Highlights and Prospects on Higgs Physics at the (HL-)LHC

Julian Wollrath

Department of Physics & Astronomy
University of California, Irvine

on behalf of the ATLAS and CMS Collaborations

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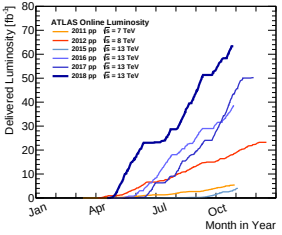
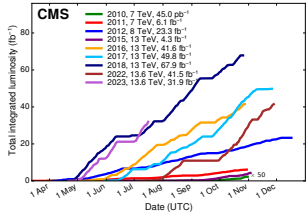
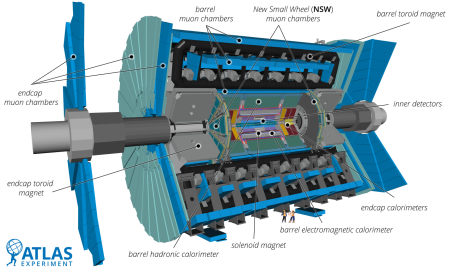
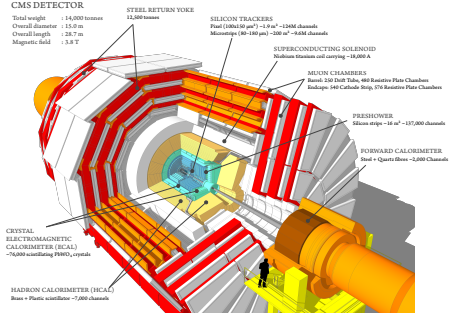
ATLAS and CMS experiments at the LHC



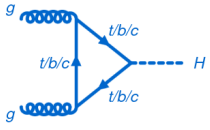




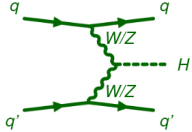


- LHC Run 2 $\sqrt{s} = 13\,\text{TeV}$ ~56 000 Higgs bosons produced per fb^{-1}
- $\mathcal{O}(0.1\,\%)$ selected for physics analyses (trigger, reconstruction, identification inefficiency,...)
- HL-LHC → 3000 fb^{-1} of data $\sqrt{s} = 14\,\text{TeV}$

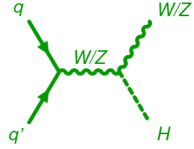
Single Higgs boson production



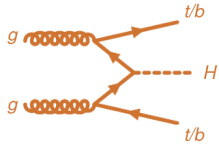
ggF (87%)



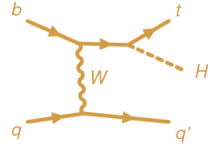
VBF (7%)



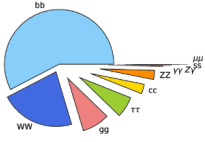
VH (4%)



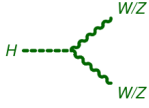
ttH/bbH (2%)

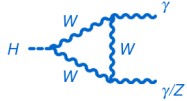


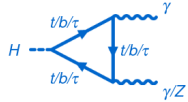
tH (0.1%)

