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Precise prediction for the mass of the light MSSM Higgs boson for the case of a heavy gluino

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Abstract

State-of-the-art predictions for the mass of the lightest MSSM Higgs boson usually involve the resummation of higher-order logarithmic contributions obtained within an effective-field-theory (EFT) approach, often combined with a fixed-order calculation into a hybrid result. For the phenomenologically interesting case of a significant hierarchy between the gluino mass and the masses of the scalar top quarks the predictions suffer from large theoretical uncertainties related to non-decoupling power-enhanced gluino contributions in the EFT results employing the $\overline{\text{DR}}$ renormalisation scheme. We demonstrate that the theoretical predictions in the heavy gluino region are vastly improved by the introduction of a suitable renormalisation scheme for the EFT calculation. It is shown that within this scheme a recently proposed resummation of large gluino contributions is absorbed into the model parameters, resulting in reliable and numerically stable predictions in the large gluino region. We also discuss the integration of the results into the public code `FeynHiggs`.

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1 Introduction

In models which allow a direct prediction of the mass of the Higgs boson resembling the one of the Standard Model (SM) in terms of the model parameters important constraints on the parameter space can be obtained from the comparison of the predicted value with the precise mass measurement of the detected Higgs signal [1–3]. The most thoroughly studied model in this context is the Minimal Supersymmetric extension of the Standard Model (MSSM). The accuracy of the prediction for the light $\mathcal{CP}$-even Higgs-boson mass of the MSSM has been significantly improved during the last years (see [4–14] for recent works), in particular for the case where some or all of the supersymmetric (SUSY) particles are relatively heavy. This has been achieved with effective-field-theory (EFT) methods, where the heavy SUSY particles are integrated out. The contributions obtained in this way employ the $\overline{\text{MS}}$ and $\overline{\text{DR}}$ renormalisation schemes for the running from the low scale to the SUSY scale(s) and the matching with the full theory at the high scale. Hybrid results [5, 7, 13, 15–20], combining a fixed-order calculation with an EFT treatment for resumming higher-order logarithmic contributions, provide accurate predictions both for low and high values of the SUSY scale.

Appropriate EFT descriptions have been developed for different patterns of possible SUSY spectra, including split-SUSY type scenarios where the mass of the gluino — the superpartner of the gluon — is much lighter than the masses of the scalar quarks [21, 22]. However, no proper treatment of the case where the gluino is significantly heavier than the scalar quarks is available up to now. As a consequence, large theoretical uncertainties in the Higgs-mass prediction occur for values of $|M_3| \gtrsim 2M_{\text{SUSY}}$ [14], where M_3 denotes the gluino mass parameter, and M_{SUSY} denotes the geometric mean of the soft-SUSY breaking masses of the stops, the superpartners of the top quark. This is a serious drawback for realistic analyses of SUSY phenomenology since the LHC searches have pushed the experimental bounds on the gluino mass to the region above ~ 2 TeV, while the superpartners of the top quark are still allowed to have masses around the TeV scale [23–31].

The large theoretical uncertainties for the case where the gluino is heavier than the stop particles can be traced to corrections to the squared masses of the stops that are proportional to $|M_3|^2$ at the one-loop level in the $\overline{\text{DR}}$ scheme as well as corrections linear in $|M_3|$ originating from one-loop corrections to the stop mixing parameter X_t. If instead an on-shell (OS) renormalisation for the stop masses and the stop mixing parameter (it is sufficient in this context to impose a condition on the renormalised off-diagonal self-energy of the two scalar top quarks) is employed, the momentum subtraction arising from the on-shell counterterms leads to a cancellation of the leading contributions that are proportional to $|M_3|^2$ and $|M_3|$. Accordingly, the two-loop fixed-order prediction for the mass of the SM-like Higgs boson of the MSSM in the OS scheme depends only logarithmically on the gluino mass [32–34], while the corresponding $\overline{\text{DR}}$ result contains contributions that are enhanced by powers of $|M_3|$ [33]. However, for EFT calculations the OS scheme is not applicable. As a consequence, large non-decoupling effects for a heavy gluino occur both in pure EFT results (using a single SUSY scale) and also in the EFT parts of hybrid results via the threshold corrections at the SUSY scale that are evaluated in the $\overline{\text{DR}}$ scheme.

