SECOND HHH DUBROVNIK WORKSHOP SUMMARY

Greg Landsberg

4.12.25

CERN Higgs Working Group Workshop

https://indico.cern.ch/e/hhh2025

Bit of History

- The first HHH Workshop took place in Dubrovnik in July 2023

- Brainstorming workshop where the ground work for HHH searches started
- Bringing together experimentalists from ATLAS and CMS, and theorists

The HHH White Paper

- An important outcome of the workshop was the HHH White paper https://arxiv.org/abs/2407.03015 [EPJC **84** (2024) 1183]

Eur. Phys. J. C (2024) 84:1183
https://doi.org/10.1140/epjc/s10052-024-13376-3

THE EUROPEAN PHYSICAL JOURNAL C

Review

HHH whitepaper

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Received: 26 July 2024 / Accepted: 14 September 2024 / Published online: 19 November 2024
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Abstract We here report on the progress of the HHH Workshop, that took place in Dubrovnik in July 2023. After the discovery of a particle that complies with the properties of the Higgs boson of the Standard Model, all Standard Model (SM) parameters are in principle determined. However, in order to verify or falsify the model, the full form of the potential has to be determined. This includes the measurement of the triple and quartic scalar couplings.

We here report on ongoing progress of measurements for multi-scalar final states, with an emphasis on three SM-like scalar bosons at 125 GeV, but also mentioning other options. We discuss both experimental progress and challenges as well as theoretical studies and models that can enhance such rates with respect to the SM predictions.

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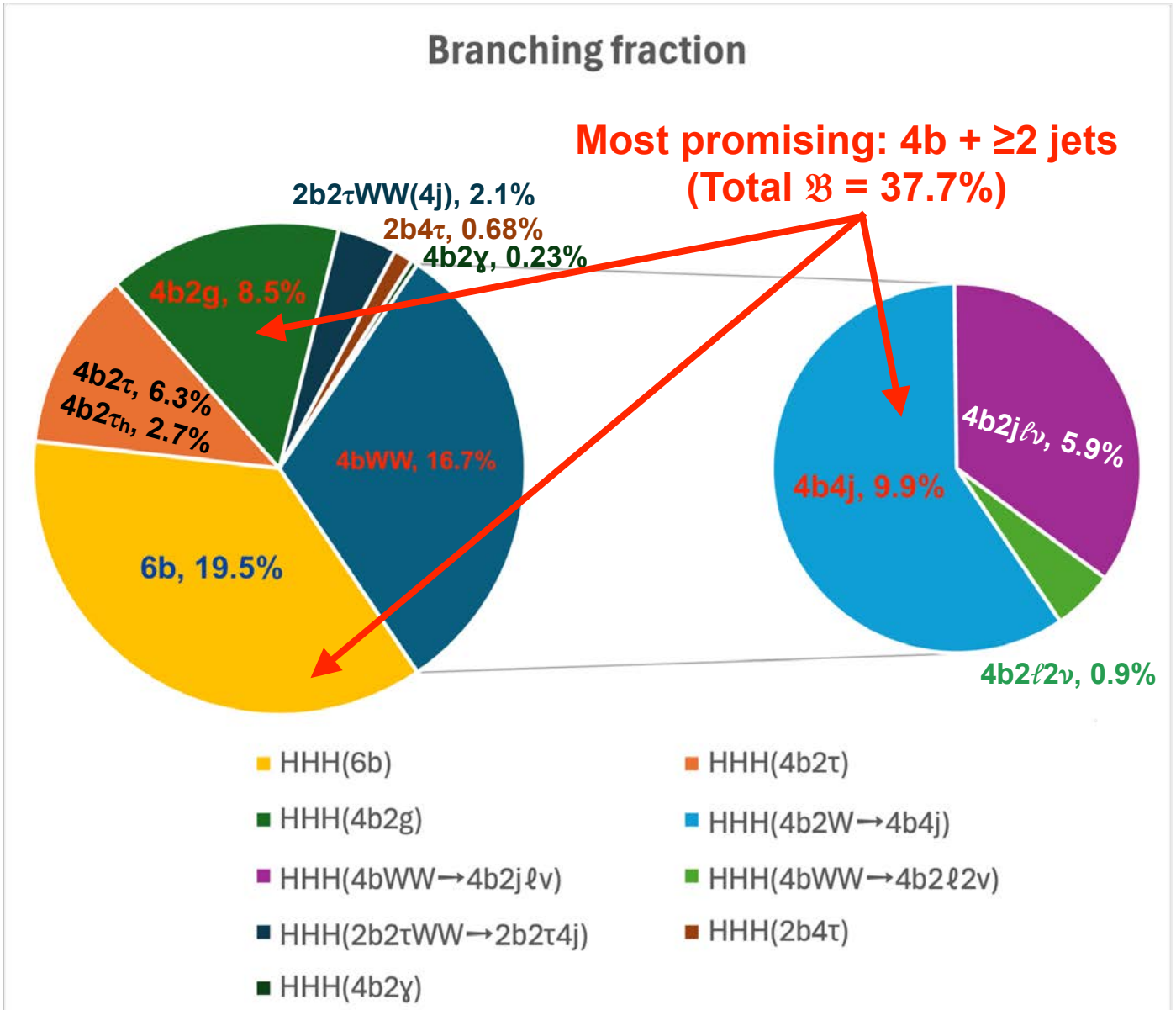
Decay Channels



TRSM Scenario

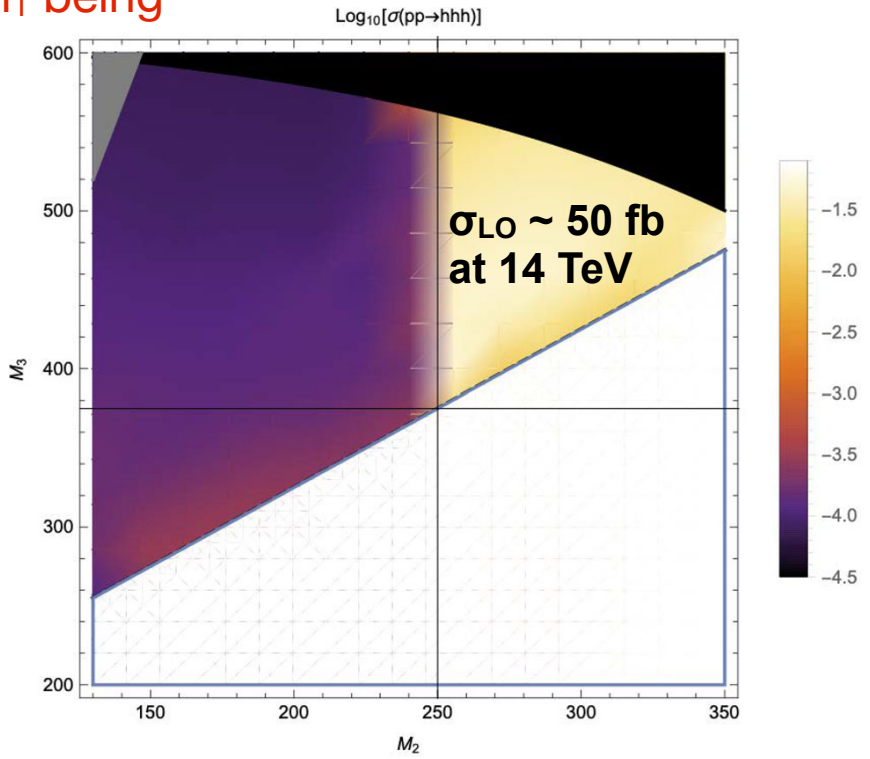
- Even more significant cross section enhancement is achieved in two real singlet models (TRSM)
  - Introduces two real singlets in addition to the SM Higgs doublet