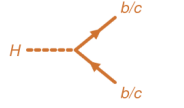


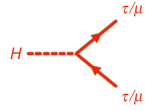
Higgs boson decay BR



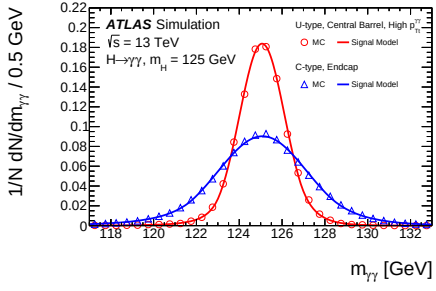


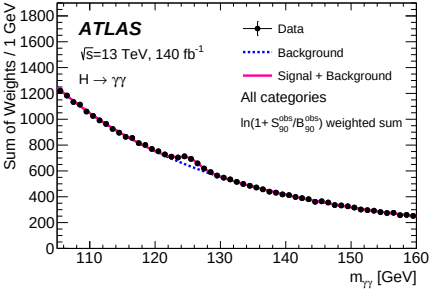


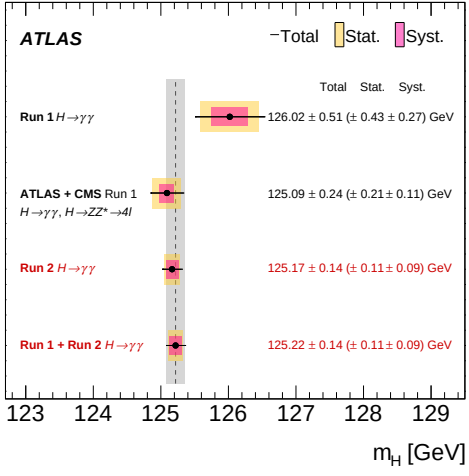




Higgs boson mass measurement: $H \to \gamma\gamma$

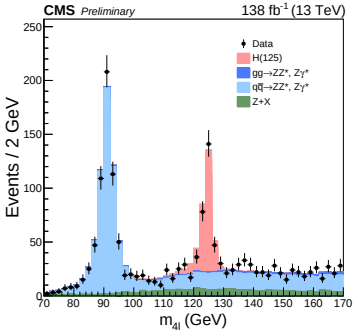


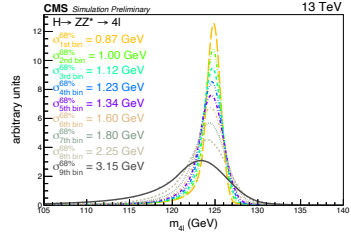


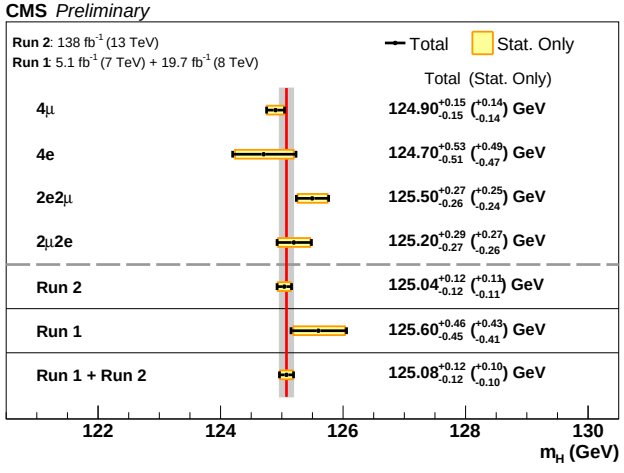


[Phys. Lett. B 847 (2023) 138315]

Higgs boson mass measurement: $H \to ZZ^* \to 4l$

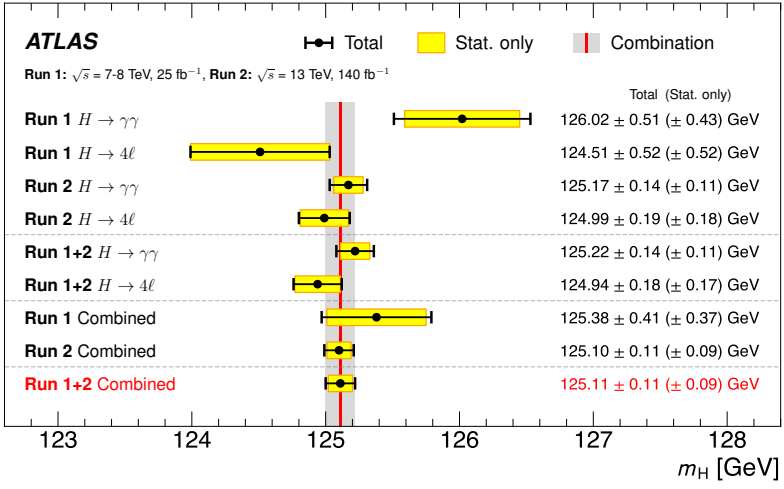






[CMS-PAS-HIG-21-019]

Current best Higgs boson mass measurement

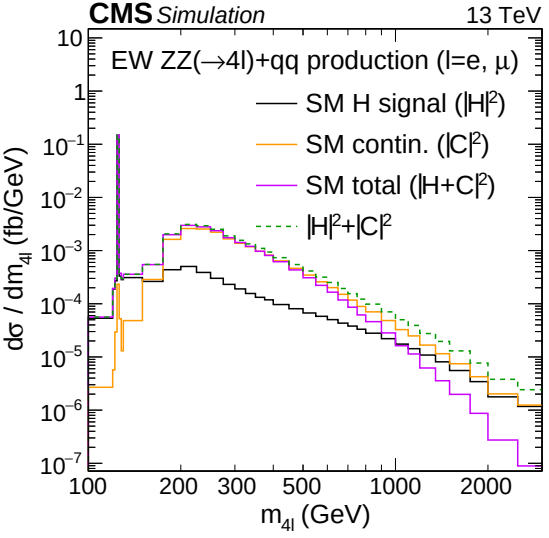


[Phys. Rev. Lett. 131 (2023) 251802]

Higgs boson width

- Width precisely predicted within SM: 4.07 MeV [R.L. Workman et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2022, 083C01 (2022)]
- Small value → difficult to measure
- Measure in $H \to ZZ$ compare on- and off-shell production:

