LHC-HH: Outlook and Plans

S.Manzoni
on behalf of:
E. Brost, R. Gröber, N. Lu, J. Mazzitelli, M. Mühlleitner

The 19th Workshop of LHC Higgs Working group

30th November 2022

LHC-HH team

Conveners:

- Liza Brost → Stefano Manzoni
- Nan Lu
- Ramona Gröber
- Javier Mazzitelli
- Margarete Mühlleitner

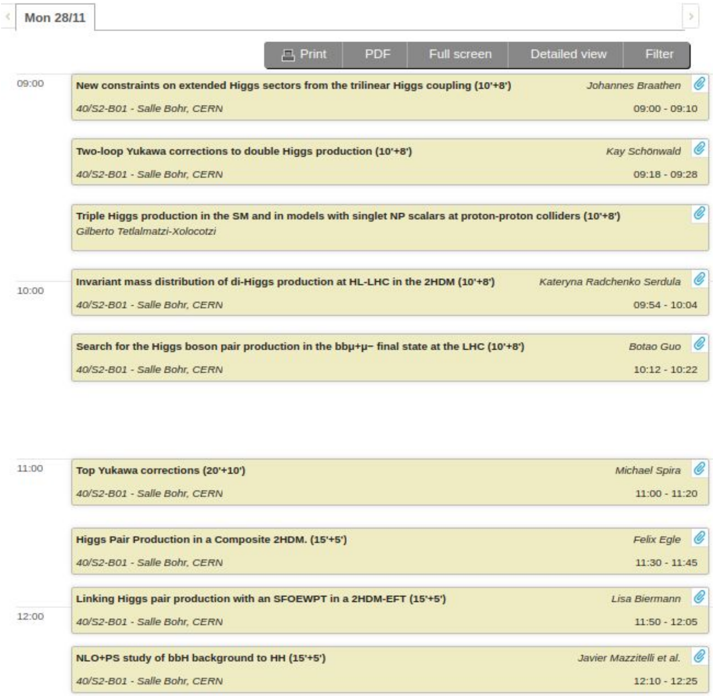
Thank you to Liza for her work in the last years!

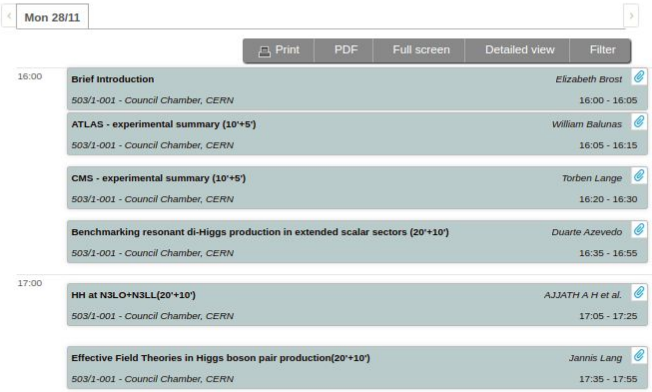
Introduction

LHC-HH cross-group very active and growing community:

- Higgs Pairs: May 30th - June 3rd, 2022 in Dubrovnik, Croatia
  - 137 participants, 56 talks - link to the agenda
- At this workshop we organized two parallel sessions:
  - 5 lighting talks - link to the agenda
  - 4 contributions - link to the agenda
- Plenary session:
  - 5 talks - link to the agenda

Thank you to all the speakers for the very nice presentations!





Ongoing work in the LHC-HH cross group

task	status
ggF: top-quark mass renormalization scheme uncertainty	Phys. Rev. D 103, 056002 (2021)
ggF: NLO EFT frameworks and new shape benchmarks, HEFT vs SMEFT	In progress
ggF: combination of H and HH (in connection with WG2 activities)	In progress
ggF: cross section / MC for gg → H + bb	In progress
ggF/VBF: cross section and MC prediction for various m_H values	In progress, need different coupling values
VBF: fiducial cross-sections vs. coupling modifiers	Need external inputs
VBF: cross-sections for ggF HH+2j at hard matrix-element	Ongoing. MC studies @ LHC-HH
Resonant: benchmarks for spin-0 HH, SH and SS to be probed with 100-300/fb, including interference with non-resonant HH	J. High Energ. Phys. 11 (2022)
Compositeness models: covered by EFT?	started

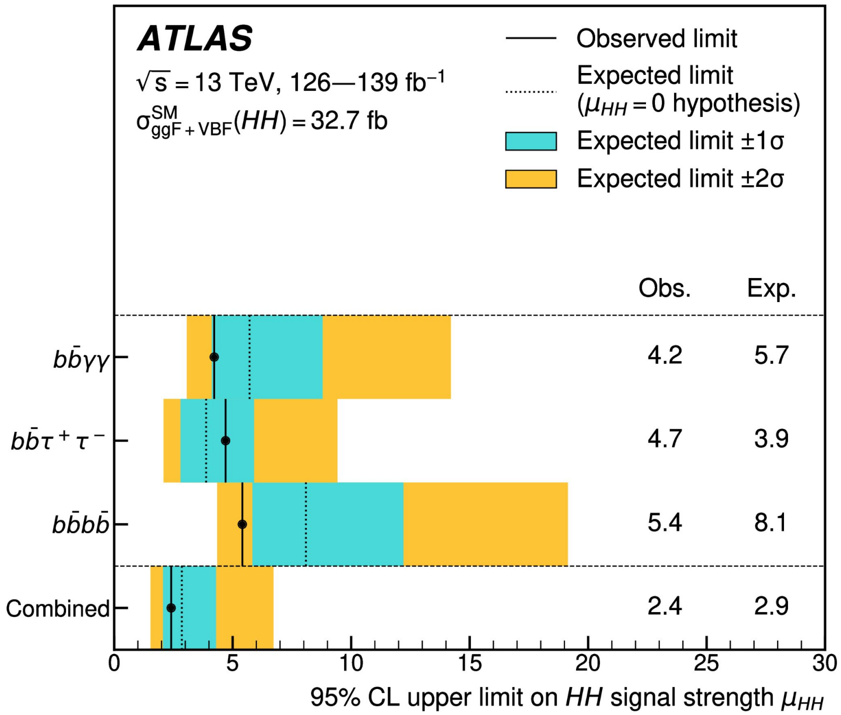
(green) = reports this week (yellow) = needs personpower

