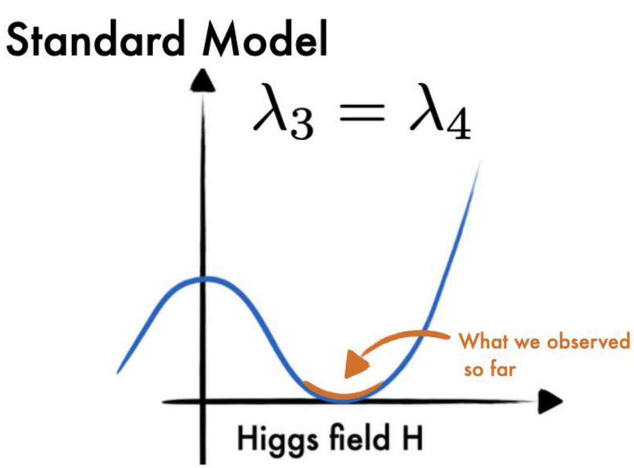
TRIPLE HIGGS PRODUCTION AT THE LHC AND BEYOND

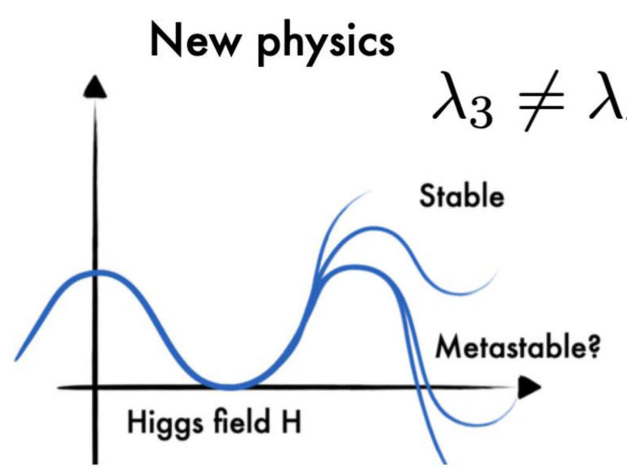
Outline

- ✦ Why triple Higgs studies?
- ✦ Production and decay
- ✦ Complementarity with HH studies
- ✦ First searches for HHH production
- ✦ Future directions

Introduction

- In the SM, after the EWSB, the Higgs potential is given by $\mathscr{L} = \frac{1}{2}m_h^2 h^2 + \lambda v h^3 + \frac{1}{4}\lambda h^4$, with $\lambda = \frac{m_h^2}{2v}$
- Thus, the standard model fixes the relative size of the triple and quartic Higgs boson self-coupling, which guarantees the EW vacuum stability under such a potential
- Generally speaking, this does not have to be the case and in beyond-the-SM scenarios, the two couplings, referred to as λ_3 and λ_4, could differ from one another: $\mathscr{L} = \frac{1}{2}m_h^2 h^2 + \lambda_3 v h^3 + \frac{1}{4}\lambda_4 h^4$
- This has important implications for the EW vacuum shape and stability





Why Looking for HHH Production?

- Just like HH production gives a tree-level access to the trilinear coupling λ_3, HHH production is the lowest level process directly accessing λ_4 (at tree level)
  - Importantly, it also is quite sensitive to the λ_3 coupling (also at tree level), and as such complements HH production as a tool for studies of λ_3
  - It also offers the most straightforward way to check if the SM relationship, $\lambda_3 = \lambda_4$, holds
- Until recently, this process has not received a lot of theoretical or experimental attention, which has now changed (as of ~2 years ago)
- Very active area of studies, both theoretical and experimental, as evident from the creation of the HHH Working Group within the WG4 of the LHC Higgs Working Group earlier this year (more on that later)

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Kick-Off 2023 Workshop

- ✦ We had a kick-off HHH Workshop in Dubrovnik in July 2023

- ✦ Resulted in the HHH White Paper [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

Check for updates

Review

HHH whitepaper

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HHHappy Crowd

HHH Production

- The main challenge is a very small production cross section for HHH, even at the FCC-hh
- Calculations in the SM exist at NNLO accuracy in QCD:
  - $\sigma_{HHH} \approx$ 0.1 fb (@13-14 TeV, LHC)
  - $\sigma_{HHH} \approx$ 6 fb (@100 TeV, FCC-hh)

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

- Seemingly impossible process to study at the LHC, so why bother now?
  - Because of a number of BSM scenarios!
  - Include non-resonance and resonance enhancementc of the HHH cross section
- Before looking at these details, let's see why the cross section is so small

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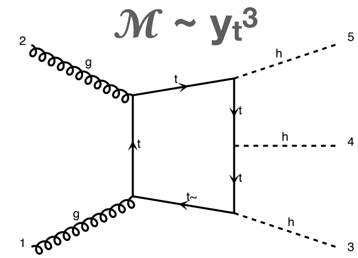
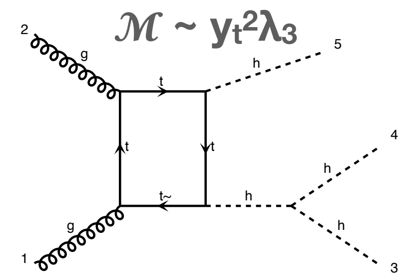
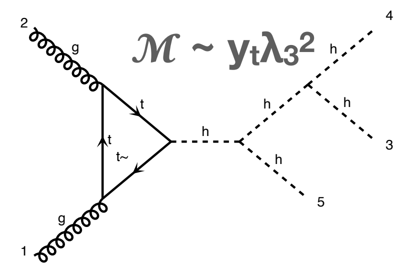
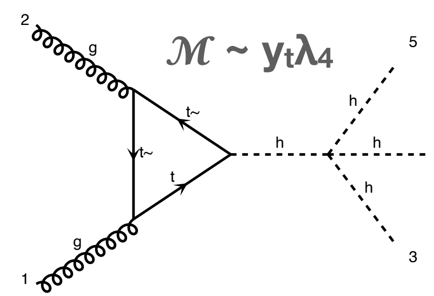
Diagrammatics

- There are four classes of Feynman diagrams contributing to the production (dominated by gluon fusion)
  - LO: 50 top quark loop diagrams + 50 bottom loop ones; ignore the latter
- Four classes:
  - Pentagon: ~y_t^3 - 24 diagrams; destructively interfere with the "signal"
  - Box: ~$y_t^2\lambda_3$ - 18 diagrams, proportional to λ_3 - destructive inerference
  - Triangle: ~$y_t\lambda_3^2$ - 6 diagrams, proportional to λ_3^2 - destructive interference
  - Quartic: ~$y_t\lambda_4$ - 2 diagrams, sensitive to quartic coupling - do not interfere with other diagrams to the fist order
- Given the $\lambda_3 = \lambda_4 = 0.13$, while $y_t \approx 1$ in the SM, box diagrams dominate in the SM
  - Strong destructive interference suppresses the SM cross section (similar to the HH case)