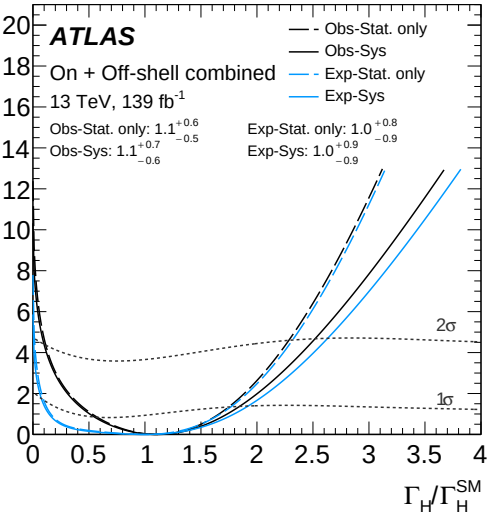
$$\frac{\sigma^{\text{on-shell}}_{gg\to H\to ZZ^*} \sim \frac{g^2_{ggH} g^2_{HZZ}}{m_H \Gamma_H}}{\sigma^{\text{off-shell}}_{gg\to H^*\to ZZ} \sim \frac{g^2_{ggH} g^2_{HZZ}}{(2m_Z)^2}}$$



[Nat. Phys. 18 (2022) 1329]

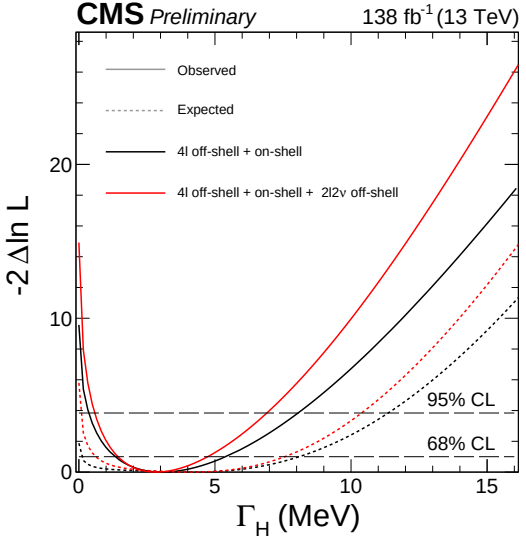
Higgs boson width

[Phys. Lett. B 846 (2023) 138223]



$\Gamma_H = 4.5^{+3.3}_{-2.5}\,\text{MeV}$

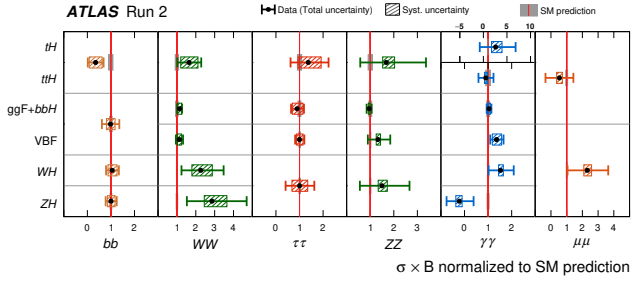
[CMS-PAS-HIG-21-019]

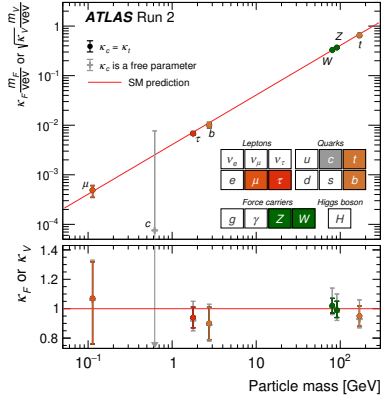


$\Gamma_H = 2.9^{+1.9}_{-1.4}(4.1 \pm 3.5)\,\text{MeV}$

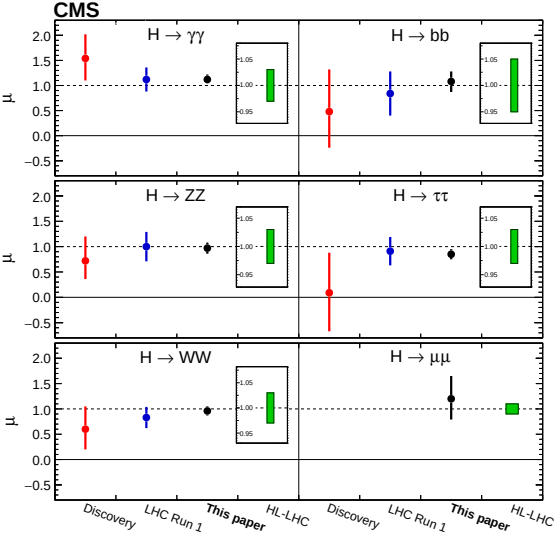
Cross-section and coupling modifiers

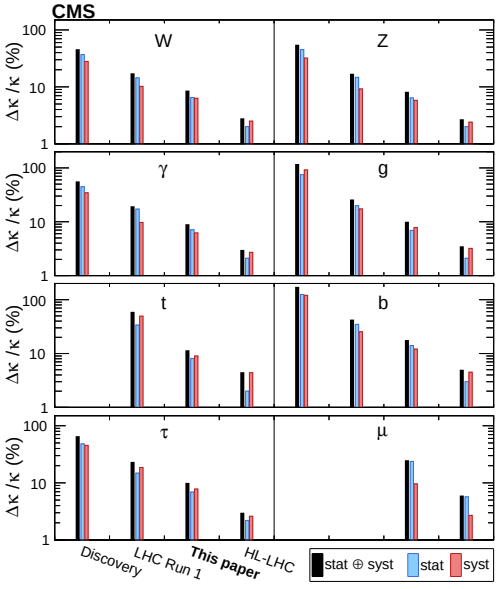
[Nature 607, 52 (2022)]