$$\Phi = \begin{pmatrix} 0 \\ \frac{\phi_h + v}{\sqrt{2}} \end{pmatrix}, S = \frac{\phi_S + v_S}{\sqrt{2}}, \quad X = \frac{\phi_X + v_X}{\sqrt{2}}$$

  - After EWSB and mixing, results in three Higgs bosons h_1, h_2, h_3, with $M_1 < M_2 < M_3$; h_1 being the SM Higgs boson

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = R \begin{pmatrix} \phi_h \\ \phi_S \\ \phi_X \end{pmatrix}$$

  - The following production mechanism is possible:
    - $pp \to h_3 \to h_2 h_1 \to h_1 h_1 h_1$
  - Up to 2.5 orders of magnitude cross section amplification for relatives light $h_{2,3}$



Abouabid et al., EPJC 84 (2024) 1183

TRSM LHC Exclusion

- Projected exclusion for 10 benchmark points allows to probe them in the 6b final state with just 300 fb^{-1} of data, i.e., with LHC Run 2+3 data

Abouabid et al., EPJC 84 (2024) 1183

Label	(M_2, M_3) [GeV]	$\varepsilon_{\text{Sig.}}$	$S\|_{300\text{fb}^{-1}}$	$\varepsilon_{\text{Bkg.}}$	$B\|_{300\text{fb}^{-1}}$	$\text{sig}\|_{300\text{fb}^{-1}}$ (syst.)	$\text{sig}\|_{3000\text{fb}^{-1}}$ (syst.)
A	(255, 504)	0.025	14.12	8.50×10^{-4}	19.16	2.92 (2.63)	9.23 (5.07)
B	(263, 455)	0.019	17.03	3.60×10^{-5}	8.12	4.78 (4.50)	15.10 (10.14)
C	(287, 502)	0.030	20.71	9.13×10^{-5}	20.60	4.01 (3.56)	12.68 (6.67)
D	(290, 454)	0.044	37.32	1.96×10^{-4}	44.19	5.02 (4.03)	15.86 (6.25)
E	(320, 503)	0.051	31.74	2.73×10^{-4}	61.55	3.76 (2.87)	11.88 (4.18)
F	(264, 504)	0.028	18.18	9.13×10^{-5}	20.60	3.56 (3.18)	11.27 (5.98)
G	(280, 455)	0.044	38.70	1.96×10^{-4}	44.19	5.18 (4.16)	16.39 (6.45)
H	(300, 475)	0.054	41.27	2.95×10^{-4}	66.46	4.64 (3.47)	14.68 (4.94)
I	(310, 500)	0.063	41.43	3.97×10^{-4}	89.59	4.09 (2.88)	12.94 (3.87)
J	(280, 500)	0.029	20.67	9.14×10^{-5}	20.60	4.00 (3.56)	12.65 (6.66)

- These models contain both 3- and 2-body resonances, making it easier to cope with the backgrounds
- These are phenomenological projections, which likely will be exceeded by ATLAS and CMS

Second HHH Workshop

- Based on the success of the first HHH workshop, hosted the second one in Dubrovnik 2 months ago
- One of the goals was to organize contribution to the CERN Higgs Working Group YR5

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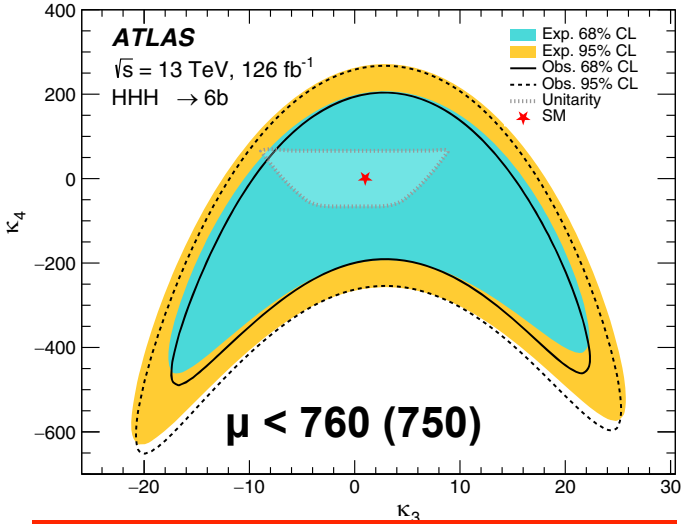
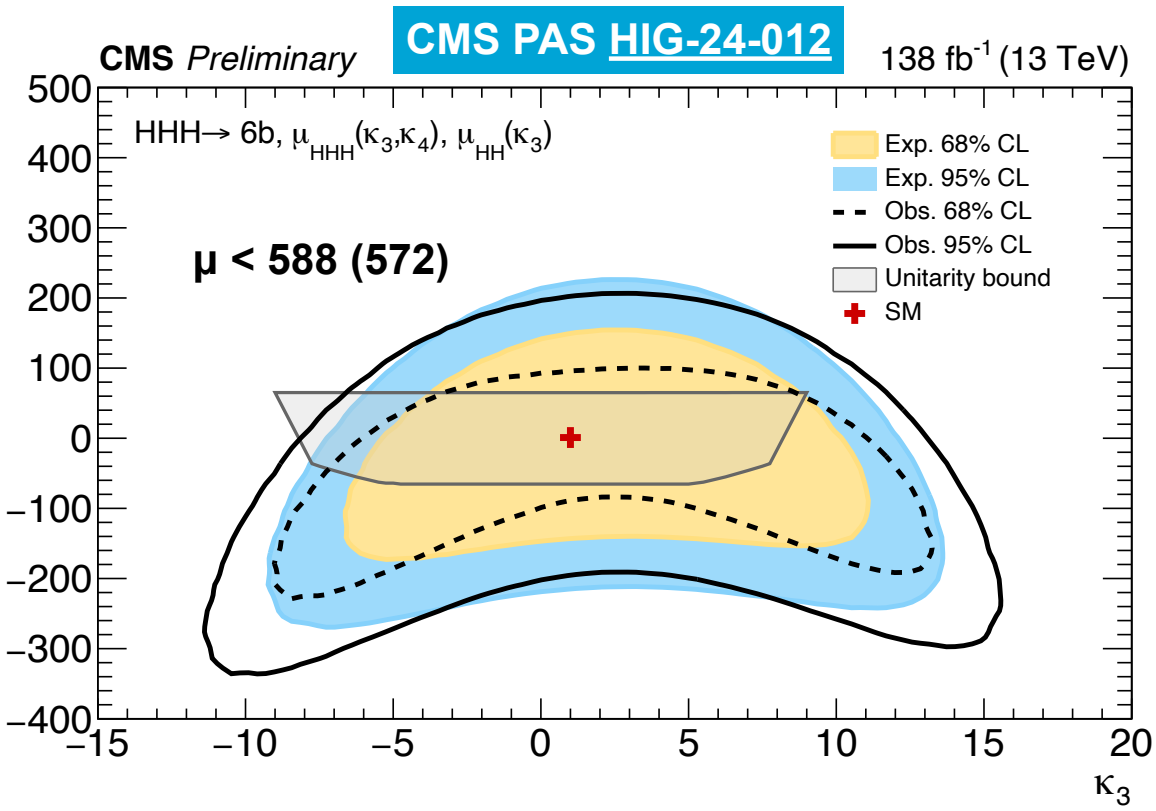
Even HHHappier

