WG4 HH and multi-Higgs: Outlook and Plans

Arantxa Ruiz Martínez (IFIC, CSIC-UV) on behalf of the LHC Higgs WG4

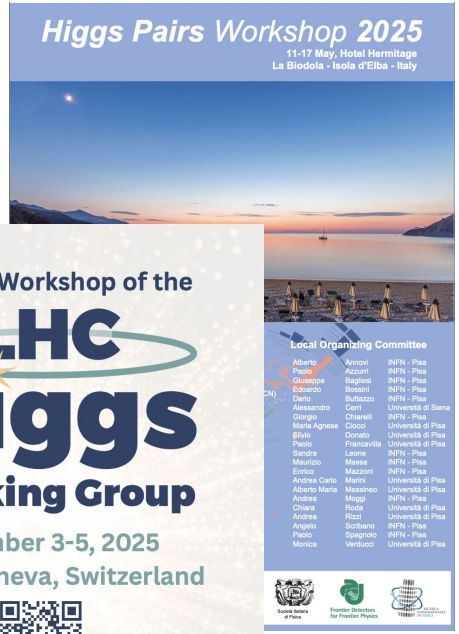
The 22nd Workshop of the LHC Higgs Working Group, 3-5 December 2025

LHC Higgs WG4 coordinates

- LHC Higgs WG4 (di-Higgs and multi-Higgs) twiki page: https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHWGHH
- Mailing list: lhc-higgs-hh@cern.ch
- WG4 conveners:
  - **ATLAS**: Arantxa Ruiz Martínez
  - **CMS**: Fabio Monti (outgoing) → Angela Taliercio (incoming) **THANK YOU!**
  - **Theory**: Ludovic Scyboz, Andreas Papaefstathiou
- New HHH subgroup created in December 2024
  - Mailing list: lhc-higgs-hhh@cern.ch
  - HHH subgroup conveners:
    - **ATLAS**: William Balunas
    - **CMS**: Greg Landsberg
    - **Theory**: Benjamin Fuks

LHC Higgs WG4 activities in 2025

- **Higgs Pairs Workshop, Isola d'Elba, 11-17 May 2025:** https://indico.cern.ch/event/1399335/
- **LHC Higgs WG4 meetings in 2025:** https://indico.cern.ch/category/16972/
  - LHCHWG Report 5 preparation
  - HH reweighter tool tutorial to account for interference effects
  - HH signal reweighting for EFT interpretations
  - BSM benchmarks for HH / SH / HHH production
- **General Assembly:**
  - WG4 Plenary session:
    - ATLAS+CMS HH experimental overview
    - Summary of the HHH Workshop in Dubrovnik
    - NNLO+PS HH with top mass corrections in GENEVA
  - WG4 Parallel session:
    - 4 talks including ATLAS+CMS HHH recent results
    - 6 lightning talks

