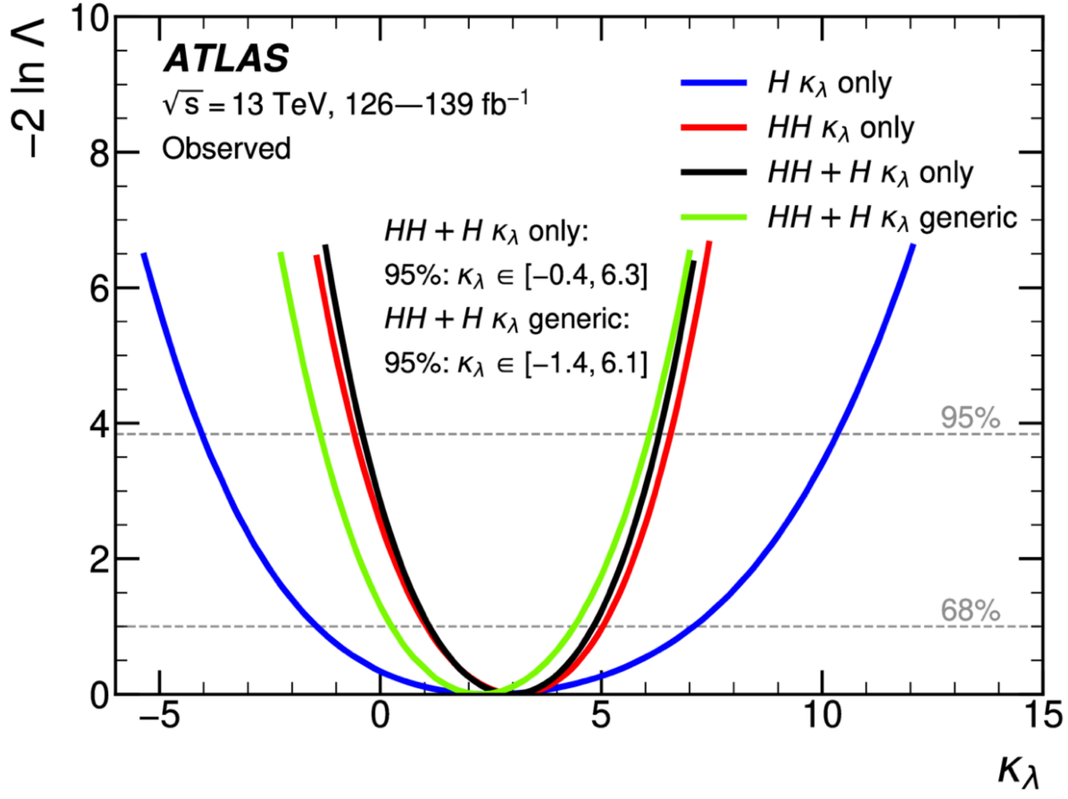


H and HH combination

- Stronger constraint on κ_λ than HH alone
- Decouple κ_λ from other SM couplings e.g. κ_t

- Future: EFT: H + HH combination
  - taskforce in WG2&WG4 of LHCHWG
  - If you're interested to participate in this task force, please join mattermost here

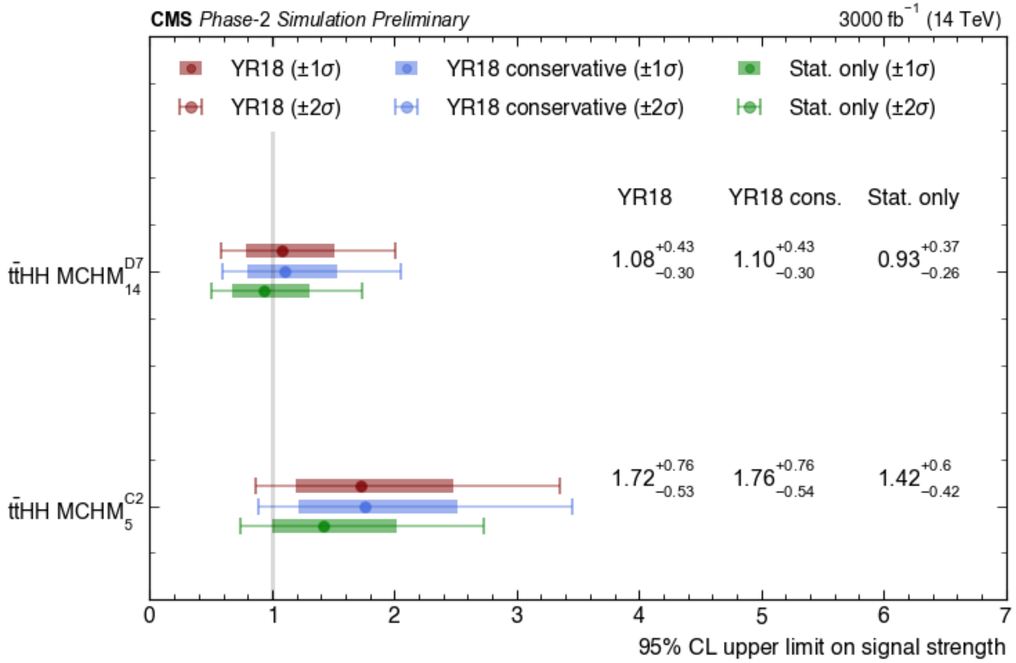




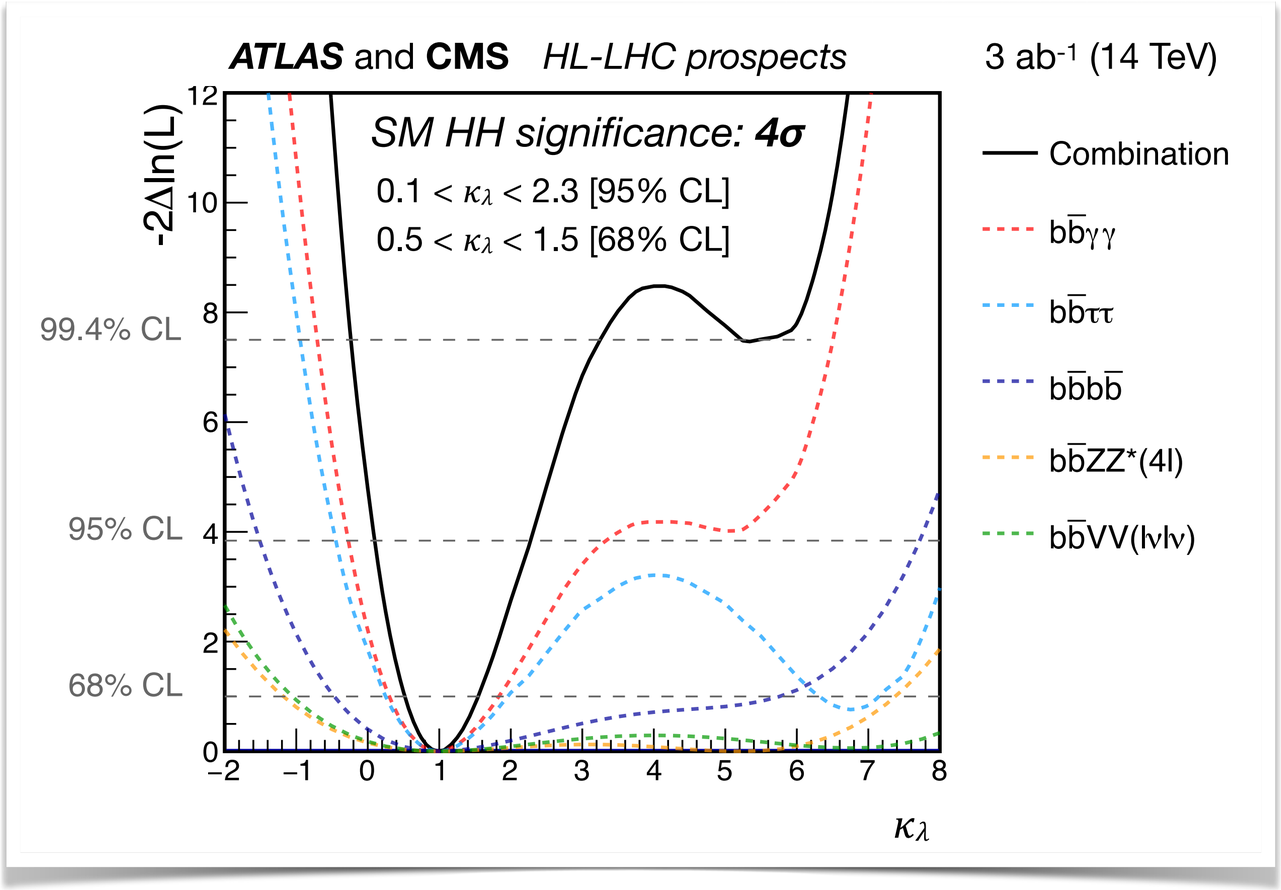
Phys. Lett. B 843 (2023) 137745

Overview of HL-LHC Higgs prospect studies

- **Yellow Report 18 "Higgs Physics at the HL-LHC and HE-LHC"** arXiv:1902.00134
- **ATLAS and CMS Snowmass white paper:** ATLAS-PHYS-PUB-2022-018/CMS-PAS-FTR-22-001



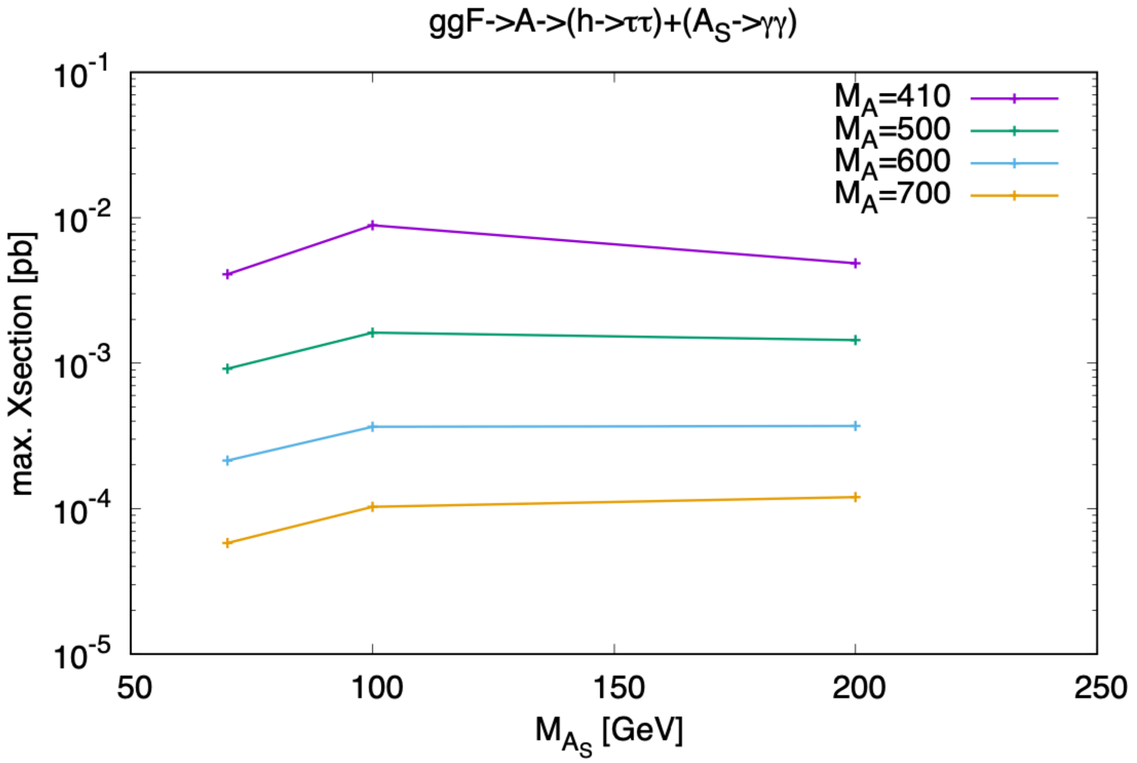
- σ(SM ttHH) < 3.14 x SM



- HH: promising to reach **5σ Significance combining** CMS and ATLAS
- Accessible to Higgs self-coupling: 50% precision from ggHH mode