Workshop Highlights

- One of the workshop highlights was a brand new CMS HHH(6b) search, based on modern attention-based deep neural network SPANet, which reached the best sensitivity to date on the quartic HHHH coupling
  - See Marko Stamenkovic's talk this morning for detail



ATLAS, PRD 111 (2025) 032006

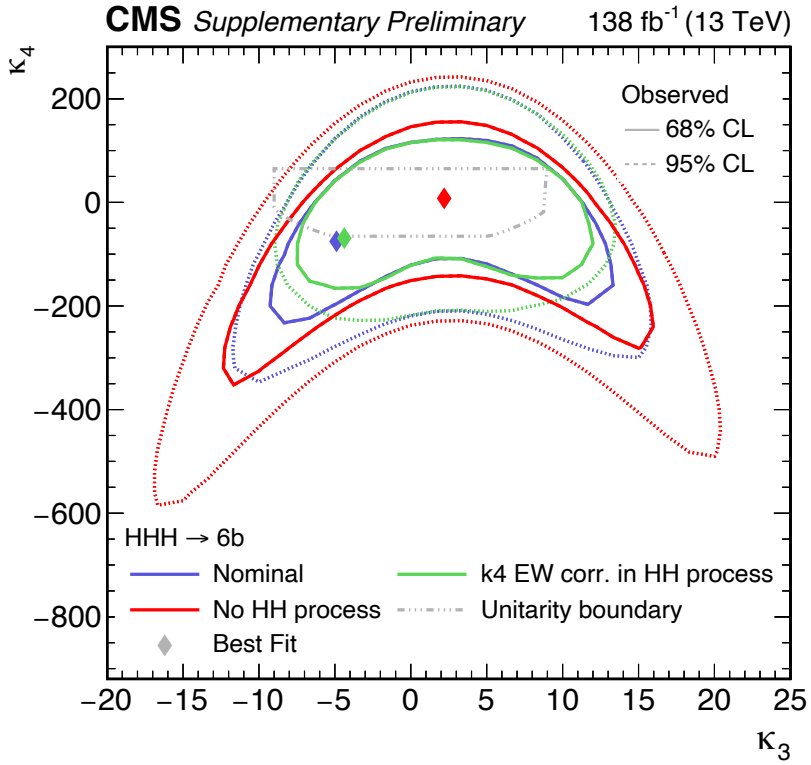


Comparison with ATLAS

- The comparison with ATLAS revealed that the ATLAS does not vary the HH background as κ_3 changes, while CMS does
  - This has sizable effect on the limits
- One of the conclusions of the workshop was that we should include both κ_3 and κ_4 effects on the HH background:

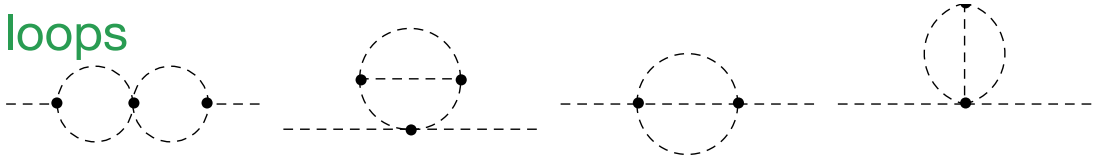
$$\mu_{2h}^{\text{HL-LHC}} = 2.18 - 1.50\kappa_3 - 1.00\cdot10^{-3}\kappa_4 + 3.24\cdot10^{-1}\kappa_3^2 + 3.95\cdot10^{-3}\kappa_3\kappa_4 + 5.54\cdot10^{-5}\kappa_4^2 - 1.56\cdot10^{-3}\kappa_3^2\kappa_4 - 3.78\cdot10^{-5}\kappa_3\kappa_4^2 + 9.56\cdot10^{-6}\kappa_3^2\kappa_4^2,$$