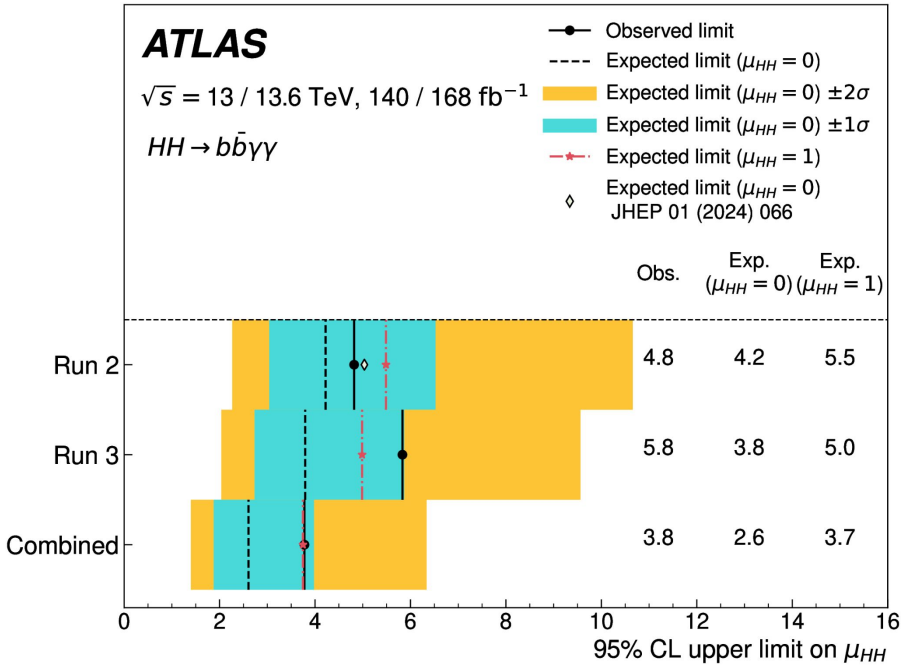


Experimental highlights

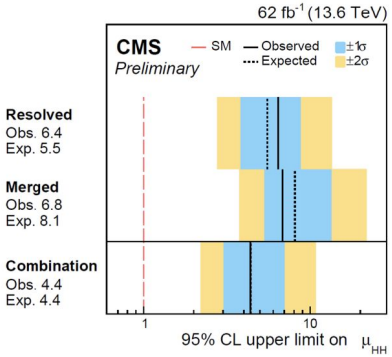
See talks by V. Cairo, J. Wang and M. Stamenkovic

HH → bbγγ Run 2 + Run 3 (> 300/fb) [arXiv:2507.03495]

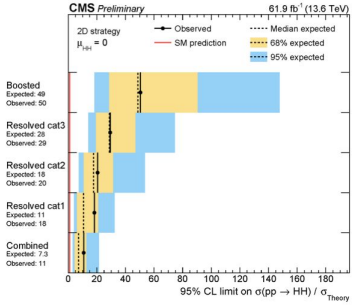
First HH result to reach 1σ expected significance!



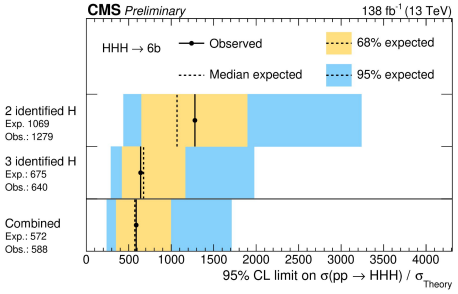
HH → bbbb Run 3 [CMS-PAS-HIG-24-010]



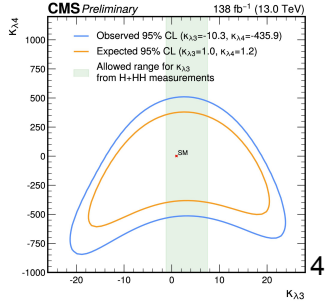
HH → bbγγ Run 3 [CMS-PAS-HIG-25-007]



HHH → 6b Run 2 [CMS-PAS-HIG-24-012]



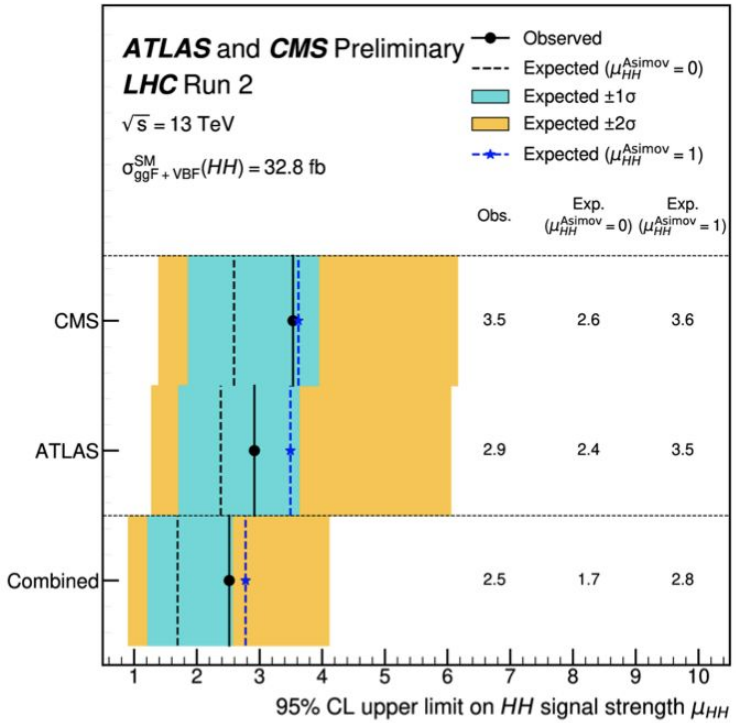
HHH → 4b2γ Run 2 [CMS-PAS-HIG-24-015]