A possible solution would be the derivation of a complete EFT where the effects of a heavy gluino are systematically integrated out from the MSSM. While in the context of other observables such an approach has been investigated [35–37], a complete EFT calculation for a heavy gluino that could be applied for the Higgs-mass prediction in the MSSM has not been carried out so far. In [38] it was proposed to deal with this problem by reexpressing the threshold corrections in a pure (single-scale) EFT result derived in the $\overline{\text{DR}}$ scheme in terms of an "OS-like" renormalisation scheme. However, this prescription is not a viable option since its derivation was based upon an incorrect result for the transition of the OS stop mixing parameter to the $\overline{\text{DR}}$ stop mixing parameter. If the correct formula is used, a large logarithm appears in the $\mathcal{O}(\alpha_t\alpha_s)$ threshold correction spoiling the underlying assumptions of the EFT approach. Recently, the authors of [39] proposed a resummation of terms that are enhanced by powers of the gluino mass as a possibility to alleviate fine-tuning issues in the MSSM and the NMSSM.

In the present paper we demonstrate how state-of-the-art hybrid results that contain a resummation of higher-order logarithmic contributions (the same holds for pure EFT results), can be consistently improved such that large theoretical uncertainties for the case of a heavy gluino are avoided. Our approach is based on the introduction of a suitable renormalisation scheme for the EFT part of the hybrid result, for which the occurrence of power-enhanced corrections from the gluino mass is avoided. We explicitly demonstrate that the terms resummed via the prescription of [39] are absorbed by the parameters of the adopted renormalisation scheme. In our numerical analysis we show that reliable theoretical predictions can be obtained also for large hierarchies between the gluino mass and the stop masses. We also discuss the integration of the results into the hybrid framework of the public code `FeynHiggs` [15, 16, 19, 32, 40–44].

The paper is organized as follows. In Sec. 2, we discuss how corrections arise that are enhanced by powers of the gluino mass and how they can be absorbed by a suitable choice of the renormalization scheme. We investigate the numerical implications in Sec. 3. Conclusions are given in Sec. 4. In the the appendix it is shown that our results incorporate the resummation that was proposed in [39].

2 Treatment of contributions enhanced by the gluino mass

In the following we present a systematic approach for the incorporation of terms that can be enhanced by powers of the gluino mass $|M_3|$ into the prediction for the mass of the SM-like Higgs boson in the MSSM. We will show that our results automatically incorporate the resummation of large gluino contributions that was recently proposed [39].

In a fixed-order calculation within the OS scheme the leading contributions that are enhanced by powers of the gluino mass cancel out between the unrenormalised diagrams and the counterterms as a consequence of the fact that the OS scheme is a momentum-subtraction scheme. As an example, it is well-known that the unrenormalised self-energies of the scalar top quarks, $\Sigma(p^2)$, receive contributions at the one-loop level that scale proportional to the squared gluino mass in the limit of a heavy gluino. These terms cancel, however, in the renormalised self-energies of the two stop mass eigenstates,

$$\Sigma^{\text{ren}}(p^2) = \Sigma(p^2) - \text{Re}\left(\Sigma(p^2 = m^2)\right) + \ldots, \tag{1}$$

where the ellipsis denotes terms involving the field renormalisation constant and m is the mass of the scalar top quark. In the $\overline{\text{DR}}$ scheme, on the other hand, the mass counterterm does not have a finite part, and a cancellation like in Eq. (1) does not occur.

In order to treat the case where the gluino is much heavier than the rest of the mass spectrum with EFT methods, the gluino should be integrated out. For this purpose, matching conditions between the full MSSM and the MSSM without gluino have to be calculated. In this matching procedure, all particles except the gluino can be treated as massless. Consequently, it follows purely from dimensional analysis that no terms enhanced by powers of the gluino mass can enter the matching of the Higgs four-point function and also of all other dimensionless Green functions (terms depending logarithmically on the gluino mass are possible).