Haisch et al., arXiv:2505.20463

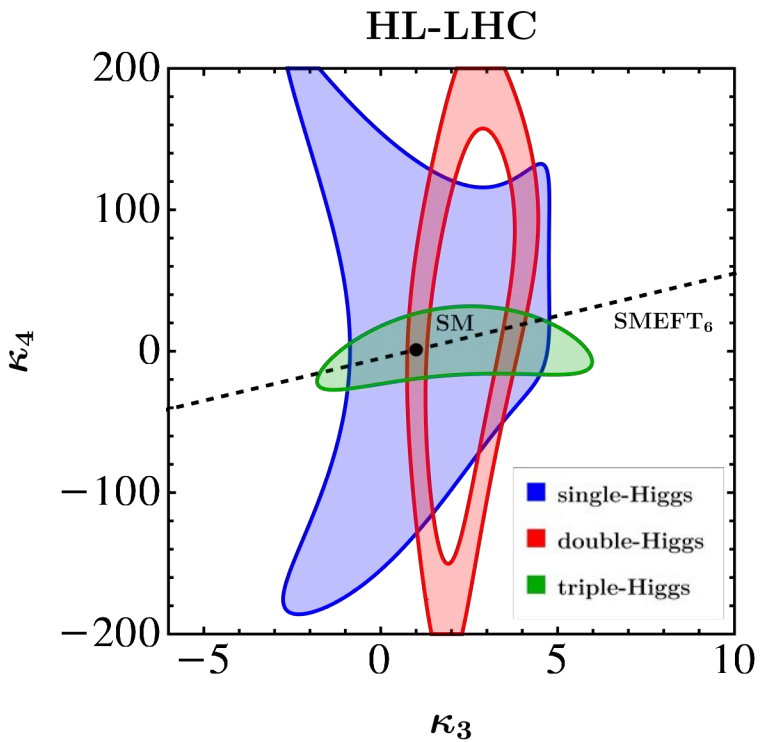


Sensitivity to λ_4 from Loops

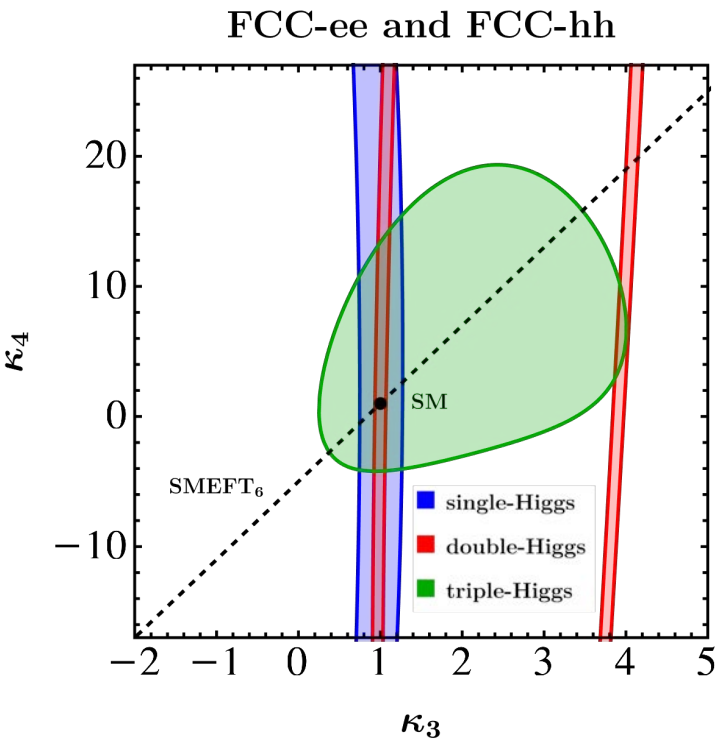
- Just like single Higgs boson production is sensitive to λ_3 at 1-loop level, there is also a sensitivity to λ_4 at two loops



- Similarly, double-Higgs production is sensitive to λ_4 at 1-loop level
- However, sensitivity is significantly worse than for HHH production (expectedly!)
- Talk by Giulia Zanderighi



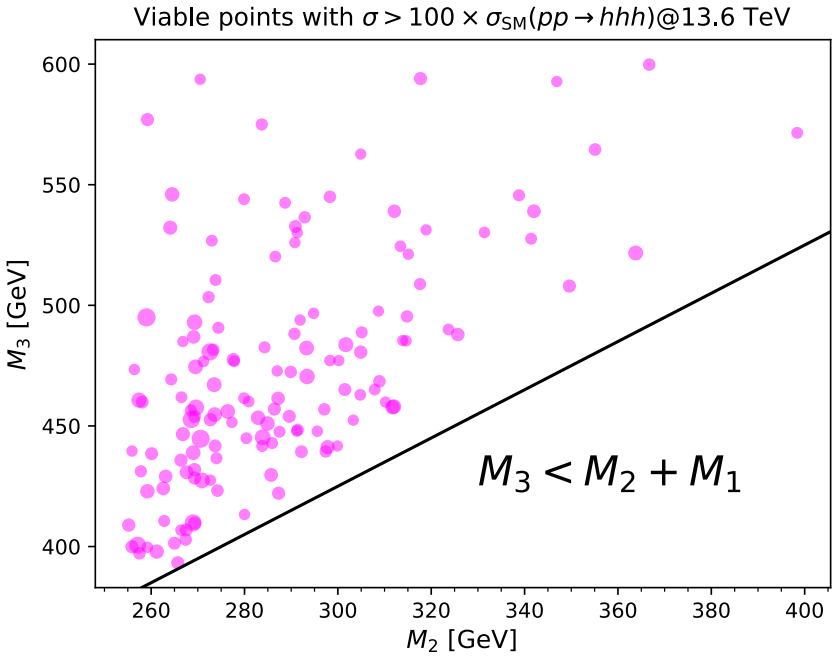
Haisch et al., arXiv:2505.20463



Connections with Cosmology

- There are a number of connections between the Higgs potential and both the EW vacuum stability and the EWPT in early universe
- The HHH production clearly contributes to these connections by constraining the parameters of the Higgs potential and is complementary to the cosmological observations, including the use of gravitational waves to study the EWPT
  - In particular, the strength of the first-order FOPT is proportional to $1/\lambda_4$
- For example, one could connect the enhanced HHH production in TRSM with the conditions needed for FO EWPT
- A scan within TRSM indicates the regions of the parameter space where the HHH cross section is enhanced by more than a factor of 100
- Analysis of all these points showed that FOPT is not realized in this parameter space (and generally for the case when both real singlets have non-zero vev at the present time)
- Talks by Tristan Du Pree and Osama Karkout