Experimental highlights: ATLAS + CMS

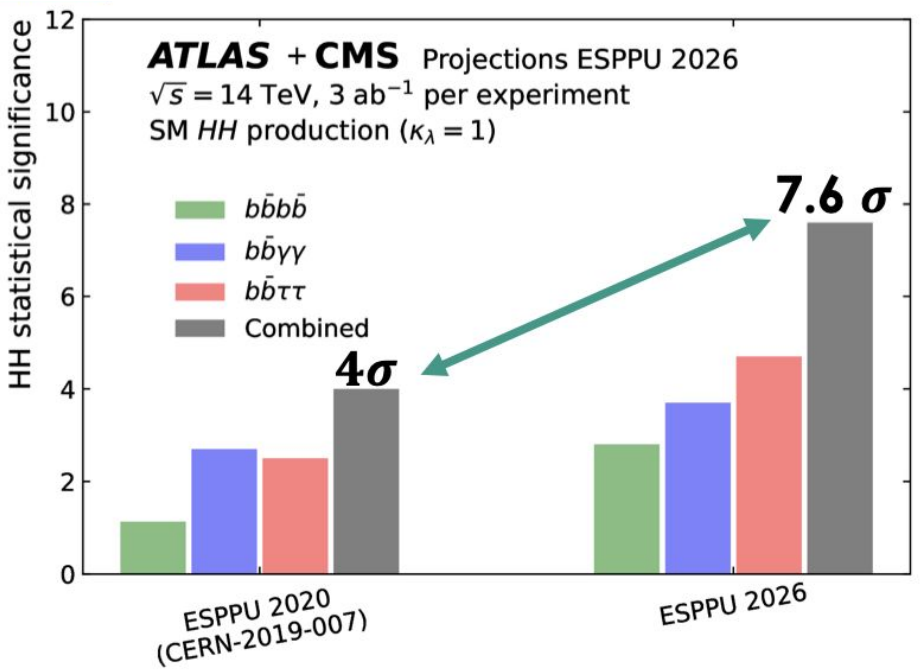
ATLAS+CMS HH legacy Run 2 combination

https://cds.cern.ch/record/2947512



ATLAS+CMS HH Projections ESPPU 2026

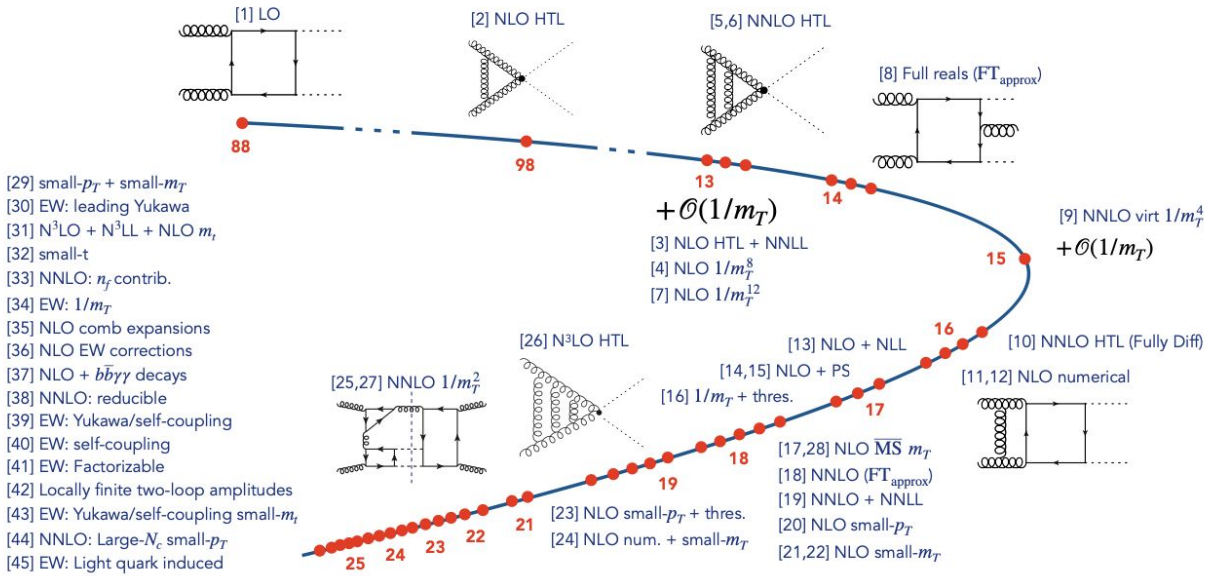
arXiv:2504.00672



Theory highlights

Gluon fusion: theory overview

(Slide design inspired by: G. Salam)



[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, Jones, Kerner, Schlenk, Schubert, Zirke 16; [12] Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Zirke 16; [13] Ferrera, Pires 16; [14] Heinrich, Jones, Kerner, Luisoni, Vryonidou 17; [15] Jones, Kuttimalai 17; [16] Gröber, Maier, Rauh 17; [17] Baglio, Campanario, Glaus, Mühlleitner, Spira, Streicher 18; [18] Grazzini, Heinrich, Jones, 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, Jones, 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; [30] Davies, Mishima, Schönwald, Steinhauser, Zhang 22; [31] Ajjath, Shao 22; [32] Davies, Mishima, Schönwald, Steinhauser 23; [33] Davies, Schönwald, Steinhauser 23; [34] Davies, Schönwald, Steinhauser, Zhang 23; [35] Bagnaschi, Degrassi, Gröber 23; [36] Bi, Huang, Huang, Ma Yu 23 [37] Li, Si, Wang, Zhang, Zhao 24; [38] Davies, Schönwald, Steinhauser, Vitti 24; [39] Heinrich, Jones, Kerner, Stone, Vestner [40] Li, Si, Wang, Zhang, Zhao 24; [41] Davies, Schönwald, Steinhauser, Zhang 24; [42] C. Anastasiou, J. Karlen, G. Sterman, A. Venkata 24; [43] Davies, Schönwald, Steinhauser, Zhang 25; [44] Davies, Schönwald, Steinhauser 25; [45] Bonetti, Rendler, Bobadilla 25;

