Higgs Highlights of the HL-LHC projections by ATLAS and CMS

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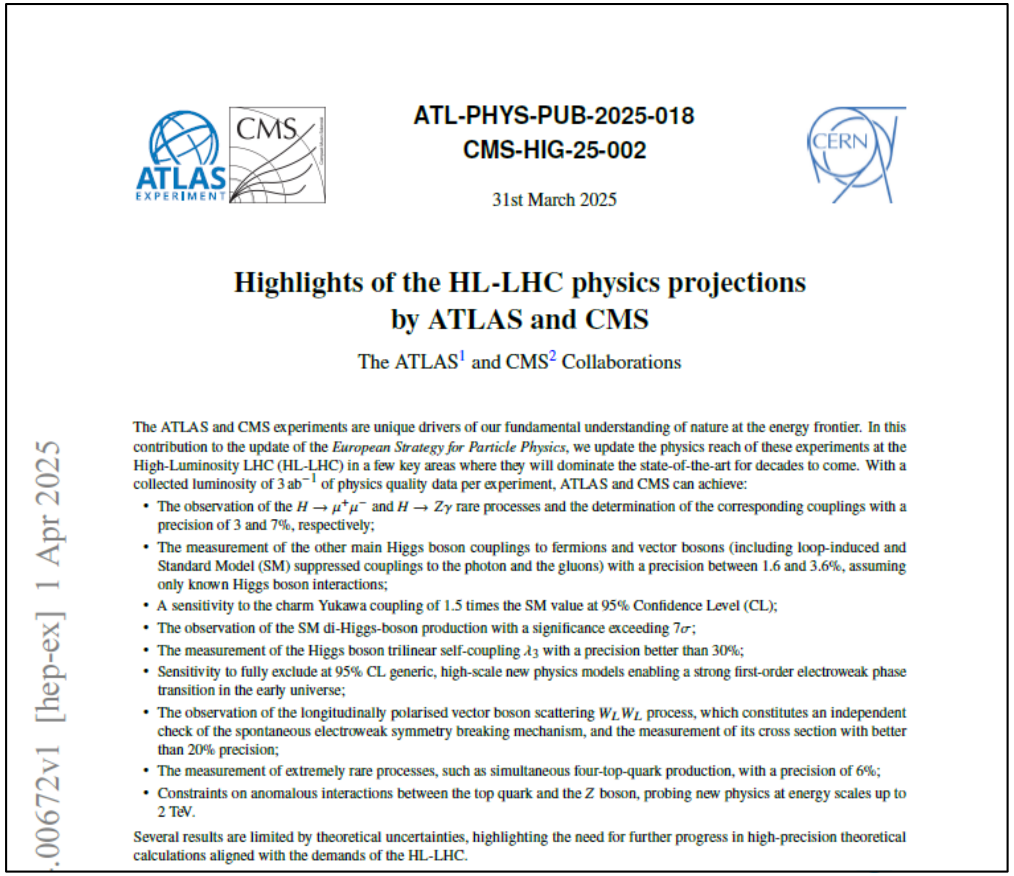

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Highlights of the HL-LHC physics projections by ATLAS and CMS

The ATLAS[1] and CMS[2] Collaborations

The ATLAS and CMS experiments are unique drivers of our fundamental understanding of nature at the energy frontier. In this contribution to the update of the *European Strategy for Particle Physics*, we update the physics reach of these experiments at the High-Luminosity LHC (HL-LHC) in a few key areas where they will dominate the state-of-the-art for decades to come. With a collected luminosity of 3 ab^{-1} of physics quality data per experiment, ATLAS and CMS can achieve:

- The observation of the $H \to \mu^+\mu^-$ and $H \to Z\gamma$ rare processes and the determination of the corresponding couplings with a precision of 3 and 7%, respectively;
- The measurement of the other main Higgs boson couplings to fermions and vector bosons (including loop-induced and Standard Model (SM) suppressed couplings to the photon and the gluons) with a precision between 1.6 and 3.6%, assuming only known Higgs boson interactions;
- A sensitivity to the charm Yukawa coupling of 1.5 times the SM value at 95% Confidence Level (CL);
- The observation of the SM di-Higgs-boson production with a significance exceeding 7σ;
- The measurement of the Higgs boson trilinear self-coupling λ_3 with a precision better than 30%;
- Sensitivity to fully exclude at 95% CL generic, high-scale new physics models enabling a strong first-order electroweak phase transition in the early universe;
- The observation of the longitudinally polarised vector boson scattering $W_L W_L$ process, which constitutes an independent check of the spontaneous electroweak symmetry breaking mechanism, and the measurement of its cross section with better than 20% precision;
- The measurement of extremely rare processes, such as simultaneous four-top-quark production, with a precision of 6%;
- Constraints on anomalous interactions between the top quark and the Z boson, probing new physics at energy scales up to 2 TeV.