Resonant diHiggs production in BSM

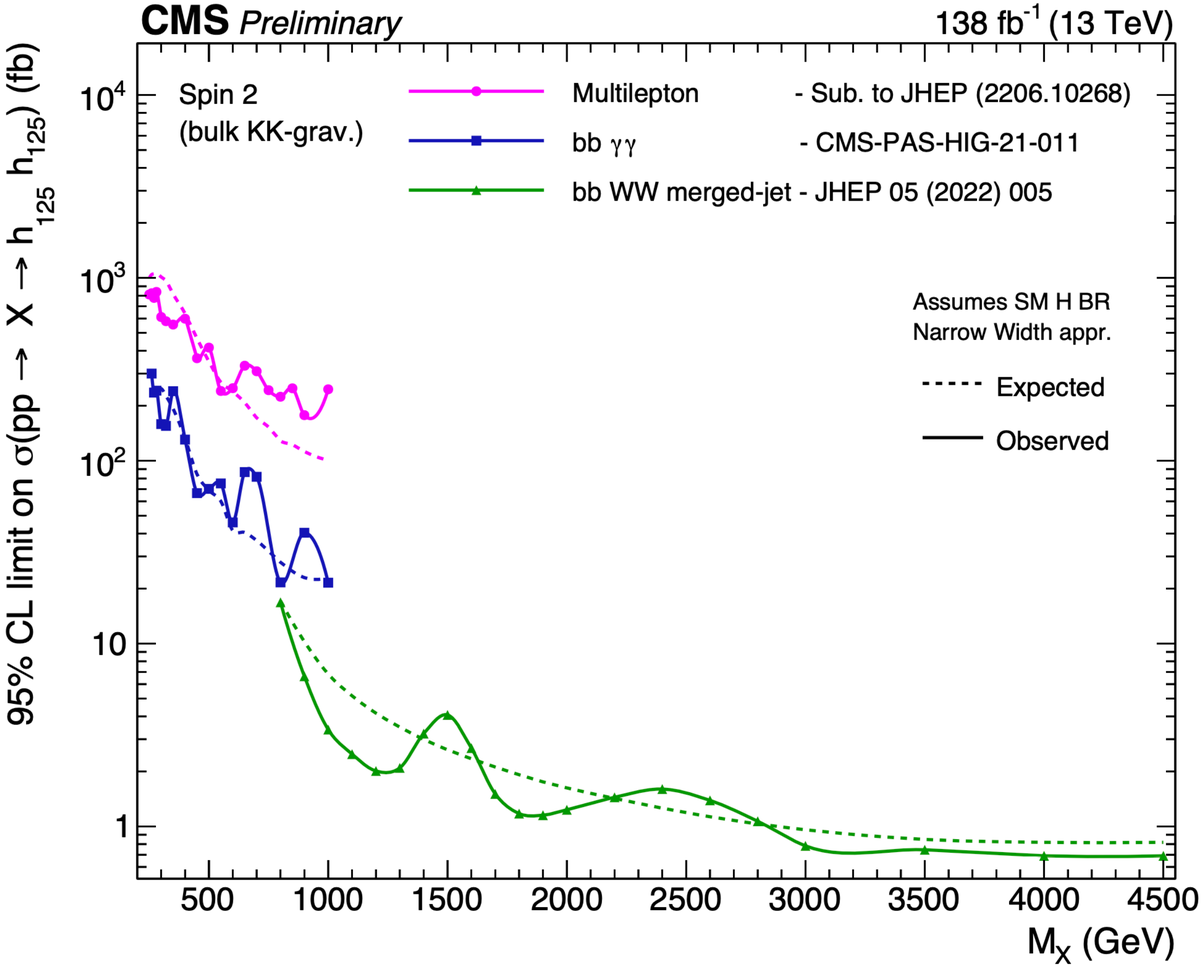
- Resonant di-Higgs production is motivated in many BSM models:
  - e.g. heavy spin-0 scalar in two-Higgs-doublet model, spin-2 gravitons, Next-to-Minimal Supersymmetric Standard Model (NMSSM)…

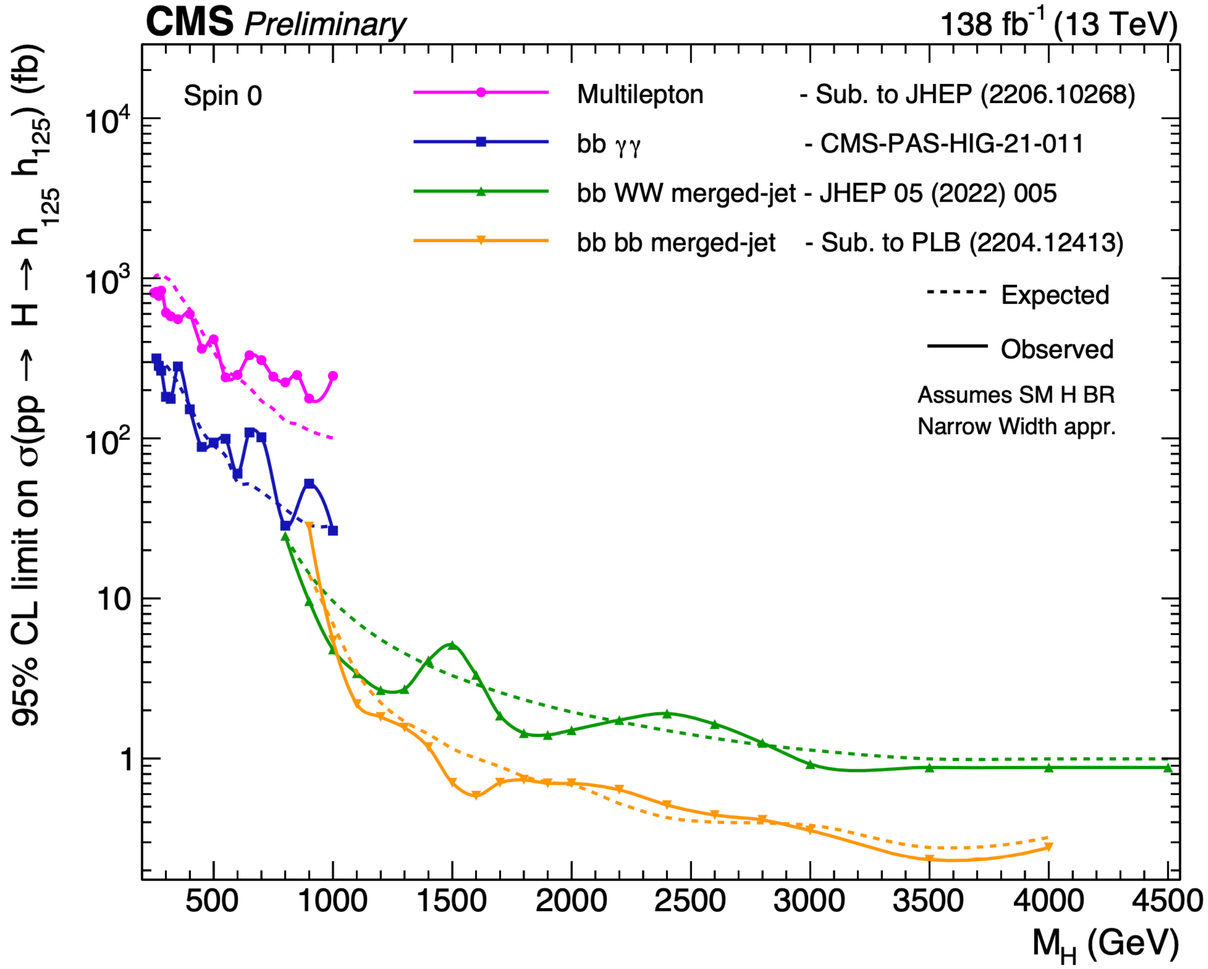


Ellwanger, U., Hugonie, C. Benchmark planes for Higgs-to-Higgs decays in the NMSSM. Eur. Phys. J. C 82, 406 (2022)

