Chapter 2

Theory: New physics at colliders

(Independent research group leader: Dr. U. Haisch)

Currently, the research group “New physics at colliders” comprises U. Haisch and the PhD student J. Weiss. Former members L. Schnell and S. Schulte successfully completed their PhD studies before transitioning out of physics. S. Schulte was supported by the MPP, while L. Schnell was funded by the Collaborative Research Center SFB1258, where U. Haisch serves as a principal investigator. The group’s primary focus is on exploring new physics at both the high-energy and high-intensity frontiers. Below, we provide a brief overview of the main research directions and key findings from 2022 to 2025.

2.1 Standard Model Effective Field Theory at work

(R. Gauld, U. Haisch, M. Niggetiedt, L. Schnell, and J. Weiss)

This year marks the 40th anniversary of the effective Lagrangian for new interactions and flavor conservation, which is now known as the Standard Model effective field theory (SMEFT). Since its introduction, the SMEFT has made significant strides and has become a well-established framework for constraining indirect signs of beyond the Standard Model (BSM) physics at the Large Hadron Collider (LHC). This effort places rigorous demands on the theoretical Standard Model (SM) predictions and increasingly also on the precision of the BSM calculations.

2.1.1 Energy beats precision

Hadron colliders are commonly seen as tools for discovery. While their precision is limited by the messy QCD environment, their high center-of-mass energies enable the direct production of new, heavy particles. In contrast, lepton colliders, which operate at lower energies, can achieve high precision and indirectly probe new heavy physics. An example of this is LEP, which examined the electroweak (EW) sector of the SM with unparalleled accuracy at the permille level. The flaws in this argument are well known to practitioners of effective field theory (EFT). When investigating heavy BSM physics with a mass scale M at energies $E \ll M$, the corrections to observables scale as $(E/M)^n$. For observables with $n > 0$, hadron colliders benefit from their high center-of-mass energy. The question is whether the energy boost at hadron colliders is sufficient to overcome the precision advantages of lepton colliders.

In the work [1], we highlighted that relevant constraints on the anomalous magnetic moment (a_τ) and electric dipole moment (d_τ) of the tau lepton can be obtained from tau-pair production measurements at the LHC. Our conclusion stems from the observation that the leading relative deviations from the SM prediction for $pp \to \tau^+\tau^-$, due to a_τ and d_τ, are amplified at high energies. As a result, less precise measurements at hadron colliders can provide comparable or even better sensitivity to new physics than high-precision low-energy measurements at lepton colliders. We derived constraints on a_τ and d_τ using the full LHC Run 2 data set for tau-pair production and compared our results with the current best limits on the tau anomalous moments. The obtained bound is the most stringent limit on a_τ to date, improving on the previous best constraints by roughly an order of magnitude.

The insights gained in [1] have been utilized in [2] to perform model-independent analyses of possible BSM modifications in neutral-current Drell-Yan (DY) production in both e^+e^- and pp collisions, with a focus on light-quark dipole oper-

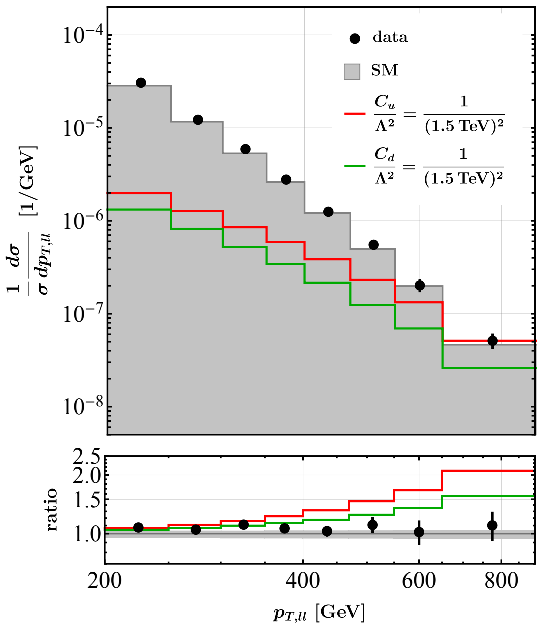

Figure 2.1: Comparison of the normalized $p_{T,ll}$ distribution. Black points represent the relevant ATLAS measurement, while the gray histogram corresponds to the SM prediction. Predictions for the BSM effects are displayed for two Wilson coefficient choices, depicted as red and green curves. Figure taken from [2].