Several results are limited by theoretical uncertainties, highlighting the need for further progress in high-precision theoretical calculations aligned with the demands of the HL-LHC.

Introduction

- HL-LHC = the next collider
- Here: update of ATLAS + CMS physics reach in a few key areas
  - … in which we will dominate the state-of-the-art for decades to come
- A long list…
  - $H \to \mu\mu$, $H \to Z\gamma$, charm Yukawa coupling, HH production, trilinear & quartic Higgs coupling, Higgs potential, $W_L W_L$ scattering, rare processes, anomalous interactions…
  - only a few highlights of the highlights shown in these slides
- All projections are very conservative

➔ Status of Higgs boson physics prior to the next collider

Higgs boson couplings

Based on κ framework

- Sizable improvements for two more elusive couplings
- Theory uncertainties dominant for most couplings

improved mass resolution (detector upgrades)

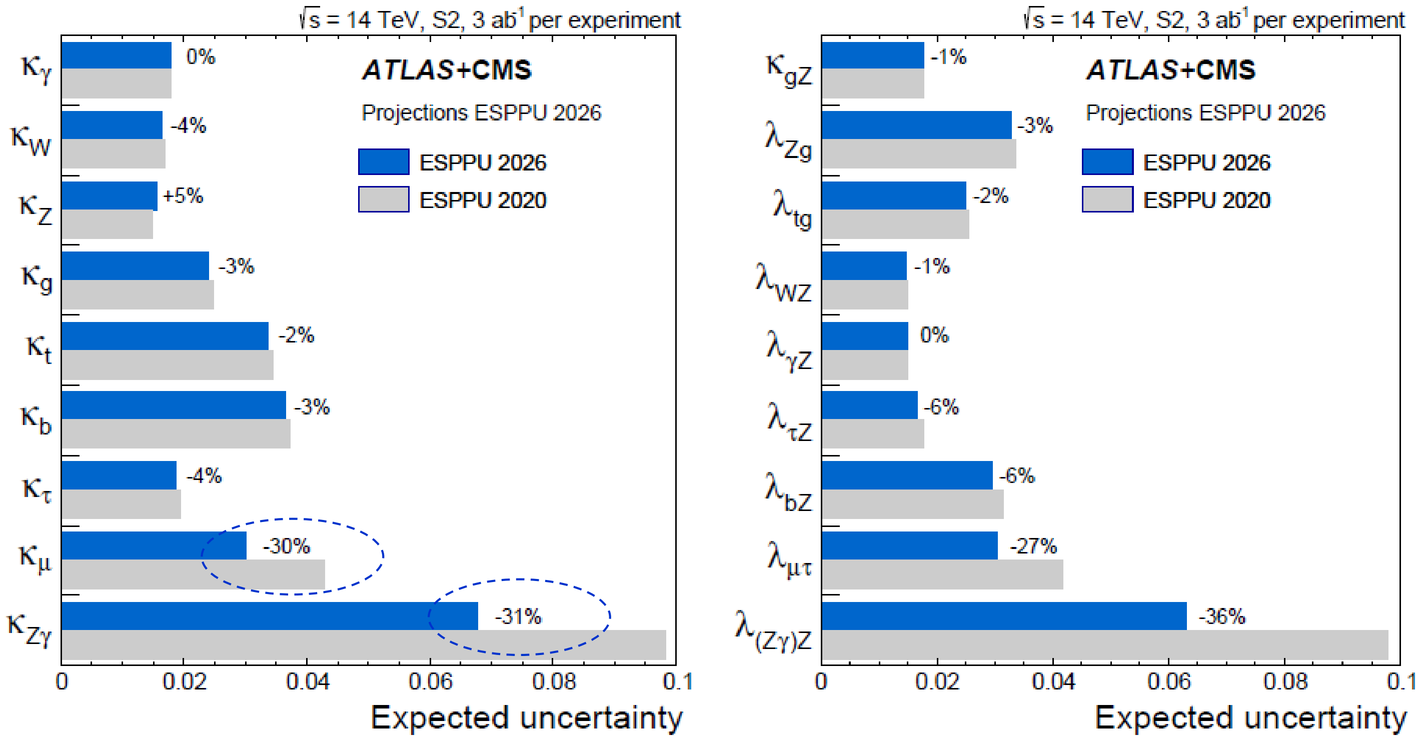


Figure A.1: ESPPU 2026 projections of coupling modifier uncertainties (left) and their ratios (right), compared to the previous HL-LHC projections [2]. The shown percentages represent the relative difference between the two projections. The precision of κ_Z is slightly lower due to the refined treatment of the ZH theory uncertainty.