Cross-section and coupling modifiers

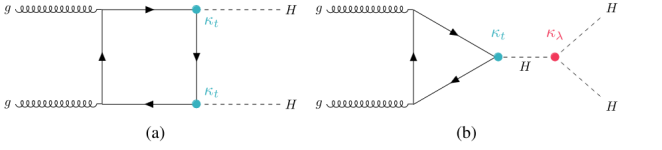




[Nature 607 (2022) 60-68]

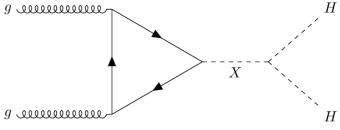
Higgs boson pair-production

Non-resonant production:



	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%

Resonant production:

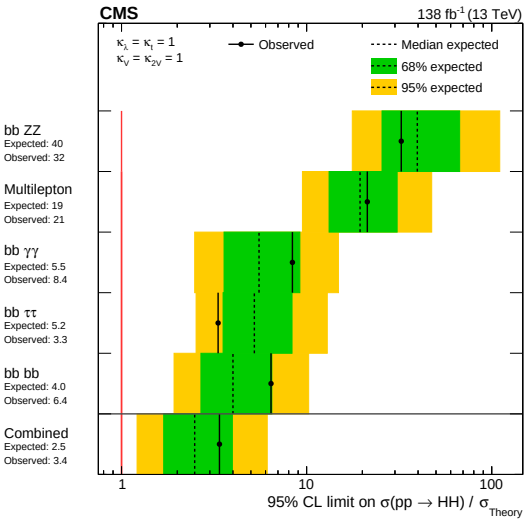


$\sigma^{\mathrm{SM}}_{ggF+VBF} = 32.78\,\mathrm{fb}$

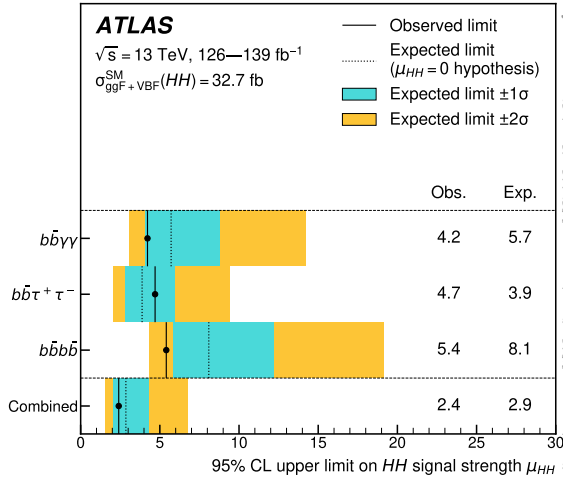
→ ATLAS+CMS ~9000 HH events @ $\sqrt{s} = 13\,\mathrm{TeV}$

Non-resonant overview results

[Nature 607 (2022) 60-68],[CERN-EP-2024-043]



$bbWW$: $\mu_{HH} < 14(18)$ @ 95 % CL



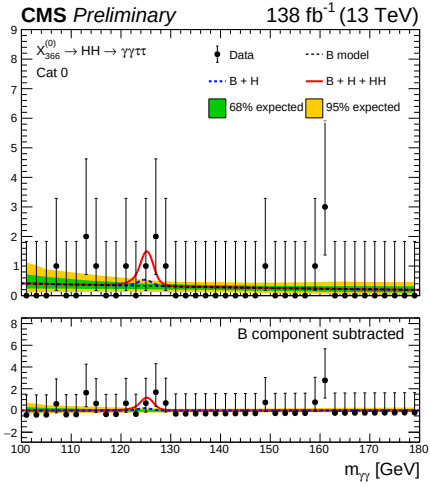
$bbll$: $\mu_{HH} < 9.2(16.2)$ @ 95 % CL
$bb\gamma\gamma$: $\mu_{HH} < 4.0(5.0)$ @ 95 % CL
$bb\tau\tau$: $\mu_{HH} < 5.9(3.1)$ @ 95 % CL

[Phys. Lett. B 843 (2023) 137745],[JHEP 02 (2024) 037],[JHEP 01 (2024) 066],[ATLAS-CONF-2023-...]

