PROCEEDINGS OF SCIENCE

Higgs precision at FCC-hh

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The proposed hadron collider phase of the Future Circular Collider, FCC-hh, will record 30 ab^{-1} of proton-proton collisions at a center of mass energy of 85 TeV, providing an unprecedented dataset that extends both the energy and precision frontiers and enables high-statistics studies of rare processes, particularly within the Higgs sector.
With billions of single-Higgs events, the FCC-hh will measure rare decays such as $H \to \mu^+\mu^-$, $H \to \gamma\gamma$, and $H \to Z\gamma$ with percent-level precision and probe the top Yukawa interaction with unmatched accuracy through $t\bar{t}H$ production. The collection of tens of millions of Higgs-pair events will allow a few-percent-level determination of the Higgs self-coupling, a key parameter for understanding electroweak symmetry breaking and vacuum stability. Together with inputs from the FCC-ee, these measurements will test the Higgs sector with unparalleled accuracy.
This proceeding presents a selection of results submitted for the 2026 European Strategy for Particle Physics Update and provides an overview of the FCC-hh physics potential.

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1. Introduction

The Future Circular Collider (FCC) integrated program [1–3] represents a proposal for a unified, long-term vision in high-energy accelerator-based particle physics. It consists of two complementary stages, both hosted in a new 91 km tunnel potentially to be built near CERN.

The first stage, FCC-ee, is a high-luminosity electron–positron collider operating at centre-of-mass energies from 90 to 365 GeV. It is designed to deliver precise measurements of the electroweak and Higgs sectors through detailed studies of the Z, W, Higgs, and top quarks. These measurements will provide powerful indirect sensitivity to new physics effects beyond the Standard Model (SM).

The second stage, FCC-hh, envisions a proton–proton collider operating at a centre-of-mass energy of approximately 85 TeV, offering an unparalleled discovery reach for new particles and interactions. Together, the two machines form a coherent research infrastructure capable of addressing the most fundamental open questions in particle physics, while serving the international scientific community over a timescale of five decades. In fact, the baseline FCC program foresees about 15 years of FCC-ee operation, followed by a 10-year transition period to dismantle the lepton collider and install the hadron one, and subsequently 25 years of FCC-hh operation—a timeline comparable to that of the combined LEP and LHC programs.

The FCC-hh will build upon the legacy of the High-Luminosity LHC, extending its reach by roughly an order of magnitude in both centre-of-mass energy and peak luminosity. This will enable both the direct exploration of the multi-TeV energy regime and precision studies of SM processes at unprecedented scales. In particular, the high Higgs-boson production rates expected at FCC-hh will open a new era of precision Higgs physics. It will be possible to measure rare decays such as $H \to \gamma\gamma$, $H \to \mu^+\mu^-$, and $H \to Z\gamma$, as well as probe processes that require higher energies, notably $t\bar{t}H$ and Higgs-pair production. These measurements will provide a unique window into the structure of the Higgs sector and its couplings, complementing the precision program of FCC-ee and enabling stringent tests of the SM.

All the studies summarized here, and submitted for the European Strategy [4] to reinforce the FCC-hh physics case, consider the most recent nominal running scenario at 85 TeV [5] with a target total integrated luminosity of 30 ab^{-1} to be collected by two general purpose experiments over the entire run time. In several cases, also other conditions are considered in order to study how key benchmark measurements change with collision energy and luminosity. The detector simulation is carried out with the fast detector simulation package DELPHES [6]. The baseline detector concept used for the FCC-hh physics studies can be found in Ref. [3] and its Delphes parametrization is outlined in Ref. [7].

2. Higgs rare decays

The first benchmark physics case presented in this summary is the measurement of the Higgs boson coupling to muons. This analysis [8] focuses on the rare decay channel $H \to \mu^+\mu^-$, using a differential approach that explores the Higgs high-p_{T} region, where experimental uncertainties are typically smaller and the signal-to-background ratio improves.

To minimize the systematics assumptions and ensure a robust prediction, the strategy relies on measuring the ratio of signal strengths between the $H \to \mu^+\mu^-$ and $H \to ZZ \to 4\mu$ processes.

This observable benefits from the permille-level precision expected on $H \to ZZ$ from the FCC-ee program, while common theoretical and experimental systematics, such as production cross-section and luminosity uncertainties, largely cancel in the ratio.