Di-Higgs boson physics

Access to triple Higgs coupling

- Last ESPPU projected a ATLAS+CMS combined statistical significance of 4 σ for HH production
  - based on state-of-the-art with 2016 data
- Much improved techniques already applied for full Run 2 analysis
  - graph-based architectures, deep-learning
- Further improvements in Run 3
  - triggers, b-tagging, τ_h reco → S3 scenario
- At HL-LHC (assuming SM):
  - 5 σ discovery already with 2 ab^{-1} (S2)
  - combined significance at 3 ab^{-1}: **7.6 σ** (S3)
  - $\kappa_3 \in [0.6, 1.4]$ (ATLAS), $\kappa_3 \in [0.6, 1.5]$ (CMS)
  - combined uncertainty -26% / $+29\%$

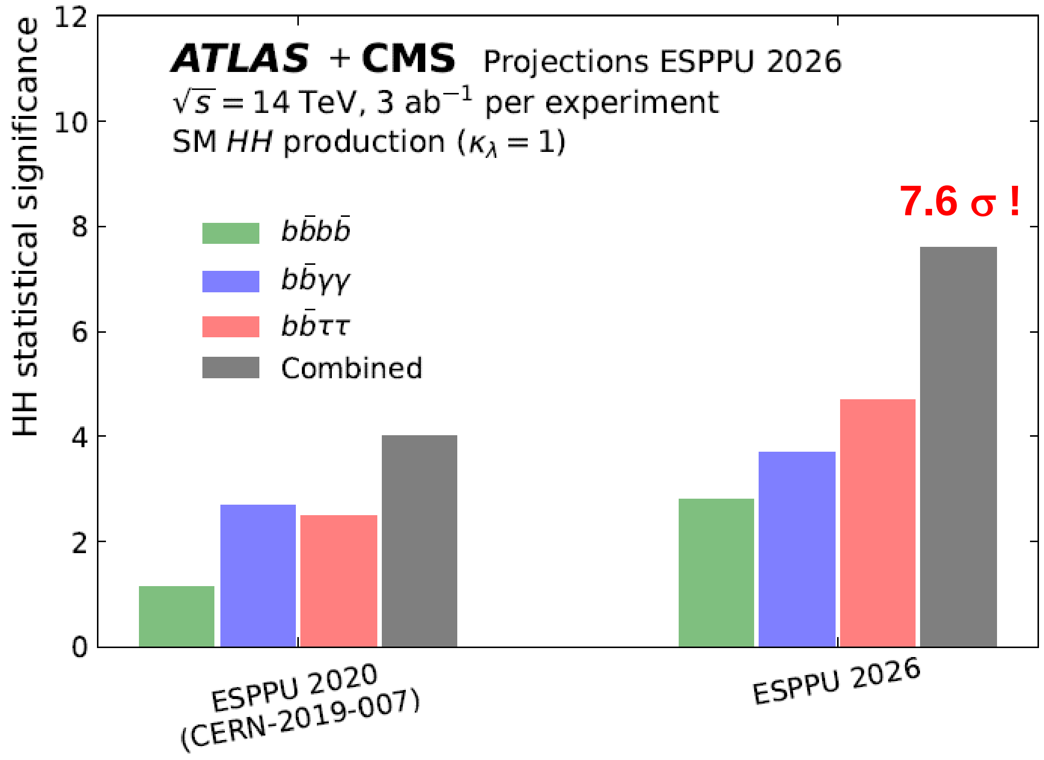
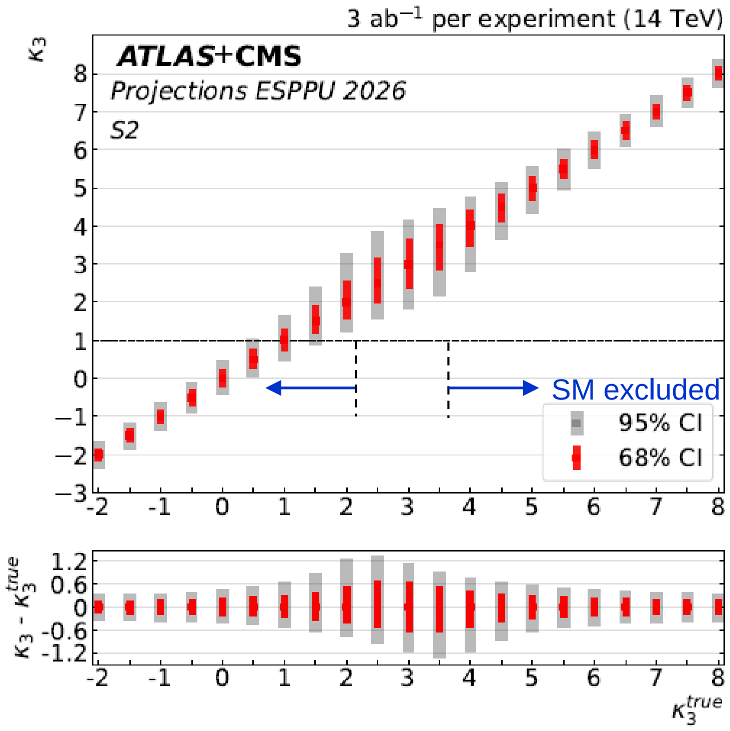
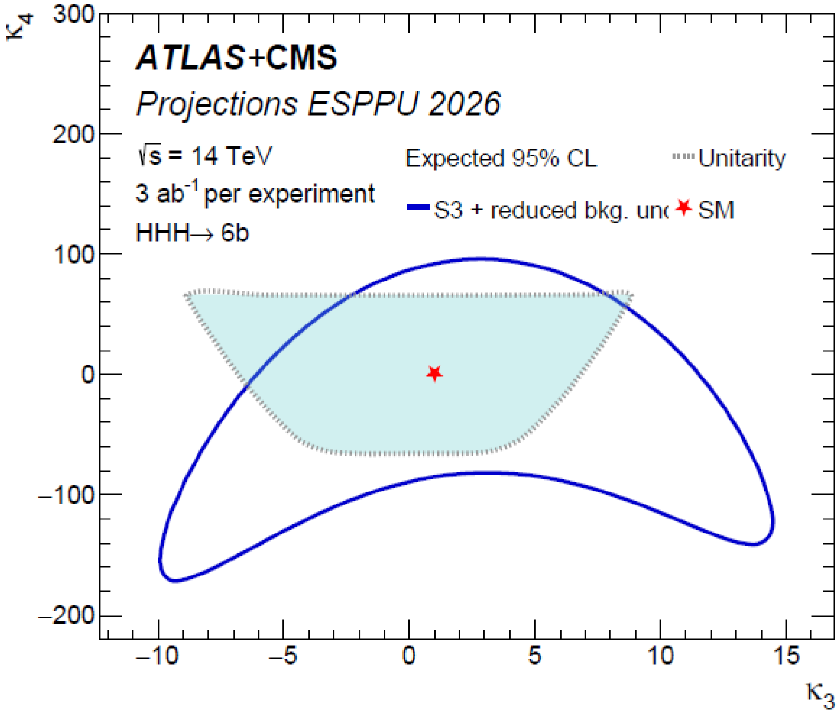


Figure 3: Comparison of the ESPPU 2020 and ESPPU 2026 projected 3 ab^{-1} HH sensitivities from various final states, and their combinations.