Karkout et al., JHEP 11 (2024) 077



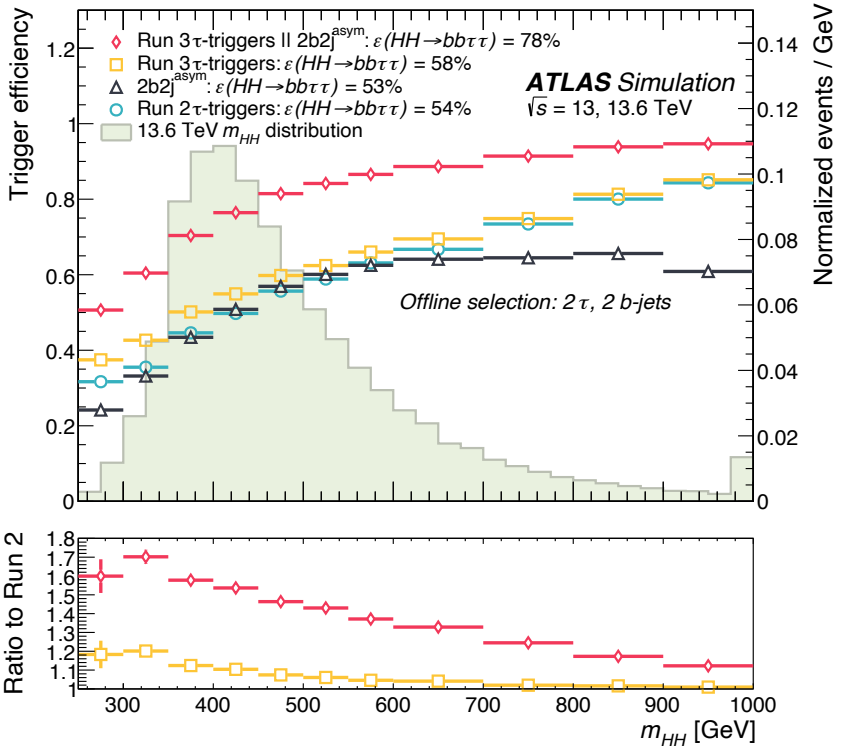
Experimental Challenges

- Given how small the cross section is, there are a number of experimental challenges
  - Efficient triggering on all-hadronic final states
  - Performant flavor tagging
  - Resolving the combinatorics (particularly for 6b channel)
  - Reliable background predictions
  - Large background rejection
- Many of them were addressed in the HHH White Paper and subsequent experimental studies
- A number of presentations from ATLAS and CMS experimentalists on these topics

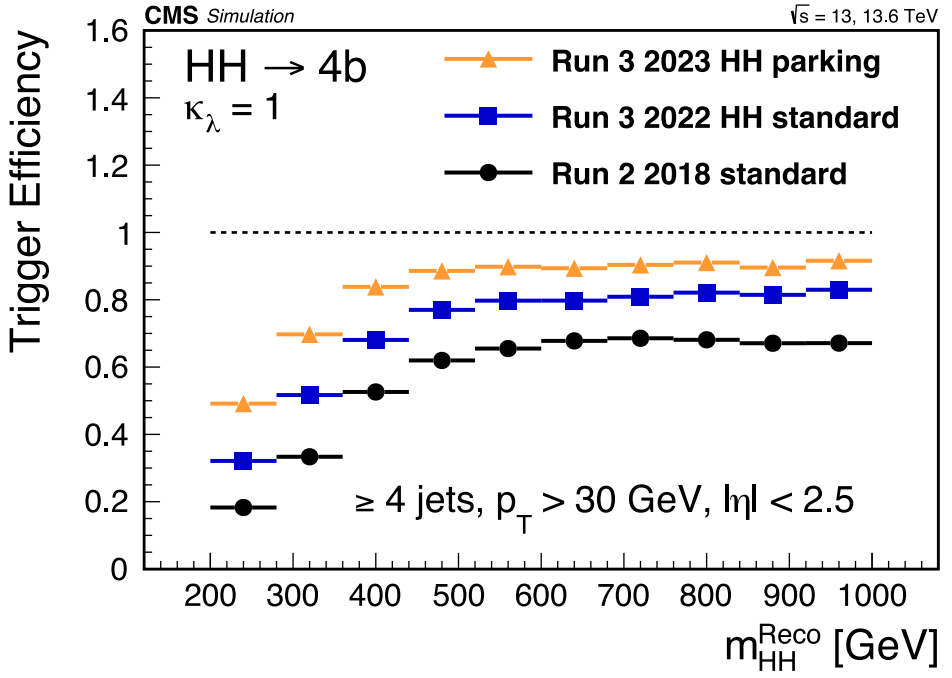
Triggering

- Both ATLAS and CMS have significantly revisited trigger strategy for HH(4b) and HH(2b2τ) for Run 3
- The HHH(6b) and HHH(4b+X) studies could piggy-back from these developments, showing an impressive improvement in the trigger performance (talks by Dennis Roy, Roshan Joshi)

ATLAS, JINST 20 (2025) P03002



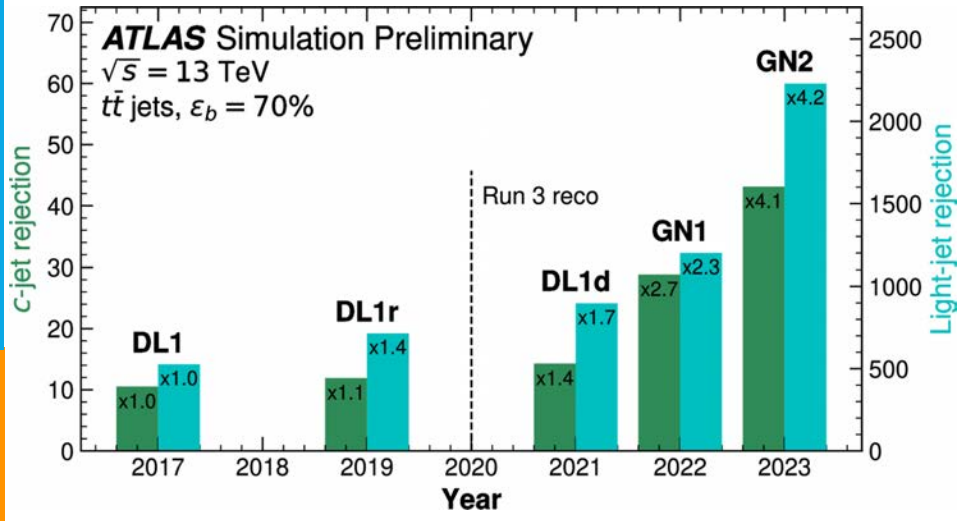
CMS Phys. Rept. 1115 (2025) 678



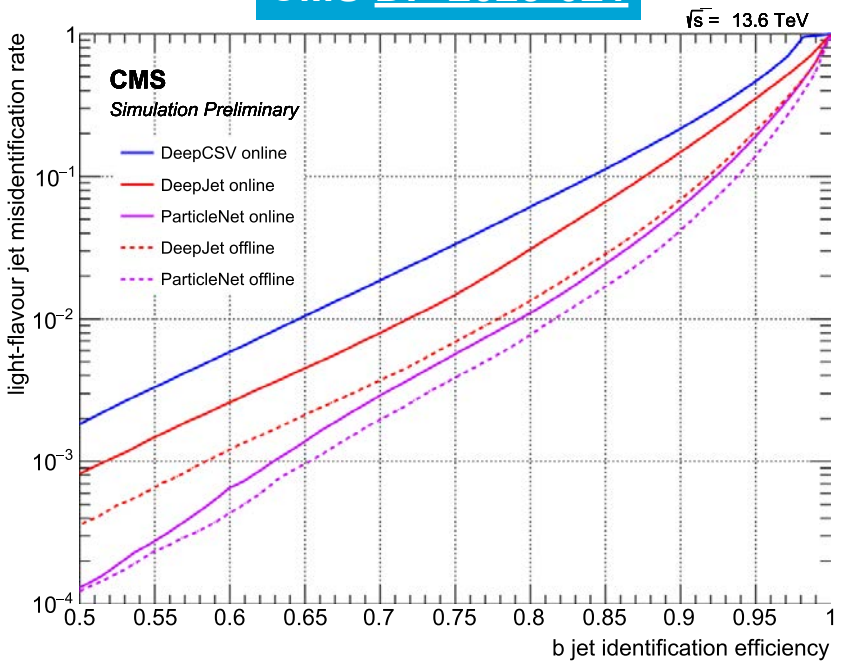
Flavor Tagging

- Similar improvement in the area of flavor tagging, including double-b taggers made possible by advanced machine-learning techniques (GNNs, transformers)
- Background rejection improved by an order of magnitude or more, both online and offline, at a constant signal efficiency
- Talks by Clara Ramon Alvarez, Jurjan Bootsma, Loukas Gouskos