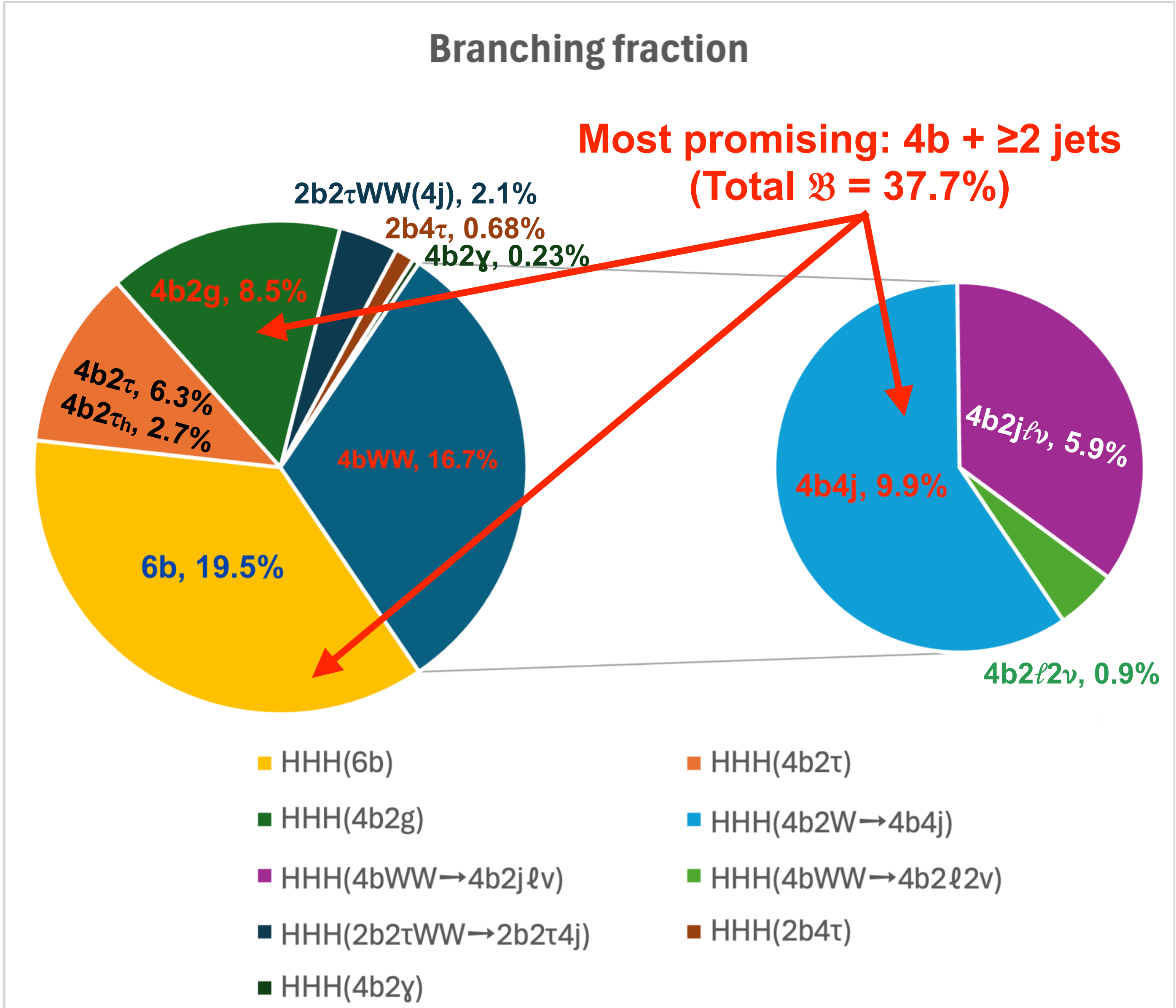






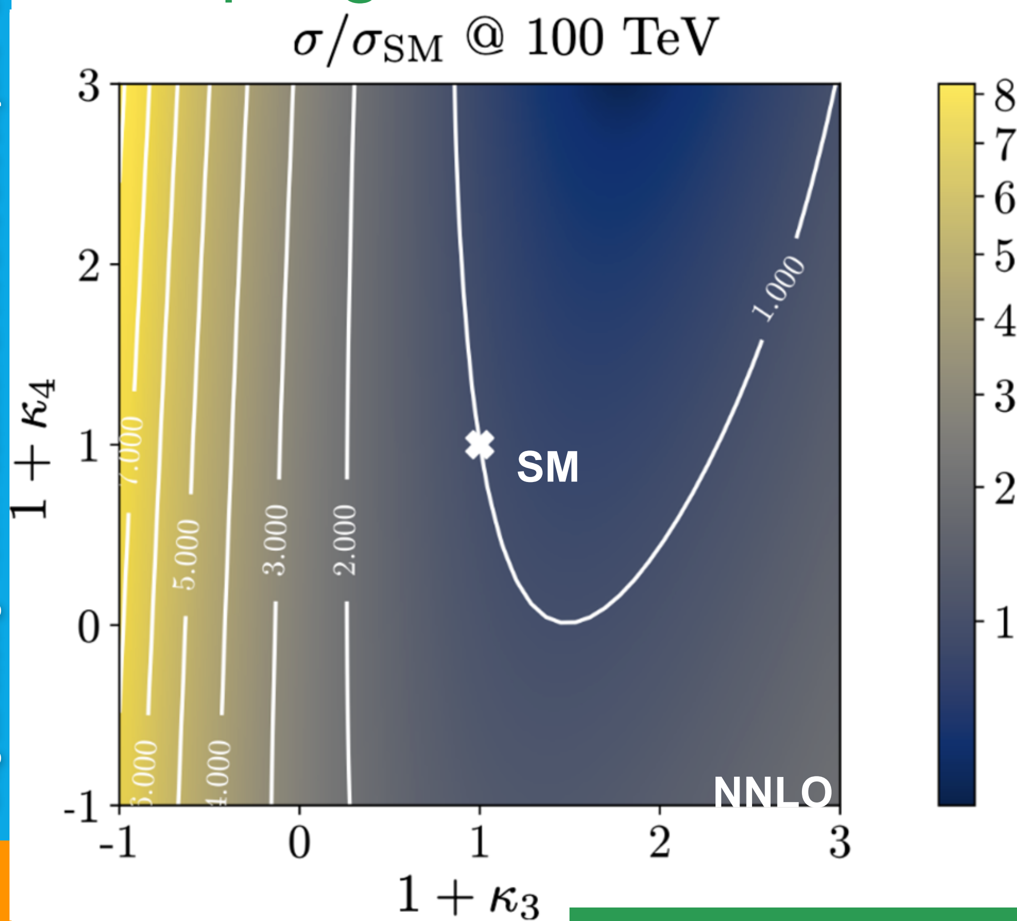


Decay Channels

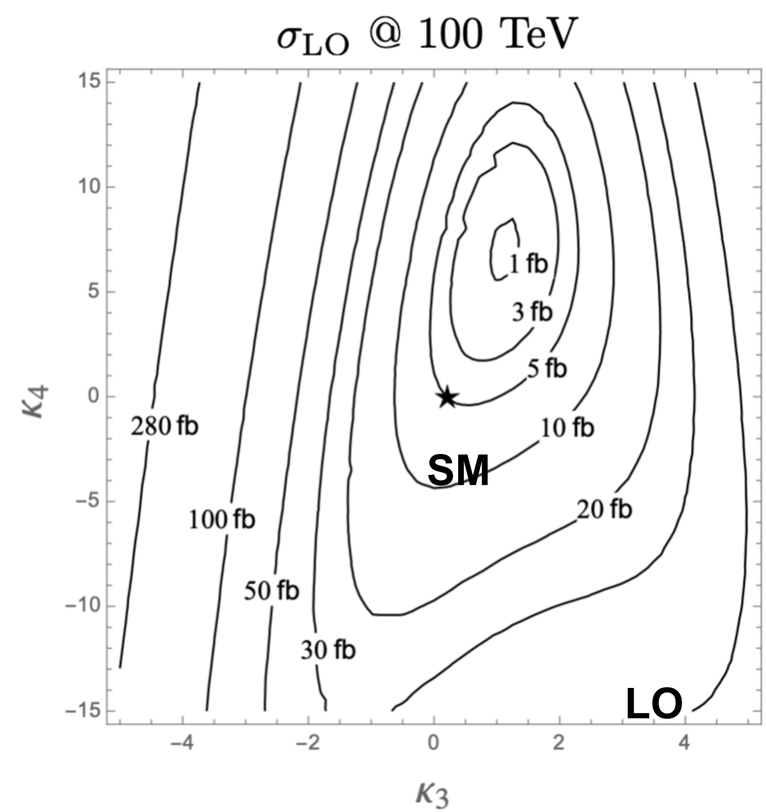


Coupling Dependence

- Here is the cross section dependence on the coupling modifiers $\kappa_i = \lambda_i/\lambda_{SM}$,



Very significant enhancement for large κ



Abouabid et al., EPJC 84 (2024) 1183

TRSM Scenario

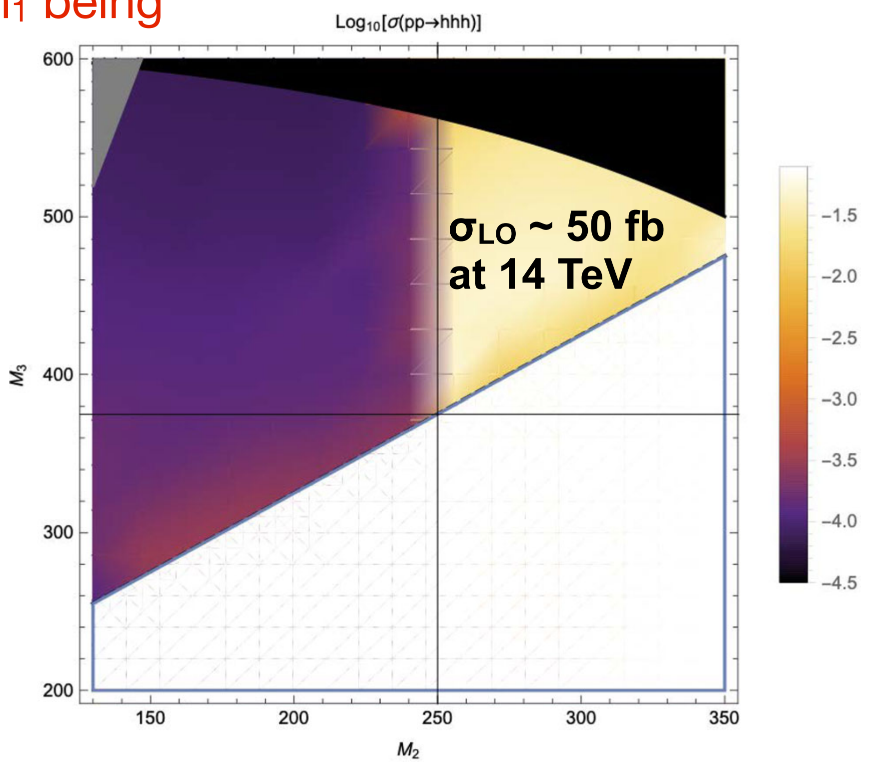
- Even more significant cross section enhancement is achieved in two real singlet models (TRSM)
  - Introduces two real singlets in addition to the SM Higgs doublet

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

  - 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]	$\varepsilon_{Sig.}$	$S\|_{300fb^{-1}}$	$\varepsilon_{Bkg.}$	$B\|_{300fb^{-1}}$	$sig\|_{300fb^{-1}}$ (syst.)	$sig\|_{3000fb^{-1}}$ (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

Other Extensions

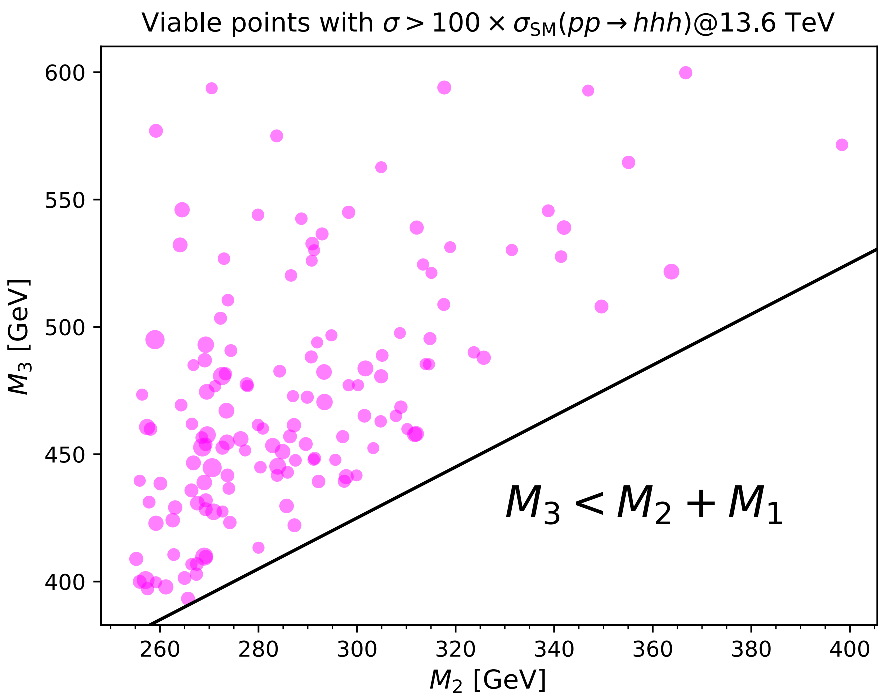
- The HHH resonance signature is also possible in other SM extensions, e.g., C2HDM (complex two Higgs doublet model), N2HDM (next-to-2HDM), and NMSSM
  - In this models, one could have pp → h_2h_1 → $h_1h_1h_1$, i.e., without a 3-body resonance, but with a 2-body resonance present
    - Di-Higgs production can win over single-Higgs production!
  - The cross section is similarly enhances by 2-3 orders of magnitude for reasonably light extra Higgs bosons, and can be as high as ~100 fb at the LHC
  - These channels also could be probed at the (HL-)LHC

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

Karkout et al., JHEP 11 (2024) 077

- 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 parameters space (and generally for the case when both real singlets have non-zero vev at the present time)



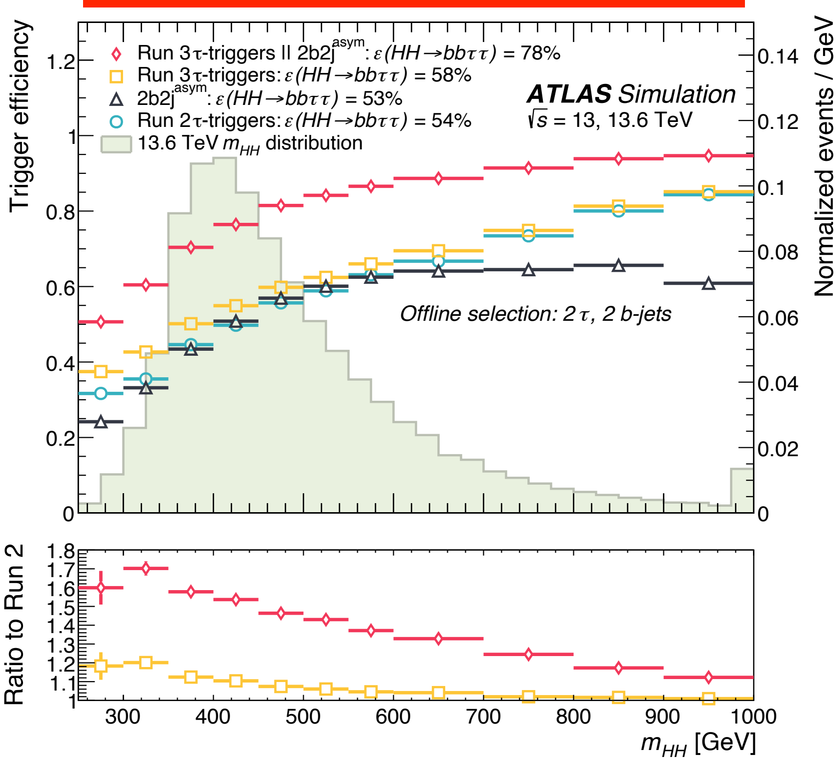
Experimental Challenges

- 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
- Will highlighted a few in this talk