Run 2 experimental results

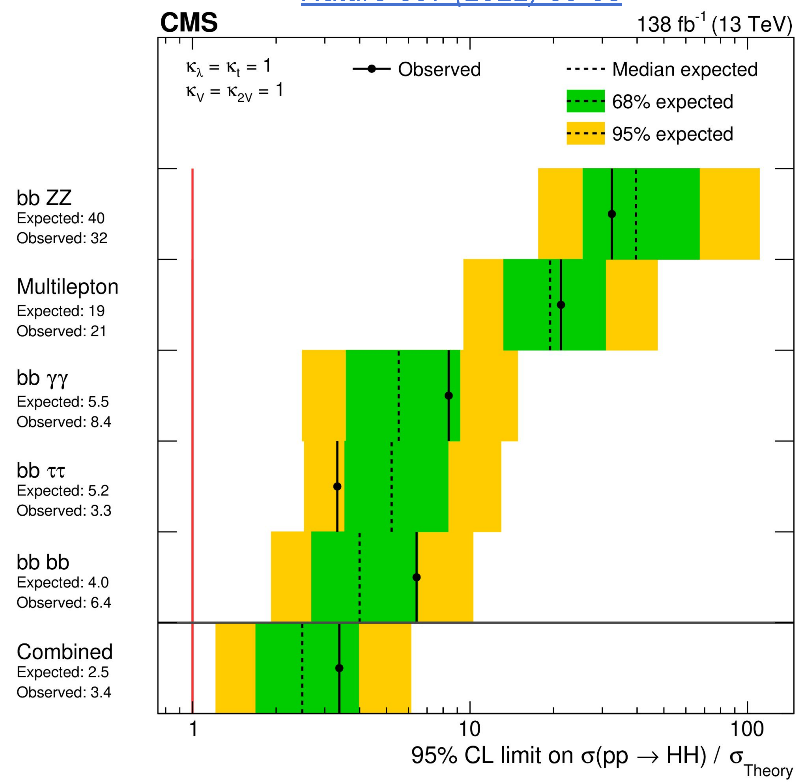
See slides of W. Balunas and T. Lange

- ATLAS and CMS have published a significant amount of new results in the last 1-2 years
- Also statistical combinations have been provided

arXiv:2211.01216



Nature 607 (2022) 60-68

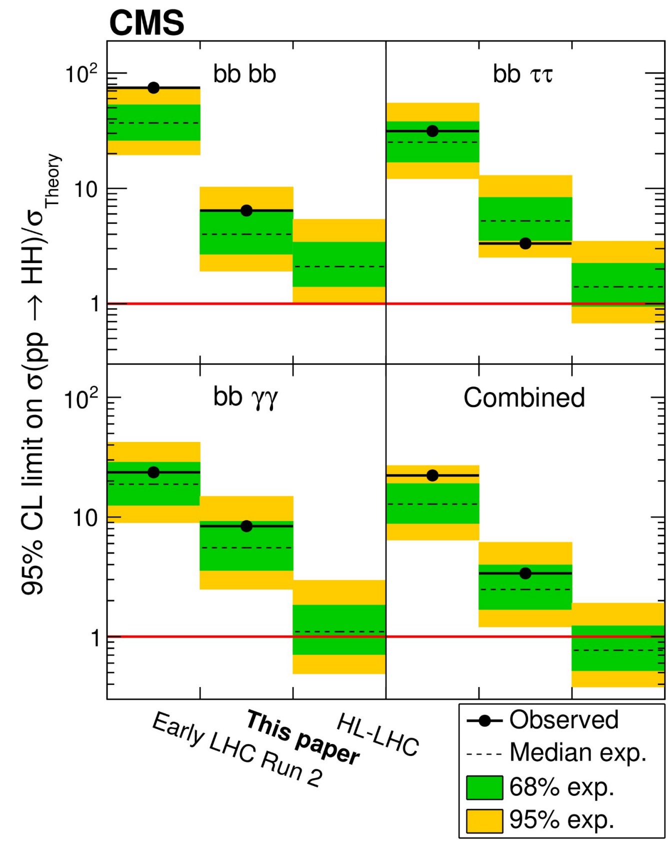


- ATLAS: obs 2.4 x σ^{SM}_{HH} (exp. 2.9 x σ^{SM}_{HH})
- CMS: obs 3.4 x σ^{SM}_{HH} (exp. 2.5 x σ^{SM}_{HH})

Run 2 experimental results

		$\sigma_{HH}/\sigma_{HH}^{SM}$ 95% CL		
		Obs.	Exp.	Improvement wrt. 36 fb^{-1} tot. (w/o lumi)
$HH \rightarrow bb\gamma\gamma$	ATLAS	4.2	5.7	×4.6 (2.3)
	CMS	8.4	5.5	×3.4 (1.9)
$HH \rightarrow bb\tau\tau$	ATLAS	4.7	3.9	×3.8 (2)
	CMS	3.3	5.2	×4.8 (2.5)
$HH \rightarrow bbbb$	ATLAS	5.4	8.1	×2.6 (1.3)
	CMS	3.9	7.8	×4.7 (2.4)
boosted	CMS	9.9	5.1	
resolved+boosted	CMS	6.4	4.0	
$HH \rightarrow bbZZ$	ATLAS	–	–	–
	CMS	32	40	–
Multilepton	ATLAS	–	–	–
	CMS	21	19	–
Combination	ATLAS	2.4	2.9	×3.4 (1.7)
	CMS	3.4	2.5	×5.1 (2.6)

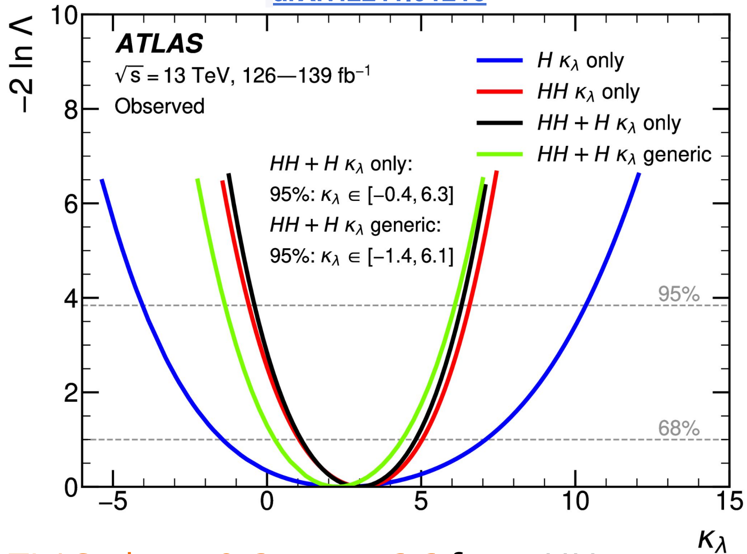
Nature 607 (2022) 60-68



- The new analyses exceeded the luminosity expectations!
- Thanks to object-performance improvements (b-tag, τ-id, ParticleNet…), and investigation of new topologies