Signal extraction is performed via maximum likelihood fits to the invariant mass distributions $m_{\mu^+\mu^-}$ and $m_{4\mu}$ in bins of the Higgs transverse momentum, p_{T}^H. As example, Fig. 1 shows the two distributions in the p_{T}^H bin 100–150 GeV for the Higgs signal and the muon continuum background.

In the nominal FCC-hh scenario at 84 TeV, a precision of 1.32% is achieved on the ratio when simultaneously fitting all p_{T}^H bins (Fig. 2), with the total uncertainty dominated by the systematic component while the measurement in the high-p_{T} region is statistically limited. This result corresponds to an absolute precision on the Higgs-to-muon coupling of 0.66‰, which represents a substantial improvement over the expected 4% precision attainable at the FCC-ee alone.

The right panel in Fig. 2 shows how the precision changes with different collider conditions, i.e. with energy 72–120 TeV and integrated luminosity 12–42 ab^{-1}. The analysis demonstrates stable performance across the different running scenarios, with the 120 TeV scenario delivering the least sensitive result because of the reduced luminosity.

These projections indicate that the FCC-hh will enable a sub-percent-level measurement of the muon Yukawa coupling, providing a direct probe of the second-generation fermion sector in the SM. The same methodology can be extended to other rare Higgs decays, such as $H \to \gamma\gamma$ and $H \to Z\gamma$, which are also statistically limited at the FCC-ee.

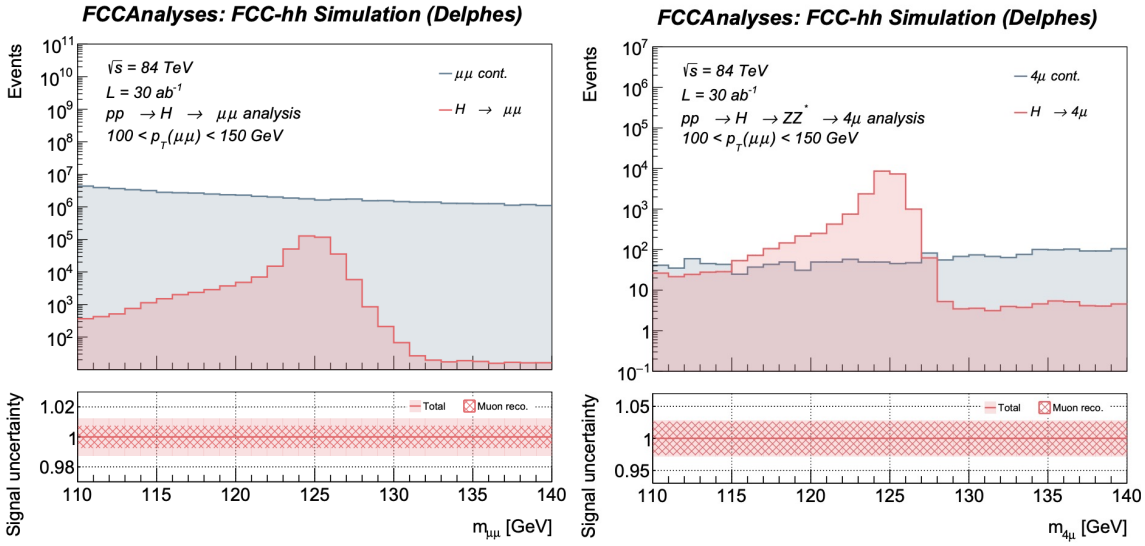

Figure 1: Distributions of $m_{\mu^+\mu^-}$ (left) and of $m_{4\mu}$ (right) in the p_T^H bin 100–150 GeV for the $H \to \mu^+\mu^-$ and $H \to ZZ \to 4\mu$ analysis, respectively. In the plots, the Higgs signals is in red and the muon continuum background in blue. The bottom panel indicates the relative signal systematic uncertainties [8].