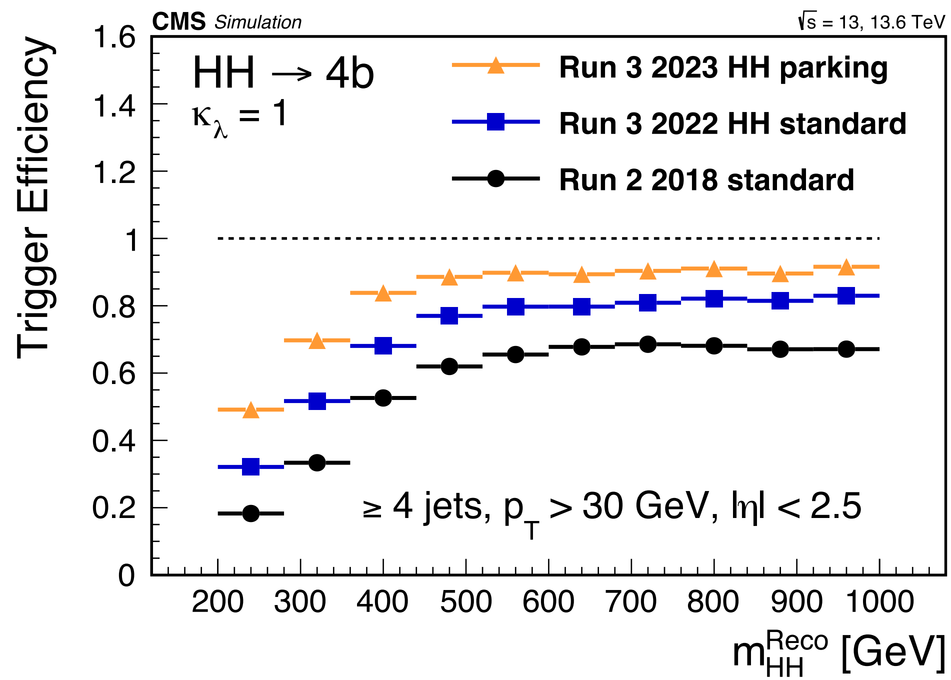
Triggering

- Both ATLAS and CMS have significantly revisited trigger strategy for HH(4b) 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

ATLAS, JINST 20 (2025) P03002



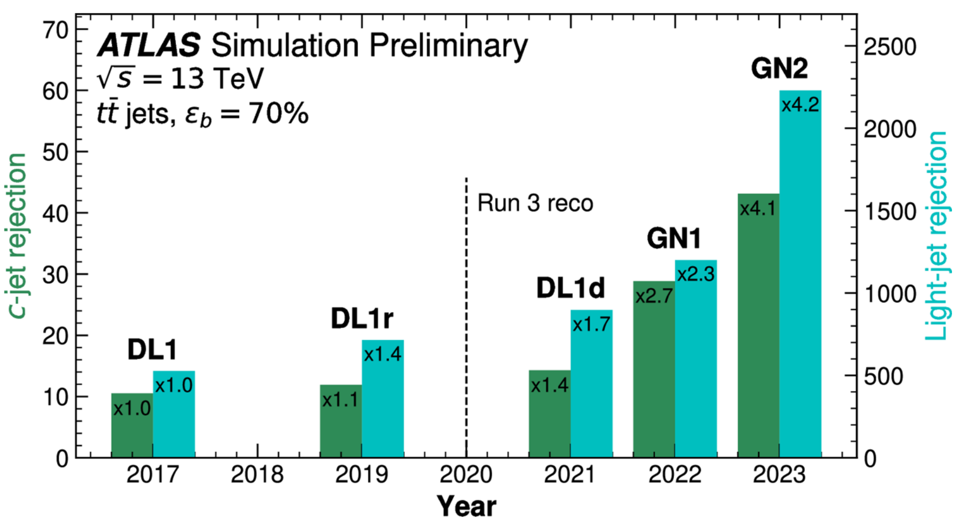
CMS Phys. Rept. 1115 (2025) 678



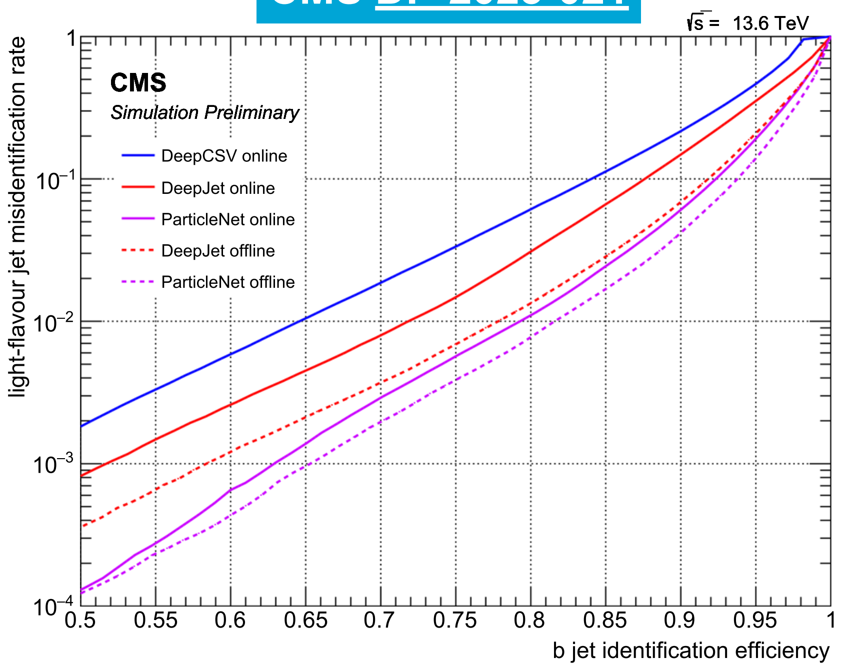
Flavor Tagging

- 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

ATLAS FTAG-2023-01



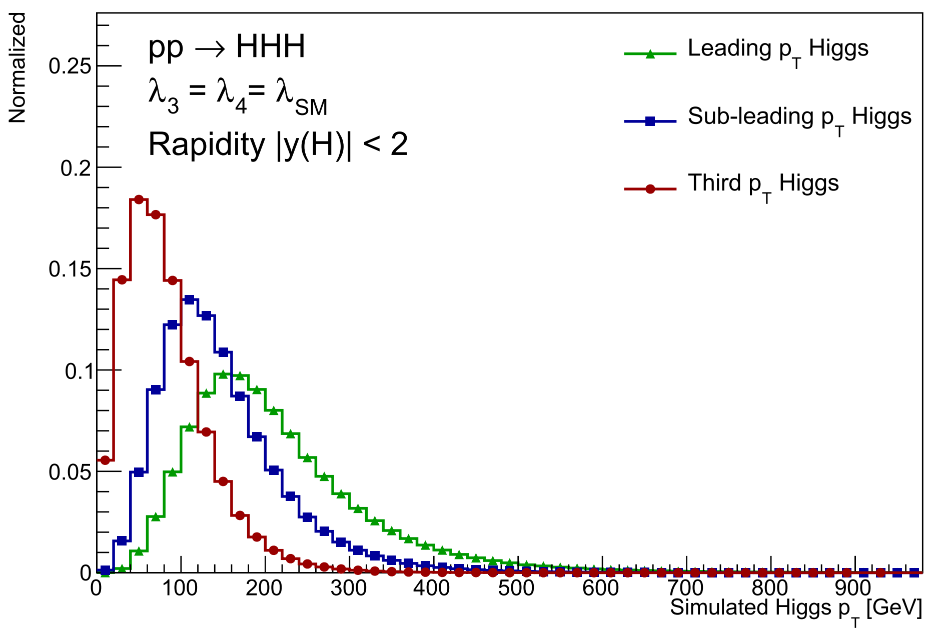
CMS DP-2023-021

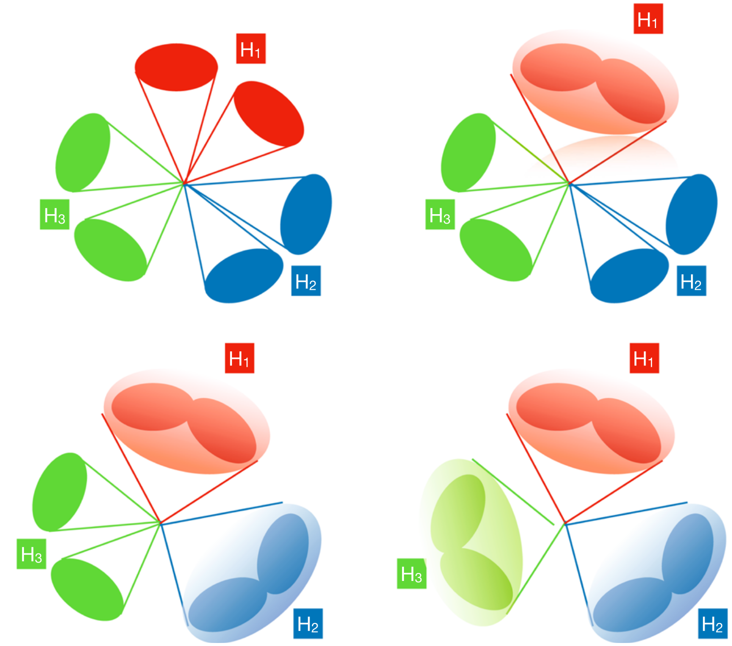


Boost or Bust!