New non-resonant results

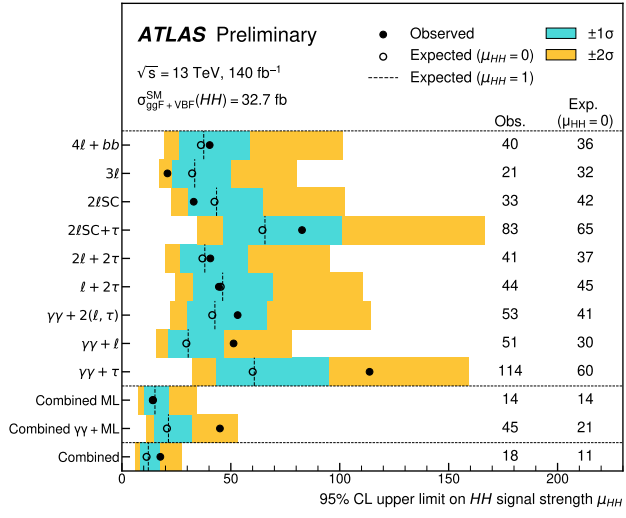
CMS $HH \to \gamma\gamma\tau\tau$ & ATLAS $HH \to$ multilepton

[CMS-PAS-HIG-22-012]



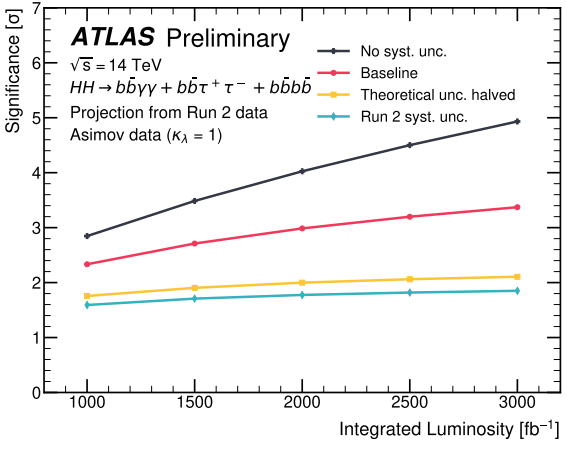
$\gamma\gamma\tau\tau$: $\mu_{HH} < 33(26)$ @ 95 % CL

[ATLAS-CONF-2024-005]

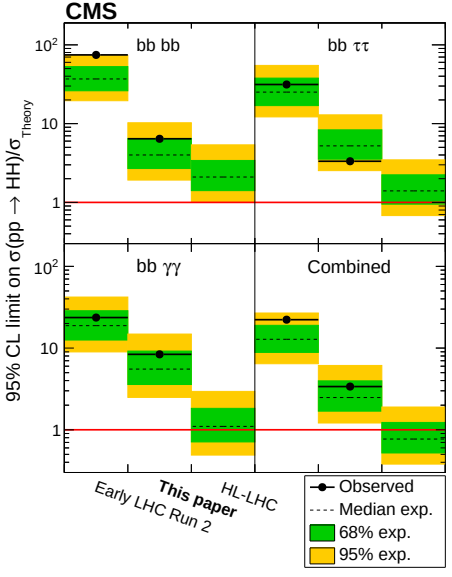


Non-resonant overview projections

[ATL-PHYS-PUB-2022-053]

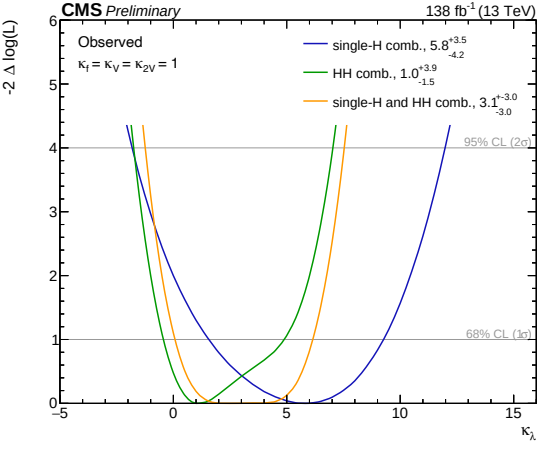


[Nature 607 (2022) 60-68]