ATLAS FTAG-2023-01

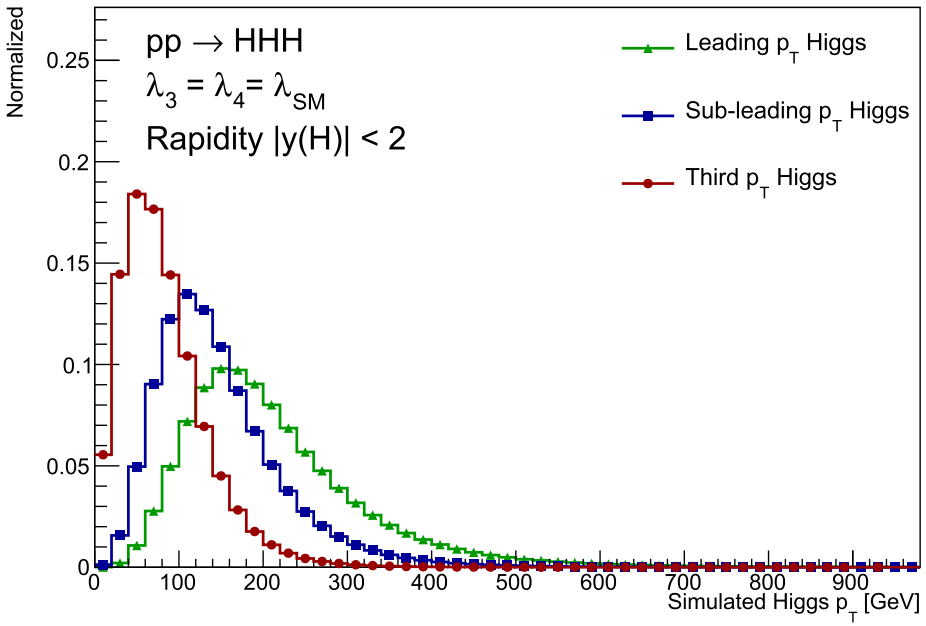


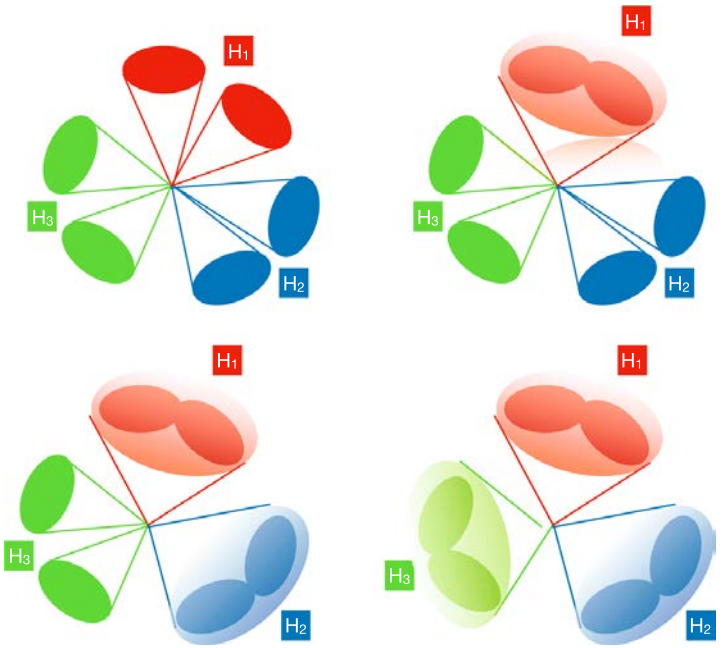
CMS DP-2023-021



Boost or Bust!

- Generally the combinatorics of arranging 6b jet into 3 Higgs candidates is large: $C_6^2 C_2^4 C_2^2 / 3! = 15$ combinations
- However, the Higgs bosons are produced with a quite large p_T (~200 GeV for the leading one!), so jet merging is often observed
- With one merged jet, the combinatorics becomes $C_2^4 C_2^2 / 2! = 3$, and with two or more merged jets, the combinatorics is 1!