Contributions that are enhanced by powers of the gluino mass can, however, enter in the matching of Green functions with a mass dimension greater than zero. If we perform the matching before electroweak symmetry breaking, these Green functions are all related to soft SUSY-breaking parameters which, apart of the gluino mass parameter M_3, can be treated as being zero at the tree-level in the heavy gluino limit. Diagrams involving gluinos generate non-zero contributions at the loop-level which are proportional to powers of the gluino mass. The highest possible power in M_3 is given by the mass dimension of the respective parameter.

In the context of the calculation of the lightest SM-like Higgs-boson mass, the soft SUSY-breaking parameters of the scalar top quarks are most relevant.[1] Their one-loop matching relations read

$$\left(m_{\tilde{t}_{L,R}}^{\text{MSSM}/\tilde{g}}\right)^2(Q) = \left(m_{\tilde{t}_{L,R}}^{\text{MSSM}}\right)^2(Q)\left[1+\frac{\alpha_s}{\pi}C_F\frac{|M_3|^2}{m_{\tilde{t}_{L,R}}^2}\left(1+\ln\frac{Q^2}{|M_3|^2}\right)\right], \tag{2}$$

$$X_t^{\text{MSSM}/\tilde{g}}(Q) = X_t^{\text{MSSM}}(Q) - \frac{\alpha_s}{\pi}C_F M_3\left(1+\ln\frac{Q^2}{|M_3|^2}\right), \tag{3}$$

where MSSM/$\tilde{g}$ denotes the MSSM without the gluino, M_3 is the gluino mass parameter (we consider here the general case where M_3 can have complex values), $m_{\tilde{t}_{L,R}}$ are the left and right soft-breaking masses of the stop sector, X_t is the stop mixing parameter, $\alpha_s = g_3^2/(4\pi)$ (with g_3 being the strong gauge coupling), $C_F = 4/3$ and Q is the scale at which the matching is performed. Higher-order corrections to these relations are subleading (i.e., of the form $|M_3|^2\alpha_s^n$ with $n \geq 2$ in case of the mass parameters and of the form $|M_3|\alpha_s^n$ in the case of the stop mixing parameter).

After integrating out the gluino at the gluino mass scale, the parameters are evolved down to the stop mass scale, where in the simplest setup all other non-SM particles are integrated out. Since the gluino is not present in the EFT below the gluino mass scale, no terms enhanced by powers of the gluino mass can enter in all the parts of the calculation that are performed at a scale below the gluino mass scale.

Deriving all necessary matching conditions for integrating out the gluino as well as the corresponding RGEs is cumbersome. [2] Instead, we focus here specifically on terms that

[1] The presented argumentation is straightforwardly transferable to other sectors having a smaller numerical impact (e.g. the sbottom sector), which are not discussed here. Note that also the Higgs soft-breaking masses receive threshold corrections (see [39]). In the present paper, we work in the approximation of setting the electroweak gauge coupling to zero in the non-logarithmic two-loop corrections. Thus, the matching of the Higgs soft-breaking parameters does not enter the calculation of the SM-like Higgs mass.

[2] In the recent study [37] all one-loop matching conditions for operators of dimension four to six were derived for the MSSM without gluino in the gaugeless limit, but in addition also the appropriate two-loop threshold corrections and RGEs would be needed.

are enhanced by powers of the gluino mass. As argued above, these terms arise only in the matching relations of the soft SUSY-breaking masses. Instead of performing the full matching, we can also absorb the terms that are enhanced by powers of the gluino mass into the definition of the parameters. For the case of the mass parameters it is useful to adopt the $\overline{\text{MDR}}$ scheme employed in [45] for this purpose,

$$\left(m_{\tilde{t}_{L,R}}^{\overline{\text{MDR}}}\right)^2 = \left(m_{\tilde{t}_{L,R}}^{\overline{\text{DR}}}\right)^2 \left[1 + \frac{\alpha_s}{\pi} C_F \frac{|M_3|^2}{m_{\tilde{t}_{L,R}}^2} \left(1 + \ln \frac{Q^2}{|M_3|^2}\right)\right]. \tag{4}$$