Resonant di-Higgs searches

narrow width

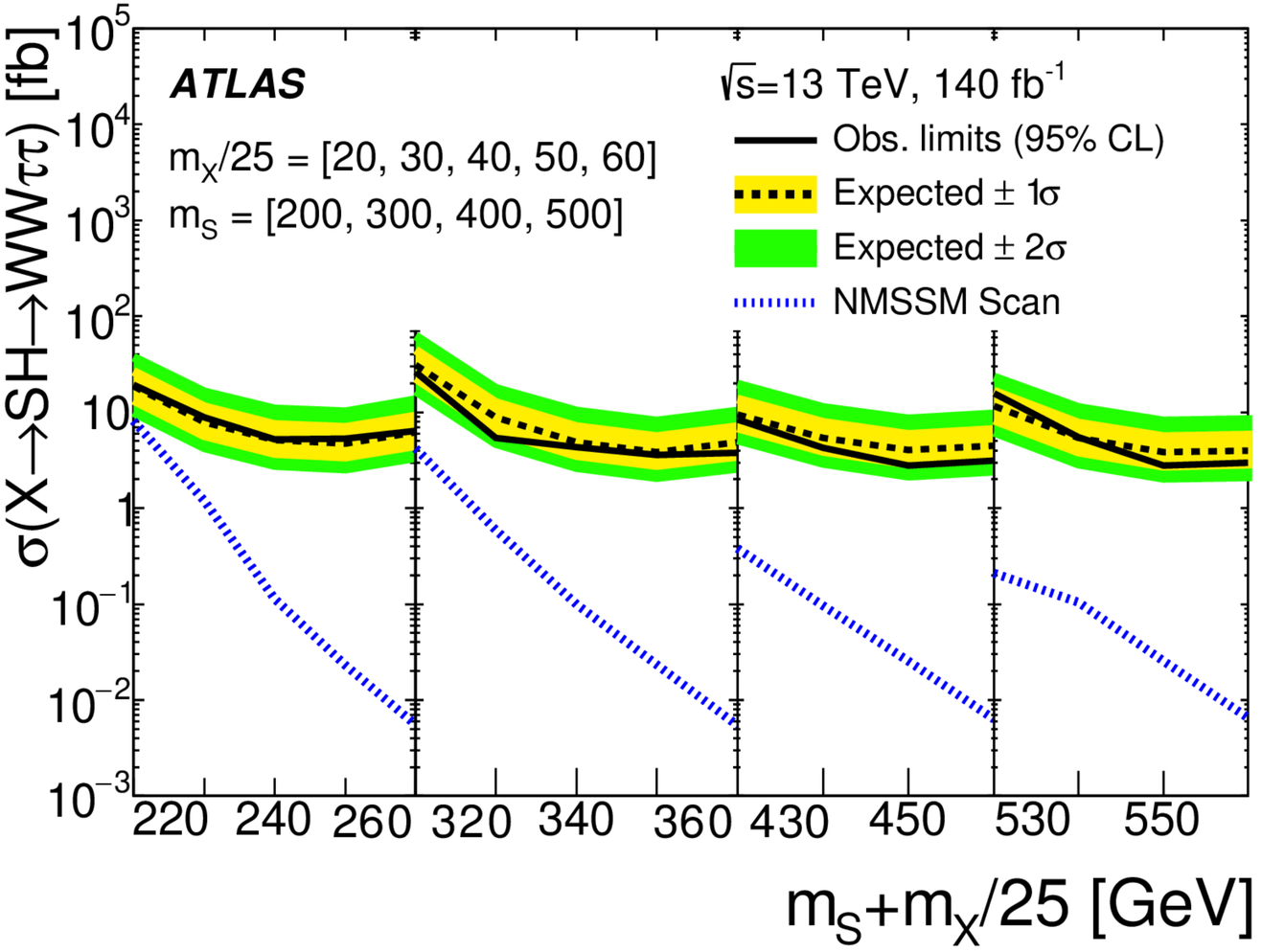




CMSPublic/SummaryResultsHIG ATLAS results

Heavy Resonant Scalar decaying to scalar singlet + SM Higgs

JHEP 10 (2023) 009

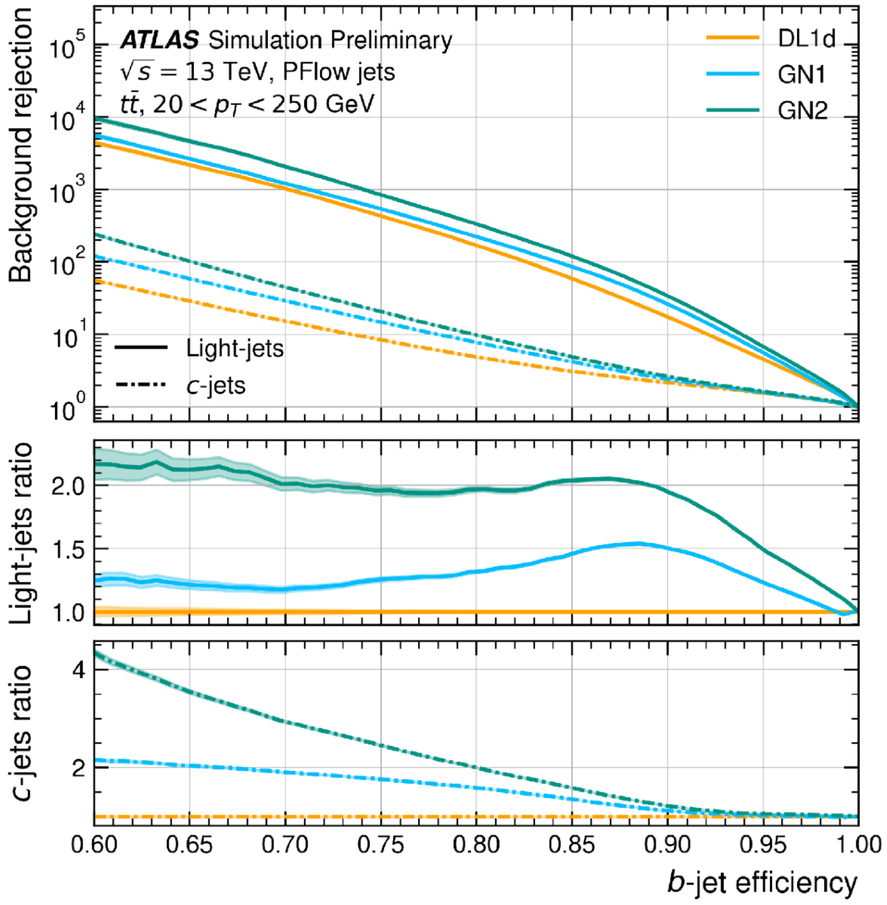


narrow width

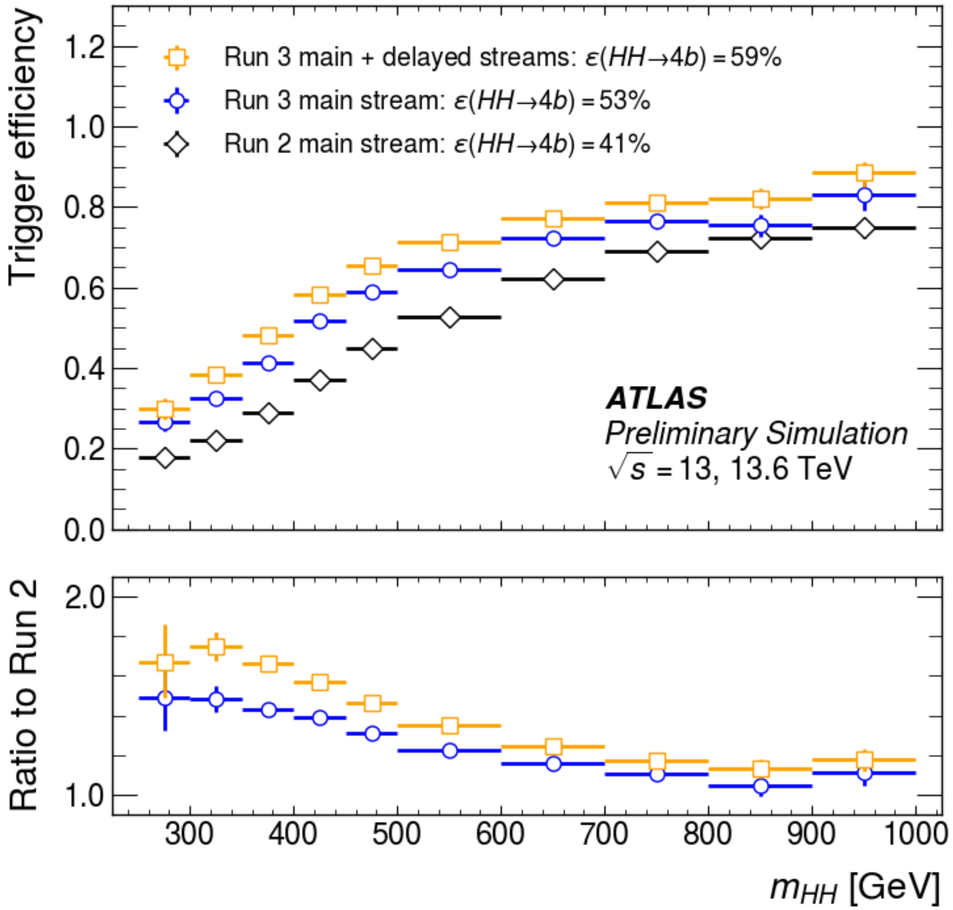
CMSPublic/SummaryResultsHIG ATLAS results

HH preparation Run 3: ATLAS

- new developments in b-tagging and trigger



FTAG-2023-01

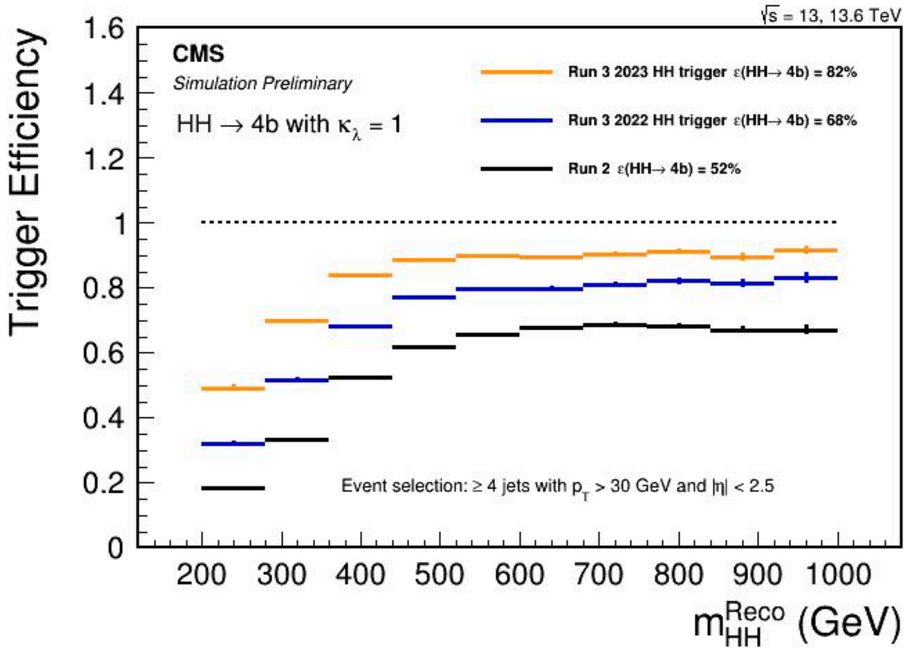


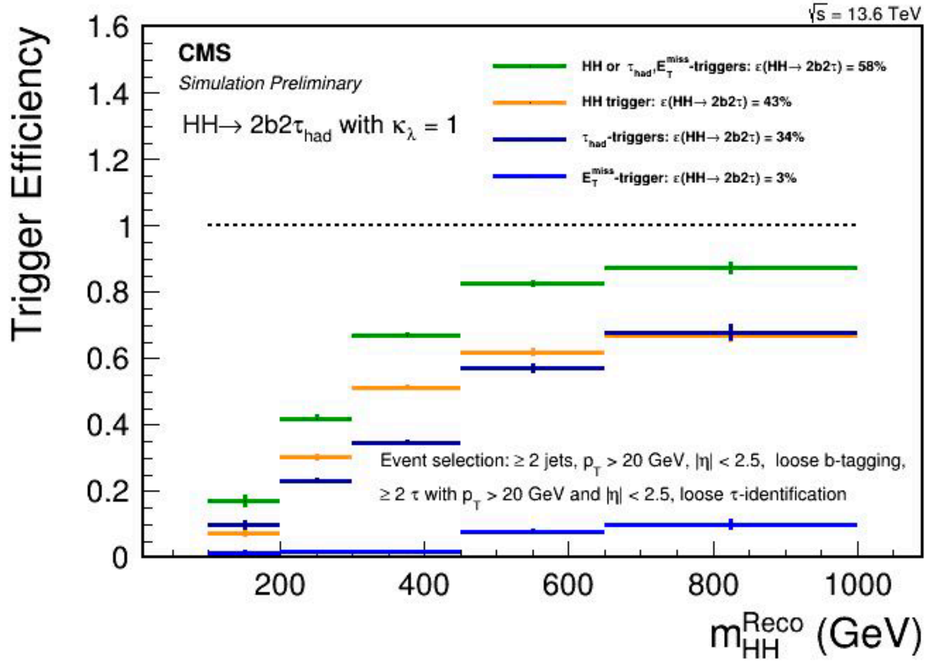
BJet Trigger PublicResults

HH preparation Run 3: CMS

CMS-DP-2023-050

- **new HH triggers:**
  - 2023: HT > 280 GeV, 4 jets with pT > 30 GeV, PNet@AK4(2 highest b-tag score) > 0.55
  - 2022: 4 jets pT > 70, 50, 40, 35 GeV, PNet@AK4(2 highest b-tag score) > 0.65
- **Data parking :** allows a higher rate and acceptance at the cost of delayed reconstruction, this new HLT trigger records events at 180 Hz at $2x10^{34}$ $cm^{-2}s^{-1}$ instantaneous luminosity