3. Top Yukawa coupling

The associated production of a Higgs boson with a top–antitop pair ($t\bar{t}H$) provides the most direct probe of the top Yukawa coupling modifier, κ_t. Current precision at the LHC is about

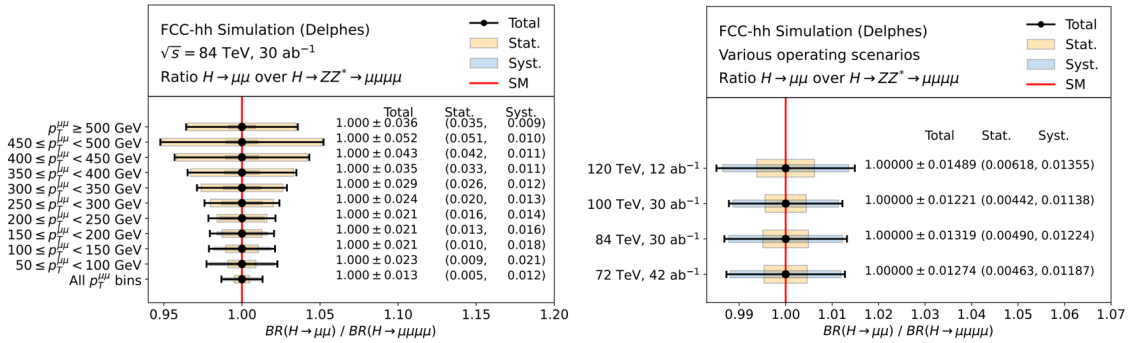

Figure 2: (Left) Differential measurements of the ratio $BR(H \to \mu^+\mu^-)/B(H \to 4\mu)$ in p_T^H bins. (Right) Comparison of the best precision achieved from a differential measurement of the ratio $BR(H \to \mu^+\mu^-)/B(H \to 4\mu)$ between different FCC-hh operating scenarios [8].

11% [10, 11], to be improved to 3.4% at the HL-LHC [12]. Owing to the high luminosity and centre-of-mass energy of the FCC-hh, a substantial improvement over these values becomes possible even with Higgs boson rare decay channels.

The study [9] for FCC-hh focuses on the $t\bar{t}H$ process in the diphoton final state, $H \to \gamma\gamma$, selecting events with at least one leptonic top-quark decay. Despite its small branching fraction, the diphoton channel benefits from an exceptionally clean signature and excellent photon energy resolution, enabling precise reconstruction of the Higgs resonance. Events are categorized into six bins of the diphoton transverse momentum, $p_T^{\gamma\gamma}$, to exploit the enhanced sensitivity at high p_T. In each category, a profile-likelihood fit to the diphoton invariant mass distribution in the range $110 < m_{\gamma\gamma} < 140$ GeV (see Fig. 3) is used to extract the signal.

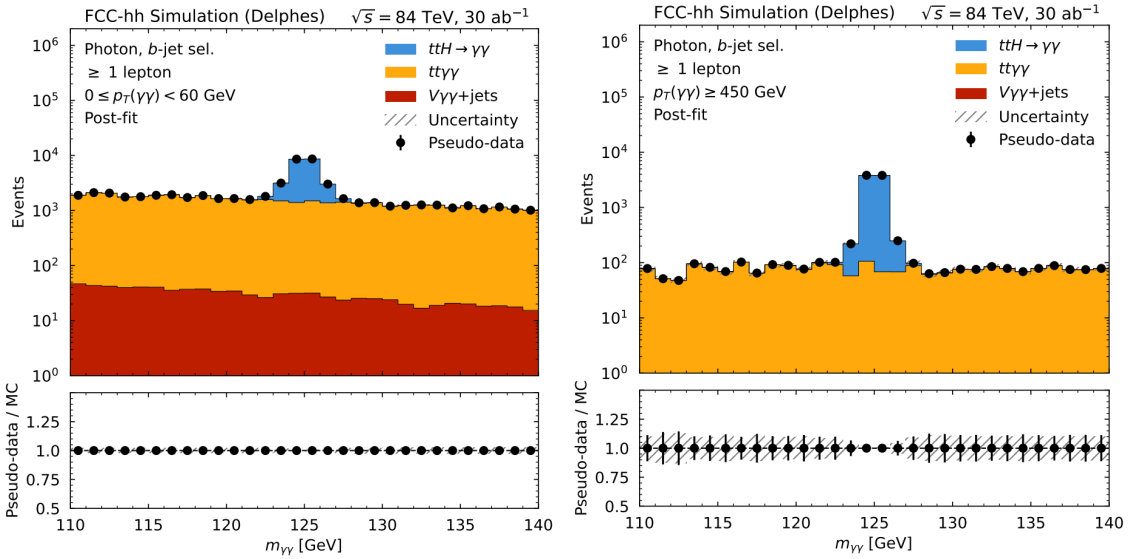

Figure 3: Distributions of $m_{\gamma\gamma}$ for the $t\bar{t}H \to \gamma\gamma$ signal in blue and the main two background processes in orange and red for two example p_T^H bins [9].