(Slide borrowed from S. Jones)

Theory highlights

- SM QCD corrections:
  - ggxy tool [Kay Schonwald]
  - NNLO+PS with GENEVA [Giulia Marinelli]
  - Top-mass log resummation [Sebastian Jaskiewicz]
- Partial EW calculations (full EW presented in the 2024 meeting):
  - Top-Yukawa- and light-quark-induced [Sauro Carlotti]
  - Light quarks [Philipp Rendler]
- SMEFT/HEFT reweighting [Matheus Coelho], HEFT NLO [Konstantin Schmid]
- NMSSMScanner/TRSM scan tool [Martin Gabelmann], new BSM benchmarks [Maggie Mühlleitner], κ_4 sensitivity [Gilberto Tetlalmatzi-Xolocotzi]

LHCHWG Report 5

- **WG4 first wave of contributions** structured as follows:
  - ggF HH production: QCD and EW higher-order corrections and theoretical uncertainties (finalizing)
  - NLO EW effects and dependence on κ_3 and κ_4 (finalizing)
  - VBF HH simulation tools (LHCHWG-2025-012, arXiv:2511.02488, in SciPost refereeing)
  - VBF and VHH production (finalizing)
- **WG4 second wave of contributions** starting:
  - BSM benchmarks, resonant HH production and interference effects
  - HHH production
  - HEFT/SMEFT
- First round of contributions wrapping up, finalizing recommendations, thank you very much to all the contributors for the huge effort!
- Recommendations being provided at $\sqrt{s}$ = 13, 13.6, 14 TeV and m_H = 125, 125.09, 125.38 GeV
- Update recommendations in WG4 twiki to summarize state-of-the-art calculations (more dynamic)
- Please let us know if you are interested in contributing to the second round!