We extend the $\overline{\text{MDR}}$ scheme by also defining it for the stop mixing parameter,

$$X_t^{\overline{\text{MDR}}}(Q) = X_t^{\overline{\text{DR}}}(Q) - \frac{\alpha_s}{\pi} C_F M_3 \left(1 + \ln \frac{Q^2}{|M_3|^2}\right). \tag{5}$$

Using this scheme, the resummation formulas derived in [39] are easily recoverable (see App. A).

If the EFT calculation is performed in the $\overline{\text{MDR}}$ scheme no terms enhanced by powers of the gluino mass appear.[3] At the same time the occurrence of large logarithms in the threshold corrections that would spoil the underlying assumptions of the EFT approach (as it happens for the "OS-like" scheme proposed in [38]) is avoided in this way. It should be noted that the threshold corrections between the SM and the MSSM still depend logarithmically on the gluino mass. These terms are, however, numerically less problematic.

In order to incorporate the EFT calculation using the $\overline{\text{MDR}}$ scheme into a hybrid result involving on-shell parameters or into a framework using another scheme, for instance $\overline{\text{DR}}$ parameters, the respective parameters need to be related to the corresponding quantities in the $\overline{\text{MDR}}$ scheme. We briefly describe in the following how this can be achieved for the case of OS and $\overline{\text{DR}}$ parameters.

On-shell input parameters

Often the OS scheme is used for the definition of the stop parameters. It relates the mass parameters directly to physical observables (more precisely, pseudo-observables) and is therefore often used in phenomenological studies.

For the case of OS input parameters the incorporation of the EFT calculation using the $\overline{\text{MDR}}$ scheme can be carried out along the lines of the procedure that is employed in the hybrid framework of `FeynHiggs` for combining the fixed-order and EFT approaches [7, 15, 16, 19]. As usual, the fixed-order corrections can be evaluated directly in the OS scheme. As explained above, for the EFT calculation the OS scheme is not applicable, since it would induce large logarithms in the threshold corrections. Instead, we improve the hybrid result by carrying out the EFT calculation with the stop parameters defined in the $\overline{\text{MDR}}$ scheme rather than the $\overline{\text{DR}}$ scheme as it was used up to now. In order to obtain the input parameters of the EFT calculation in the $\overline{\text{MDR}}$ scheme we need to convert the input parameters given in the OS scheme to the $\overline{\text{MDR}}$ scheme. As argued in [16, 19], only one-loop logarithms need

[3] If three-loop threshold corrections are taken into account, also subleading terms (i.e., terms of two-loop order) in the $\overline{\text{MDR}}$ definition have to be taken into account [45, 46].

to be taken into account in this conversion. This implies that the incorporation of the EFT results using the $\overline{\text{MDR}}$ scheme instead of the $\overline{\text{DR}}$ scheme does not require changes in the formulas presented in [16]. We perform the conversion at the scale M_{SUSY}. This implies that we use M_{SUSY} as matching scale between the SM and the MSSM. Using $|M_3|$ as alternative scale choice does not lead to large shifts in M_h.

$\overline{\text{DR}}$ input parameters

For the study of high-scale SUSY breaking models, often the $\overline{\text{DR}}$ scheme is used as it is appropriate for running down the parameters from the high scale. This is also the scheme that is usually employed in pure EFT calculations. For the case of $\overline{\text{DR}}$ input parameters the following procedure should be employed. The high-scale $\overline{\text{DR}}$ parameters are run down to the gluino mass scale. At this scale, they are converted to the $\overline{\text{MDR}}$ scheme using Eq. (4). After this conversion the fixed-order as well as the EFT calculation can be carried out in the $\overline{\text{MDR}}$ scheme.