Conclusion and outlook

- The discovery of the Higgs boson and the study of its properties have expanded our vision of particle physics
- diHiggs production directly probes the Higgs boson self-coupling, results so far agrees with SM
  - CMS Run 2 HH combination limits (bbbb, bbττ, bbγγ, multileption and bb4l) on SM diHiggs cross section: 3.4 (2.5) X SM at 95% CL
  - ATLAS Run 2 H+HH combination measures self-coupling [-0.4,6.3] 95% CL
  - Hints for new physics could be unravelled as data accumulates and analysis advance
- Looking forward to diHiggs searches in LHC Run 3 and beyond!

Apologies for all I could not cover

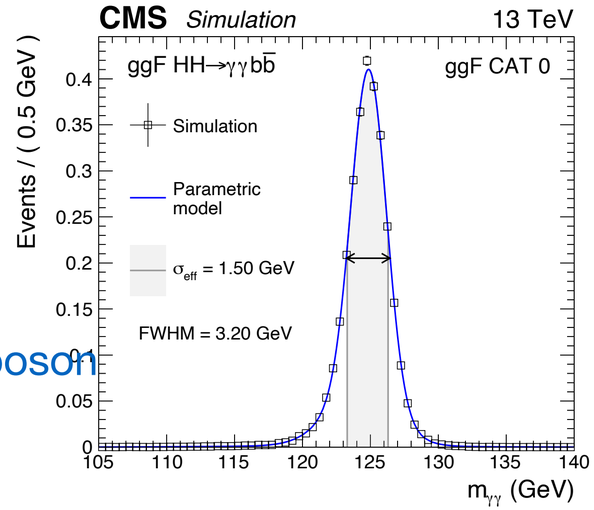
Thank you!

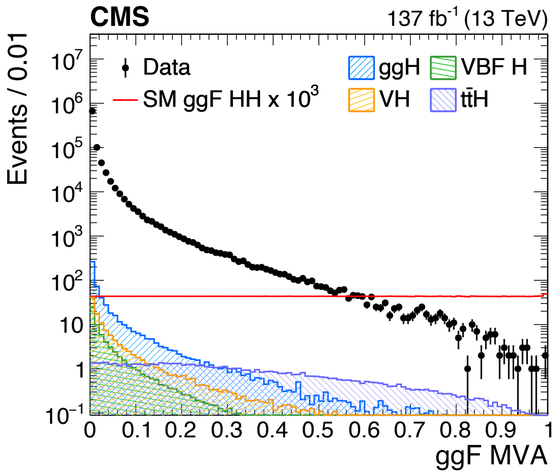
backup slides

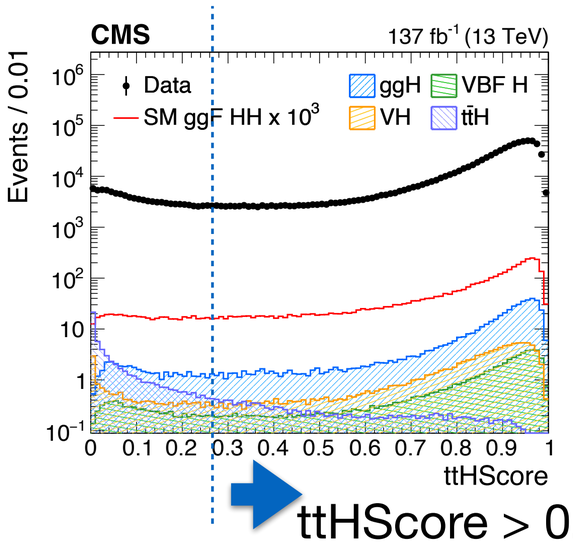
HH→bbγγ search CMS full Run 2 data

JHEP 03 (2021) 257

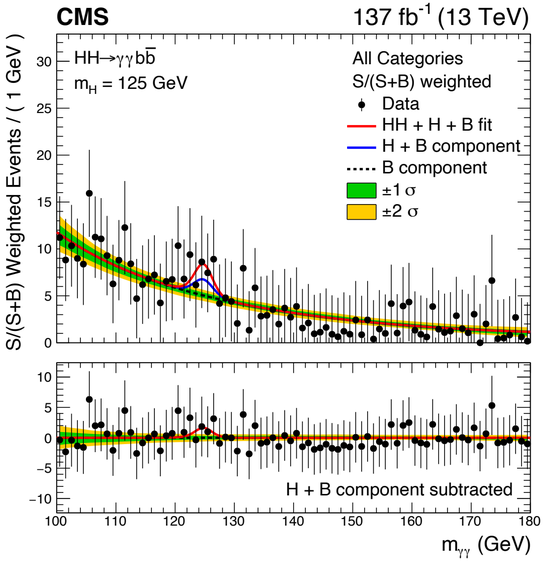
- One of the most sensitive channels for HH search:
  - good resolution of $m_{\gamma\gamma}$
  - relatively low background rates
- Analysis strategy:
  - dedicated ttH classifier to reject ttH backgrounds
  - HH categories based on MVA classifier and mass of Higgs boson pair system: 12 ggF and 2 VBF categories
  - ttH categories to constraint the top-Higgs coupling