Run 2 experimental results

arXiv:2211.01216



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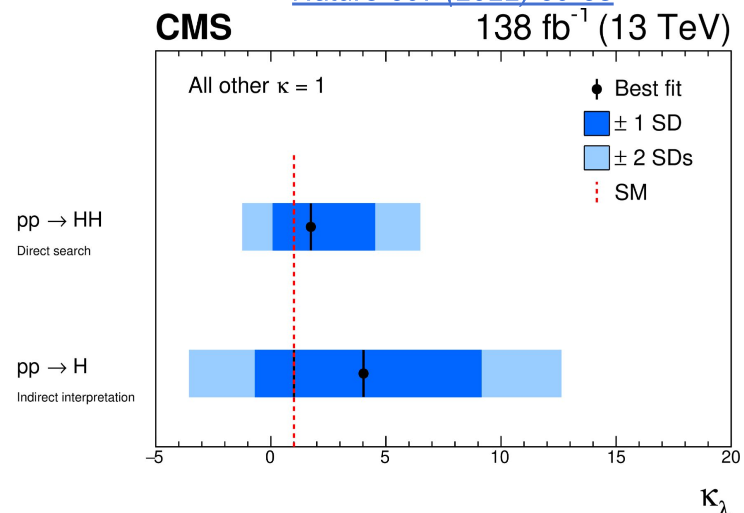


CMS: $-1.24 < \kappa\lambda < 6.49$ from HH

ATLAS obs.: $-0.6 < \kappa\lambda < 6.6$ from HH
ATLAS obs.: $-0.4 < \kappa\lambda < 6.3$ from HH+H

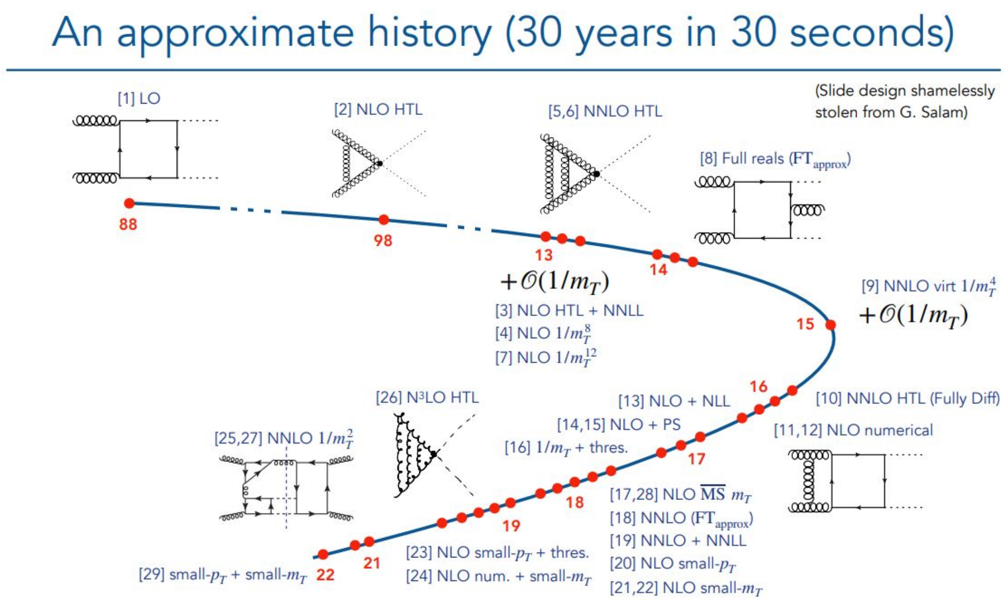
	HH-only ATLAS $\kappa\lambda$ 95%CL interval	
	expected	observed
36 fb^{-1}	[-5.0, 12]	[-5.8, 12]
Full Run 2	**[-2.1, 7.8]**	**[-0.6, 6.6]**
2018 HL-LHC projection (starting from 36 ifb)	[−0.4, 7.3] (stat only [−0.1,2.7] ∪ [5.5,6.9])	
2022 HL-LHC projection	[0.0, 2.5] (stat only [0.3, 1.9])	

Experimental results improve significantly along Run 2

Looking forward for Run 3 data analysis…

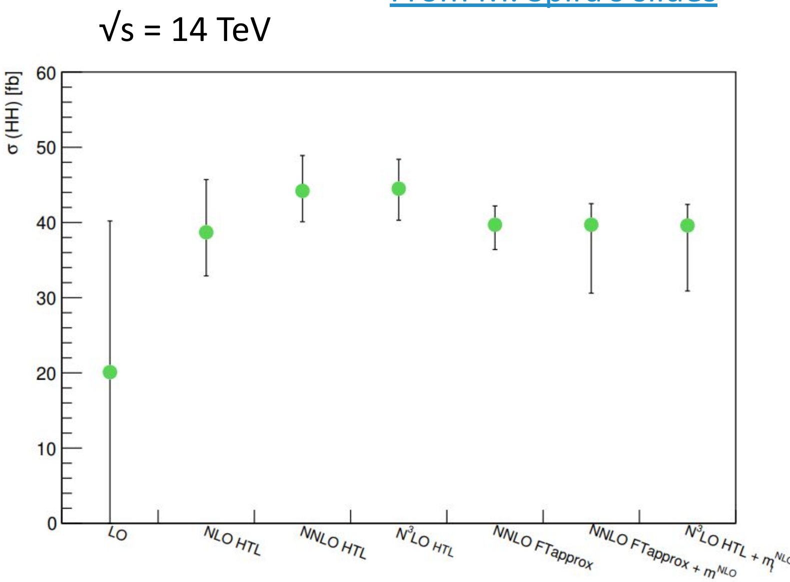
A Look to theory status of HH

From S. Jones's slides



[1] Glover, van der Bij 88; [2] Dawson, Dittmaier, Spira 98; [3] Shao, Li, Li, Wang 13; [4] Grigo, Hoff, Melnikov, Steinhauser 13; [5] de Florian, Mazzitelli 13; [6] Grigo, Melnikov, Steinhauser 14; [7] Grigo, Hoff 14; [8] Maltoni, Vryonidou, Zaro 14; [9] Grigo, Hoff, Steinhauser 15; [10] de Florian, Grazzini, Hanga, Kallweit, Lindert, Maierhöfer, Mazzitelli, Rathlev 16; [11] Borowka, Greiner, Heinrich, SPJ, Kerner, Schlenk, Schubert, Zirke 16; [12] Borowka, Greiner, Heinrich, SPJ, Kerner, Schlenk, Zirke 16; [13] Ferrera, Pires 16; [14] Heinrich, SPJ, Kerner, Luisoni, Vryonidou 17; [15] SPJ, Kuttimalai 17; [16] Gröber, Maier, Rauh 17; [17] Baglio, Campanario, Glaus, Mühlleitner, Spira, Streicher 18; [18] Grazzini, Heinrich, SPJ, Kallweit, Kerner, Lindert, Mazzitelli 18; [19] de Florian, Mazzitelli 18; [20] Bonciani, Degrassi, Giardino, Gröber 18; [21] Davies, Mishima, Steinhauser, Wellmann 18, 18; [22] Mishima 18; [23] Gröber, Maier, Rauh 19; [24] Davies, Heinrich, SPJ, Kerner, Mishima, Steinhauser, David Wellmann 19; [25] Davies, Steinhauser 19; [26] Chen, Li, Shao, Wang 19, 19; [27] Davies, Herren, Mishima, Steinhauser 19, 21; [28] Baglio, Campanario, Glaus, Mühlleitner, Ronca, Spira 21; [29] Bellafronte, Degrassi, Giardino, Gröber, Vitti 22;