We perform the conversion between the $\overline{\text{DR}}$ and the $\overline{\text{MDR}}$ parameters at the gluino mass scale. Consequently, we also set the matching scale of the SM to the MSSM to the scale of the gluino mass. If instead the conversion between $\overline{\text{DR}}$ and $\overline{\text{MDR}}$ parameters were performed at the stop mass scale, the conversion would induce large logarithmic contributions, see Eq. (4).

3 Numerical results

In this Section, we discuss the numerical implications of using the $\overline{\text{MDR}}$ scheme in the EFT calculation. We focus on a single-scale scenario in which all non-SM mass parameters are chosen to be equal to a common mass scale named M_{SUSY}, which is set to 1.5 TeV. As only exception, we allow the gluino mass parameter M_3 to take a different value. We choose all soft SUSY-breaking trilinear couplings to be zero except for the stop trilinear coupling which is fixed by setting the stop mixing parameter X_t. The ratio of the Higgs vacuum expectation values, $\tan\beta$, is set to 10.

The left panel of Fig. 1 shows the prediction for the lightest Higgs boson mass in the hybrid approach obtained by the latest version of `FeynHiggs` (version `2.15.0`) as a function of the ratio $|M_3|/M_{\text{SUSY}}$. In addition to the $\overline{\text{DR}}$ scheme, which was used up to now by default in the EFT calculation of `FeynHiggs` for the definition of the stop parameters, we implemented the $\overline{\text{MDR}}$ scheme as defined in Section 2. For this plot the input parameters of the stop sector are assumed to be defined in the OS scheme, setting $\widehat{X}_t^{\text{OS}} = 2$, where $\widehat{X}_t = X_t/M_{\text{SUSY}}$.

The blue solid line shows the result obtained using the $\overline{\text{DR}}$ scheme in the EFT calculation. This means, in particular, that the stop parameters are $\overline{\text{DR}}$ parameters defined at the scale M_{SUSY}. Since the input parameters are defined in the OS scheme, there is no quadratic and linear dependence on M_3 at the two-loop level as the calculation up to this level is based on the fixed-order result in the OS scheme. However, terms that are enhanced by powers of the gluino mass emerge from the two-loop threshold correction to the Higgs quartic coupling of $\mathcal{O}(\alpha_t\alpha_s)$. This threshold correction generates three-loop NNLL (next-to-next-to-leading