A range of systematic uncertainty scenarios is considered, including both constant and p_T-

dependent object-identification uncertainties, as well as luminosity and theoretical cross-section uncertainties.

Assuming an integrated luminosity of 30 ab^{-1} at $\sqrt{s}$ = 84 TeV, the expected precision on the inclusive $t\bar{t}H$ cross section times the $H \to \gamma\gamma$ branching ratio spans from 1.7% (optimistic) to 6.7% (pessimistic), with the nominal scenario yielding 2.2%. The measurement is strongly systematics-limited, with a statistical contribution of only 0.4%. The differential measurement in the nominal scenario is reported in left Fig. 4.

A likelihood scan of the top Yukawa modifier κ_t shows that the FCC-hh can achieve a precision between 0.9% and 3.4%, with an expected 1.2% precision in the nominal scenario (see right Fig. 4). These results represent more than an order-of-magnitude improvement over the current LHC measurements and significantly surpass the HL-LHC projections. The projection can be made more robust and less assumption-dependent through the use of the $t\bar{t}H/t\bar{t}Z$ cross-section ratio, which can partially cancel theoretical and luminosity uncertainties.

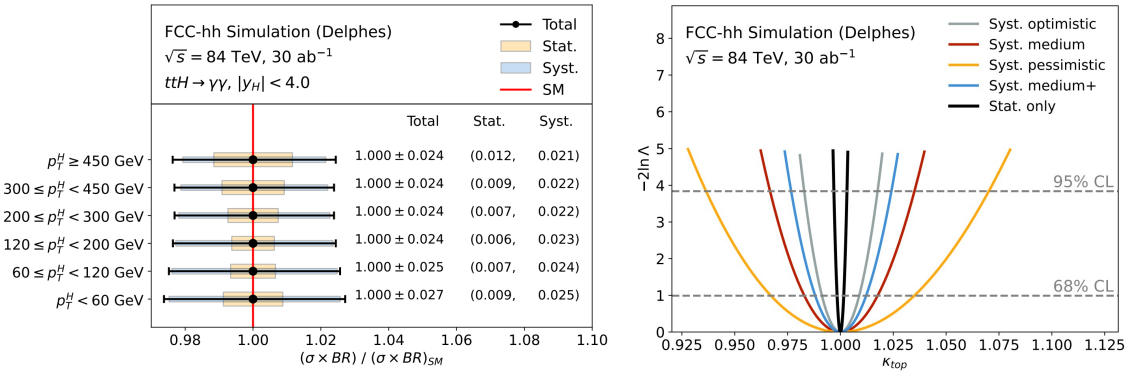

Figure 4: (Left) Differential measurements in the nominal scenario of the $t\bar{t}H$ cross section times $BR(H \to \gamma\gamma)$ in p_T^H bins. (Right) Likelihood scan of the Yukawa coupling modifier κ_t for different uncertainty scenarios [9].

4. Higgs self-coupling

The $HH \to b\bar{b}\gamma\gamma$ channel provides a clean experimental signature and excellent sensitivity despite its small branching fraction. The analysis strategy [13] exploits a categorization in the variable $m_X = m_{b\bar{b}\gamma\gamma} - m_{b\bar{b}} - m_{\gamma\gamma} + 250$ GeV to separate the region populated by the SM signal ($m_X > 350$ GeV), followed by a dedicated DNN to suppress backgrounds (see Fig. 5) and a fit to the $m_{\gamma\gamma}$ spectrum in bins of the dijet invariant mass, m_{bb} (see Fig. 6).

Under conservative assumptions on the non-resonant background, a statistical precision of 3.5% on the self-coupling modifier κ_λ can be achieved, degrading to around 5% when systematic uncertainties are included (see left Fig. 7). Right Fig. 7 shows how the precision changes with collision energy and assumed dijet resolution. The results demonstrate that detector and reconstruction improvements, such as enhanced m_{bb} regression performance, could further extend the FCC-hh reach.