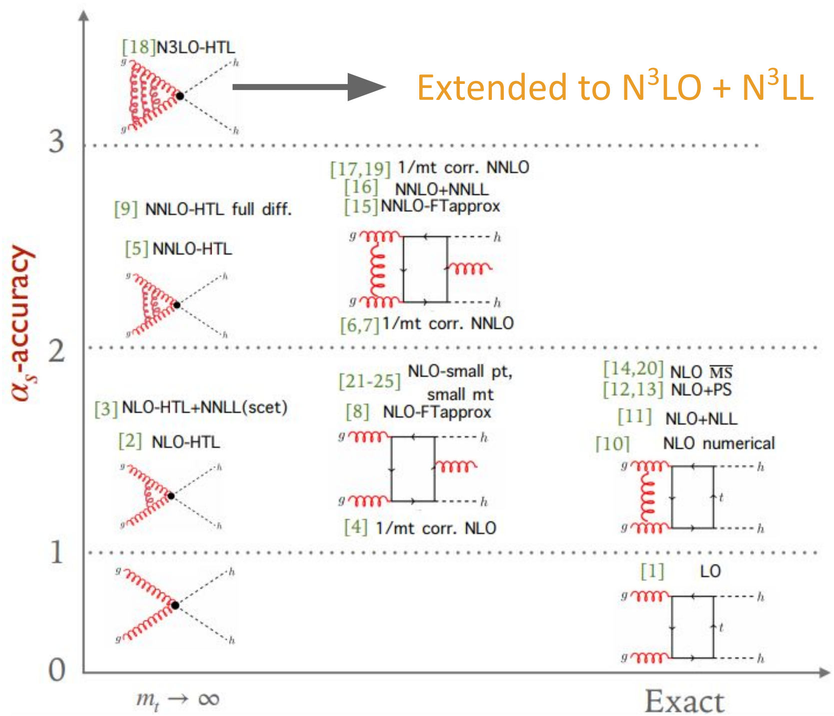
From M. Spira's slides



- Huge effort on the last years of the theory community to improve the precision of the calculation
- NNLOFTapprox affected by uncertainties due to factorization/renormalization scale and m_t scale/scheme choice **~ 25%**

A Look to theory status of HH: $N^3LO + N^3LL$

[See slides of A.H. Ajjath](#)



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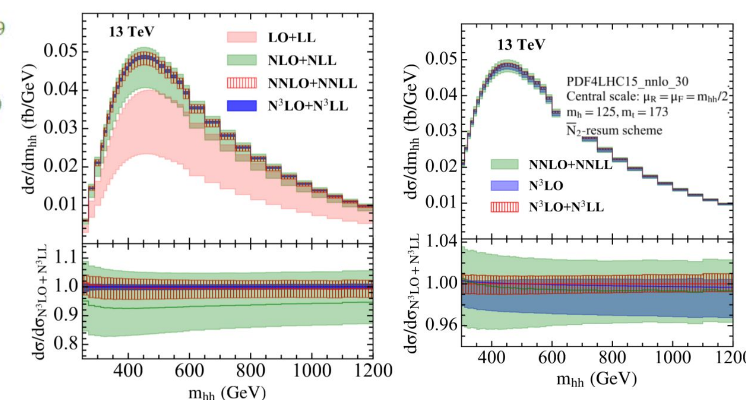
[6,7] Grigo, et.al '14, '15
[8] Maltoni,Vryonidou,Zaro '14
[9] Florian, et.al '16
[10] Borowka, et.al '16, '16
[11] Ferreira, Pires '16
[12] Heinrich et.al '17
[13] Jones, Kuttimalai '17
[14] Baglio,et.al '18
[15] Grazzini,et.al '18
[16] Florian, Mazzitelli '18
[17] Davies, Steinhauser '19
[18] Chen, Li, Shao, Wang '19, '19
[19] Davies, et.al '19
[20] Baglio,et.al '21
[21] Davies et al '18, '18, '19
[22] Mishima '18
[23] Bonciani, et.al '18
[24] Grover, Maier, Rauh '19
[25] Bellafronte, et.al '22

[arXiv:2209.03914](#)

Infinite top mass approximation

$\sqrt{s}$ [TeV]	Order k	N^kLO	N^kLO+N^kLL	
			N_2 scheme	$\overline{N}_2$ scheme
13	0	$13.80^{+31\%}_{-22\%}$	$16.01^{+32\%}_{-23\%}$	$21.02^{+36\%}_{-24\%}$
	1	$25.81^{+18\%}_{-15\%}$	$30.04^{+10.8\%}_{-10.3\%}$	$29.36^{+12.6\%}_{-8.8\%}$
	2	$30.41^{+5.3\%}_{-7.8\%}$	$31.51^{+2.5\%}_{-3.0\%}$	$31.21^{+3.0\%}_{-3.3\%}$
	3	$31.31^{+0.50\%}_{-2.8\%}$	$31.37^{+0.84\%}_{-0.49\%}$	$31.35^{+0.88\%}_{-0.85\%}$



- Scale reduction to percent-level:
  - Factor 2 reduction from N^3LO to $N^3LO + N^3LL$
  - Factor 4 reduction from NNLO to N^3LO
- Good perturbative convergence
- Results combined also with the finite top-quark mass effect -> scale unc. at sub-percent level

- $\mathbf{N^kLO \otimes N^lLO}_{m_t}$: $d\sigma^{\mathbf{N^kLO\otimes N^lLO_{m_t}}} = d\sigma^{\mathrm{N^lLO}}_{m_t} \frac{d\sigma^{\mathrm{N^kLO}}_{m_t\to\infty}}{d\sigma^{\mathrm{N^lLO}}_{m_t\to\infty}} = d\sigma^{\mathrm{N^lLO}}_{m_t} + \left(d\sigma^{\mathrm{N^kLO}}_{m_t=\infty} - d\sigma^{\mathrm{N^lLO}}_{m_t=\infty}\right) \frac{d\sigma^{\mathrm{N^lLO}}_{m_t}}{d\sigma^{\mathrm{N^lLO}}_{m_t\to\infty}}$.