ators emerging at the dimension-six level within the SMEFT framework. Specifically, we derived constraints on the relevant Wilson coefficients from measurements of Z production at the SLC and LEP, as well as Z+jet production at the LHC. We found that, due to the energy enhancement of the amplitudes, the less precise measurements of the Z-boson transverse momentum spectrum ($p_{T,ll}$) in Z+jet production at the LHC show greater sensitivity to light-quark dipole operators than the high-precision measurements of $Z \to q\bar{q}$ performed at e^+e^- machines. The energy enhancement of the amplitudes is illustrated in Figure 2.1. Our new constraints exclude the parameter space that could potentially explain the observed discrepancy between theoretical predictions and experimental data for the Lam-Tung relation at high $p_{T,ll}$. This finding contrasts with the results of previous work by other authors, who used Wilson coefficient values that are inconsistent with our new bounds.

2.1.2 SMEFT precision frontier

While one-loop QCD matching calculations in the SMEFT for LHC processes have seen a degree of automation, and the one-loop renormalization group (RG) evolution of the Wilson coefficients for dimension-six SMEFT operators is a solved problem, two-loop calculations within the SMEFT are still in its infancy. Much of the research conducted by U. Haisch and his collaborators over the past three years has been dedicated to advancing the SMEFT precision program.

Expanding on prior work conducted in collaboration with members of G. Zanderighi's research group, the article [3] presented a calculation of next-to-next-to-leading order (NNLO) QCD corrections to the Higgsstrahlungs (Vh) processes in hadronic collisions within the SMEFT framework. The fixed-order predictions were combined with a parton shower (PS), enabling NNLO+PS precision for the full set of SMEFT operators that describe the interactions between the Higgs and two vector bosons, as well as the couplings of the Higgs to a W or Z boson and light fermions. A POWHEG-BOX implementation of the computed NNLO SMEFT corrections was provided, facilitating a realistic exclusive description of Vh production at the level of hadronic events. This feature makes it a crucial tool for future Higgs characterization studies by the ATLAS and CMS collaborations. Using the new Monte Carlo (MC) code, the numerical impact of NNLO+PS corrections on the kinematic distributions in $pp \to Zh \to l^+l^-h$ production was examined, employing well-motivated SMEFT benchmark scenarios.

The most direct method to probe the cubic Higgs self-coupling at the LHC is through double-Higgs production via gluon-gluon fusion (ggF). However, additional constraints on this coupling can also be derived from single-Higgs production and decays, with the $gg \to h$ channel offering the highest sensitivity. To fully leverage the potential of this channel, we computed in [4] the corrections to the two-loop amplitudes for $gg \to h$, $gg \to hg$, $qg \to hq$, and $q\bar{q} \to hg$ arising from a modified cubic Higgs self-coupling. The exact dependence on the Higgs and top-quark masses over the entire $2 \to 2$ phase space was determined by numerically solving a system of differential equations for the relevant master integrals. The calculated amplitudes are essential for assessing the impact of these corrections on exclusive $pp \to h$+jet production at the level of hadronic events. As an application, we computed the non-universal, kinematic-dependent cubic Higgs self-coupling corrections to the transverse momentum distribution of the Higgs boson ($p_{T,h}$) in ggF Higgs production for arbitrary

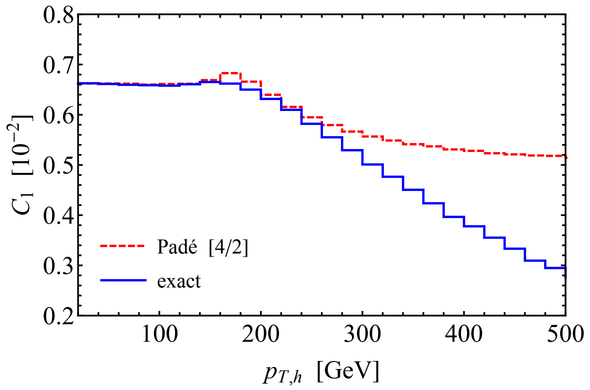

Figure 2.2: Non-universal corrections to the $p_{T,h}$ spectrum in $pp \to h$+jet production arising from a modified cubic Higgs self-coupling. The blue solid line corresponds to our exact computation, while the red dashed line represents a Padé approximation derived in a different paper. Figure adapted from [4].

transverse momentum values. Figure 2.2 presents the main findings of our work. A comprehensive analysis is currently in progress, building on the results from [4], to evaluate the capability of future LHC runs in constraining deviations in the cubic Higgs self-coupling by leveraging differential information from Higgs plus jet events.