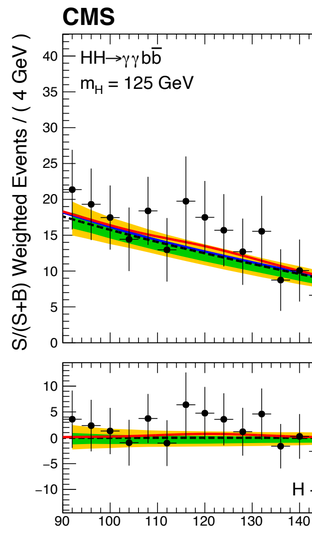




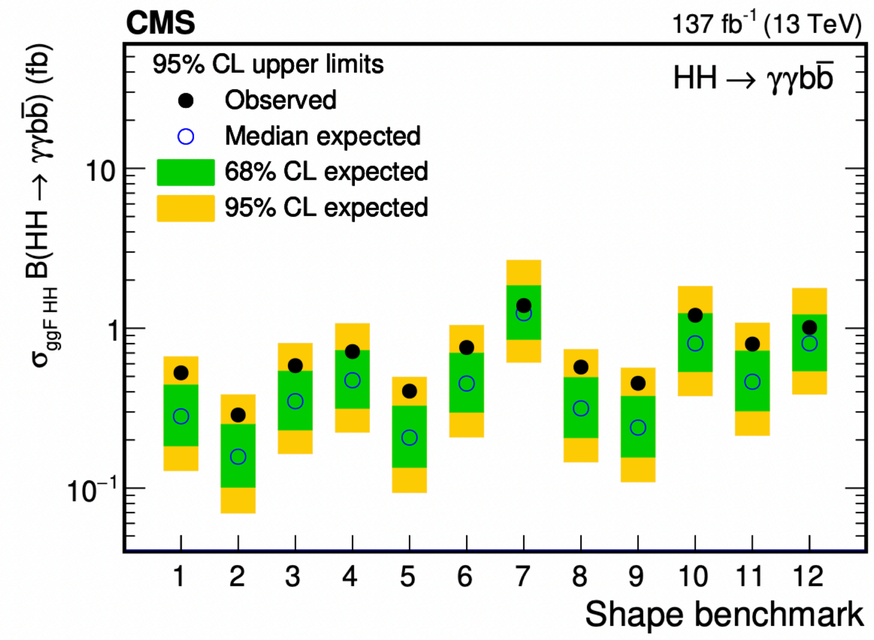


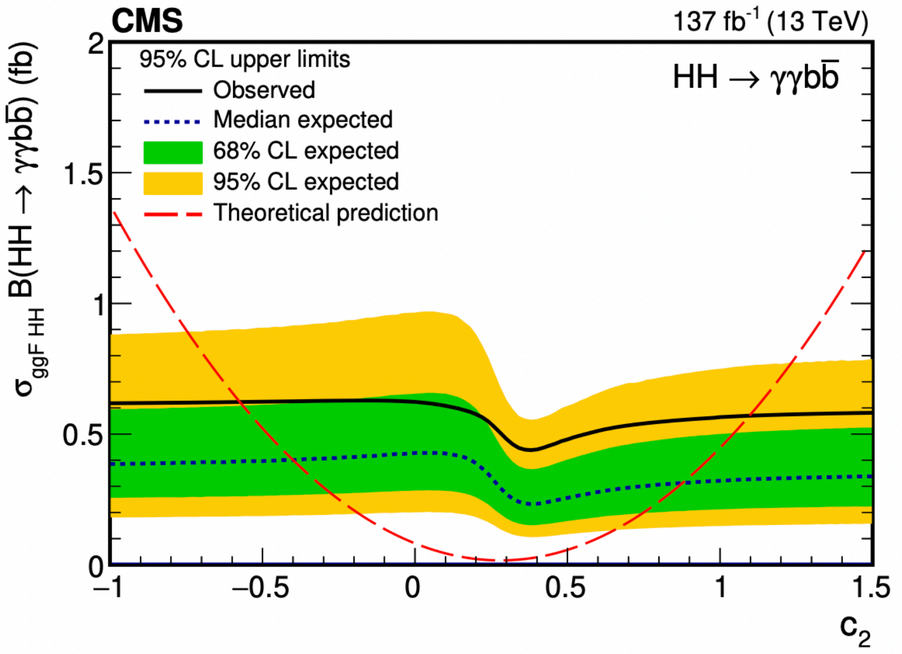
ttHScore > 0.26



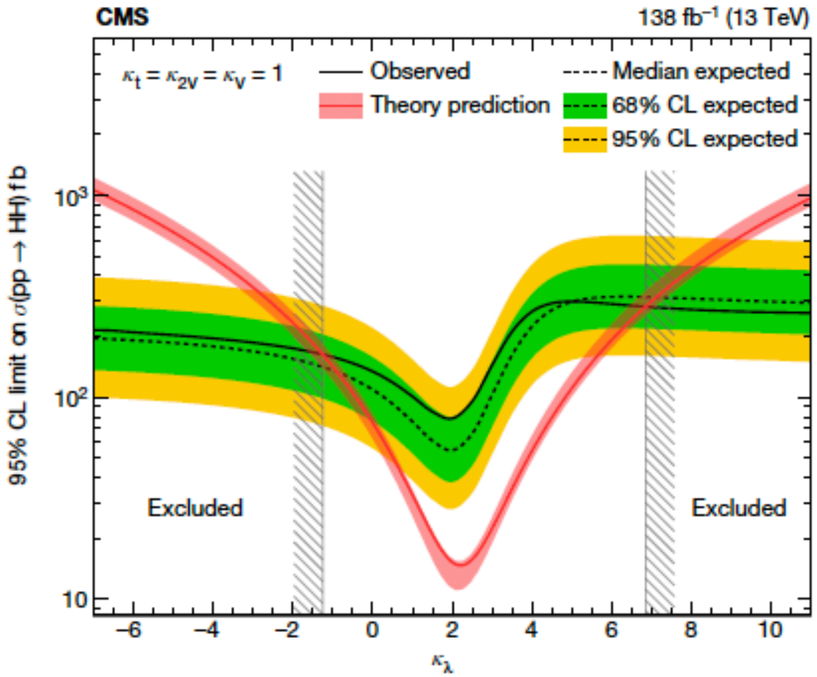


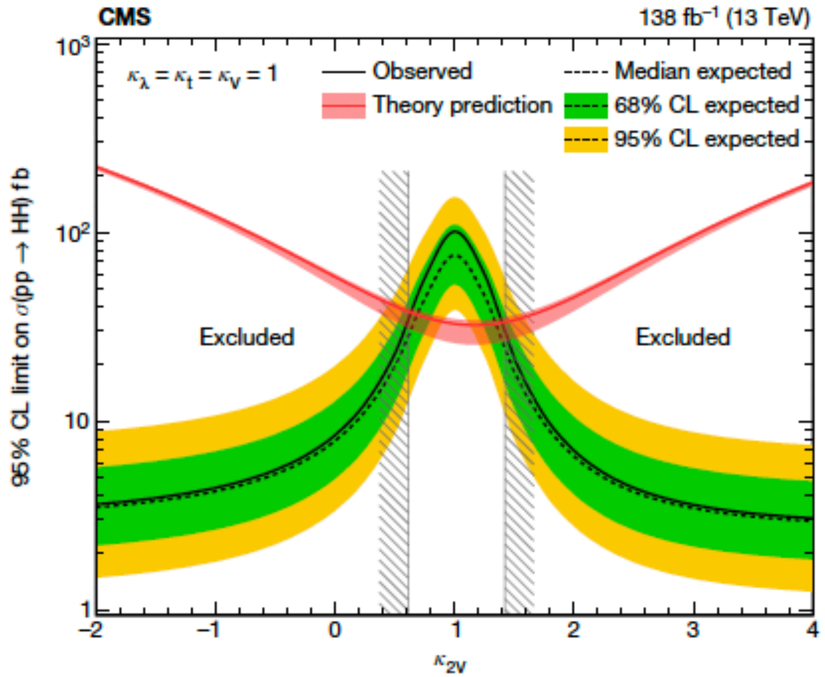
HH→bbγγ CMS EFT studies





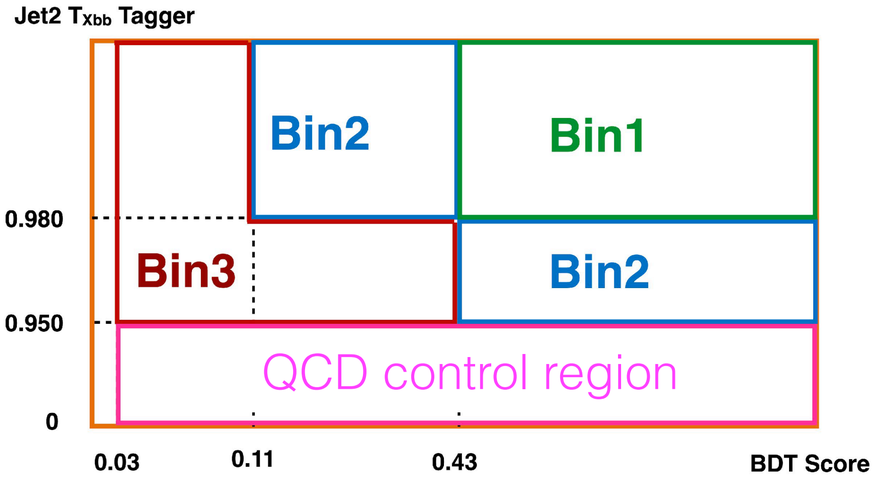
HH combination CMS



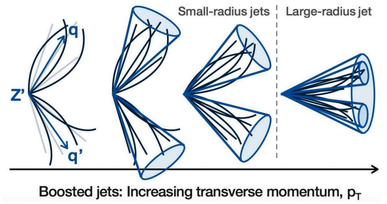


HH→4b boosted in CMS

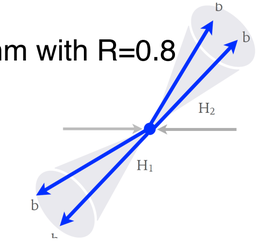
- Trigger is crucial: requiring large total hadronic transverse energy in the event (H_T) or AK8 jet with large p_T
  - Trigger efficiency:10 ~ 95% for jets with 300 < p_T < 450 GeV, fully efficient for jets with p_T > 500 GeV
- ParticleNet boosted high-p_T (>300 GeV) Higgs candidate jets