First wave of contributions for LHCWG Report 5

QCD corrections:

- Full NLO QCD + PS [Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Schubert, Zirke]
- Full NLO with m_t & m_H [Baglio, Campanario, Glaus, Mühlleitner, Ronca, Spira, Streicher]
- Amplitude expansion with small p_{TH}, small m_t [Bonciani, Degrassi, Giardino, Gröber, Bagnaschi]
- Full NLO with ggxy [Davies, Schönwald, Stenhauser, Stremmer]
- NNLO FTapprox [Grazzini, Heinrich, Jones, Kallweit, Kerner, Lindert, Mazzitelli]
- NNLO+PS with GENEVA [Alioli, Marinelli, Napoletano]
- NNLO with full m_t dependence [Davies, Schönwald, Stenhauser, Vitti]
- N3LO in the HTL [Chen, Li, Shao, Wang]
- N3LO + N3LL in the HTL [A H, Shao]
- Partial m_t effects [A H, Chen, Li, Shao, Wang]

Top-quark mass effects:

- m_t scheme and scale uncertainties at NLO [Baglio, Campanario, Glaus, Mühlleitner, Ronca, Spira, Streicher]
- m_t log resummation [Jaskiewicz, Jones, Szafron, Ulrich]

EW corrections:

- Full NLO EW [Bi, Huang, Huang, Ma, Yu] + separate contributions

SM ggF HH production

Contributions from 27 institutions, comprehensive summary of results

See talk by M. Bonetti at the Lightning session for LHCHWG Report 5

[Bhattacharya, Campanario, Carlotti, Chang, Mazzitelli, Mühlleitner, Ronca, Schlenk, Spira]
[Davies, Schönwald, Steinhauser, Zhang] [Mühlleitner, Schlenk, Spira]
[Davies, Schönwald, Steinhauser, Zhang] [Davies, Schönwald, Steinhauser, Zhang]
[Heinrich, Jones, Kerner, Stone, Vestner] [Bonetti, Rendler, Torres Bobadilla]
[Bhattacharya, Campanario, Carlotti, Chang, Mazzitelli, Mühlleitner, Ronca, Spira]

First wave of contributions for LHCHWG Report 5

SM ggF HH production

- HH cross section recommendations being finalized (combination of NNLO FTapprox, the current recommendation):

$$\sigma = \sigma_{\text{NNLO FT}_{\text{approx}}} \times K\left(\frac{\text{N}^3\text{LO HTL}}{\text{NNLO HTL}}\right) \times K\left(\frac{\text{NLO EW}}{\text{LO}}\right)$$

- PDF set: PDF4LHC21_40 (unc. following arXiv:2203.05506), for N3LO calculation MSHT20xNNPDF40_aN3LO_qed
- NNLO PDF uncertainty:

$$\Delta^{\text{exact}}_{NNLO} = \left| \frac{\sigma^{\text{N}^3\text{LO}}_{\text{N}^3\text{LO-PDF}} - \sigma^{\text{N}^3\text{LO}}_{\text{NNLO-PDF}}}{\sigma^{\text{N}^3\text{LO}}_{\text{N}^3\text{LO-PDF}}} \right|$$

- Central renormalization/factorization scales: $\mu_R = \mu_F = M_{HH}/2$ (arXiv:1803.02463)
- Scale uncertainties: 6 relative variations by a factor of 2 around the central scale
- Uncertainties arising from the choice of renormalization scheme and scale of the top-quark mass (m_t scheme+scale unc.) and their combination with μ_R and μ_F variations (comb. unc.) following arXiv:2008.11626