Triple and quartic Higgs boson couplings

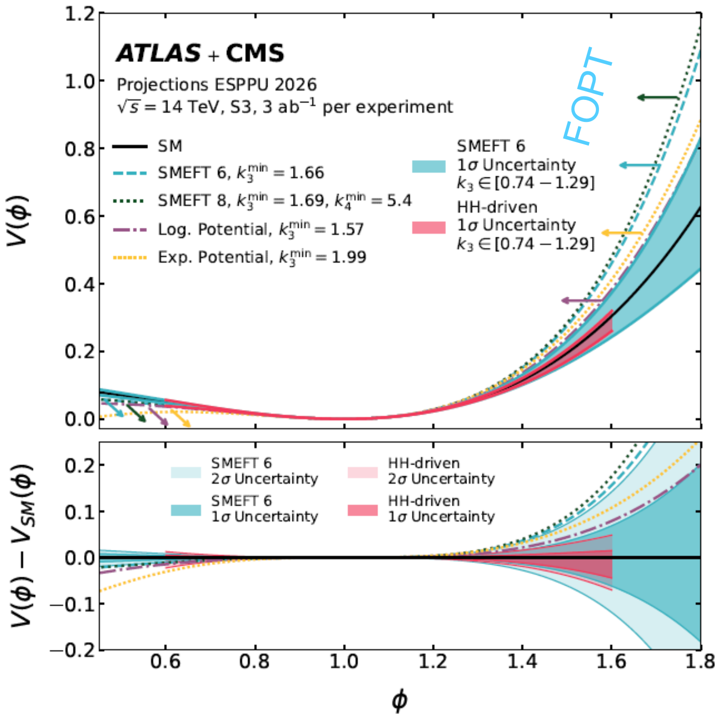




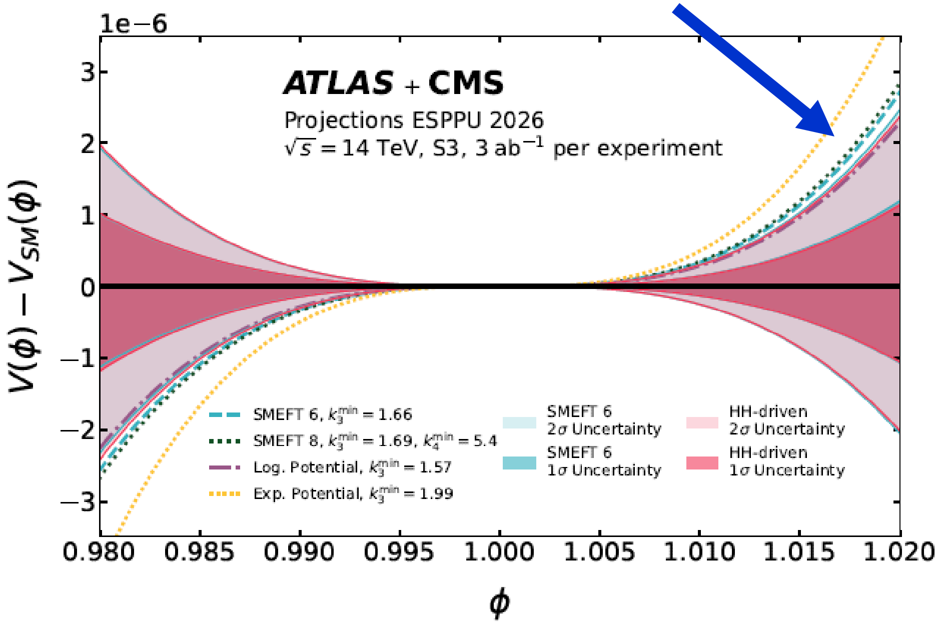
- If $\kappa_3 \neq 1$, measurement precision will depend on its actual value κ_3^{true} (destructive interference!)
- HHH production is sensitive to the quartic coupling λ_4 (currently studied in 6b decay mode)
  - $\sigma(pp \to HHH) < 86 \times SM$ @ 95% (S3, 3 ab^{-1})
  - sensitive to anomalous values of κ_4 → exclude part of parameter space allowed by unitarity constraints

Shape of the BEH potential + 1st-order phase transition

- Four non-SM BEH potential shapes studied in context of SM effective field theory
  - predict strong 1st-order phase transition in early universe (→ baryogenesis) for sufficiently large values of κ_3 and κ_4
  - not realized in the SM
- At 3 ab^{-1} and assuming the SM, ATLAS+CMS combination should be able to exclude as good as all possible strong-FOPT scenarios across the four alternative hypotheses
- Important measurement for understanding the origin of the universe



FOPT excluded!