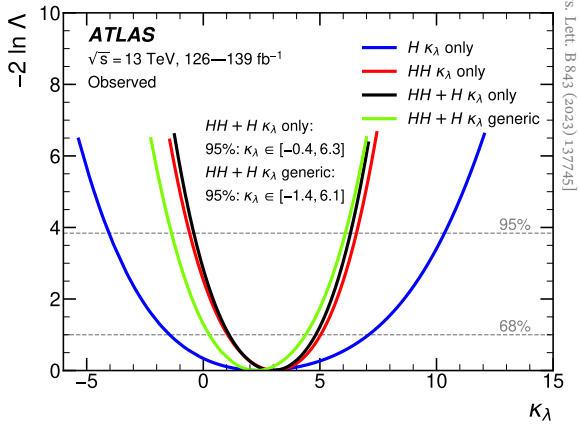


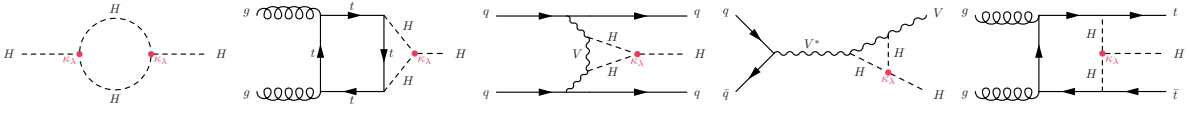
Coupling modifier constraints: self-coupling

[CMS-PAS-HIG-23-006]



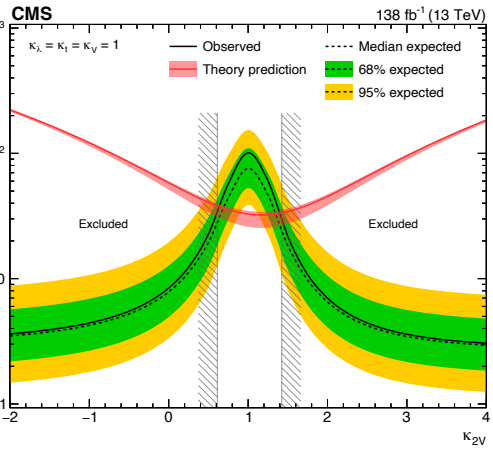
[Phys. Lett. B 843 (2023) 137745]



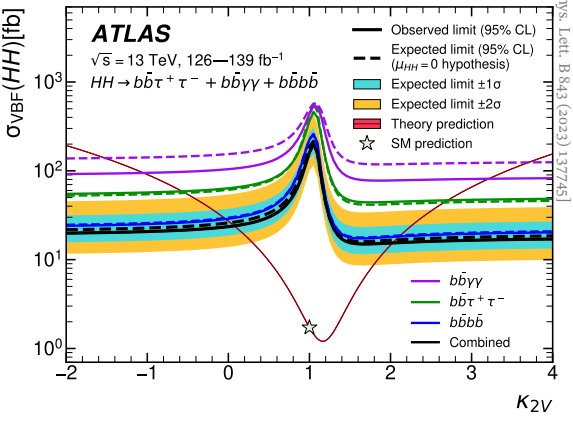


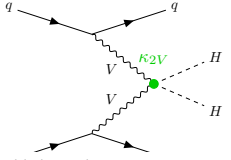
Coupling modifier constraints: two vector bosons

[Nature 607 (2022) 60-68]



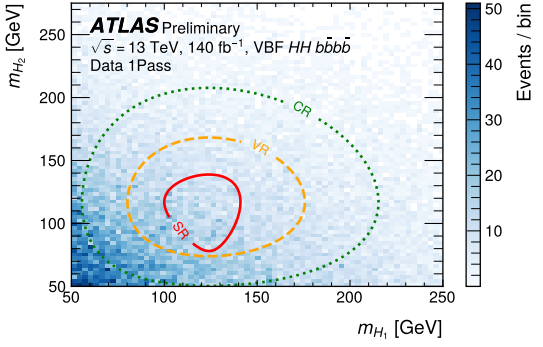
[Phys. Lett. B 843 (2023) 137745]