First wave of contributions for LHCHWG Report 5

VBF HH simulation tools

Braun, Bredt, Heinrich, Höfer, Jäger, Karlberg, Reinhardt

- State-of-the-art MC tools with NLO QCD corrections for VBF HH simulation:
  - **GoSam+Whizard:** Full EW HHjj matrix elements
  - **POWHEG-BOX:** VBF approximation (only VBF process considered, any gluon exchange between the quarks neglected)
- EW HHjj cross sections and differential distributions provided for:
  - SM [1.0, 1.0, 1.0]
  - Benchmark points for anomalous couplings
- Two regions considered: Inclusive and VBF

NLO EW effects and dependence on κ_3 and κ_4

Ding, Gillis, Haisch, Moser, Li, Pagani, Rottoli, Shivaji, Si, Wang, Windischhofer, Zhang, Zhao

- Two calculations of the HH cross section as a function of κ_3 and κ_4 considering impact of NLO EW corrections in EFT (HEFT and SMEFT)

VBF HH and VHH production

Gröber, Karlberg, Pellen, Sacchi, Spira

- Updated inclusive production cross-sections:
  - **VBF HH at N3LO QCD** (including NLO EW for SM coupling)
  - **VHH (W^+HH, W^-HH, ZHH) at NNLO QCD** based on arXiv:1212.5581
- $\sqrt{s}$=13, 13.6, 14 TeV, m_H=125, 125.09, 125.38 GeV
- SM (κ_λ = 1) & anomalous (κ_λ = 0, 2 ,3) couplings

Second wave of contributions for LHCHWG Report 5

- **BSM benchmarks, resonant HH and interference effects:**
  - New e-group created for LHCHWG Report 5 contributors with self-subscription: lhc-higgs-hh-yr5-res
  - Benchmarks for HH, YH and YY including interference with non-resonant HH, branching ratios to SM particles, EW corrections on resonant HH production (work in collaboration with WG3)
  - Contributions:
    - BSM benchmarks for Higgs cascade decays (T. Robens, T. Stefaniak, J. Wittbrodt, arXiv:1908.08554)
    - BSM benchmarks in various Extended Higgs Sectors (H. Abouabid et al., arXiv:2112.12515, see talk by M. Mühlleitner)
    - Relevance of interference effects between resonant and non-resonant contributions in UV-complete models (S. Heinemeyer et al., arXiv:2403.14776, see talk by K. Radchenko)
  - BSM benchmarks survey launched to collected feedback from ATLAS and CMS
  - Create dedicated LHCHWG twiki page with list of theorists / potential tools and documentation available for analysers to include BSM benchmarks comparisons in ATLAS and CMS papers

Second wave of contributions for LHCHWG Report 5

- **HEFT/SMEFT:**
  - New e-group created for LHCHWG Report 5 contributors with self-subscription: lhc-higgs-hh-yr5-eft
  - Potential topics:
    - Kinematic benchmarks for EFT
    - EFT operators affecting HH production modes besides ggF (ttHH, VHH)
    - Improve analytical reweighting, e.g. reduce discrepancies in $p_{T,H}$
    - Higgs boson pair production in HEFT and SMEFT: updated results at NLO QCD as functions of Wilson coefficients (G. Heinrich and collaborators)
- **HHH production:**
  - NNLO ggF cross section at $\sqrt{s}$ = 13, 13.6 TeV (only available for 14, 100 TeV, JHEP 03 (2020) 155)
  - Define new benchmarks with enhanced HHH production (discussion with WG3)
  - See talk by G. Landsberg

Final remarks

- Many new experimental results from 2025 presented:
  - ATLAS HH → bb$\gamma\gamma$ with > 300/fb, CMS HH → bbbb and HH → bb$\gamma\gamma$ using 2022+2023 data
  - CMS HHH → 6b and HHH → 4b2γ using Run 2 data
  - Legacy Run 2 ATLAS+CMS HH combination achieving observed limits of $\mu_{HH} < 2.5$
  - Projections ESPPU 2026: ATLAS+CMS HH reaching 7.6σ significance with 3000/fb
- Many new theory results and tools discussed: QCD corrections, partial EW calculations, EFT, BSM tools, etc.
- First wave of contributions for LHCHWG Report 5 wrapping up and second wave starting, please let us know if you would like to contribute!