While several of the Wilson coefficients in the SMEFT are tightly constrained by global SMEFT fits, offering a model-dependent insight into weakly-coupled BSM models with new particle masses exceeding 1 TeV, certain types of effective interactions remain poorly constrained. One such class of dimension-six operators involves four-quark contact interactions that only include third-generation fields. Motivated by this observation, we computed in [5] the one-loop and two-loop matching corrections in the SMEFT that influence EW precision measurements and flavor physics observables, with a focus on the contributions from the latter operators. Our results offer a key component for a model-independent analysis of constraints on BSM physics, particularly those affecting the third-generation four-quark operators. We provided concise analytic expressions for all the precision observables considered, which should aid their inclusion in global SMEFT analyses. In upcoming work, we will present the results of the two-loop anomalous dimensions that can be derived from [5], enabling us to study the RG flow of the relevant SMEFT contributions beyond the leading order (LO).

Another contribution to the SMEFT precision program was very recently provided in the work [6], where we performed a two-loop analysis of Higgs production via ggF from the triple-gluon operator. Specifically, we calculated the dependence of the relevant amplitudes on the Higgs and top-quark masses and discussed the renormalization procedure ensuring the ultraviolet (UV) finiteness of the two-loop $gg \to h$ form factor. This required computing an unknown two-loop SMEFT anomalous dimension. To achieve a renormalization scale-independent result for the $gg \to h$ cross section at next-to-leading order (NLO), we identified three essential contributions: (i) two-loop matching contributions involving the triple-gluon operator, (ii) one-loop matching contributions associated to the chromomagnetic top-quark dipole operator, and (iii) tree-level matching contributions arising from insertions of the Higgs-gluon operator. Our analysis highlights the necessity of including different matching and running effects at various perturbative orders. It thus serves as a blueprint for understanding the complexities and subtleties that arise in SMEFT calculations for collider processes beyond the LO. The computational methods used in the article [6] are also applicable to other calculations of two-loop corrections within the SMEFT context. Work in this direction is currently in progress.

2.2 Dark matter at the LHC

(U. Haisch, L. Schnell, and external collaborators)

Although dark matter (DM) is a fundamental component of the standard cosmological picture, its existence has only been inferred through astronomical observations, and its microscopic nature remains unknown. Theoretical considerations suggest that DM could be linked to the EW symmetry-breaking mechanism or other symmetries extending the SM of particle physics. Consequently, Higgs bosons — including the 125 GeV spin-0 particle discovered at the LHC — serve as a valuable tool for investigating potential DM candidates in collider experiments. Over the past three years, U. Haisch and collaborators have devoted much of their research to exploring collider searches for DM through the Higgs lens.

2.2.1 Higgs portal DM

Just as precision measurements of the Z boson at SLC and LEP provided new insights, the studies of Higgs properties at the LHC have opened new opportunities for indirectly searching for DM. In [7], we investigated the potential of future hadron colliders to constrain the fermionic Higgs portal, particularly in scenarios where new fermions remain undetectable in exotic Higgs decays. This portal arises in various models, such as twin-Higgs scenarios and DM models, presenting significant challenges for collider-based tests. Within an EFT framework, we assessed the sensitivity of the high-luminosity LHC (HL-LHC), the high-energy LHC upgrade, and a proposed Future Circular Collider to the fermionic Higgs portal via off-shell Higgs production in the $gg \to h^* \to ZZ \to 4l$ channel and double-Higgs production via $gg \to hh$. Our findings indicate that quantum-enhanced indirect probes surpass direct Higgs measurements in sensitivity. Furthermore, we argued that this conclusion holds across a broad range of UV completions of the EFT. Our study outlines a comprehensive search strategy for investigating the fermionic Higgs portal at future hadron colliders. In collaboration with ATLAS colleagues at the MPP, we are at the moment developing a general framework to directly extract constraints on models of Higgs portal DM using $pp \to h^* \to ZZ \to 4l$ data. Part of this research will be carried out within the framework of the Collaborative Research Center SFB1258.