- 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

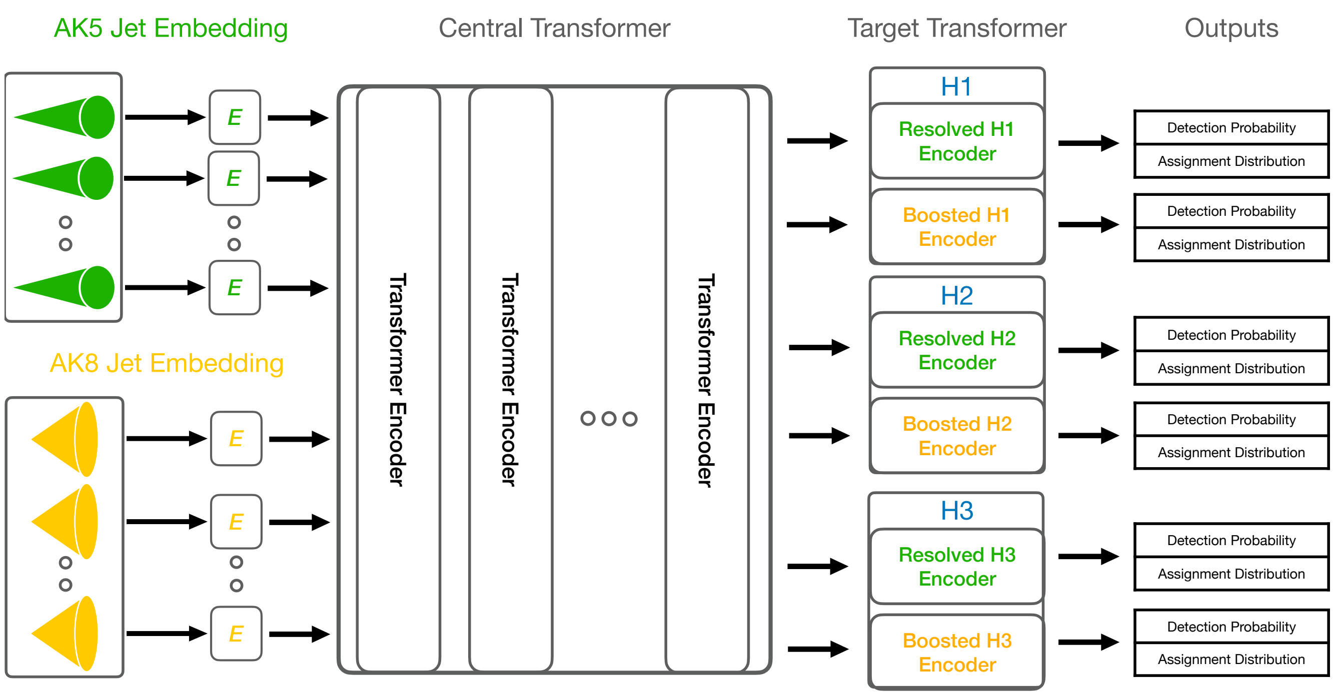




Machine Learning

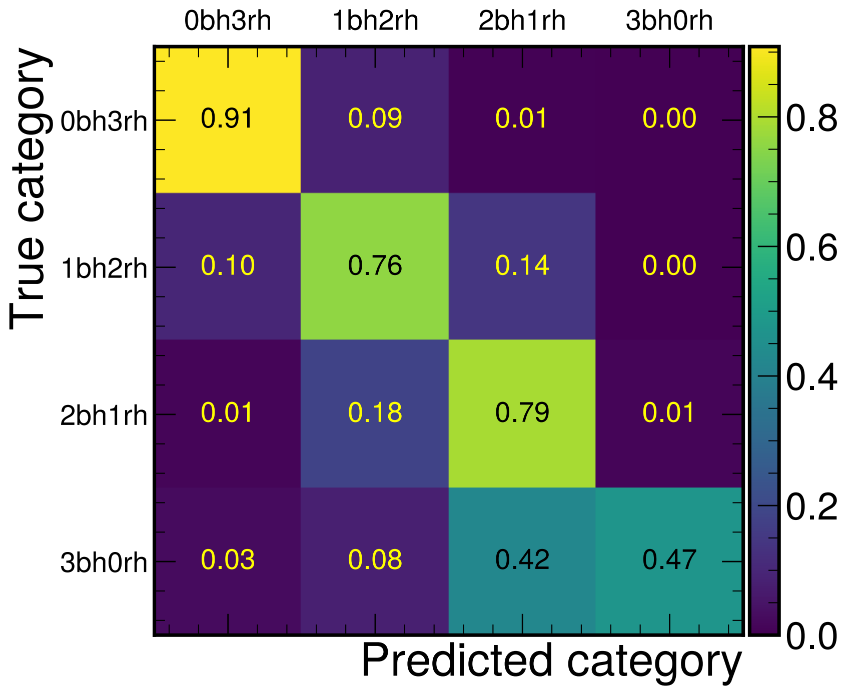
- HHH search is a fruitful ground for advanced ML approaches
  - In addition to ML in jet taggers, also in assigning multiple jets to Higgs bosons and in reducing the dominant backgrounds
- One such advanced approach pursued in the CMS H(6b) search is a symmetry-preserving attention-based transformer DNN SPAHet [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

Li et al., arXiv:2412.03819



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!



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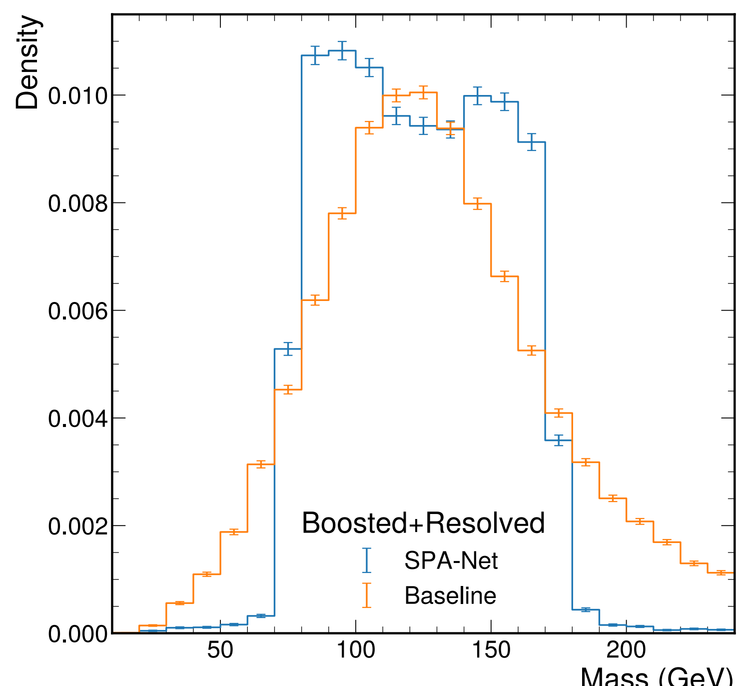
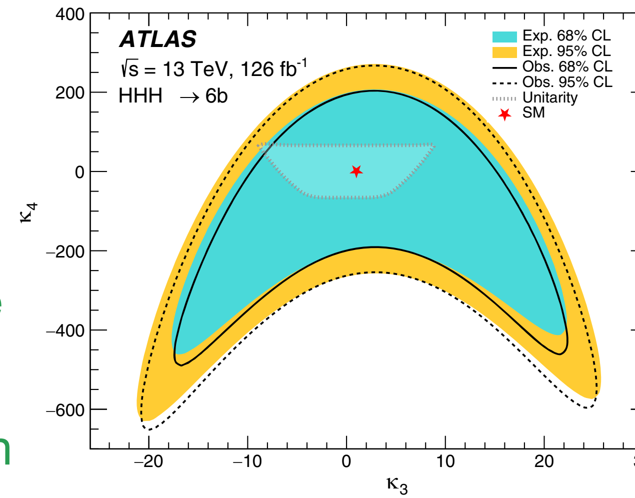


ATLAS Search

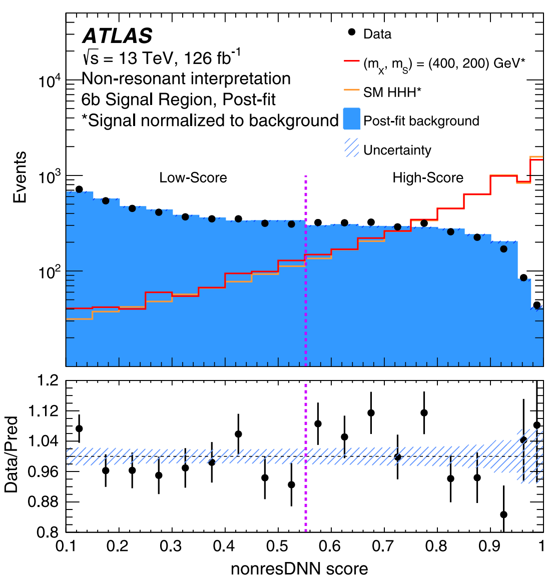
- ATLAS was the first to publish an HHH search
  - Done in the most sensitive 6b channel, both the resonance and non-resonance scenarios
  - Uses the ≥6b signal region, and 4b and 5b control regions to predict background (77% b tagging efficiency per jet)
  - Simple accounting for the combinatorics via 6b pairing minimizing $|M(h_1) - 120\ \mathrm{GeV}| + |M(h_2) - 115\ \mathrm{GeV}| + |M(h_3) - 110\ \mathrm{GeV}|$, with the nominal masses coming from simulation
    - Correct pairing is achieved in 49% of SM events and 30-84% of BSM events
  - The background rejection is achieved via a DNN with the input features based on the jet kinematics and correlations
    - Separate DNNs are trained for 4b, 5b, 6b regions, and resonant/non-resonant searches
    - The dominant QCD background is estimated from the 4b/5b control regions

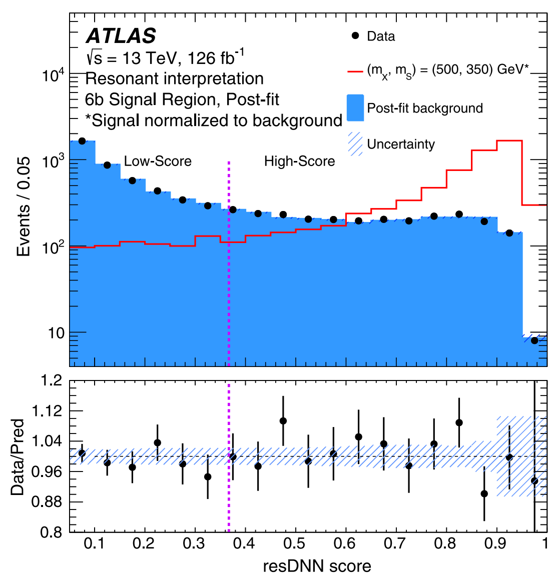
ATLAS Search (cont'd)

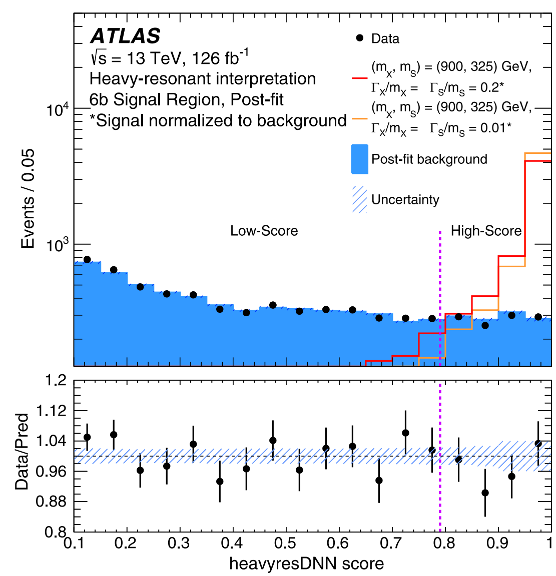
- Three models tested: nonresonant production, TRSM production, and generic heavy-resonance production of *X* and *S* scalars (heavier than within TRSM) with the $pp \to X \to Sh \to hhh$ decay
- Nonresonant case limits are shown on the left - the first limits on κ_4 ever set
- Resonant limits result in 95% cross section limits in the 50-200 fb range for the TRSM and in the 5-10 fb range for most of the heavy resonance scenario