Summary: ATLAS+CMS Higgs Highlights for HL-LHC

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With a physics-grade integrated luminosity of 3 ab^{-1} each, ATLAS and CMS can achieve many goals:

- Observation of $H \to \mu\mu$ and $H \to Z\gamma$ → measure couplings with 3% (7%) precision
- Measurement of other main H couplings with a precision of 1.6-3.6%
- Sensitivity to charm Yukawa coupling of $1.5 \times SM$ @ 95% CL
- Observation of SM HH production at $> 7\sigma$ significance
- Measurement of the Higgs trilinear coupling with a precision better than 30%
- Sensitivity to fully exclude generic high-scale new physics models enabling a strong first-order electroweak phase transition in the early universe

→ the state-of-the-art in these topics for decades to come

Backup

Triple and quartic Higgs boson couplings

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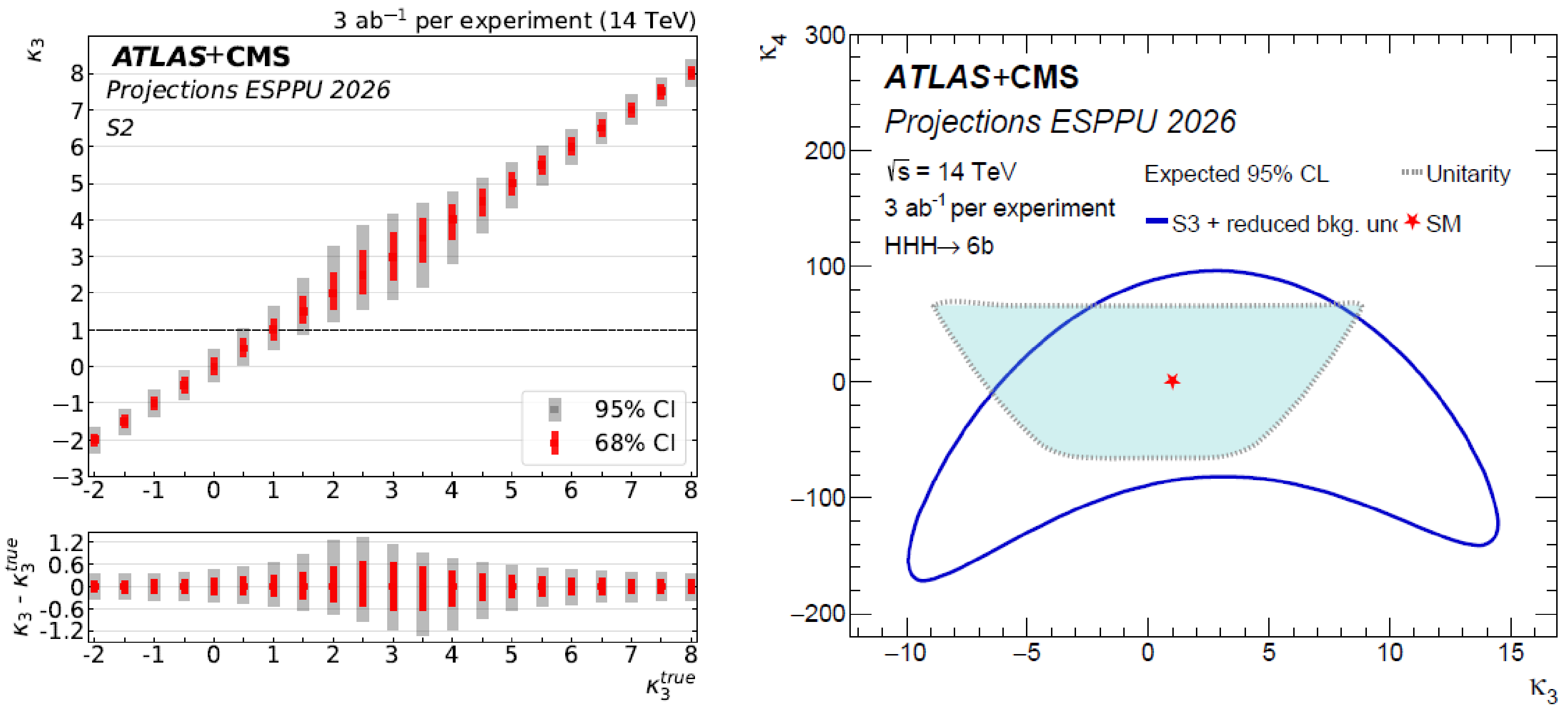

Figure 4: Left: The ATLAS+CMS projection on the precision of the determination of κ_3 as a function of κ_3^{true}. The 68% and 95% confidence intervals are shown in the upper plot, while the lower plot shows the κ_3 deviation from the simulated κ_3^{true} value and its 68% and 95% confidence intervals. Right: 95% CL constraints from the HHH search projection on κ_3 and κ_4. Results are shown for 3 ab^{-1} per experiment at $\sqrt{s} = 14$ TeV in scenario *S3* with data-driven background uncertainties. Unitarity limits, as calculated in Ref. [57], are overlaid in the region bounded by the grey dashed line.