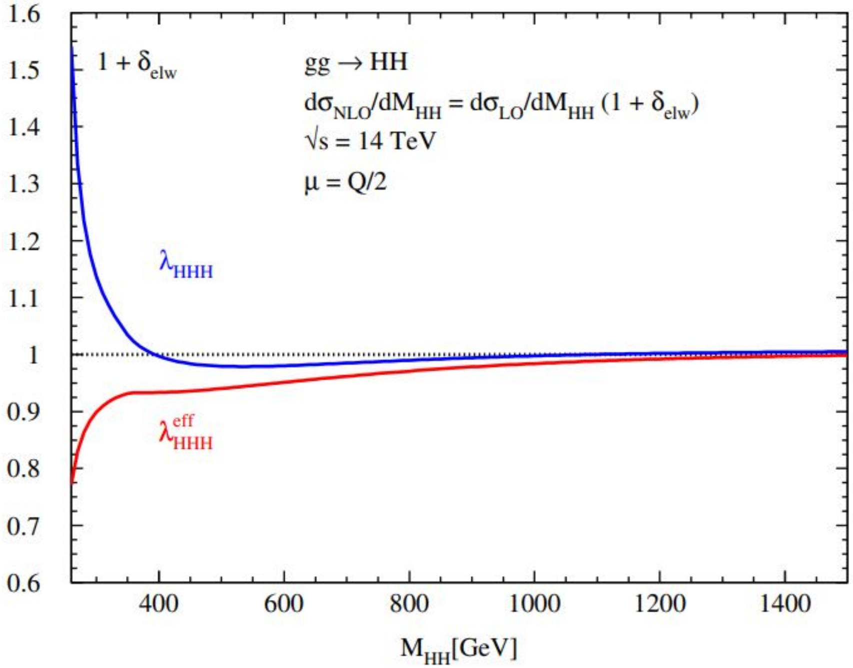
- **top Mass scheme uncertainties are unchanged**

Looking to EW corrections

See slides from M.Spira and K. Schönwald

- Not only QCD but also EW correction could be important for HH.
- Two talks on NLO EW top yukawa correction:
  - K. Schönwald analytical computation in the High energy limit (JHEP08(2022)259)
  - M.Spira Heavy top limit correction to ggHH (arxiv: 2207.02524)

From M. Spira's slides



$$\sigma = 1.002 \times \sigma_{LO} \qquad (\lambda_{HHH})$$
$$\sigma = 0.938 \times \sigma_{LO} \qquad (\lambda^{eff}_{HHH})$$

Mühlleitner, Schlenk, S.

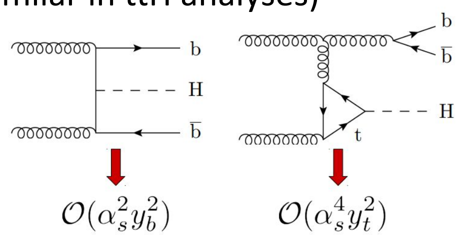
- Effect on the inclusive cross-section ~ 0.2%
- Not negligible effect on mHH distribution, especially at the threshold
- "uncertainties due to unknown full EW. corrections ~ 10 − 20%"

we need to schedule a dedicated LHC-HH meeting to discuss how to integrate these as proper recommendation/uncertainty

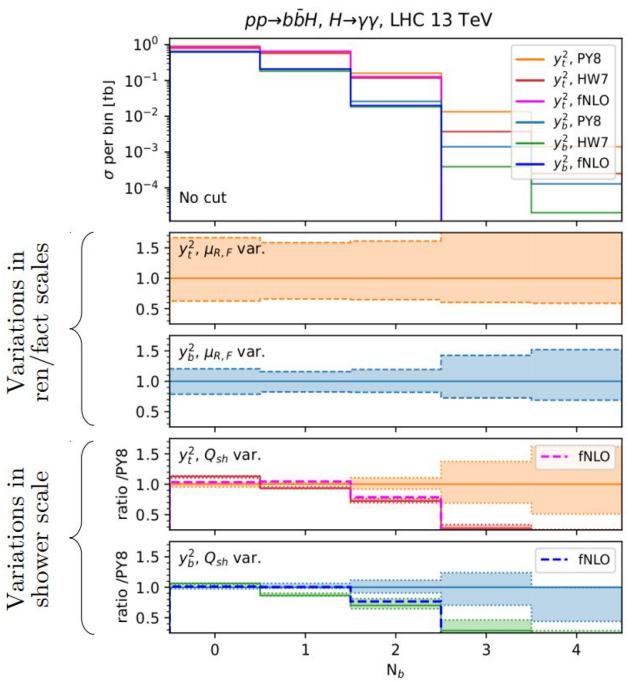
Background studies: NLO production of bbH

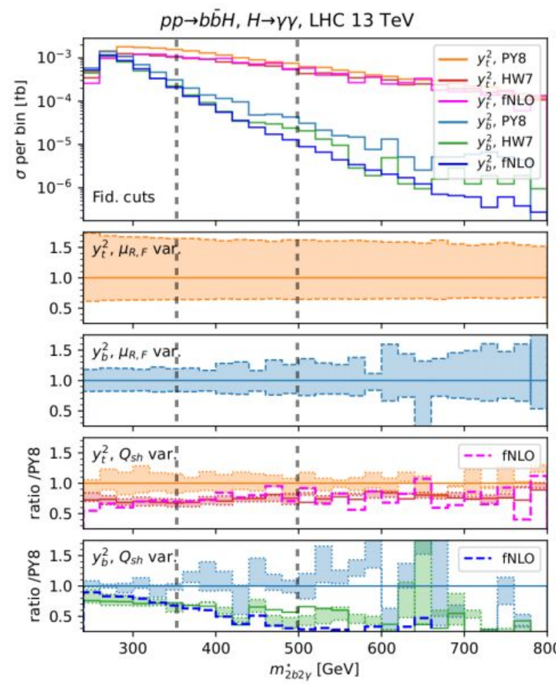
See slides from J.Mazzitelli

- Single Higgs production in association with a bottom pair is an irreducible background to all H(→bb)H searches
  - Currently in the ATLAS experiment this contribution is simulated with NNLOPS ggH + bbH simulation with Powheg
  - +100% uncertainty on top of ggH yield to cover for possible mis-modelling (similar in ttH analyses)
  - Not negligible contribution when compared to signal
- Starting from arxiv:1808.01660 -> bbH produced at NLO and matched to PS
  - Investigate bbyy final state in a phase-space region similar to Atlas analysis
  - Considering m2b2γ<350GeV, m2b2γ<500GeV and no-m2b2γ cut