ATLAS, PRD 111 (2025) 032006



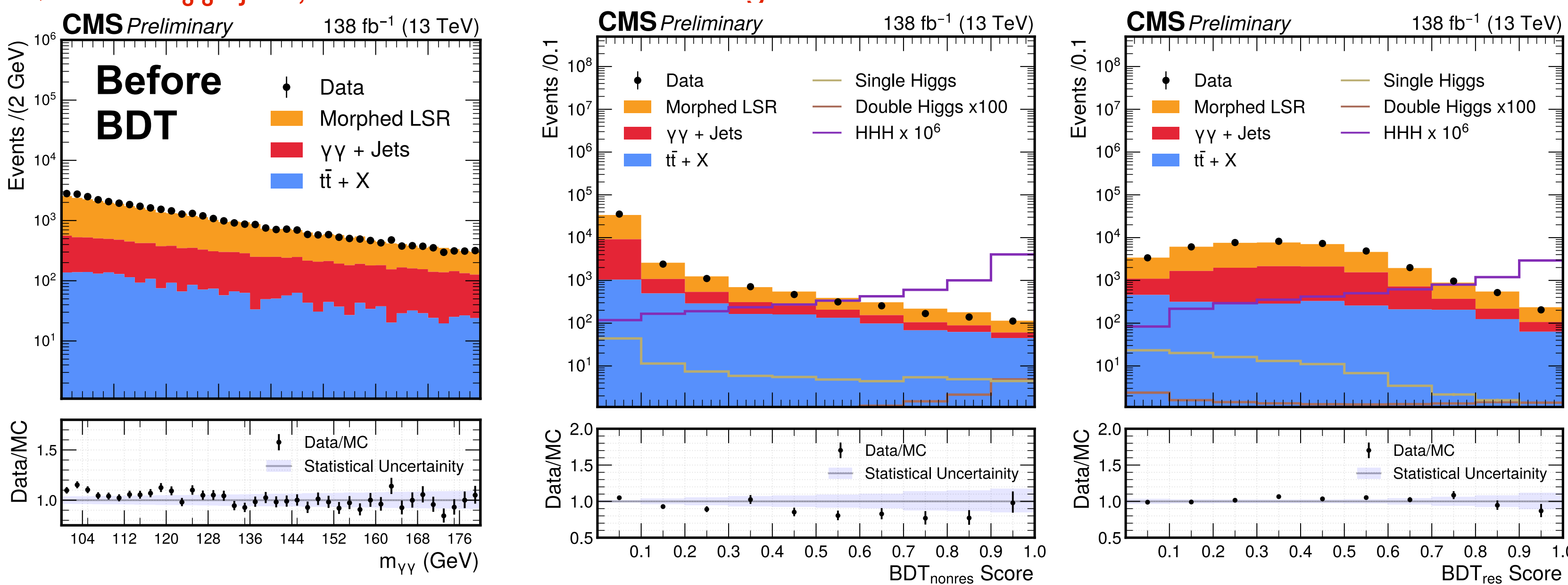




CMS Search in 4b2ɣ Channel

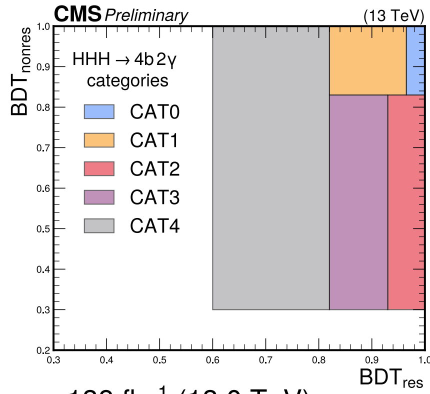
- CMS pursued a low branching fraction and low-background 4b2ɣ search in addition to the 6b one
- Only non-resonant production is considered
- Pairs 4b jets into 2 h candidates by requiring the closeness of the masses (75% accurate, with the overall efficiency of 60% for the correct pairing)
- Signal is extracted from the background-subtracted mass spectrum of the h(ɣɣ) candidate after BDT selections
  - The dominant QCD backround is estimated from a sample with photons failing tight ID selections (LSR)
  - Two BDT are trained: one for non-resonant backgrounds from QCD and ɣɣ+jets, and one for resonant backgrounds from h+X

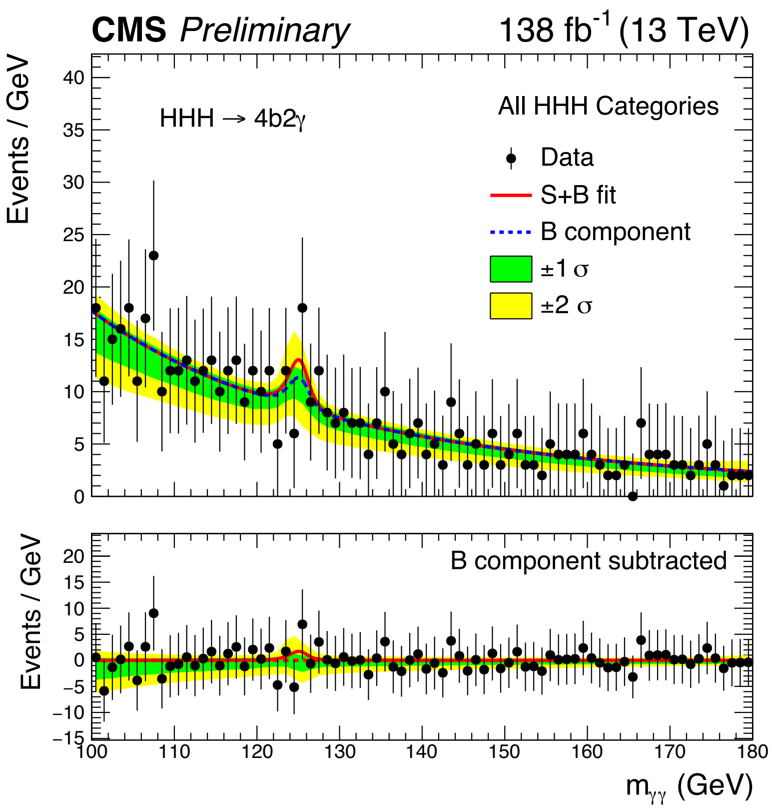
CMS PAS HIG-24-015



CMS 4b2γ Search (cont'd)

- The final selection is based on two BDT scores in 5 signal categories shown on the right
- A slight excess is observed resulting in a bit looser observed limits compared to the expected ones





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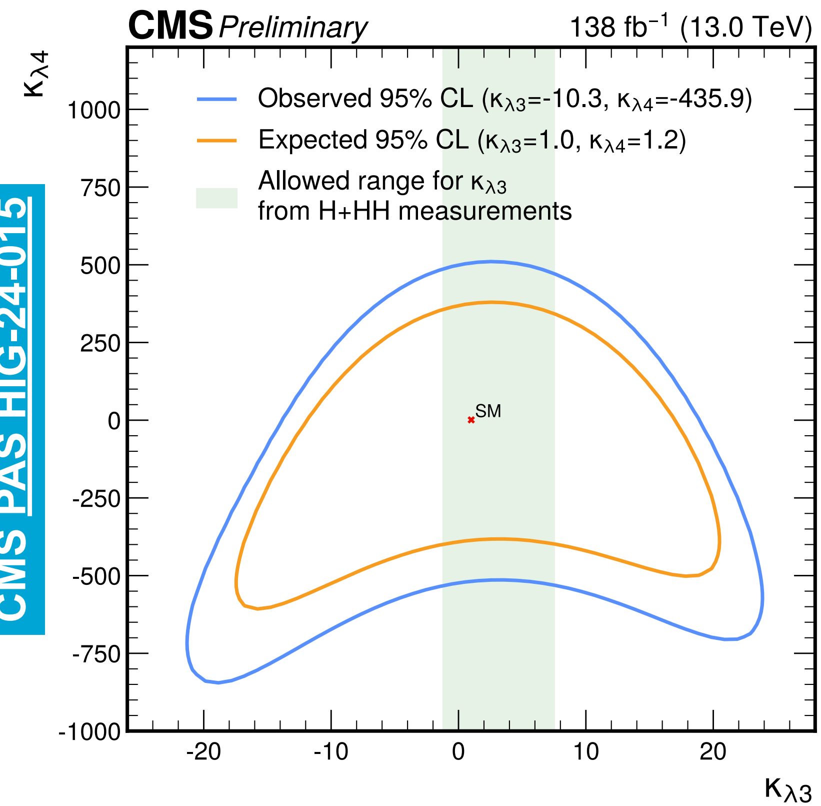
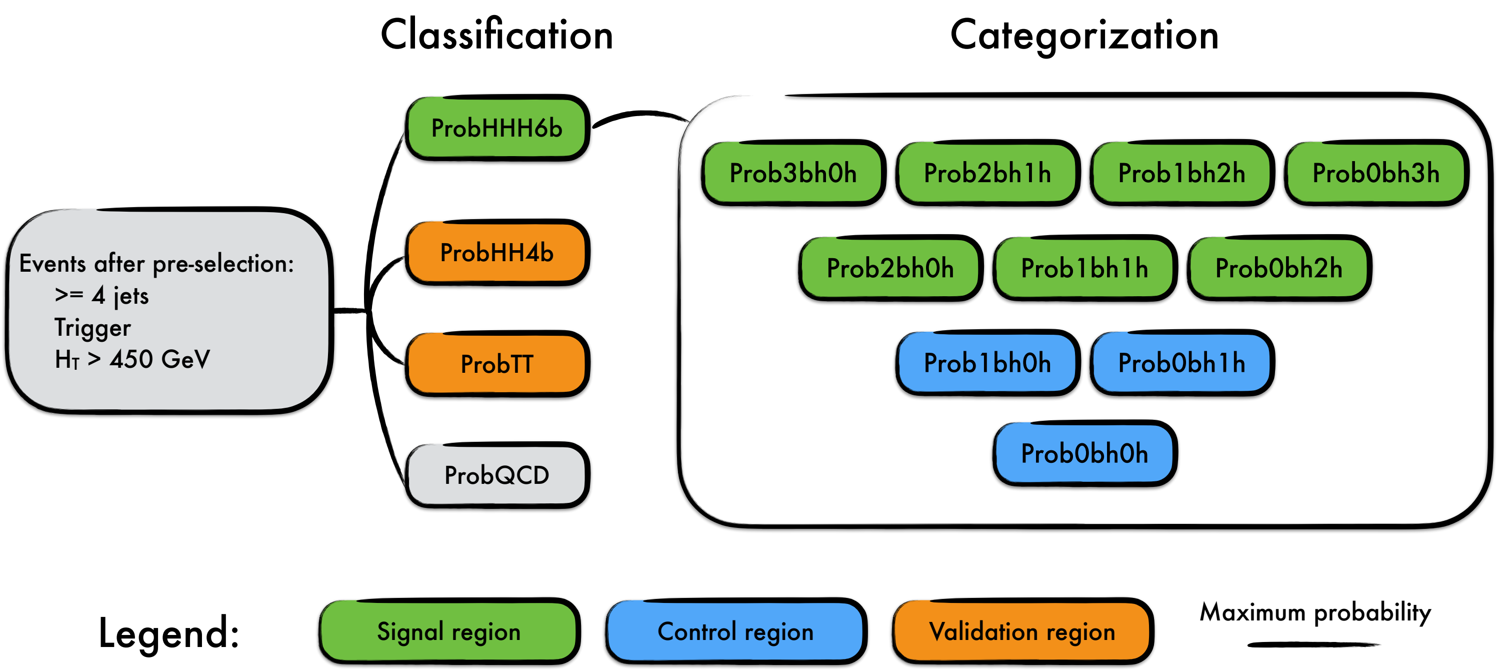