Complementary sensitivity is obtained from the $HH \to b\bar{b}\tau^+\tau^-$ channel [14], studied using advanced Graph Neural Network (GNN) techniques for event classification. Both the $\tau_{\text{lep}}\tau_{\text{had}}$

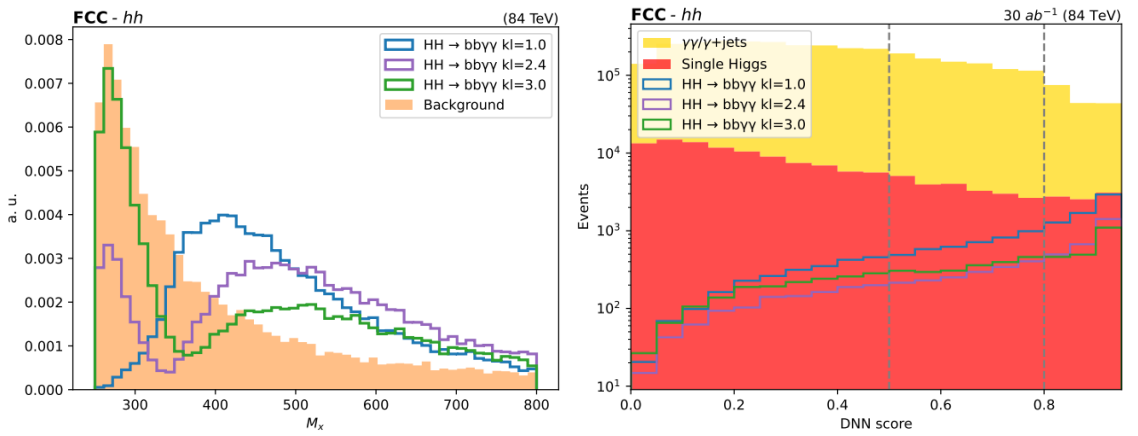

Figure 5: (Left) M_x distribution for three different signal hypothesis: κ_λ=1.0 (SM) and κ_λ=2.4,3.0. (Right) DNN score with chosen cuts for the high-M_x category [13].

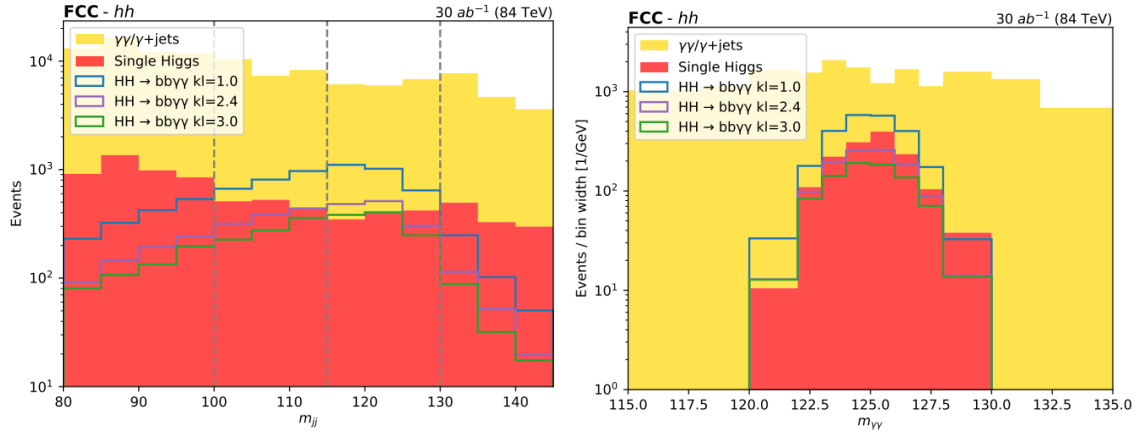

Figure 6: Di-jet mass distribution with chosen binning (left) and di-photon mass distribution in the di-jet mass bin 100–115 GeV, for signals and resonant (red) and non-resonant (yellow) background. Plots refers to high-purity, high-M_x category [13].

and $\tau_{\text{had}}\tau_{\text{had}}$ final states are considered, with events represented as fully connected graphs of reconstructed objects (see Fig. 8). The GNN approach achieves excellent signal-to-background separation, with areas under the ROC curve close to unity. An example of feature used in the GNN training is shown in left Fig 9, while the output score for the semi-leptonic channel is shown in the right panel. For the nominal FCC-hh configuration, statistical significances of $Z \sim 26$ ($Z \sim 92$) are reached for the semi-leptonic (fully hadronic) channels under the no-systematic assumption, while percent-level constraints on κ_λ remain feasible even when realistic systematic uncertainties are included. This demonstrates that the $b\bar{b}\tau\tau$ final state is competitive with the $b\bar{b}\gamma\gamma$ channel.