2.2.2 Novel 2HDM+a signatures

The 2HDM+a model is one of the main frameworks used to interpret DM searches at the LHC. So far, all the 2HDM+a benchmarks considered by the ATLAS and CMS experiments have been limited to a type-II Yukawa sector, where the Higgs bosons A, H, and $H^{\pm}$ are assumed to be mass-degenerate and heavier than approximately 600 GeV. In [8], we presented the first detailed study of 2HDM+a models with a type-I Yukawa sector, which, for moderate values of $\tan\beta$, relaxes the constraints from flavor physics, allowing the additional Higgs bosons to be even lighter than the 125, GeV Higgs boson discovered at the LHC. We explored several benchmark scenarios where the A, H, and $H^{\pm}$ states are not necessarily mass-degenerate, identifying signatures that have not yet been explored at the LHC. We also presented the dominant production channels in the studied benchmarks and estimated the expected sensitivity using truth-level analyses of LHC Run 2 data. Figure 2.3 illustrates some of the results from our sensitivity study. We also explored potential improvements in experimental searches for the newly identified 2HDM+a signatures in LHC Run 3 and future runs. The six-month visit of PhD student I. Kalaitzidou from Freiburg University was essential for the completion of the described research activity.

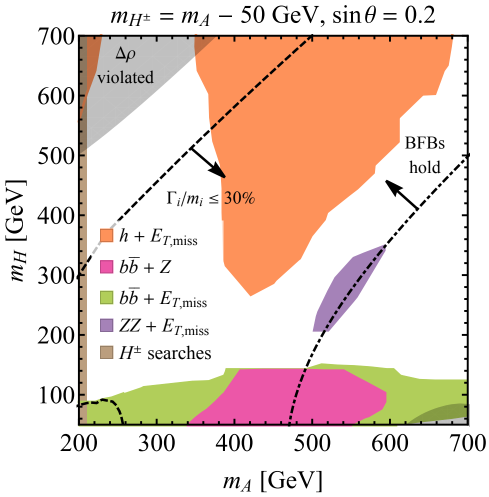

Figure 2.3: Constraints on the type-I 2HDM+a model derived from hypothetical searches for the final states $h + E_{T,\mathrm{miss}}$, $b\bar{b} + Z$, $b\bar{b} + E_{T,\mathrm{miss}}$, and $ZZ + E_{T,\mathrm{miss}}$. The figure also presents limits on the charged Higgs boson mass from current LHC searches, along with other indirect constraints. Figure adapted from [8].

Displaced decays of the Higgs boson, occurring away from the primary interaction vertex, provide a distinctive experimental signature that is actively pursued at the LHC by the ATLAS, CMS, and LHCb collaborations. In the article [9], we highlighted that such signals can arise in the context of the 2HDM+a model when the mixing angle θ between the two CP-odd weak spin-0 eigenstates is very small, and the DM sector is either decoupled or kinematically inaccessible. Using two appropriate benchmark scenarios, we analyzed the constraints on the parameter space of the 2HDM+a model imposed by existing LHC searches for long-lived particles (LLPs) in Higgs decays. Our results show that, depending on the exact mass spectrum of the spin-0 states, mixing angles θ in the range of a few 10^{-8} to 10^{-5} can be excluded by LHC Run 2 data. This underscores the critical role that displaced signature searches can play in constraining the parameter space of the 2HDM+a model. Additionally, we explored the resulting DM phenomenology, demonstrating that parameter choices that lead to interesting LLP phenomenology can also account for the observed DM abundance in the Universe today. The results and parameter benchmarks presented in our article [9] serve as a valuable foundation for interpreting future ATLAS, CMS, and LHCb searches for displaced Higgs decays into hadronic jets within the framework of the 2HDM+a model.

2.3 Flavor physics studies

(U. Haisch, L. Schnell, S. Schulte and external collaborators)

Flavor physics can provide important hints of BSM physics by observing deviations from the SM predictions in processes involving the EW interactions. These anomalies, such as unexpected behavior in meson decays or lepton-flavor violation, suggest the possible existence of new particles or interactions. Experiments at facilities like the LHCb, Belle II, and others are actively searching for such deviations at low transverse momentum (p_T), which could provide crucial insights into the nature of fundamental physics. ATLAS and CMS can complement these efforts by searching for distinctive flavorful high-p_T signatures.