CMS HHH(6b) Search

- Fresh off the press: just approved CMS HHH(6b) analysis based on SPANet classification
  - Uses events not classified as either HHH(6b) or HH(4b) by SPANet and replaces their b tag scores with the one sampled in the signal region; normalized to the total number of events in the signal-like region
  - Validated with HH(4b) events in data; limits are extracted in two categories: 2 and 3 reconstructed H candidates, and are combined



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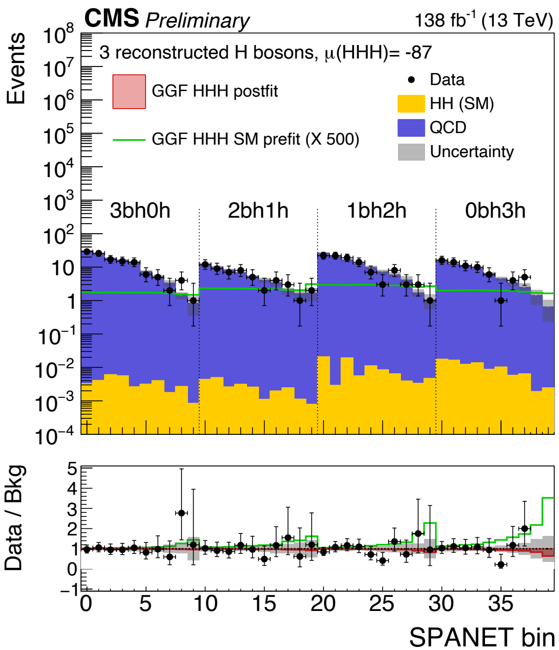
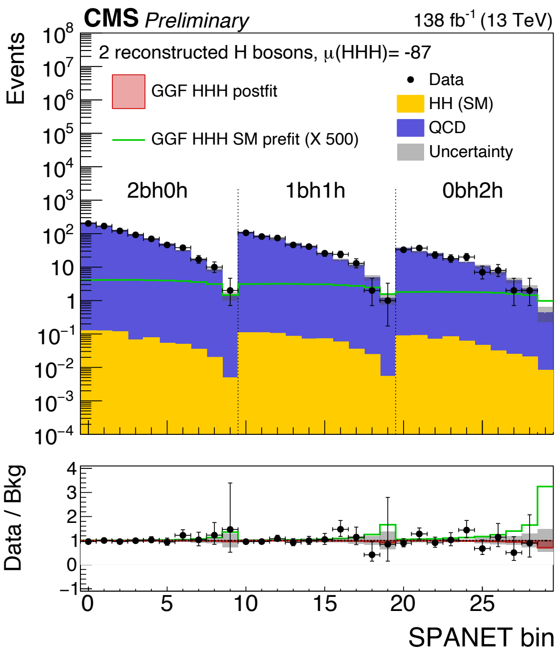
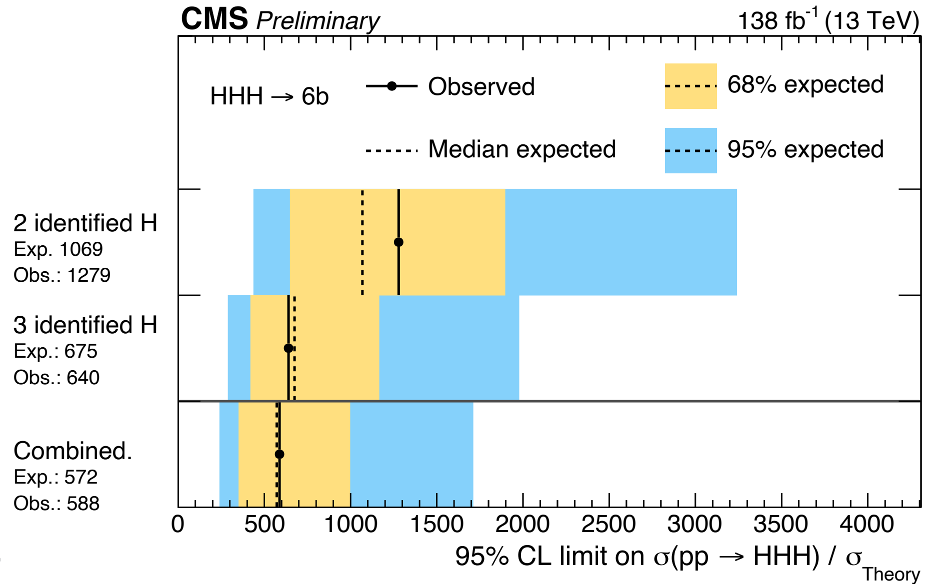
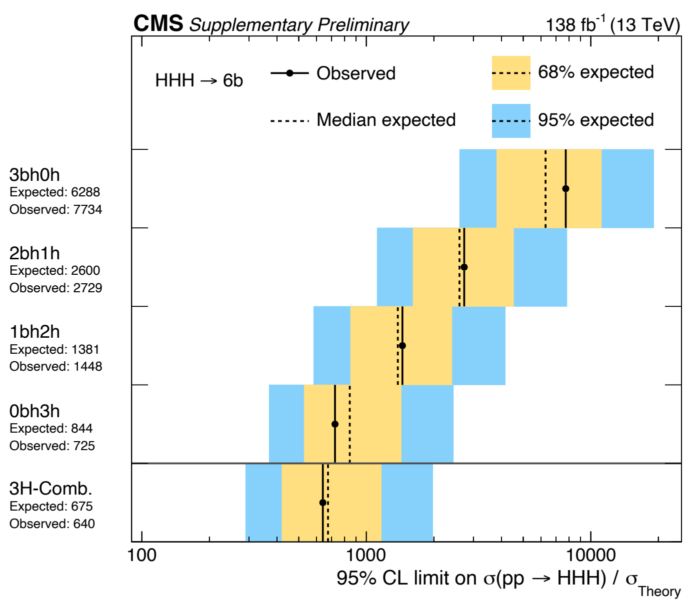