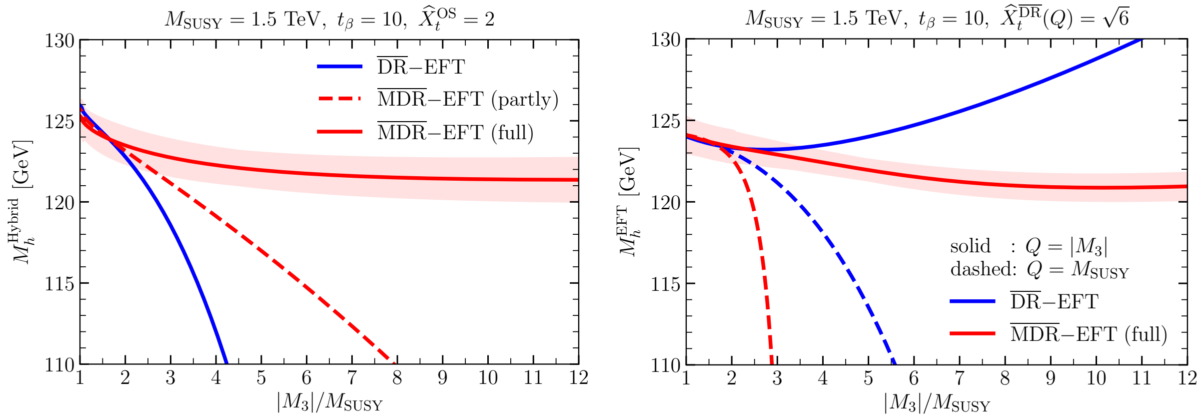

Figure 1: Prediction for M_h as a function of the ratio of the gluino mass over $M_{\rm SUSY}$. For the most accurate result, labelled as $\overline{\rm MDR}$–EFT (full), the estimate of the remaining theoretical uncertainties is shown as coloured band. The result is compared with predictions using different renormalisation schemes in the EFT calculation. *Left*: Prediction of the hybrid calculation using the OS scheme for the definition of the input parameters where for the EFT part the full $\overline{\rm MDR}$ scheme, a partial $\overline{\rm MDR}$ scheme (see text) and the $\overline{\rm DR}$ scheme are used. *Right*: Prediction of the pure EFT calculation using the $\overline{\rm DR}$ scheme for the definition of the input parameters. The result for the $\overline{\rm MDR}$ scheme with matching scale $Q = |M_3|$ is compared with the one for $Q = M_{\rm SUSY}$ and with the result for the $\overline{\rm DR}$ scheme with both scale choices.

logarithmic) terms in the expression for the Higgs-boson mass. For $\widehat{X}_t^{\rm OS} = 2$, these power-enhanced terms in the $\overline{\rm DR}$-EFT result drive the Higgs-mass prediction steeply downwards when $|M_3|$ increases as shown in the plot. The large numerical impact of the power-enhanced terms leads to a large increase of the theoretical uncertainty of the EFT result in the $\overline{\rm DR}$ scheme (and consequently also of the hybrid result into which it is implemented), see the discussion in [14]. There a drastic increase of the uncertainty was found in the region $|M_3|/M_{\rm SUSY} \gtrsim 2$ for the same scenario.

The red dashed curve on this plot corresponds to the result of the hybrid calculation in which in the EFT calculation the left and right stop soft-breaking masses are parametrized in the $\overline{\rm MDR}$ scheme at the scale $M_{\rm SUSY}$, while the stop mixing parameter X_t is still a $\overline{\rm DR}$ parameter defined at the same scale. This corresponds to the version of the $\overline{\rm MDR}$ scheme that was previously used in the literature. While for this result the Higgs-mass prediction falls less rapidly with increasing $|M_3|$ compared to the blue solid curve, the plot shows that there is a remaining approximately linear dependence of the squared Higgs mass on $|M_3|$ that leads to large theoretical uncertainties also for this result. The reason for the somewhat improved behaviour with respect to the result that is based on the $\overline{\rm DR}$ scheme can be traced to the fact that the choice of $m_{\tilde{t}_{L,R}}$ in the $\overline{\rm MDR}$ scheme absorbs the quadratic dependence $\sim |M_3|^2$ in the mentioned three-loop NNLL terms (and also of higher order terms).

The red solid curve in the left plot of Fig. 1 shows the result of the hybrid calculation making use of the extended $\overline{\rm MDR}$ scheme as described above. Accordingly, all the stop parameters entering the EFT part of the hybrid result are parametrized in the $\overline{\rm MDR}$ scheme at the scale $M_{\rm SUSY}$. In this case, all the terms scaling like powers of the gluino mass that would be induced by the two-loop $\mathcal{O}(\alpha_t\alpha_s)$ contribution to the threshold correction are absorbed into the definition of the soft-breaking parameters. We observe only a rather mild logarithmic dependence of the calculated Higgs-boson mass on $|M_3|/M_{\rm SUSY}$. These logarithms could be resummed by performing the complete matching of the full MSSM to the MSSM without a gluino as low-energy theory above the stop mass scale. This, however, is numerically much less relevant and lies beyond the scope of the present paper.

For the full $\overline{\rm MDR}$ result, we also show a coloured band indicating the remaining theoretical uncertainty estimated using the procedure developed in [14]. The comparison with the uncertainty estimate obtained in [14] for the case where the EFT part of the calculation is based on the $\overline{\rm DR}$ scheme shows that the application of the (extended) $\overline{\rm MDR}$ scheme to the EFT part of the calculation leads to a drastic reduction of the theoretical uncertainty. The uncertainty that we estimate for the full $\overline{\rm MDR}$–EFT result stays approximately constant (~ 1.5 GeV) when $|M_3|$ is raised and shows no sharp increase as found in [14].