2.3.1 Flavorful leptoquark signals

Motivated by the persistent indications of lepton-flavor non-universality in the $b \to cl\nu$ channels, we investigated DY tau-pair production at the LHC in the work [10]. In the context of models with third-generation gauge vector leptoquarks (LQs), we calculated the complete $\mathcal{O}(\alpha_s)$ corrections to the $pp \to \tau^+\tau^-$ process, achieving NLO+PS accuracy using the POWHEG method. We developed a dedicated MC code that calculates the NLO QCD corrections on-the-fly during event generation and used it to study the numerical impact of NLO+PS corrections on the kinematic distributions relevant to existing experimental searches for non-resonant tau-pair final states. Based on our phenomenological analysis, we derived NLO-accurate constraints on the masses and couplings of third-generation gauge vector LQs, using the latest LHC search results for tau pairs corresponding to the full LHC Run 2 data set. The presented NLO+PS generator provides improved signal modeling, making it an essential tool for future ATLAS and CMS searches for vector LQs in $\tau^+\tau^-$ final states at LHC Run 3 and beyond. The main conclusion from the results presented in [10] is that LQ model realizations explaining the $b \to cl\nu$ anomalies are experimentally testable at the HL-LHC through tau-pair production measurements.

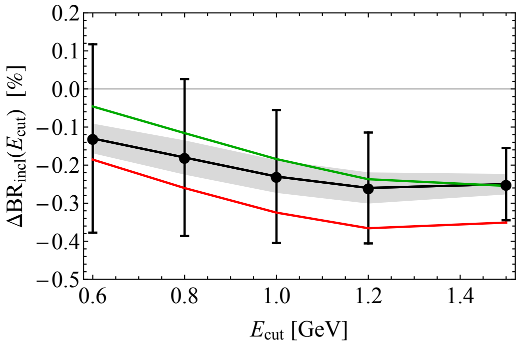

Figure 2.4: Comparison of the absolute shift in the QED corrections to $\mathrm{BR}_{\mathrm{incl}}(E_{\mathrm{cut}})$ *as a function of the lower electron energy threshold,* E_{cut}*. The black curve represents the correction determined by BaBar using PHOTOS, with both systematic and total uncertainties. The red (green) curve corresponds to our QED prediction, incorporating LL terms (all QED corrections). Figure taken from [11].*

2.3.2 QED effects in $B \to X_c e\nu$

In addition to the previously mentioned signs of lepton non-universality, a long-standing discrepancy in the flavor sector remains between the inclusive and exclusive measurements of the Cabibbo-Kobayashi-Maskawa (CKM) matrix element $|V_{cb}|$. Following the calculation of the $\mathcal{O}(\alpha_s^3)$ corrections to the total semi-leptonic decay width, the uncertainty in the inclusive determination of $|V_{cb}|$ is approximately 1.2%. At this precision, a thorough examination of QED and EW effects is essential. In the publication [11], we conducted a detailed analysis of such corrections to the total decay width and the moments of the electron energy spectrum for the inclusive semi-leptonic $B \to X_c e\nu$ decay. Our calculation includes short-distance EW corrections, the complete $\mathcal{O}(\alpha)$ partonic terms, and leading-logarithmic (LL) QED effects up to $\mathcal{O}(\Lambda^3_{\mathrm{QCD}}/m_b^3)$ in the heavy quark expansion. A comprehensive numerical comparison of our results with those obtained using the MC tool PHOTOS was presented. While the comparison shows good overall agreement, our computation includes QED effects not considered in PHO-

TOS and should therefore provide a more accurate description of photon radiation in $B \to X_c e\nu$ decays as measured by B-factories. The good agreement between our calculation and PHOTOS is demonstrated in Figure 2.4, which shows the absolute shift in the inclusive branching ratio of $B \to X_c e\nu$ when applying a lower electron energy cut, $E_e > E_{\mathrm{cut}}$. Our calculations represent an important first step toward developing a fully differential higher-order QED MC generator for inclusive semi-leptonic B decays. This research was initiated during P. Gambino's sabbatical visit to the MPP.

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