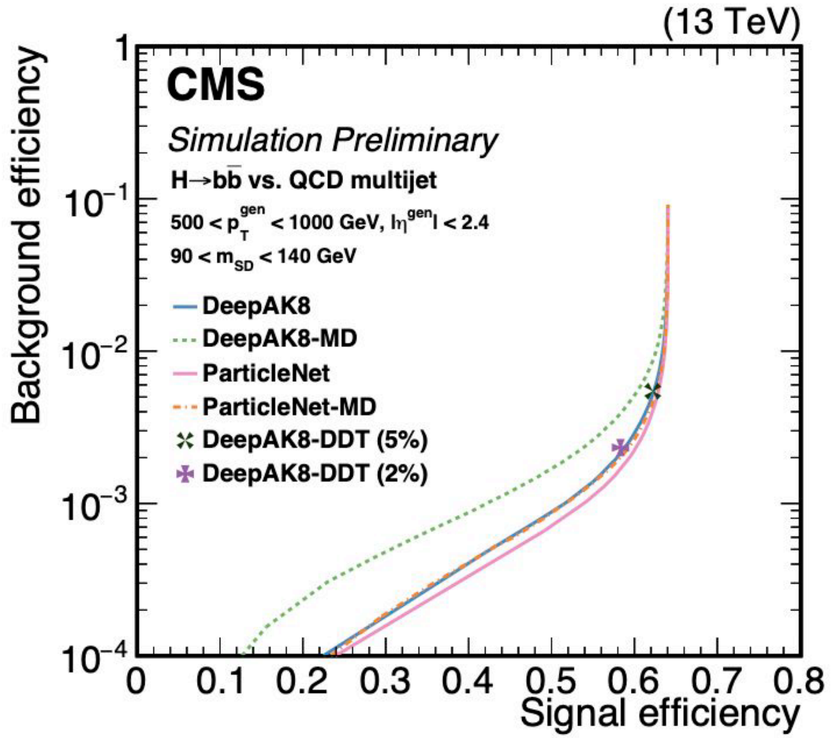


Phys. Rev. Lett. 131.041803



Anti-k_T algorithm with R=0.8 (AK8) jets

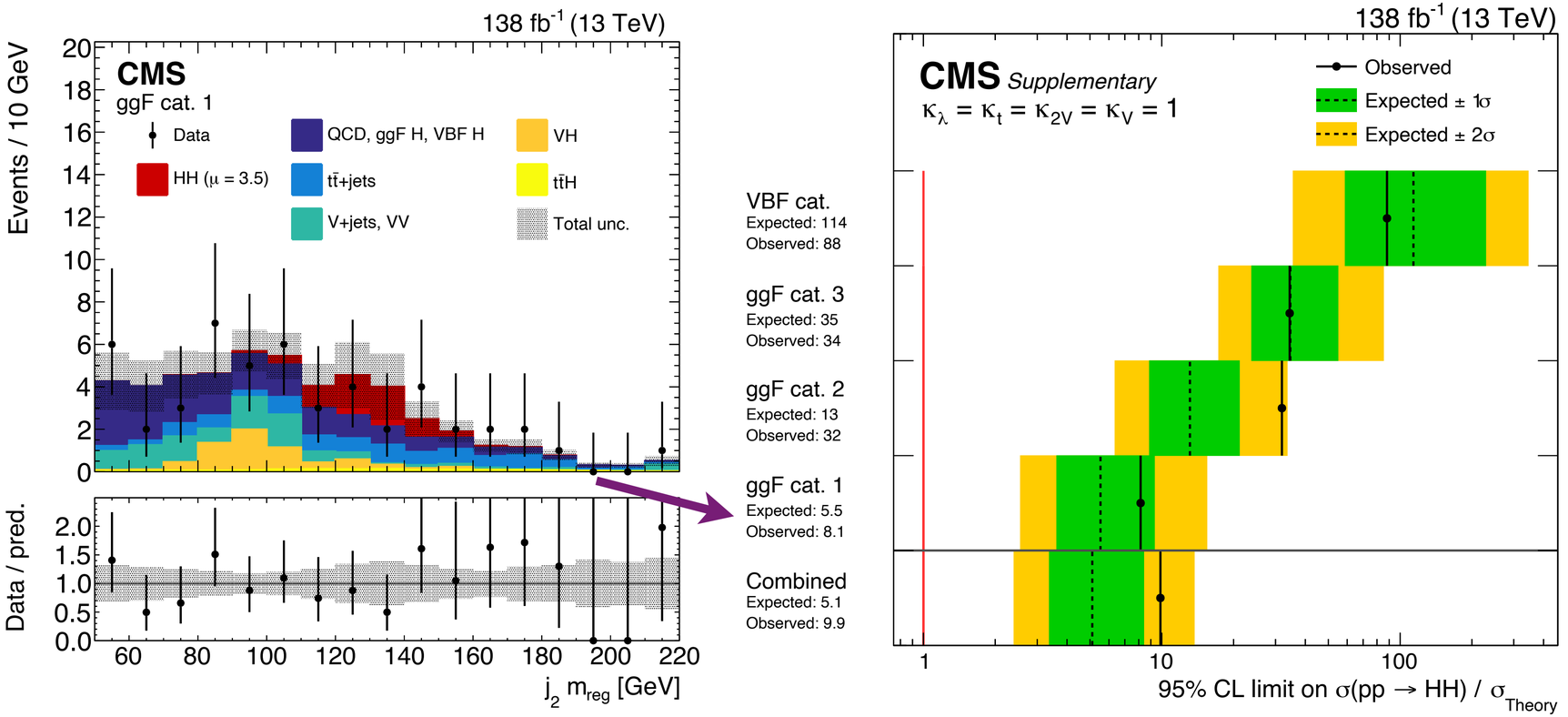




HH→4b boosted in CMS

Phys. Rev. Lett. 131.041803

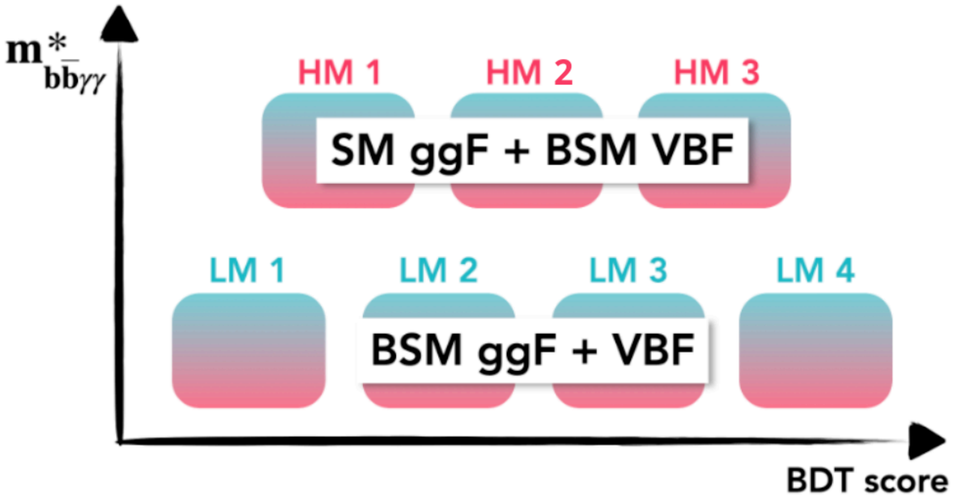
- Observed (expected) upper limit at 95% CL on HH cross section: 9.9 (5.1) × SM
- most stringent expected limit from single channel analysis in CMS

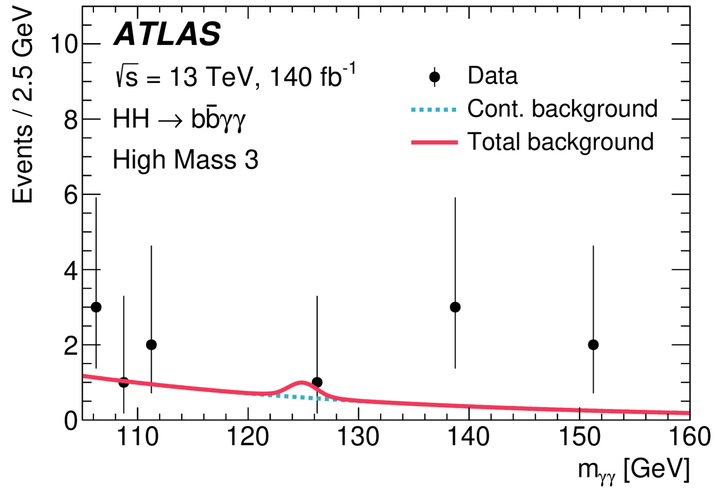


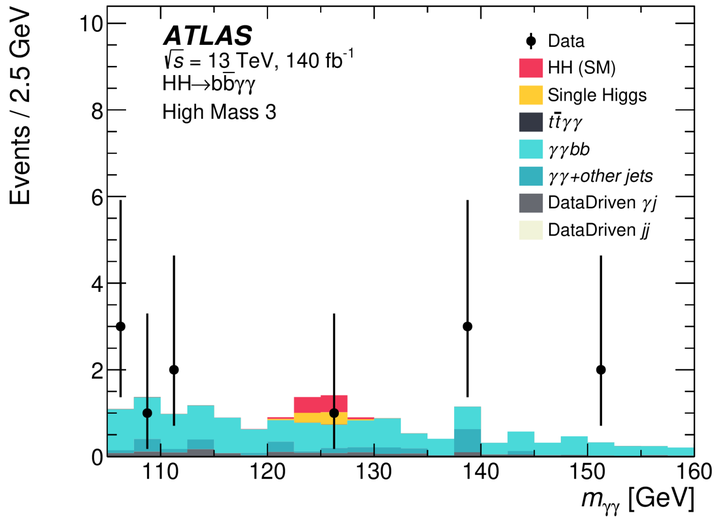
HH→bbγγ in ATLAS

arxiv: 2310.12301
Submitted to: JHEP

- two isolated photos, 2 b-jets, ttH veto
- 7 category defined using m*(bbγγ) and BDT score
- Talk by Zihang Jia







HH→bbγγ in ATLAS

arxiv: 2310.12301
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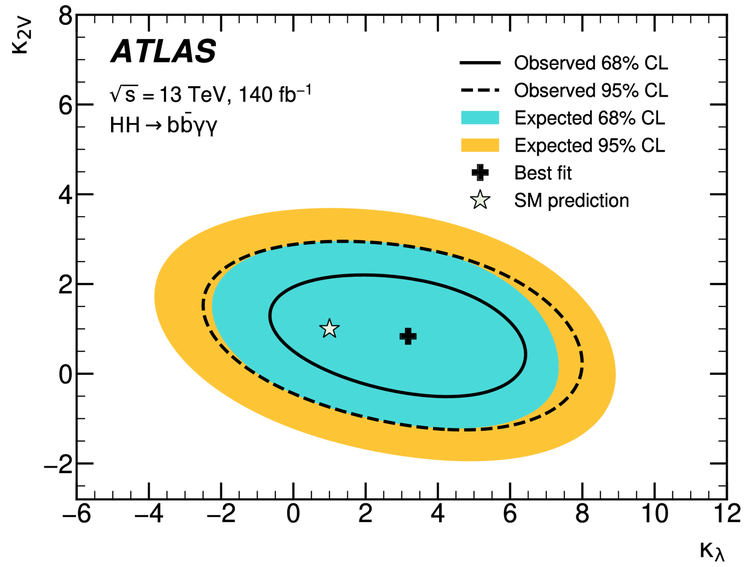
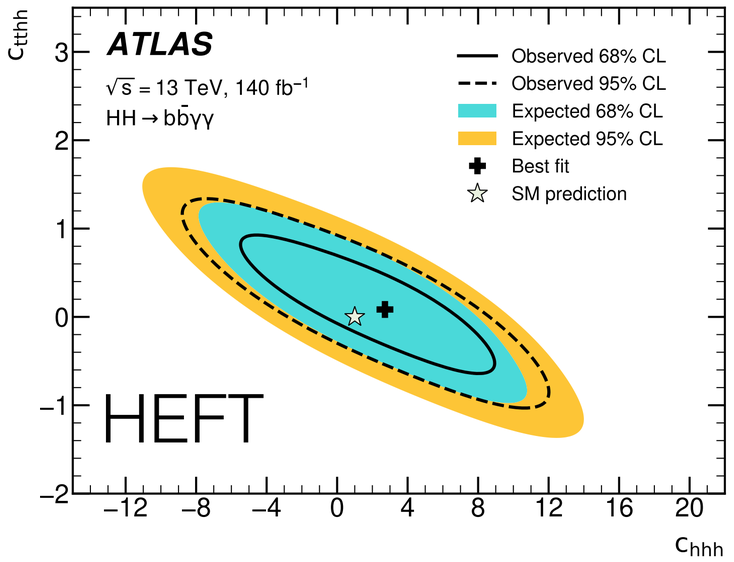
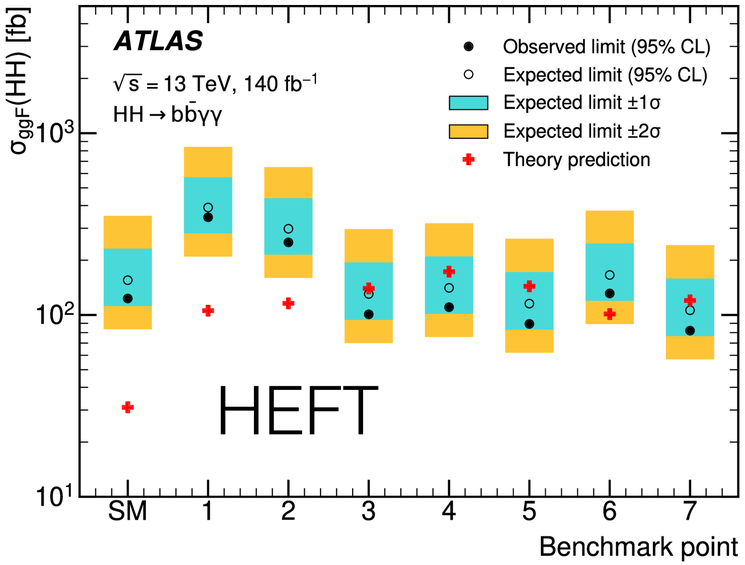
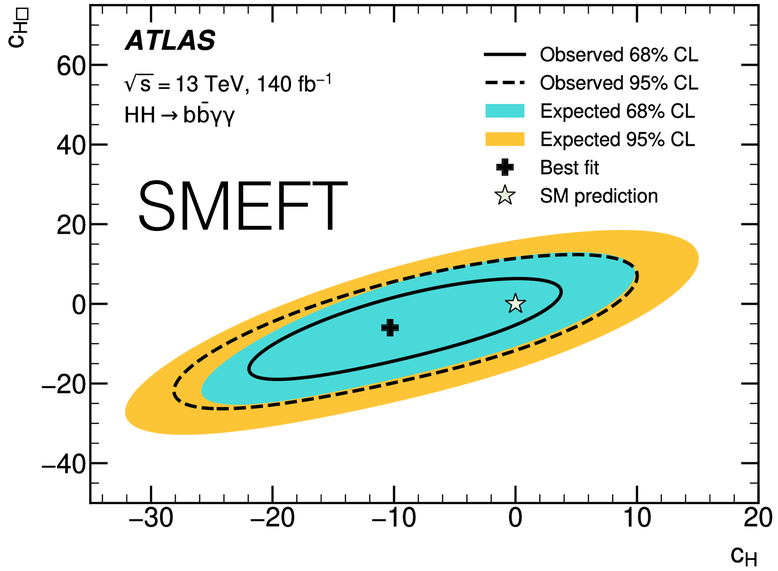