The right panel of Fig. 1 shows the lightest Higgs-boson mass calculated in the pure EFT approach as implemented in `FeynHiggs` (version `2.15.0`) as a function of $|M_3|/M_{\rm SUSY}$ using the $\overline{\rm DR}$ scheme for the definition of the input parameters. We define these parameters at the matching scale Q between the SM and the MSSM. For our result based on the (extended) $\overline{\rm MDR}$ scheme this scale should be chosen as $Q = |M_3|$ (red solid line) since the gluino should be integrated out at its own scale. For comparison we also show the $\overline{\rm MDR}$–EFT result where the matching scale is chosen as $M_{\rm SUSY}$ (red dashed line). We furthermore display the $\overline{\rm DR}$–EFT result for both scale choices. It should be noted that for $|M_3| \neq M_{\rm SUSY}$ the solid lines (matching scale $|M_3|$) and the dashed lines (matching scale $M_{\rm SUSY}$) cannot be directly compared to each other since they represent different physical situations. We fix $\widehat{X}_t^{\overline{\rm DR}} = \sqrt{6}$ for this plot.

Our result based on the (extended) $\overline{\rm MDR}$ scheme (red solid line) is parametrized in terms of $\overline{\rm MDR}$ quantities at the scale $|M_3|$, which are obtained from a one-loop conversion of the $\overline{\rm DR}$ parameters at the same scale using Eqs. (4) and (5) and making the according adjustments to the $\mathcal{O}(\alpha_t\alpha_s)$ threshold correction (for more details see Section 2). We observe only a mild logarithmic dependence of the calculated Higgs-boson mass on $|M_3|/M_{\rm SUSY}$ for this result.

The coloured band shows the estimated size of unknown higher-order corrections for the $\overline{\rm MDR}$–EFT result with $Q = |M_3|$. The theoretical uncertainty of the EFT result is estimated following largely the procedure employed in [14]. As only difference we take into account an additional uncertainty associated with unknown higher-order corrections to the relations converting the parameters from the $\overline{\rm DR}$ to the $\overline{\rm MDR}$ scheme (see Eqs. (4) and (5)). We estimate this uncertainty by replacing α_s by $\alpha_s\,[1 \pm \alpha_s/(4\pi)\,(1 + \ln Q^2/|M_3|^2)]$ in Eqs. (4) and (5) (see also the discussion in [14]). As for the case of OS input parameters for the hybrid result, the total uncertainty stays approximately constant (~ 1 GeV) when $|M_3|$ is raised.

For comparison, the red dashed line shows the EFT result based on the (extended) $\overline{\rm MDR}$ scheme where the matching scale is chosen as $Q = M_{\rm SUSY}$ instead of $Q = |M_3|$. It is clearly visible that such an inappropriate scale choice for the conversion would spoil the stability of the $\overline{\rm MDR}$–EFT result.

We now turn to the discussion of the $\overline{\rm DR}$–EFT result (blue solid and dashed lines). It is obvious that neither scale choice yields a reliable theoretical prediction of the $\overline{\rm DR}$–EFT calculation. As explained above, this is caused by the power-enhanced gluino contributions that are present in this result. The blue dashed line shows the result where the matching scale is chosen as $M_{\rm SUSY}$. In this case, the two-loop threshold correction of $\mathcal{O}(\alpha_t\alpha_s)$ depends quadratically on $|M_3|$ and so does the squared Higgs mass which contains terms proportional to $\sim |M_3|^2\,(1+\log M_{\rm SUSY}^2/|M_3|^2)$. As one can see from Eqs. (4) and (5), for the choice $Q = M_{\rm SUSY}$ the $\overline{\rm MDR}$ stop soft-breaking parameters decrease with increasing $|M_3|$. This results in the rapid fall of M_h with increasing $|M_3|$ visible for the dashed blue line.