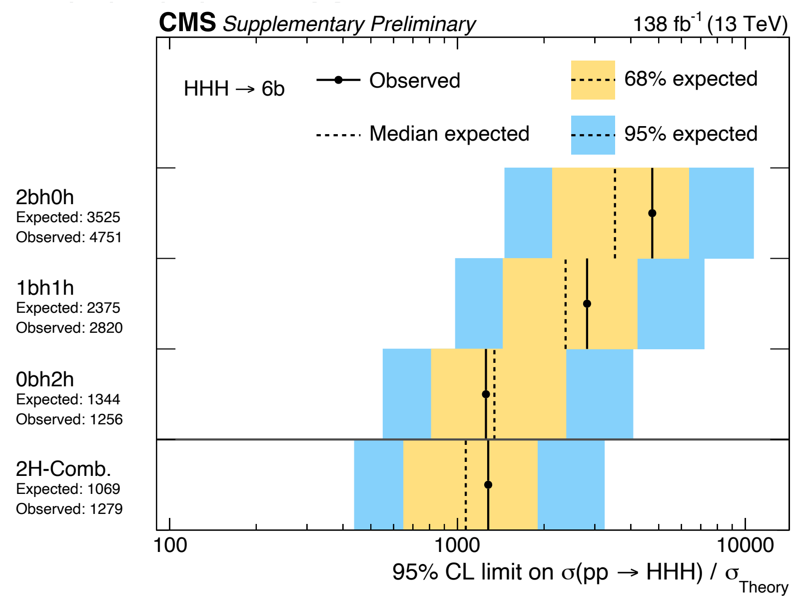
HHH Signal Strength Limits

- μ limits: 588 (572 exp.) @95% CL





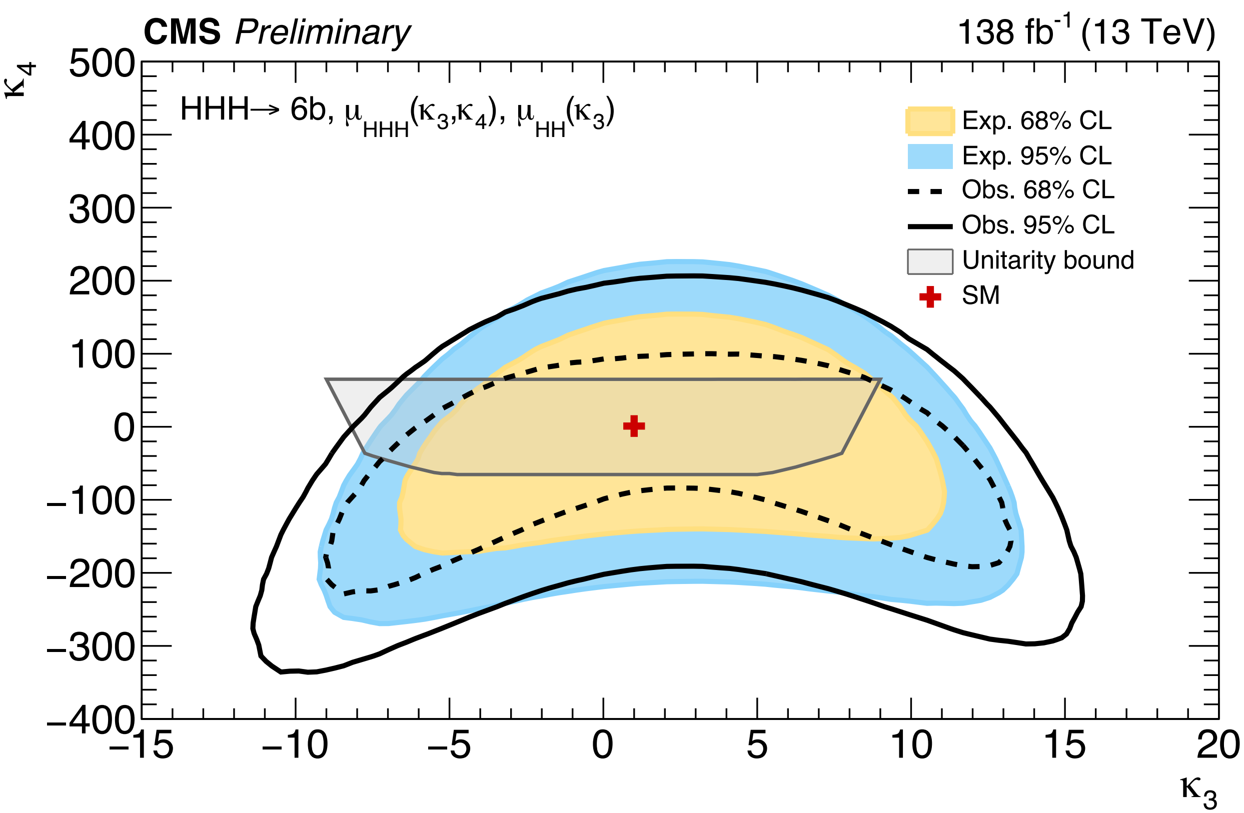
CMS PAS HIG-24-012

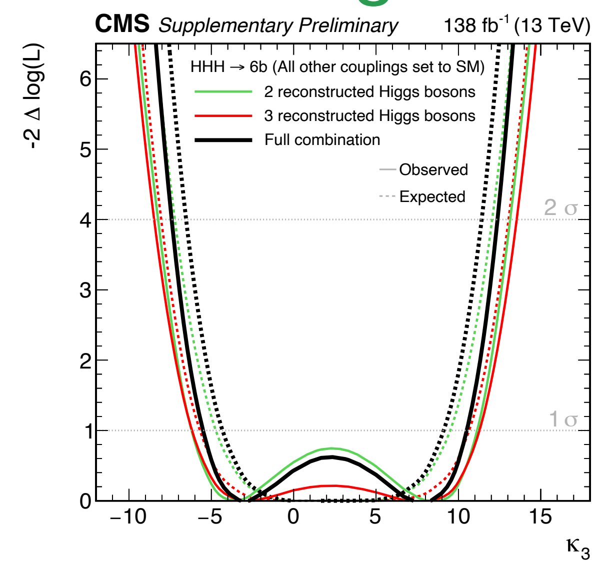


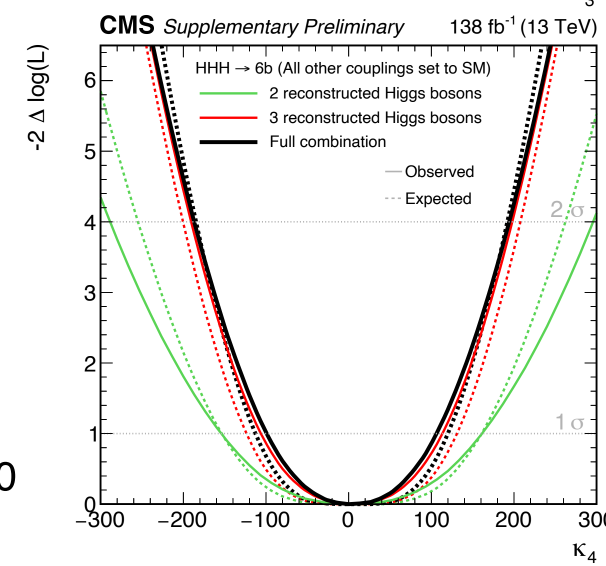
Limits on the Couplings

- ✦ For limits on coupling modifiers, the HH background is modified accordingly

CMS PAS HIG-24-012

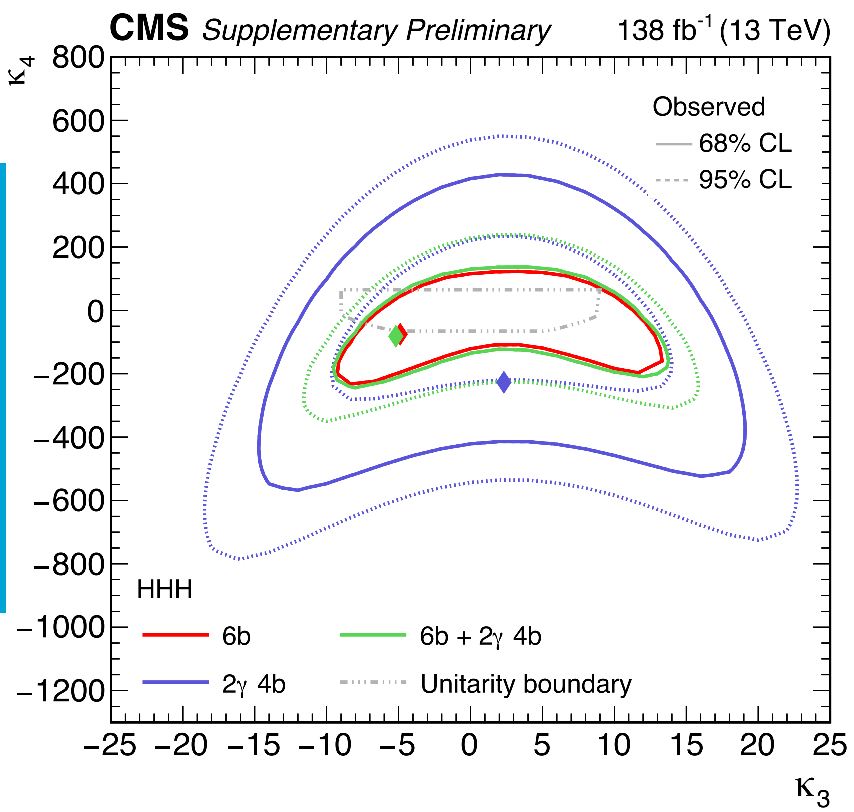


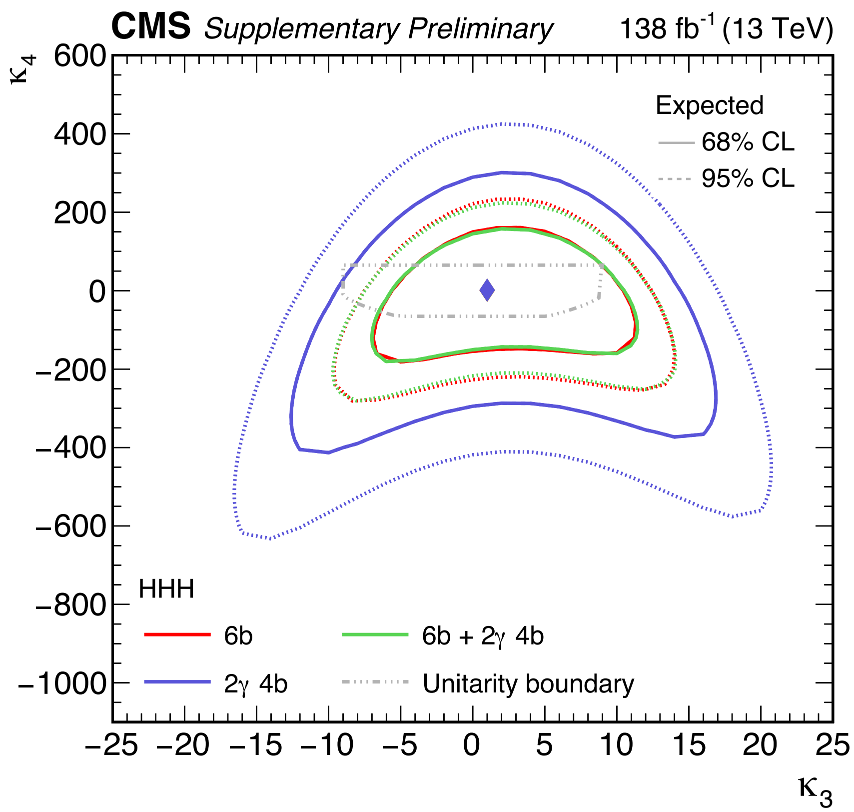




HHH Combination

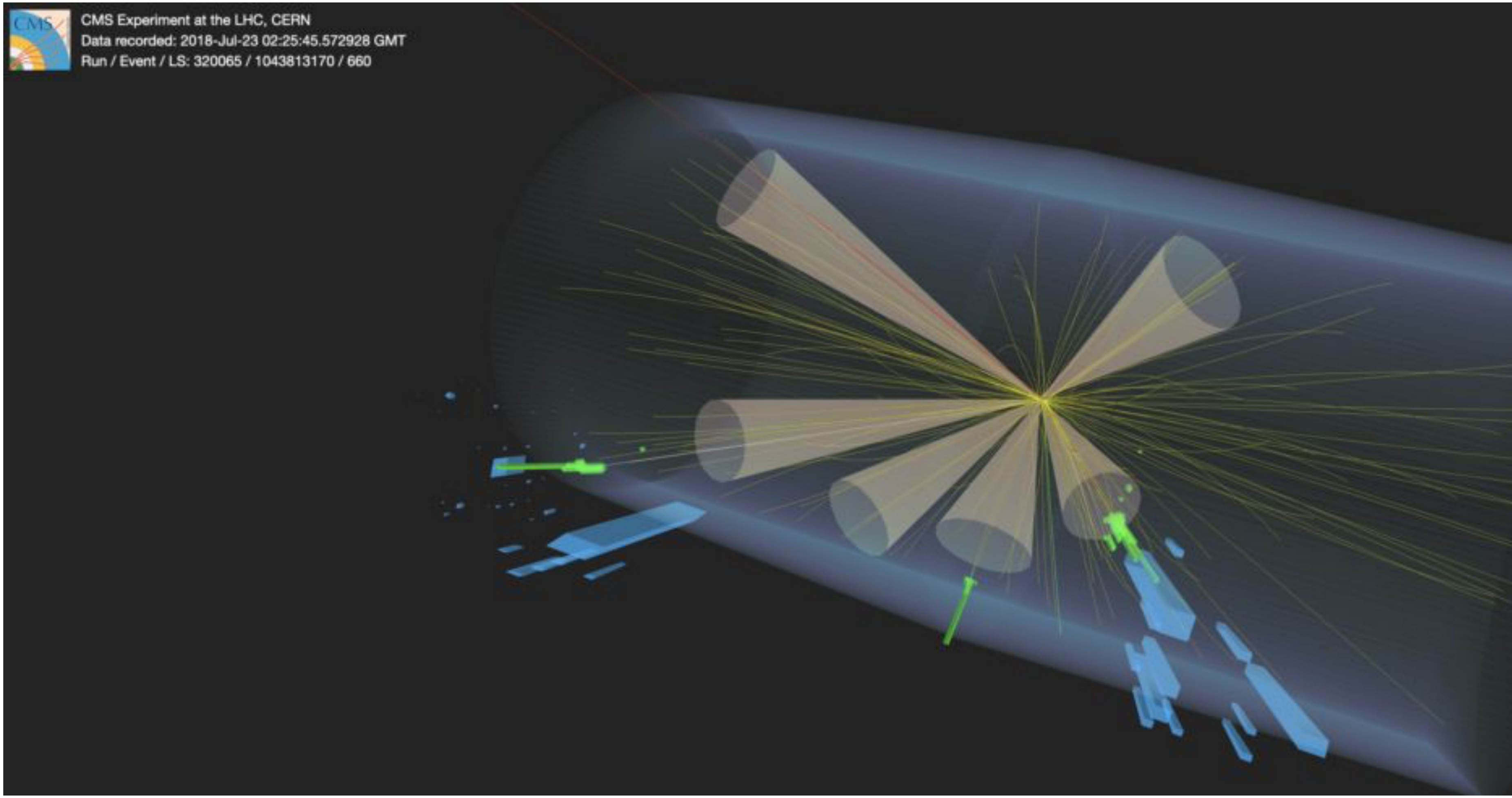
- ✦ Combination of CMS 4b2γ and 6b channels