Cut	Contr.	Run	σ [fb]	$\delta\mu_{r,f}$	Signal [fb] gg→HH→b$\bar{\text{b}}\gamma\gamma$
No cut	y_b^2	PY8	8.49 10^{-1}	+18% −20%	8.21 10^{-2}
		HW7	8.50 10^{-1}		
	y_t^2	PY8	1.57 10^{0}	+61% −35%	
		HW7	1.57 10^{0}		
Fid. cuts	y_b^2	PY8	5.42 10^{-3}	+20% −18%	2.40 10^{-2}
		HW7	3.84 10^{-3}		
	y_t^2	PY8	2.29 10^{-2}	+62% −35%	
		HW7	1.67 10^{-2}		
Fid. cuts + $m^\star_{2b2\gamma}$ < 500 GeV	y_b^2	PY8	5.26 10^{-3}	+20% −17%	1.67 10^{-2}
		HW7	3.77 10^{-3}		
	y_t^2	PY8	1.62 10^{-2}	+65% −36%	
		HW7	1.15 10^{-2}		
Fid. cuts + $m^\star_{2b2\gamma}$ < 350 GeV	y_b^2	PY8	4.44 10^{-3}	+19% −17%	0.30 10^{-2}
		HW7	3.26 10^{-3}		
	y_t^2	PY8	8.06 10^{-3}	+67% −36%	
		HW7	5.64 10^{-3}		





- Di-Higgs signal and bbH background are of similar size
- Difference in shape between HW7 and PY8 for Nb-jet due to g->bb splitting in PY8
- Top and bottom Yukawa contributions prefer different values of m2b2γ → Possible prescription when study will be finalized

Plan Interpretation: EFT

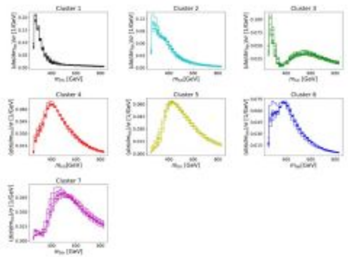
See slides of J.Lang

A note from HH-group is ready for circulation within LHC-WG concerning HH EFT:

- Tool to be used for HEFT and SMEFT interpretation
- Discussion of the translation between HEFT and SMEFT ⇒ Not trivial, better to study both EFT representations separately
- Updated HEFT benchmarks (arXiv:1908.08923)
- Discussion of theory uncertainties propagation
- Reweighting approach and inputs for experiments

Updated HEFT benchmarks Published in WG note

benchmark	c_{hhh}	c_t	c_{tt}	c_{ggh}	c_{gghh}
SM	1	1	0	0	0
1*	5.105	1.1	0	0	0
2*	6.842	1.033	$\frac{1}{6}$	$-\frac{1}{3}$	0
3	2.21	1.05	$-\frac{1}{3}$	0.5	0.5
4*	2.79	0.9	$-\frac{1}{6}$	$-\frac{1}{3}$	$-\frac{1}{2}$
5	3.95	1.17	$-\frac{1}{3}$	$\frac{1}{6}$	$-\frac{1}{2}$
6*	-0.684	0.9	$-\frac{1}{6}$	0.5	0.25
7	-0.10	0.94	1	$\frac{1}{6}$	$-\frac{1}{6}$



- Shape clusters defined using unsupervised ML
- Benchmarks chosen with clear shape features and satisfying experimental constraints
- * denotes updated benchmark point, new constraints: $0.83 \le c_t \le 1.17$ (and $|c_{tt}| \le 0.05$ for 1*)

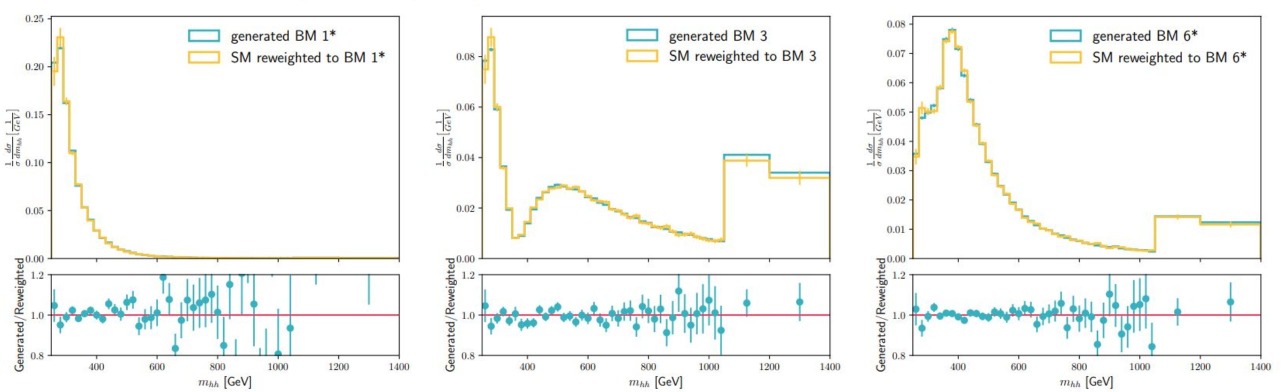
[Capozi, Heinrich '19]

$$\sigma_{hh}^{NLO} = A_1 c_t^4 + A_2 c_{tt}^2 + (A_3 c_t^2 + A_4 c_{ggh}^2) c_{hhh}^2 + A_5 c_{gghh}^2 + (A_6 c_{tt} + A_7 c_t c_{hhh}) c_t^2 + (A_8 c_t c_{hhh} + A_9 c_{ggh} c_{hhh}) c_{tt} + A_{10} c_{tt} c_{gghh} + (A_{11} c_{ggh} c_{hhh} + A_{12} c_{gghh}) c_t^2 + (A_{13} c_{hhh} c_{ggh} + A_{14} c_{gghh}) c_t c_{hhh} + A_{15} c_{ggh} c_{gghh} c_{hhh} + A_{16} c_t^3 c_{ggh} + A_{17} c_t c_{tt} c_{ggh} + A_{18} c_t c_{ggh} c_{hhh} + A_{19} c_t c_{ggh} c_{gghh} + A_{20} c_t^2 c_{ggh}^2 + A_{21} c_{tt} c_{ggh}^2 + A_{22} c_{ggh}^3 c_{hhh} + A_{23} c_{ggh}^2 c_{gghh}$$

$$\sigma_{hh}^{NLO} = Poly(\mathbf{c}, \mathbf{A}) = \mathbf{c}^T \cdot \mathbf{A}$$

$$\frac{d\sigma_{hh}}{dm_{hh}} = Poly(\mathbf{c}, d\mathbf{A}|m_{hh}) = \mathbf{c}^T \cdot d\mathbf{A}$$

$$w_{HEFT} = \frac{Poly(\mathbf{c}, d\mathbf{A}|m_{hh})}{Poly(\mathbf{c}_{SM}, d\mathbf{A}|m_{hh})}$$



Further information in the upcoming note!