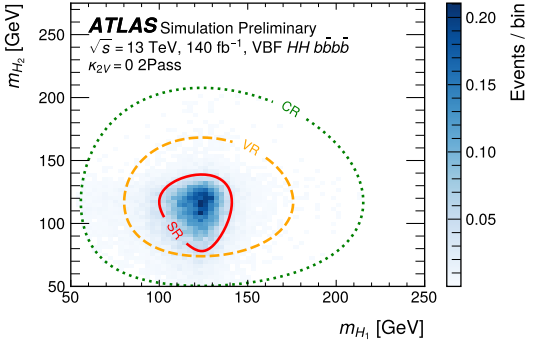


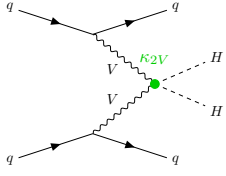


New coupling modifier constraints

VBF $HH \to 4b$ boosted



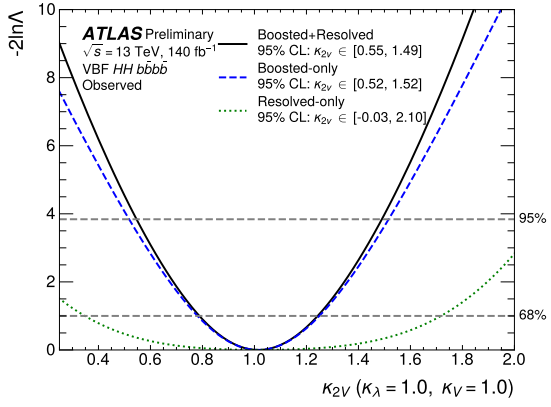


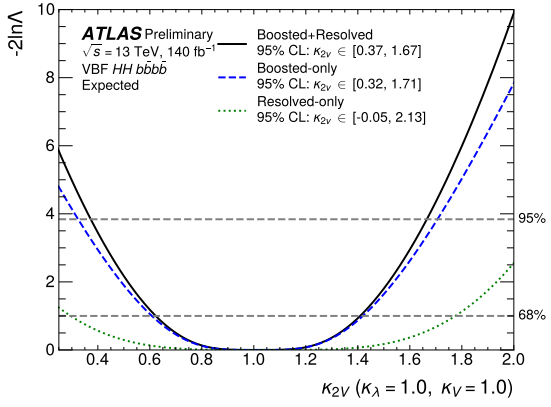


[ATLAS-CONF-2024-003]

New coupling modifier constraints

VBF $HH \to 4b$ boosted

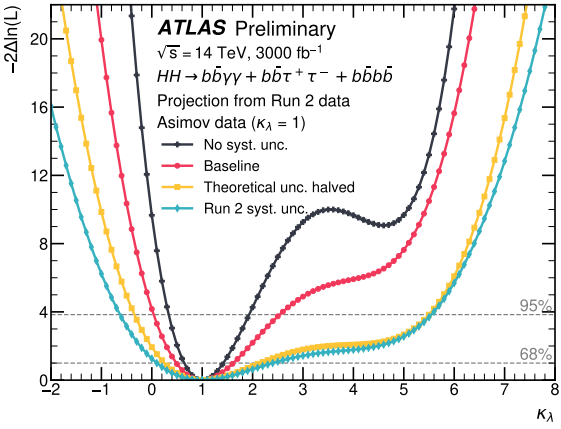


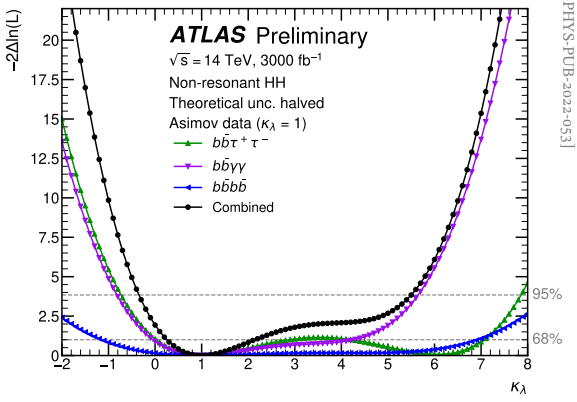


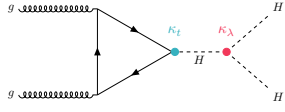
[ATLAS-CONF-2024-003]

$\to \kappa_{2V} = 0$ excluded with 3.8σ

Higgs boson self-coupling projections



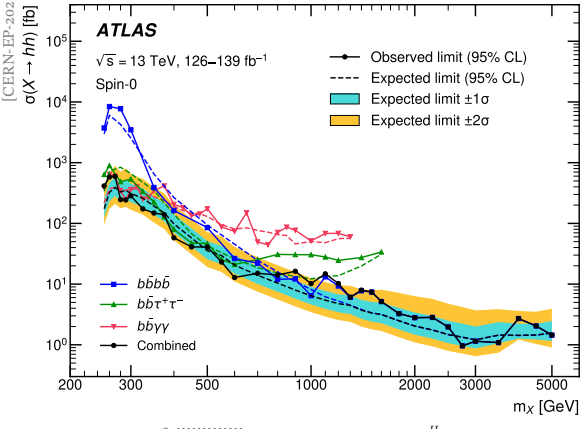


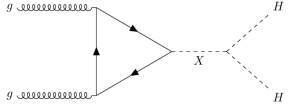


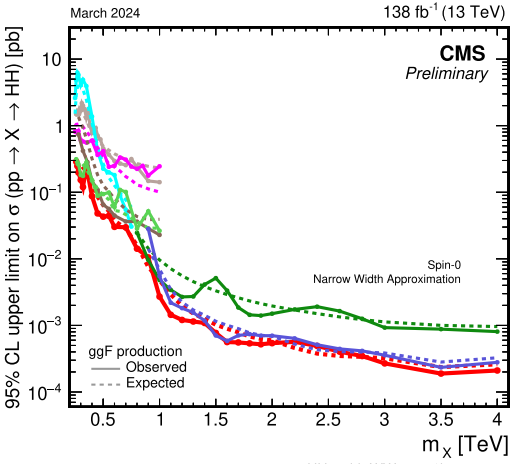
[ATL-PHYS-PUB-2022-053]

Resonant Higgs boson pair-production

[CERN-EP-2023-271]