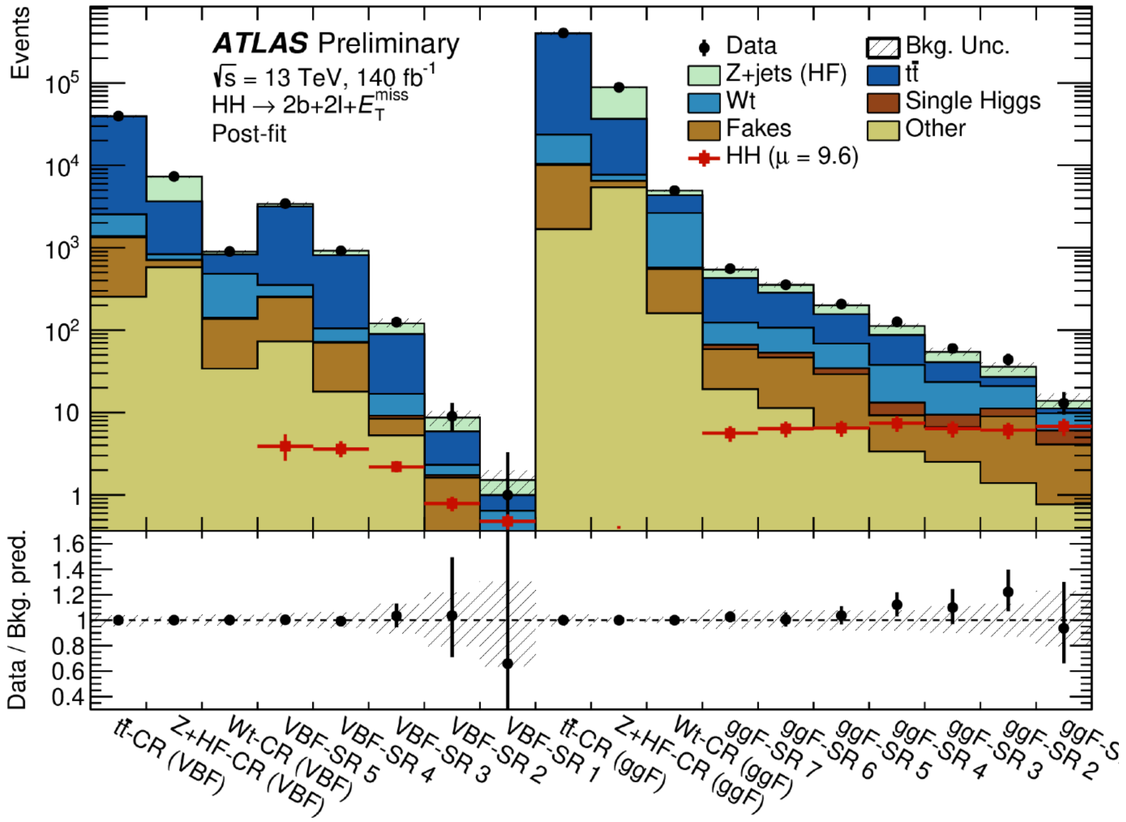


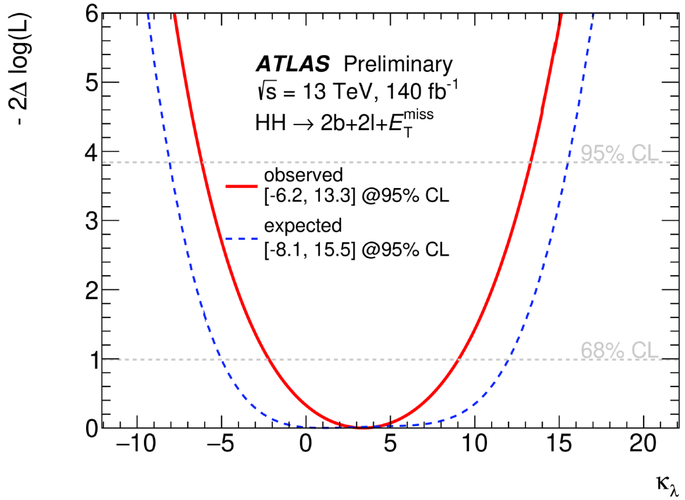


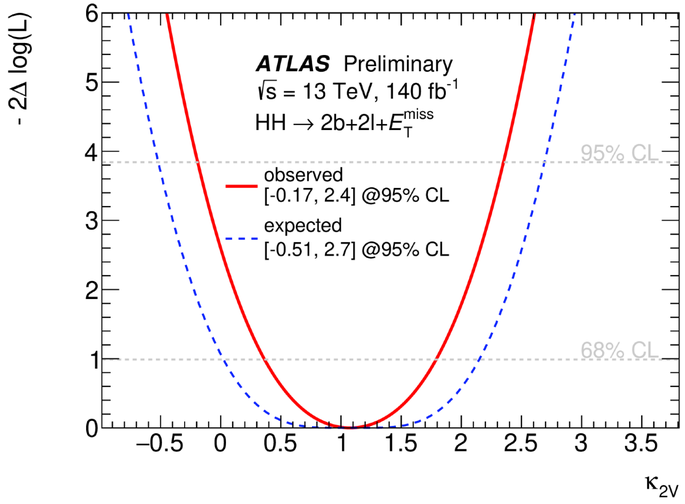
HH→bbll + MET in ATLAS

arXiv:2310.11286

- Observed (expected) upper limit at 95% CL on HH cross section: 9.6 (16.2) × SM
- significant improvement (previous 40(29))





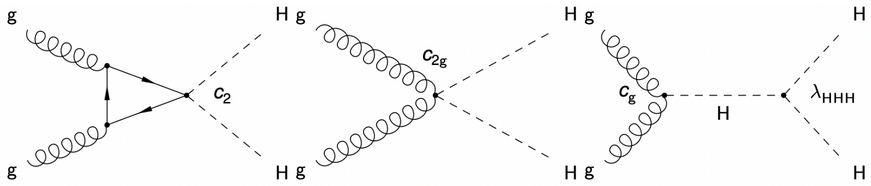


What's new in Run 2 analysis - EFT interpretation

Probe effects at lower energy scales from resonances with very large masses
- Constraint BSM EFT couplings
- Probe EFT benchmark points

- HEFT: Considering operators up to dimension 6, the tree-level interactions of the Higgs boson are modeled by five parameters κ_λ, κ_t, c_2, c_g, c_{2g}

BSM

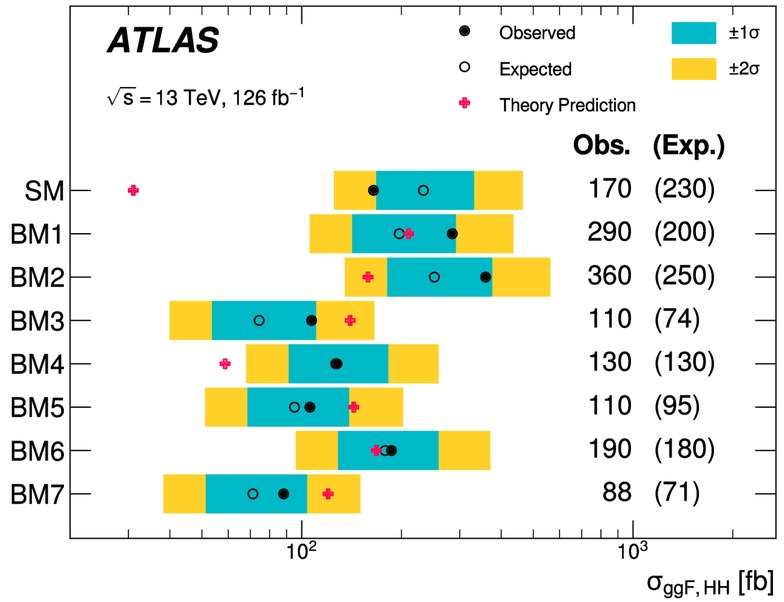


JHEP09(2018)057, JHEP03(2020)091

Benchmark	c_{hhh}	c_{tth}	c_{ggh}	c_{gghh}	c_{tthh}
SM	1	1	0	0	0
1	5.11	1.10	0	0	0
2	6.84	1.03	-1/3	0	1/6
3	2.21	1.05	1/2	1/2	-1/3
4	2.79	0.90	-1/3	-1/2	-1/6
5	3.95	1.17	1/6	-1/2	-1/3
6	-0.68	0.90	1/2	0.25	-1/6
7	-0.10	0.94	1/6	-1/6	1

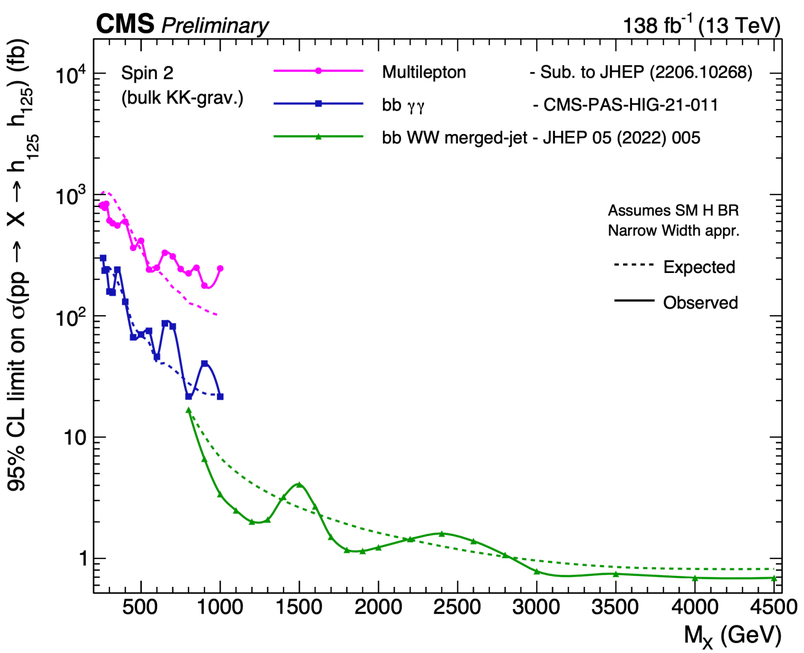
Phys. Rev. D 108 (2023) 052003

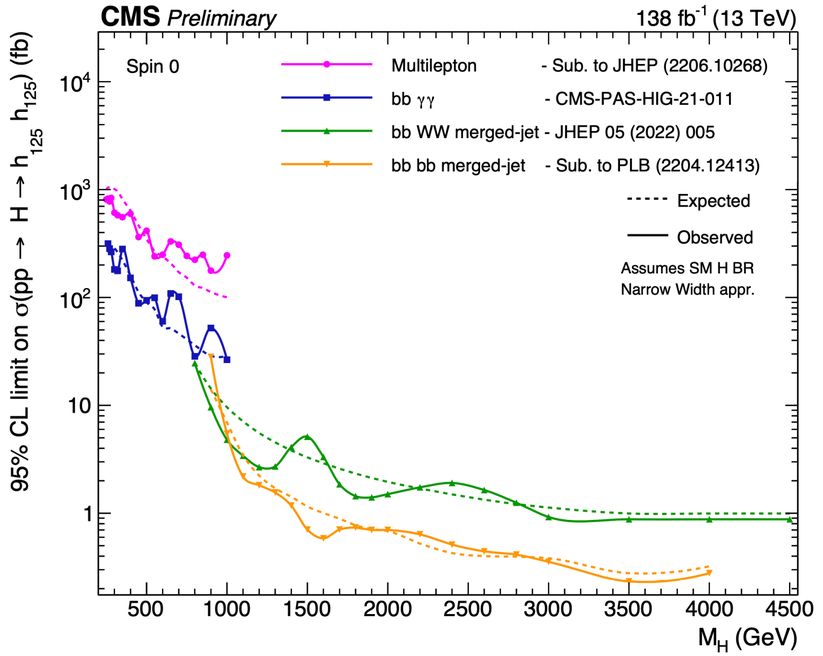
HH → bbbb



Resonant di-Higgs searches

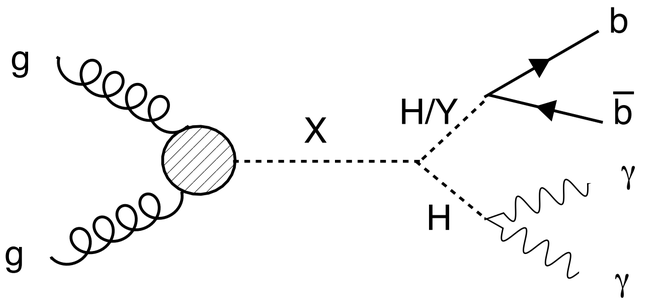
- Signal hypotheses with narrow width assumption and SM Higgs BR
  - Heavy spin 0 “Radion like” scalar
  - Heavy spin 2 “KK Graviton like” resonance