See slides from D.Azevedo and K.Radchenko

Model/Interpretation benchmark for BSM model

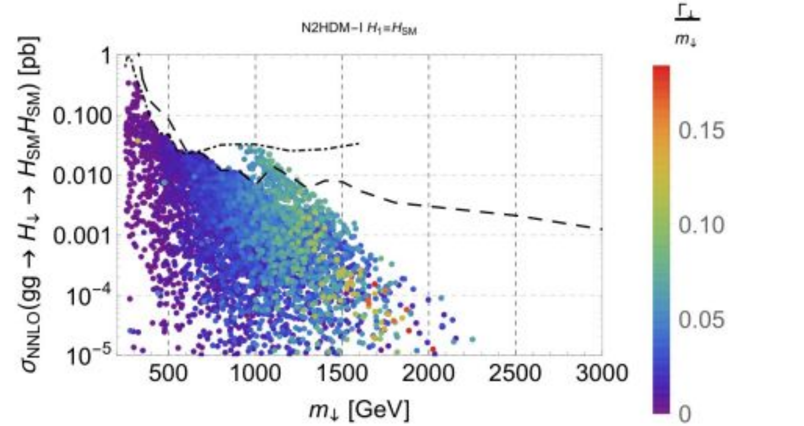
Working towards a more coherent description of possible BSM benchmark/model to be used by the experiment

Defined tasks from HH subgroup meeting

- **Interest to extend resonant searches to include large width/interference effects [motivated from several BSM models]**
- **Interferences in a model independent** way → dependence with trilinear, yukawas, masses, widths…**

Tasks:

1) Get the allowed maximum res. prod. XS (pp → H → h_SM h_SM) for mass values of the resonance, and ranges of pertinent parameters around these maxima
2) What is the differential distributions dependence on these parameters [(R2HDM Katerina's talk)]
3) Implement models for MC generators to simulate these signals

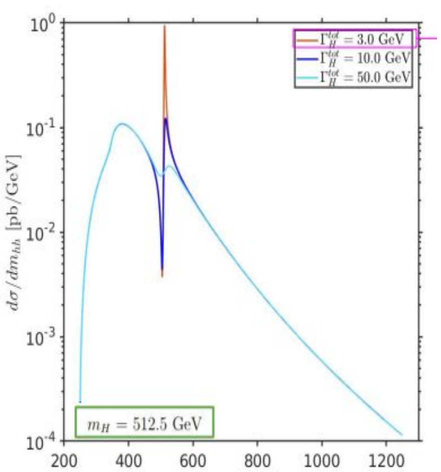


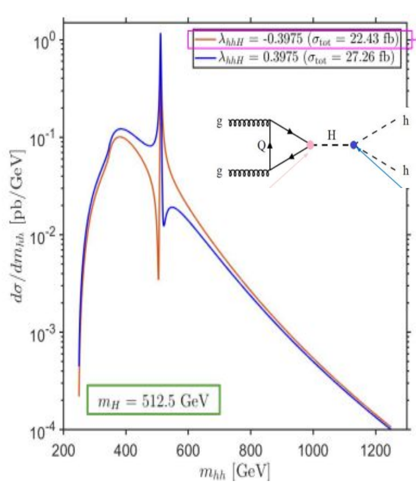
First task – preliminary results

N2HDM-I (H2 as res. of interest):

	mH2 [GeV]	max_ggH2_H1H1 [pb]	max_ggH3_H1H1 [pb]	max_ggH1H1 [pb]	min_klambda	max_klambda	min_lam112 [GeV]	max_lam112 [GeV]	min_wH2/mH2	max_wH2/mH2
0	260	0.677723	0.194092	0.692520	-0.865330	0.998518	-181.844443	374.263122	0.000001	0.082465
1	500	0.047687	0.039810	0.134563	-1.189243	0.996701	-302.660704	588.105417	0.000372	0.077238
2	1000	0.031336	0.006275	0.241003	0.011330	1.805244	342.039096	1938.246190	0.005833	0.086758
3	1500	0.002797	0.000408	0.152712	0.000074	1.193269	578.683146	3049.620909	0.007911	0.167155
4	2000	0.000236	0.000034	0.149369	0.003549	1.091706	641.205453	4924.857333	0.007941	0.274927
5	2500	0.000020	0.000002	0.067509	0.305984	0.957961	570.130128	2454.286271	0.003424	0.061114

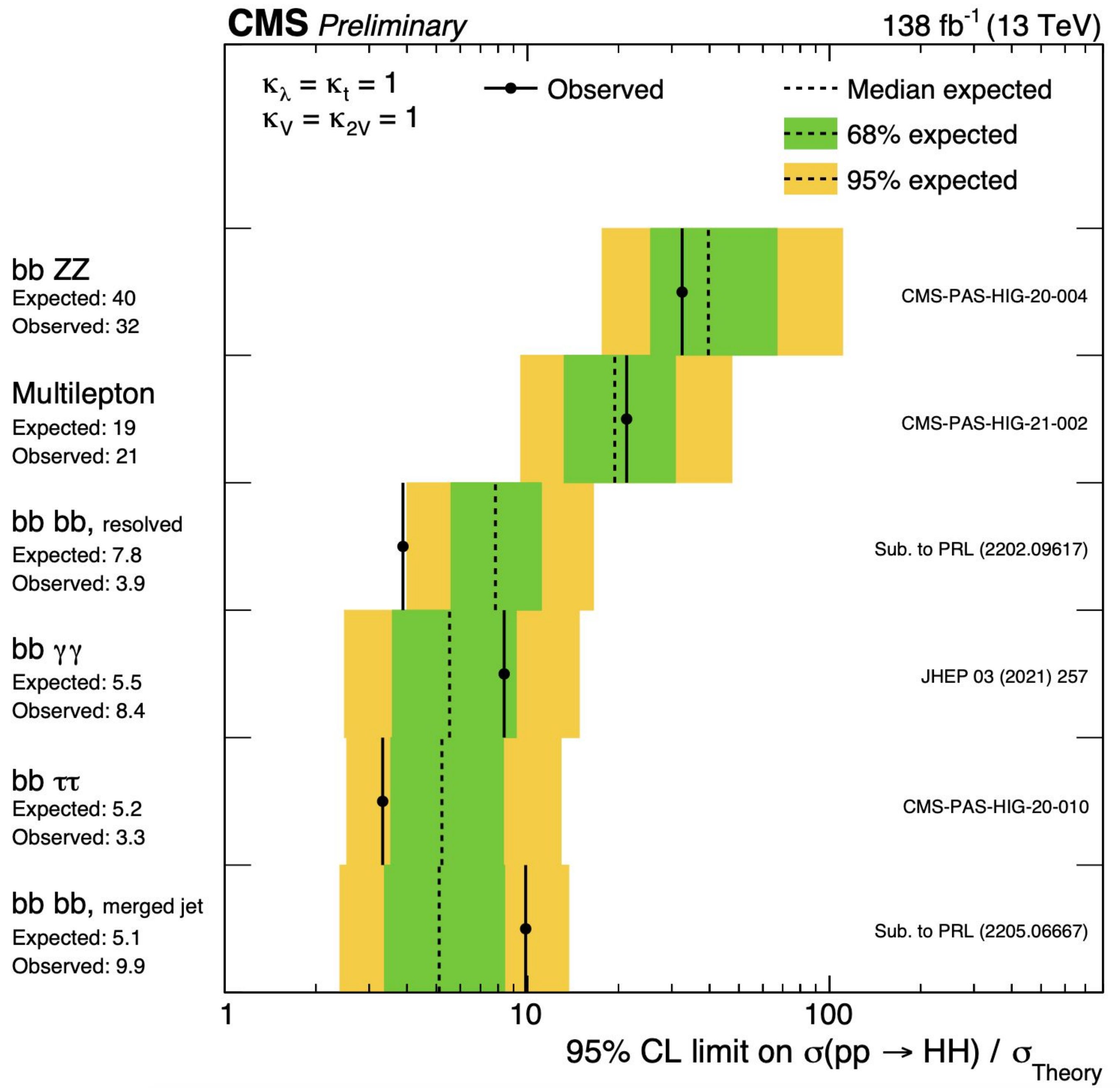
- Larger widths allowed → NWA not valid anymore
- κ_λ can be 0