HH → γγ, ττ (not in HH Comb.) HIG-22-012

HH Combination B2G-23-002

HH → bb,WW → ≥ 1l (resolved) 2403.09430, Sub. to JHEP

HH → 4W/4τ/2W2τ → ≥ 2l JHEP 07 (2023) 095

HH → bb,WW → ≥ 1l (merged-jet) JHEP 05 (2022) 005

HH → bb, ττ HIG-20-014

HH → bb,γγ 2310.01643, Acc. by JHEP

HH → bb,bb (merged-jet) PLB 842 (2023) 137392

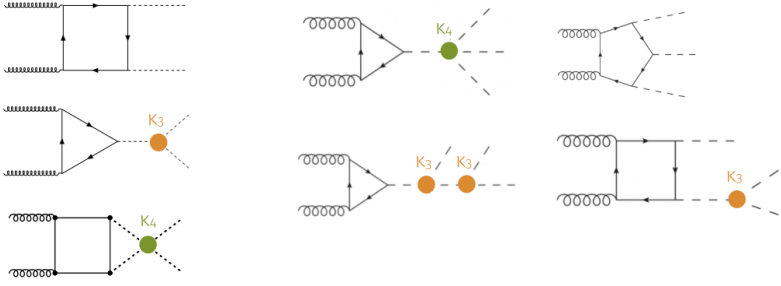
Conclusion

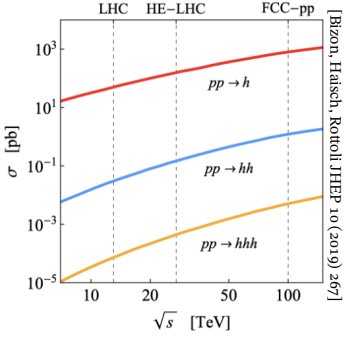
- Mass and width measured
- Couplings to bosons, third generations fermions & quarks observed, second generation quarks (i. e. charm) → HL-LHC
- Not mentioned: STXS
- HH production getting in reach with Run 3
- Modifiers for self-coupling and coupling to vector bosons getting constrained
- So far: everything consistent with the SM
- Not mentioned but also performed: other resonant *HH*-like searches
- Not mentioned but also performed: EFT interpretations
- Next: also target triple Higgs boson production:
  - Run 2 + Run 3: $\mu_{HHH} < 50$ @ 95 % CL?
  - allows to better constrain κ_4

Backup

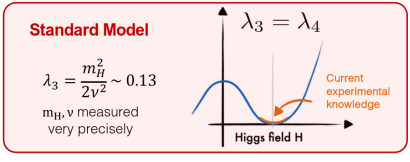
Multiple Higgs boson production

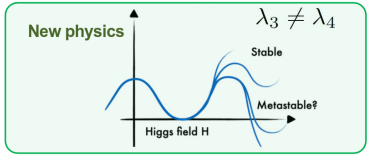
- Multiple Higgs boson production rates low: $h/hh \sim 1800$, $hh/hhh \sim 450$ @ LHC





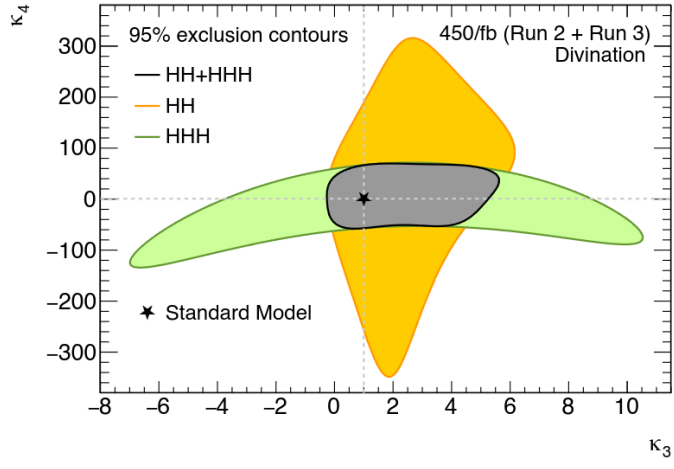
LHC Run 2 expected yields:
$pp \to hh$: ~4500 events
$pp \to hhh$: ~13 events





Searches for *HHH* and complementarity to *HH*

- Pheno studies for a future 100 TeV pp collider exist [Chen, Yan, Zhao, Zhao, Zhong – PRD 93 013007] and [Fuks, Kim, Lee – PRD 93 035026]:
  - use combined with ATLAS/CMS HH numbers as starting point for estimation
  - consider $6b$ ($\mathcal{B} = 0.2$), $4b2\tau$ ($\mathcal{B} = 0.06$), $4b2\gamma$ ($\mathcal{B} = 0.002$)
  - assume Run 2 + Run 3 can get to $\mu_{HHH} < 50$ @ 95 % CL



[Arnold, Moser, Stamenkovic – HHH Workshop Dubrovnik]