CMS PAS HIG-24-012

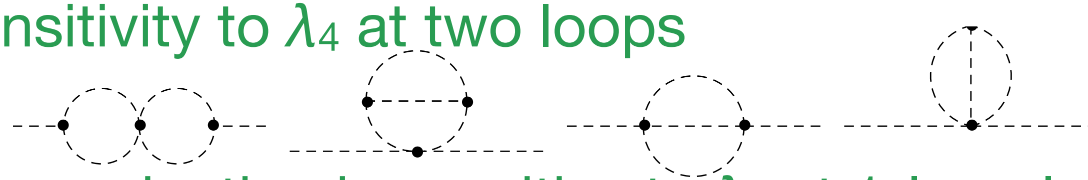
HHH Combination



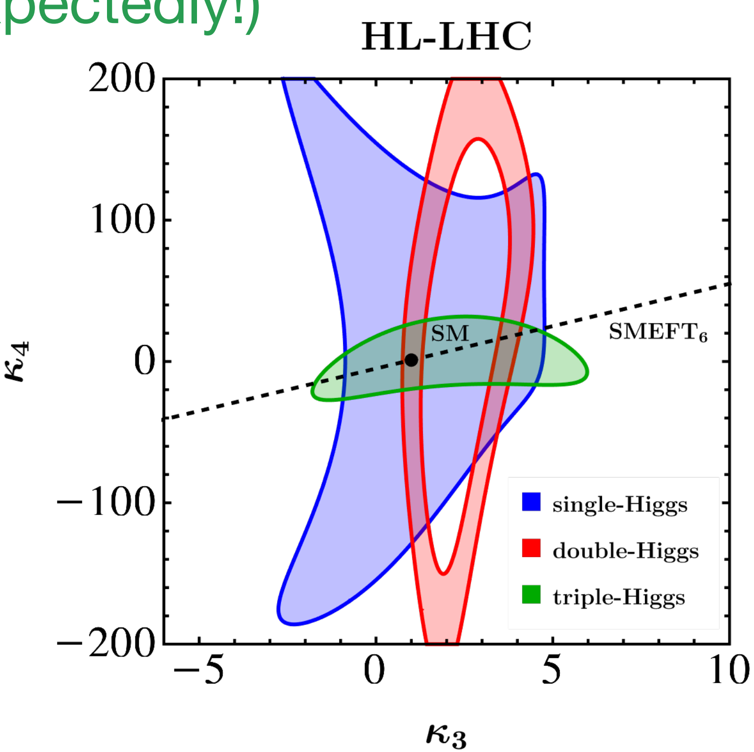
BROWN

Sensitivity to λ_4 from Loops

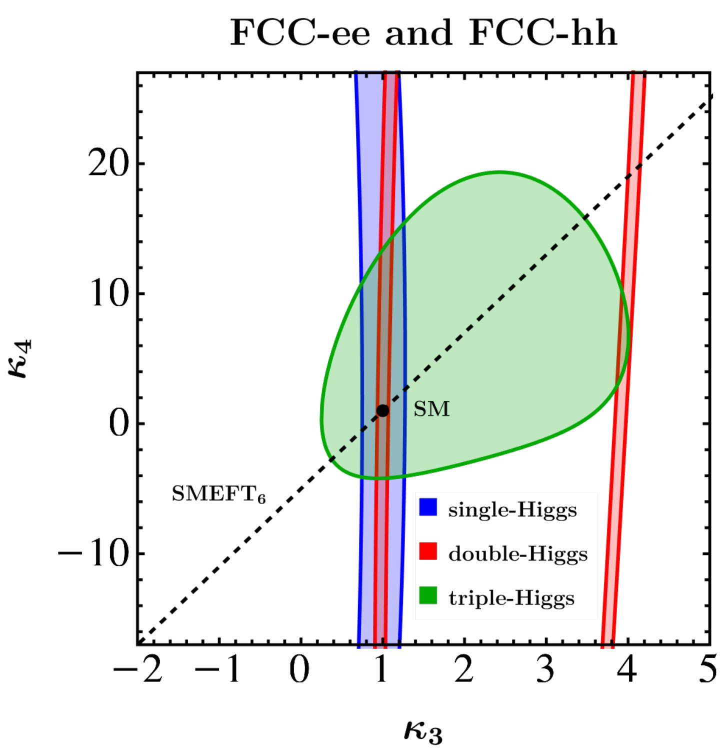
- Just like single Higgs boson production is sensitive to λ_3 at 1-loop level, there is also a sensitivity to λ_4 at two loops



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

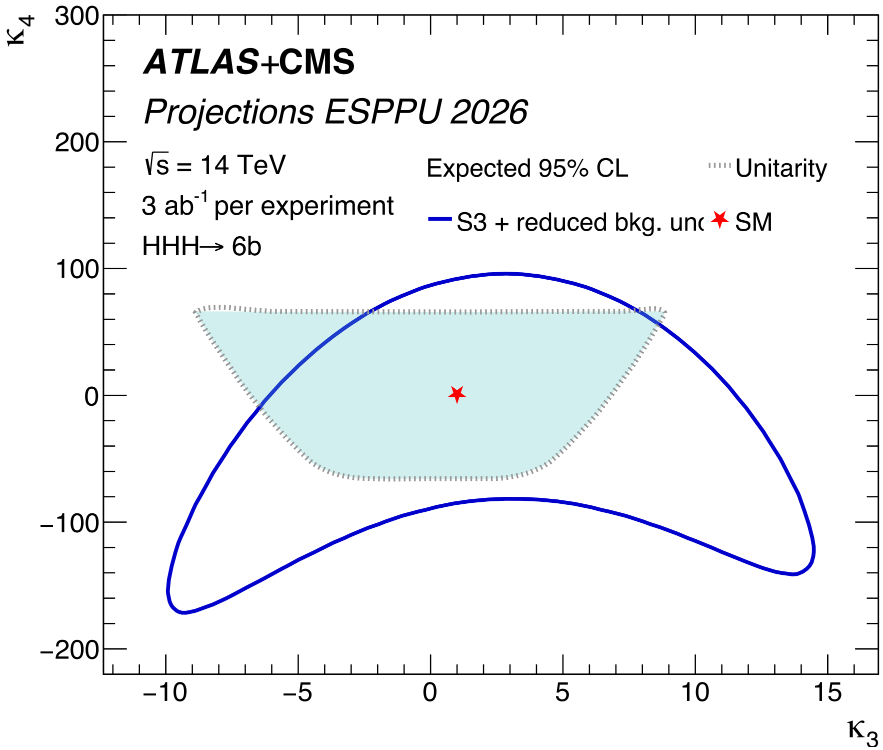


Haisch et al., arXiv:2505.20463



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 the same as in this projection - hence the brand new projection!



ATLAS & CMS, arXiv:2504.00672

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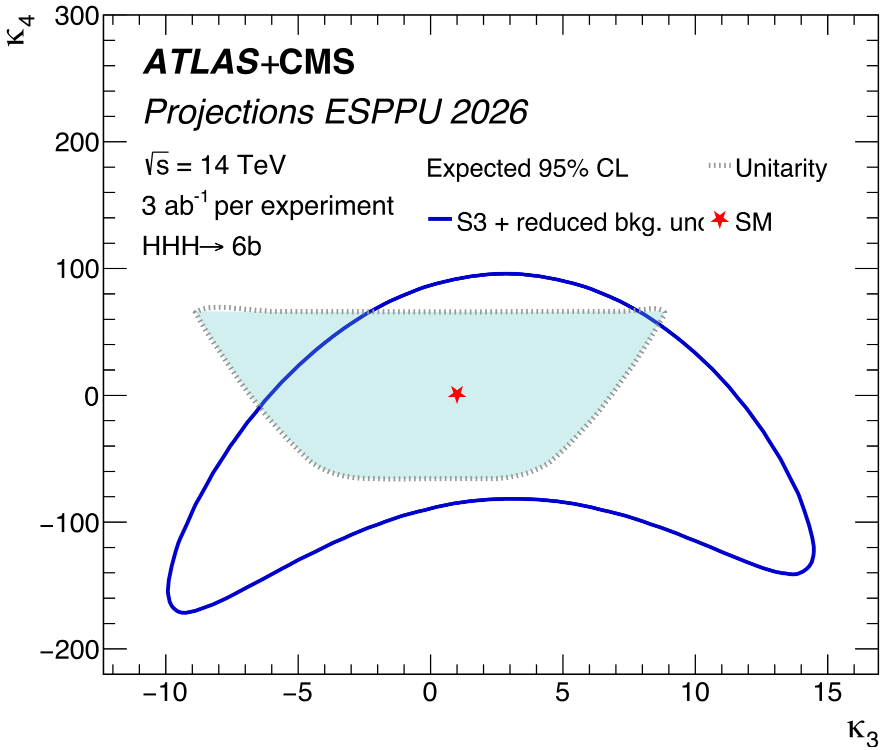

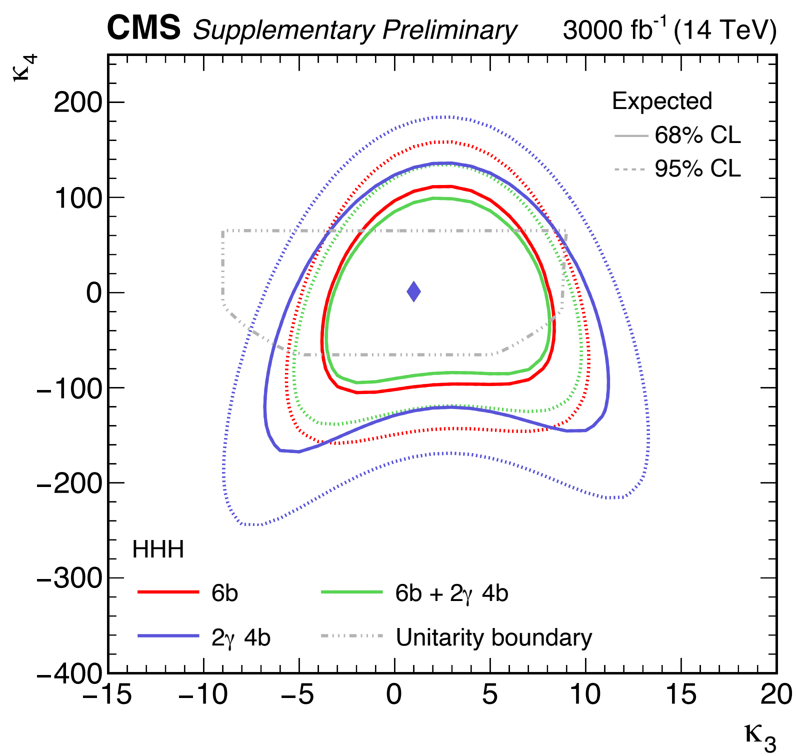

Second HHH Workshop

- ✦ Based on the success of the first HHH workshop, we are hosting the second one in Dubrovnik next week
- ✦ One of the goals is to organize contribution to the CERN Higgs Working Group YR5

LHC Working Group Subgroup

- As mentioned earlier, a new HHH subgroup of the WG4 (HH) group of the LHC Higgs Working Group has been formed earlier this year
  - First set of conveners (2025-2026)

lhc-hhh-wg4-conveners@cern.ch

William Balunas, ATLAS U of Cambridge, UK	Benjamin Fuks, Theory Sorbonne, France	Greg Landsberg, CMS Brown U, USA
		

- Mailing list: lhc-higgs-hhh@cern.ch (self-subscribed w/ conveners approval)

Conclusions

- Triple Higgs boson production at the LHC and beyond is an new addition to the Higgs potential studies
- Pushes the envelope of triggering, flavor tagging, advanced machine-learning techniques, so both challenging and exciting!
- Offers complementarity to HH production in terms of λ_3 sensitivity and unique sensitivity to λ_4
- First experimental results are already available; more to come, particularly with Run 2 + Run 3 data
- Many new theoretical studies of the collider phenomenology and cosmological implications
- Welcoming new people - an exciting area to join!

ChatGPT Conclusions

- In the realm of particles so grand,
  Where mysteries lie in each strand,
  The Higgs boson takes its place,
  With secrets held in its embrace.

  Its self-coupling, a subtle dance,
  A tryst of particles in cosmic expanse.
  Yet direct measurements remain unseen,
  As scientists strive to grasp its serene.

  Indirect constraints like whispers told,
  Unveiling truths in the particles' fold.
  With bounds and limits, we seek to find,
  The Higgs self-coupling, an enigma entwined.