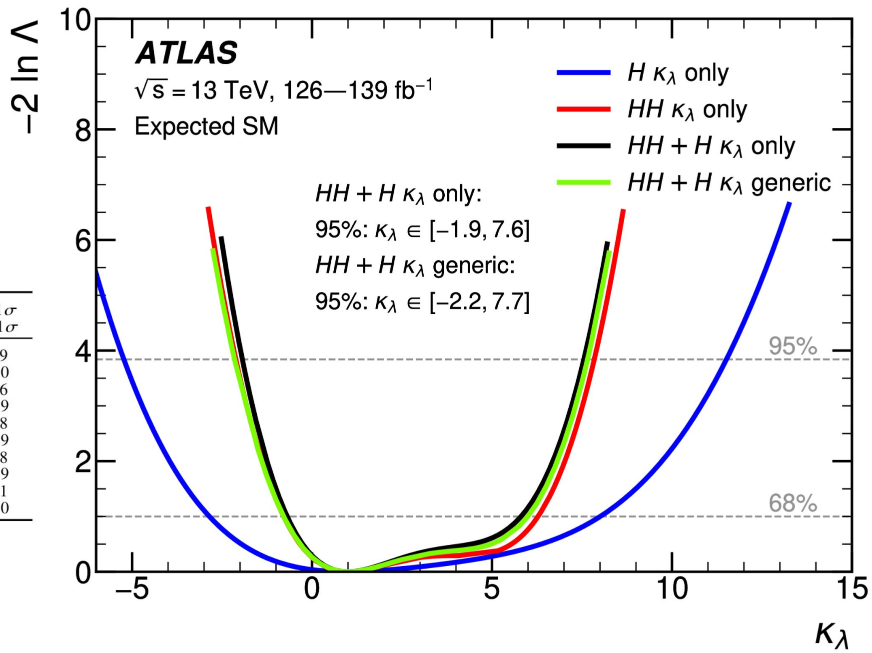
See also arxiv:2112.12515

Thank you for your attention and stay tuned for new results!


CMS Preliminary
138 fb-1 (13 TeV)
κλ = κt = 1
κV = κ2V = 1
Observed
Median expected
68% expected
95% expected
bb ZZ
Expected: 40
Observed: 32
CMS-PAS-HIG-20-004
Multilepton
Expected: 19
Observed: 21
CMS-PAS-HIG-21-002
bb bb, resolved
Expected: 7.8
Observed: 3.9
Sub. to PRL (2202.09617)
bb γγ
Expected: 5.5
Observed: 8.4
JHEP 03 (2021) 257
bb ττ
Expected: 5.2
Observed: 3.3
CMS-PAS-HIG-20-010
bb bb, merged jet
Expected: 5.1
Observed: 9.9
Sub. to PRL (2205.06667)
1
10
100
95% CL limit on σ(pp → HH) / σTheory

arXiv:2211.01216

Combination assumption	Obs. 95% CL	Exp. 95% CL	Obs. value$^{+1\sigma}_{-1\sigma}$
HH combination	$-0.6 < \kappa_\lambda < 6.6$	$-2.1 < \kappa_\lambda < 7.8$	$\kappa_\lambda = 3.1^{+1.9}_{-2.0}$
Single-H combination	$-4.0 < \kappa_\lambda < 10.3$	$-5.2 < \kappa_\lambda < 11.5$	$\kappa_\lambda = 2.5^{+4.6}_{-3.9}$
HH+H combination	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
HH+H combination, κ_t floating	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
HH+H combination, κ_t, κ_V, κ_b, κ_τ floating	$-1.4 < \kappa_\lambda < 6.1$	$-2.2 < \kappa_\lambda < 7.7$	$\kappa_\lambda = 2.3^{+2.1}_{-2.0}$



POIs	$\kappa_V{}^{+1\sigma}_{-1\sigma}$	$\kappa_t{}^{+1\sigma}_{-1\sigma}$	$\kappa_b{}^{+1\sigma}_{-1\sigma}$	$\kappa_\tau{}^{+1\sigma}_{-1\sigma}$	$\kappa_\lambda{}^{+1\sigma}_{-1\sigma}$	κ_λ [95% CL]	
κ_λ	1	1	1	1	$3.0^{+1.8}_{-1.9}$	[−0.4, 6.3]	Obs.
					$1.0^{+4.8}_{-1.7}$	[−1.9, 7.6]	Exp.
κ_λ-κ_t fit	1	$1.00^{+0.05}_{-0.04}$	1	1	$3.0^{+1.8}_{-1.9}$	[−0.4, 6.3]	Obs.
		$1.00^{+0.04}_{-0.04}$			$1.0^{+4.8}_{-1.7}$	[−1.9, 7.6]	Exp.
Generic fit	$1.00^{+0.05}_{-0.05}$	$0.93^{+0.07}_{-0.06}$	$0.90^{+0.12}_{-0.11}$	$0.93^{+0.08}_{-0.07}$	$2.3^{+2.1}_{-2.0}$	[−1.4, 6.1]	Obs.
	$1.00^{+0.05}_{-0.05}$	$1.00^{+0.07}_{-0.07}$	$1.00^{+0.12}_{-0.12}$	$1.00^{+0.08}_{-0.08}$	$1.0^{+5.0}_{-1.8}$	[−2.2, 7.7]	Exp.