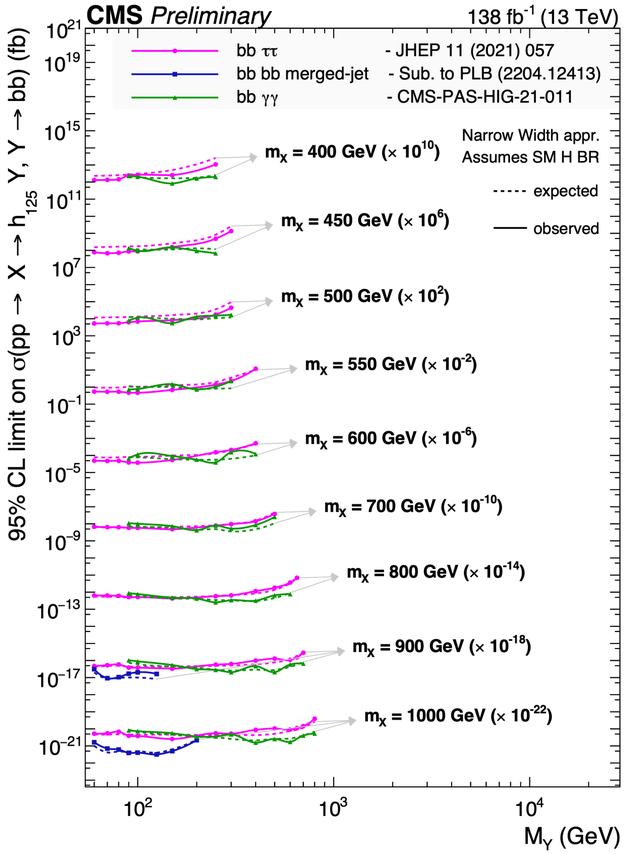


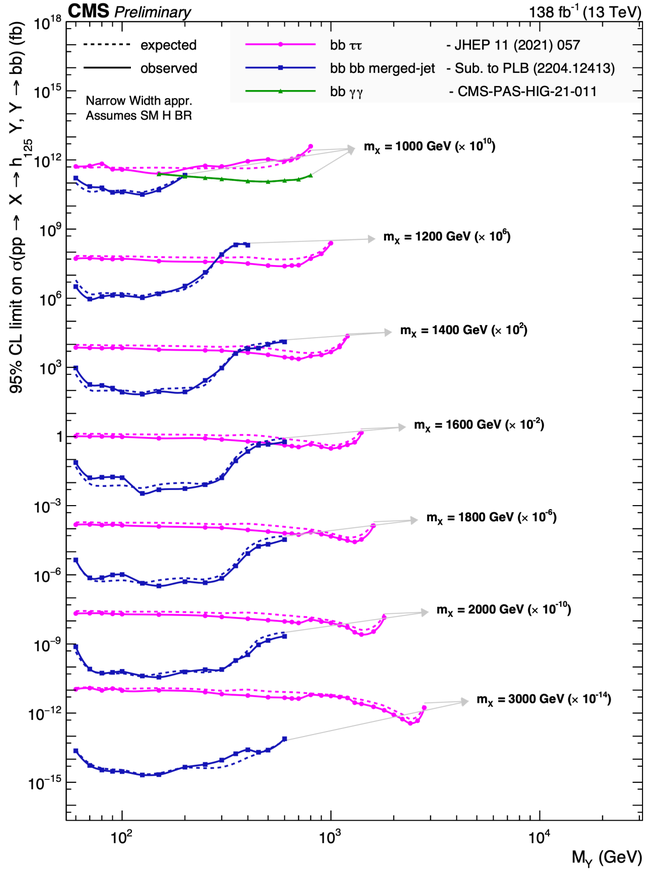


Resonant Yh_{125} searches

- Heavy Resonance X decaying into SM Higgs (h) and a light resonance/Higgs (Y)
- Y exclusively decaying into bb
- SM BR for h and narrow width approximation for X and Y





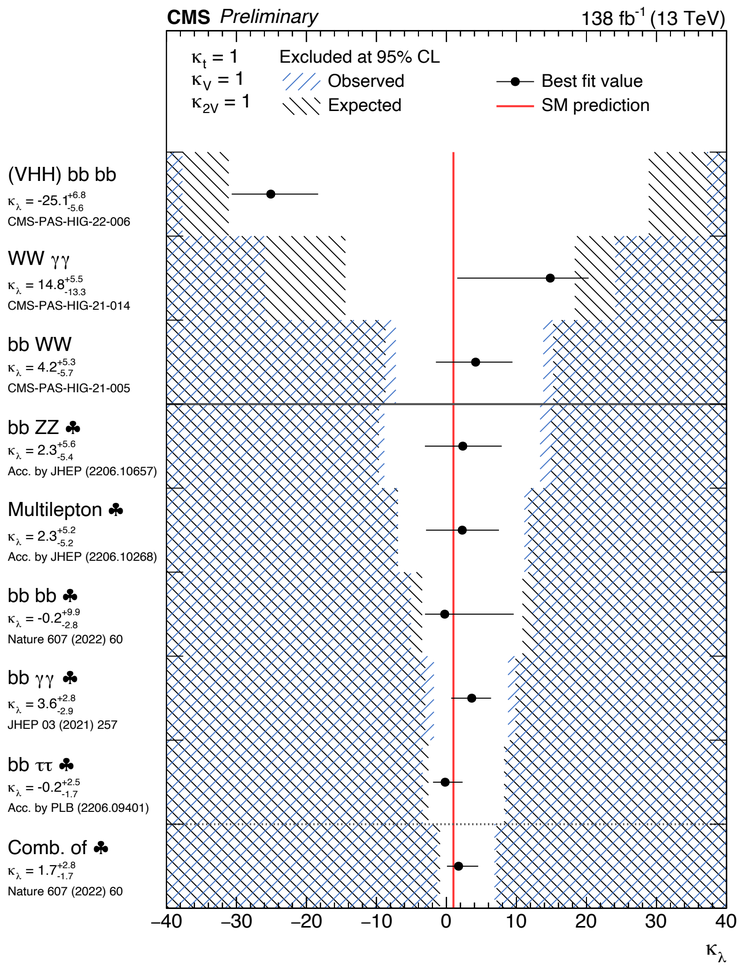


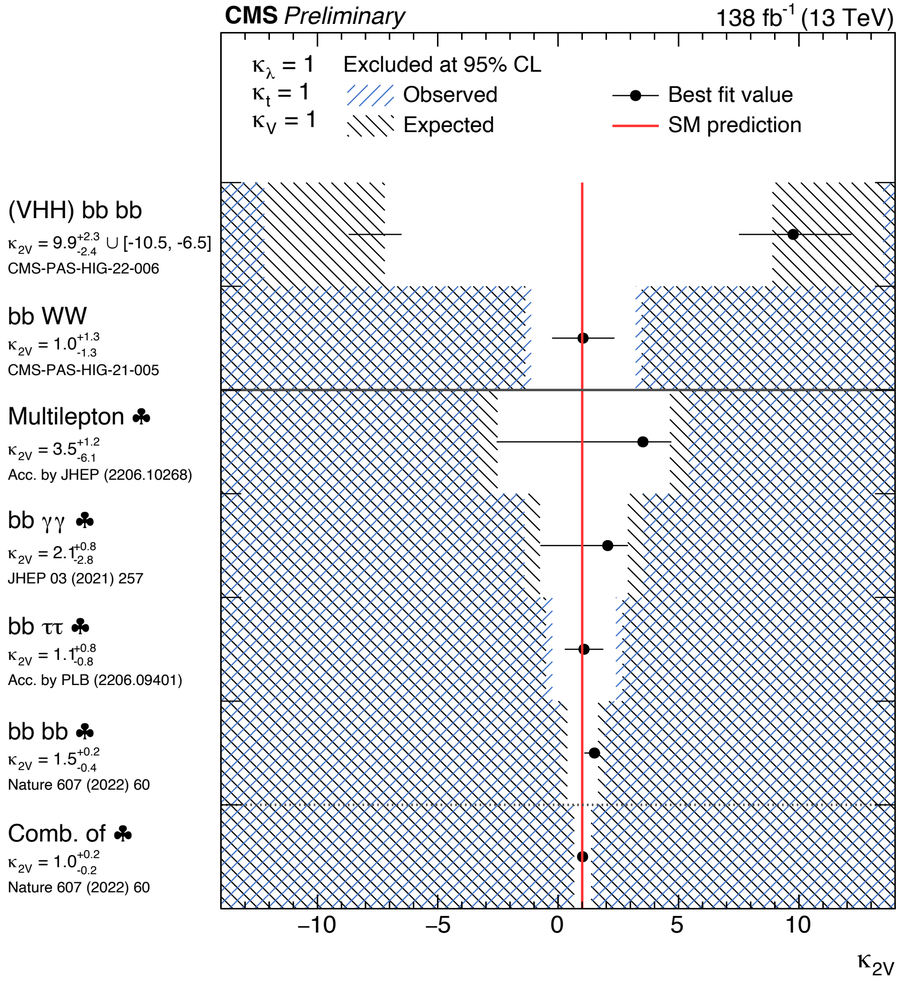
HH combination

CMSPublic/SummaryResultsHIG

- likelihood scan of couplings

- 4b boosted κ_{2V}=0 excluded at **6.3σ**;
  HH combination κ_{2V}=0 excluded at **6.6σ**
- assuming other H couplings to be SM values





What's new in Run 2 analysis - EFT interpretation

SMEFT: Standard Model effective field theory
• expansion of SM lagrangian with dim-6 operators, includes 5 Wilson Coefficients

arxiv: 2310.12301
Submitted to: JHEP

Wilson Coefficient	Operator
c_H	$(H^\dagger H)^3$
$c_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
c_{tH}	$(H^\dagger H)(\bar{Q}\tilde{H}t)$
c_{HG}	$H^\dagger H G^A_{\mu\nu} G^{\mu\nu}_A$
c_{tG}	$(\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{H}G^A_{\mu\nu}$