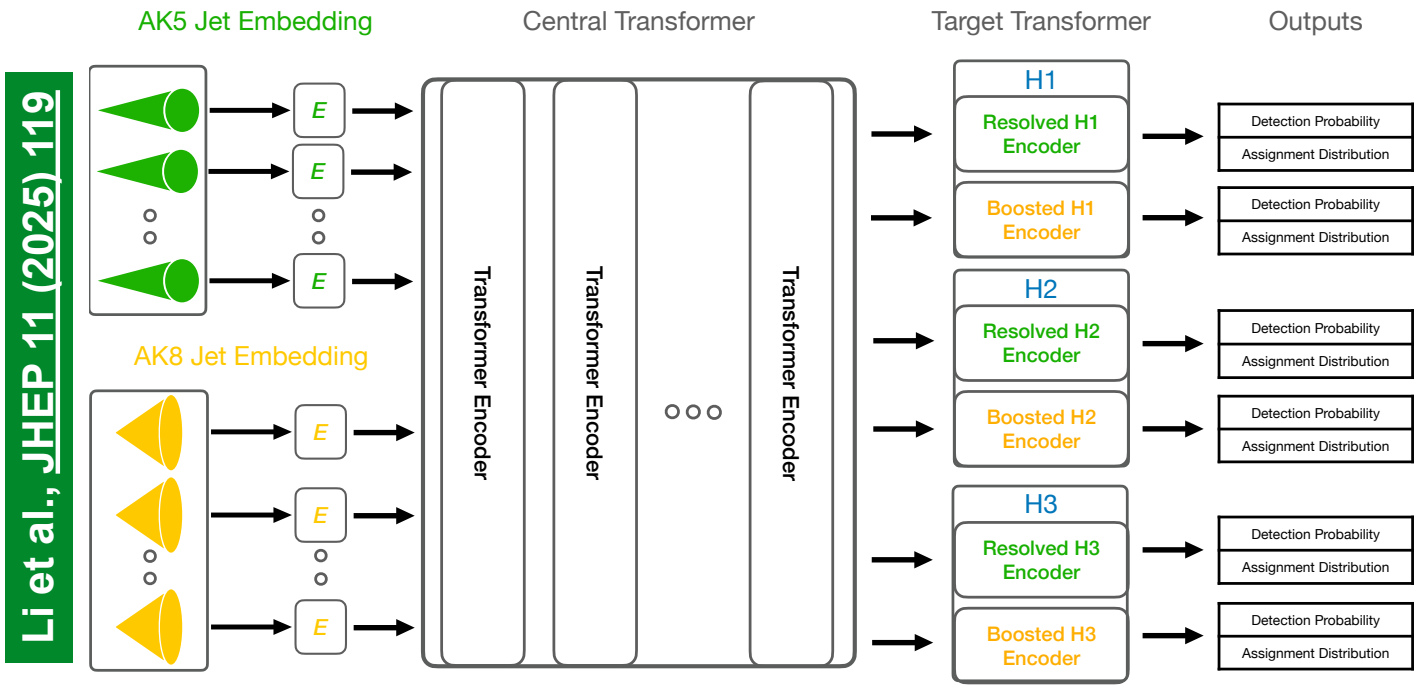




Abouabid et al., EPJC 84 (2024) 1183

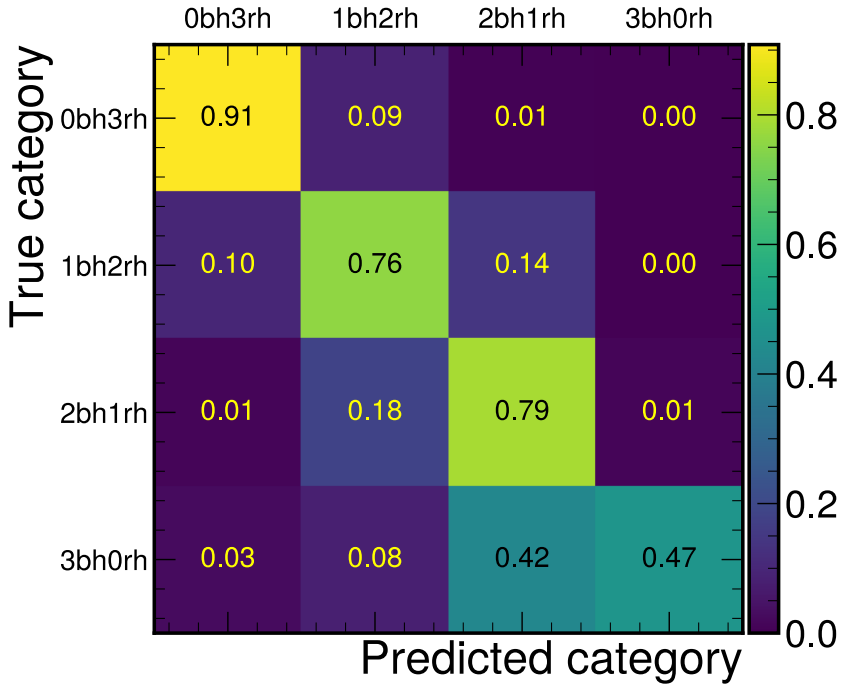
Machine Learning

- HHH search is a fruitful ground for advanced ML approaches
  - In addition to ML in jet taggers, also in assigning multiple jets to Higgs bosons and in reducing the dominant backgrounds
- One such advanced approach pursued in the CMS H(6b) search is a symmetry-preserving attention-based transformer DNN SPANet [Shmakov et al. Sci. Post. Phys. 12 (2022) 178]
- The input features include all AK5 jets and all AK8 jets, which are then matched to three Higgs boson candidates, either in the resolved or merged (low combinatorics!) regimes

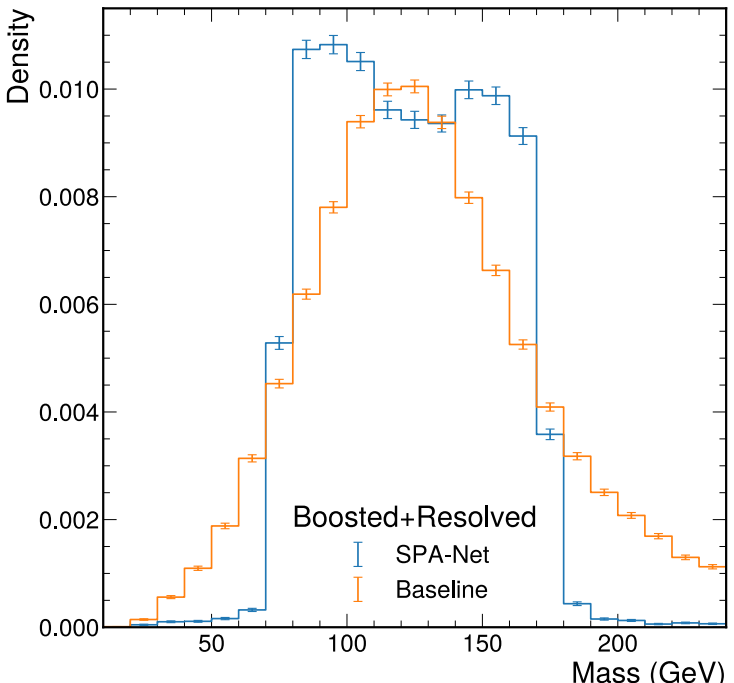


SPANet Classification

- The transformer encoding is permutation invariant and optimizes the accuracy of assigning jets to Higgs candidates
- The mass bias is explicitly removed by training on several Higgs boson mass hypotheses in the 75-175 GeV range and reweighting the events to achieve the output uniform in mass for each topology
- Outperforms the baseline model based on the minimizing the mass differences between three candidates by a factor of 2!