The combination of these channels, together with additional di-Higgs decay modes and improved analysis techniques, is expected to yield an overall precision on the Higgs self-coupling at or below the few-percent level, placing the FCC-hh in a unique position to test the SM Higgs potential and to search for subtle deviations indicative of physics beyond the SM.

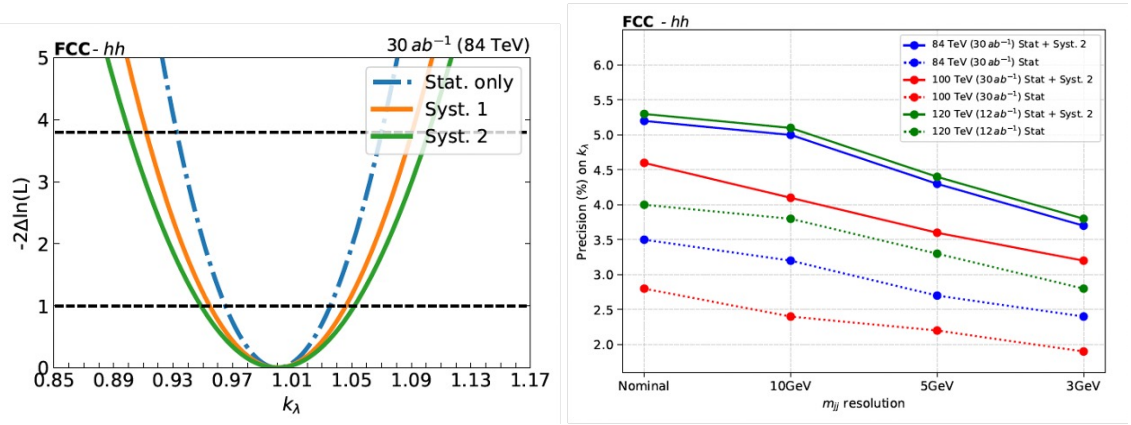

Figure 7: (Left) Expected likelihood scan as a function of κ_λ for different systematic uncertainty scenarios. (Right) Expected precision on κ_λ as a function of the m_{bb} resolution and the center of mass energy [13].

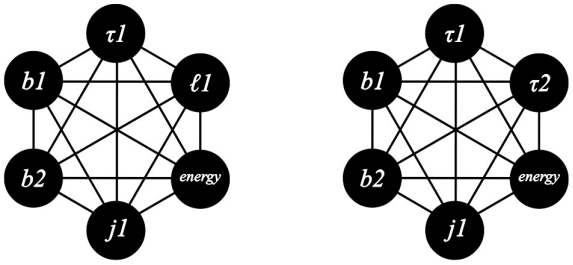

Figure 8: Schematic representation of events modeled as a fully connected graph in the $\ell\tau_h$ (left) and $\tau_h\tau_h$ (right) channel [14].

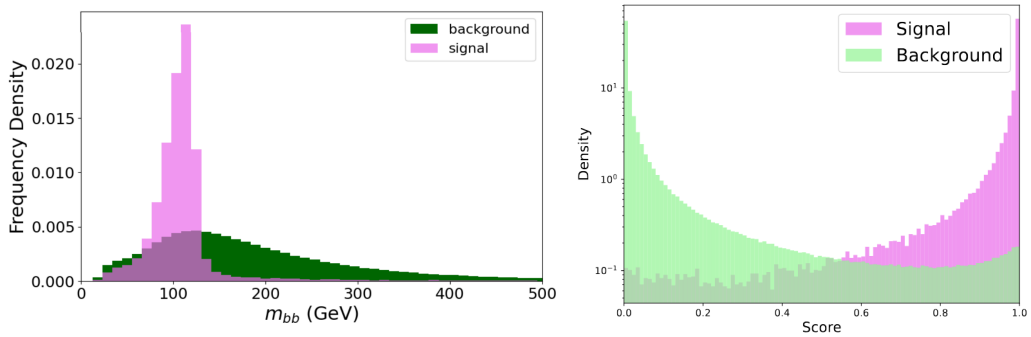

Figure 9: (Left) Normalized distribution for signal and background events of the invariant mass of the jet pair. (Right) Density distribution of the GNN output score. Plots refer to the $\ell\tau_h$ channel [14].

5. Conclusion

The FCC-hh will enable unprecedented precision in the study of the Higgs sector, with sub-percent sensitivity to rare decays and percent-level constraints on the top Yukawa and Higgs self-coupling. These results firmly establish the FCC program as a cornerstone for precision tests of the SM and searches for new physics.

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