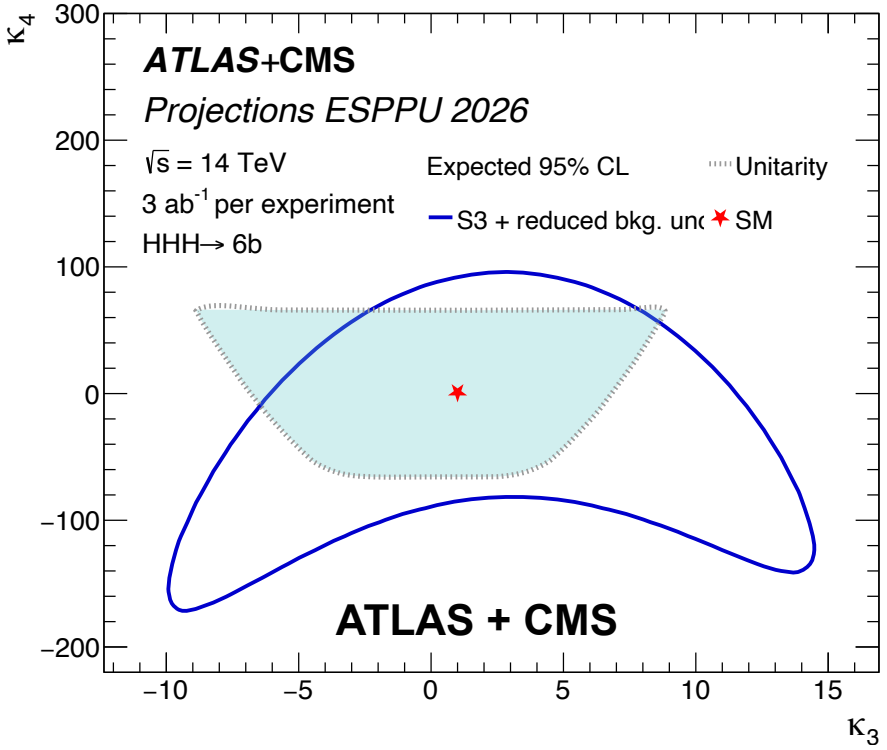


Li et al., JHEP 11 (2025) 119



Toward the Future

- ATLAS and CMS submitted projections for HL-LHC based on the published ATLAS analysis
  - Similar to early HH projections, these are very conservative and likely to be exceeded already with Run 3 data
  - In fact, the CMS Run 2 expected limits on κ_3 are already close to this projection - hence a brand new projection!



ATLAS & CMS, arXiv:2504.00672

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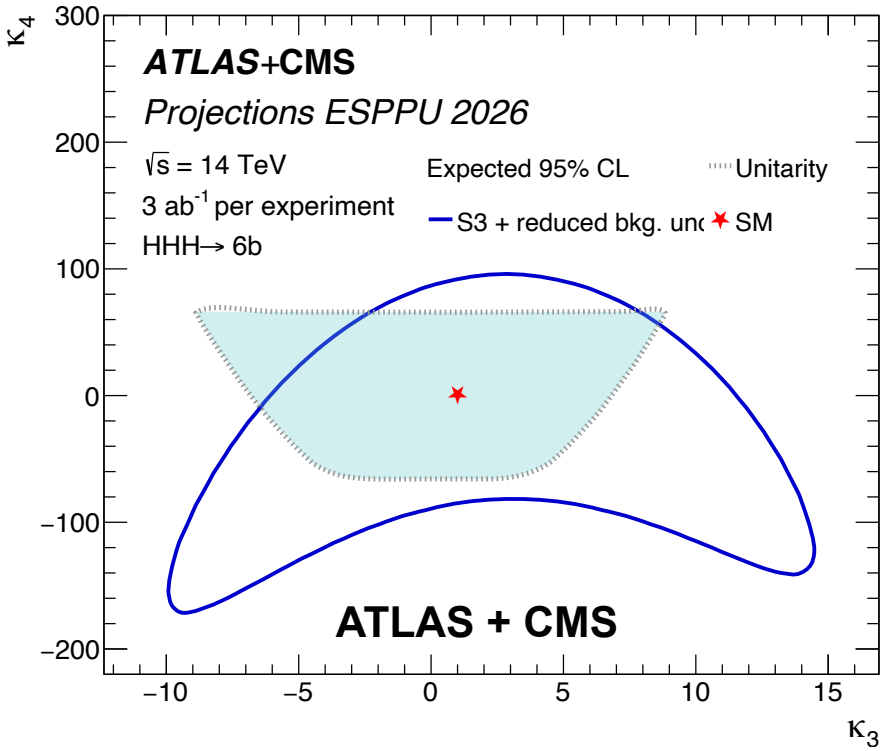
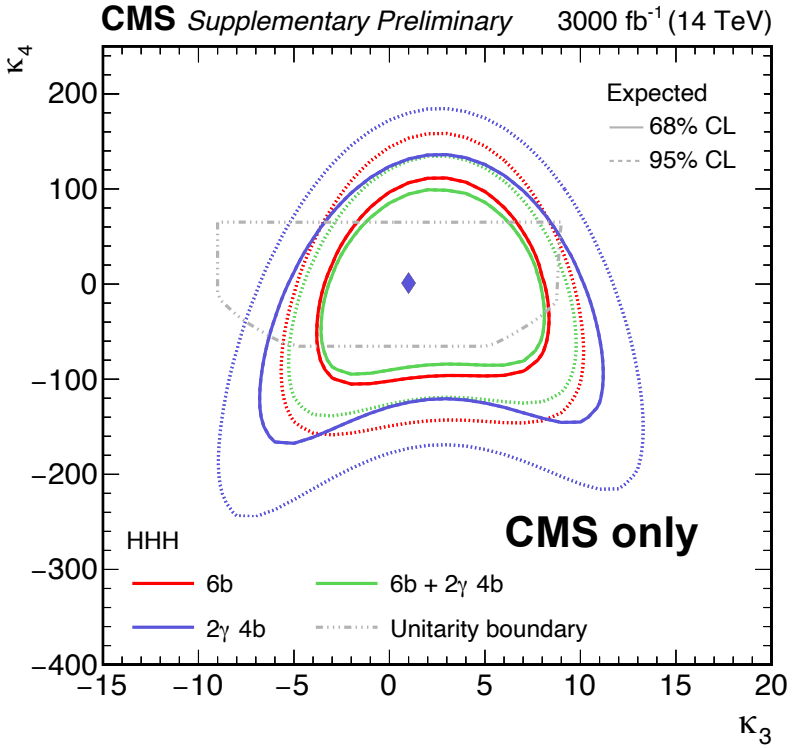
ATLAS & CMS, arXiv:2504.00672



CMS PAS HIG-24-012



Wishlist for YR5

- Discussion led by the HHH WG4 subgroup conveners
- Cross section

de Florian, Fabre, Mazzitelli
JHEP 03 (2020) 155

  - The NNLO ggF cross section and NNLO/LO K-factor have been calculated only for 14 and 100 TeV
  - The way experiments handle these is to do the 13 or 13.6 LO generation with MadGraph5_aMCNLO and use the 14 TeV K-factor
  - Close, but we should really add the 13 and 13.6 points to the NNLO calculations
- EW corrections for the HH background

Haisch et al.,
arXiv:2505.20463

  - Would like to have them calculated directly for 13 and 13.6 TeV
- New benchmark points for TRSM in view of new constraints
- Updated HL-LHC projections for ATLAS+CMS

Planning the tHHHird Workshop!

- Planning to organize it in Dubrovnik in 2027
- You are cordially invited to join!