The blue solid curve in the right plot of Fig. 1 corresponds to the $\overline{\rm DR}$–EFT result where the $\overline{\rm DR}$ parameters are defined at the scale $|M_3|$. As explained above, there is a quadratic dependence on the gluino mass in the two-loop threshold correction. However, since for the choice $Q = |M_3|$ there is no additional logarithmic suppression of the threshold correction, in this case the Higgs mass grows with increasing $|M_3|$.

4 Conclusions

In this paper, we have shown how an appropriate choice of the renormalization prescription for the stop sector of the MSSM leads to a very significant improvement of the theoretical prediction for the mass of the SM-like Higgs boson in the region where the gluino is heavier than the scalar top quarks. This region is phenomenologically important in particular in view of the strengthened limits from experimental searches for the gluino.

In pure EFT calculations and in the EFT part of hybrid results making use of the $\overline{\rm DR}$ scheme for the renormalization of the stop sector leads to the appearance of terms enhanced by powers of the gluino mass. These large non-decoupling effects of the gluino, which are formally of three-loop order for a hybrid result where the fixed-order part is evaluated in the OS scheme up to the two-loop order, lead to unreliable predictions and correspondingly large theoretical uncertainties in the large gluino region. We have shown how the occurrence of power-enhanced corrections from the gluino mass in the EFT part of the calculations can be avoided without spoiling the underlying assumptions of the EFT. In fact, we have demonstrated that the leading contributions from integrating out the gluino can be taken into account by absorbing them into the renormalisation of the stop parameters. This scheme, called $\overline{\rm MDR}$, has already been used before in the literature. We have extended it to include also the stop mixing parameter. We have furthermore shown that the recently proposed resummation of large gluino contributions [39] is taken into account in the (extended) $\overline{\rm MDR}$ scheme via the absorption of the contributions into the parameters of the model. We also discussed the implementation of the (extended) $\overline{\rm MDR}$ scheme into the public code `FeynHiggs` and its impact on the estimate of the remaining theoretical uncertainties from unknown higher-order corrections. The implementation will be publicly released in an upcoming version.

In our numerical analysis we have demonstrated that using the (extended) $\overline{\rm MDR}$ scheme for the EFT part of the hybrid result leads to a prediction for M_h that shows only a mild dependence on the gluino mass even for large hierarchies between the gluino mass and the stop masses. The theoretical uncertainties in the large gluino region are vastly improved compared to the case where the EFT result is based on the $\overline{\rm DR}$ scheme. We have demonstrated that these features only hold for the extended $\overline{\rm MDR}$ scheme, while restricting the scheme to the masses — as previously used in the literature — would not be sufficient for this purpose. We have furthermore stressed that in the case of $\overline{\text{DR}}$ input parameters the matching scale in the EFT approach should be set to $|M_3|$ for the case where $|M_3| > M_{\text{SUSY}}$, as expected from the fact that the gluino should be integrated out at its own scale. We have also pointed out that for the EFT approach using the $\overline{\text{DR}}$ scheme neither the scale choice $|M_3|$ nor M_{SUSY} leads to a reliable prediction in the large gluino region.

The presented renormalisation prescription is straightforwardly applicable to the calculation of other observables.

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A From the $\overline{\text{MDR}}$ scheme to the resummation of gluino contributions

Here, we discuss how the resummation formulas given in [39] can be recovered from the expressions in the $\overline{\text{MDR}}$ scheme. The authors of [39] considered two sets of diagrams contributing to the matching of the soft SUSY-breaking Higgs mass parameter m_{22}.

The left diagram of Fig. 1 in [39] corresponds to an A_0 Passarino–Veltman loop function. In the $\overline{\text{MDR}}$ scheme, we do not have to consider any stop self-energy insertions beyond the one-loop diagram. Defining $\xi_{L,R}$ via

$$(m_{\tilde{t}_{L,R}}^{\overline{\text{MDR}}})^2 = (m_{\tilde{t}_{L,R}}^{\overline{\text{DR}}})^2\,(1+\xi_{L,R}) \tag{6}$$

we obtain for the finite part of the diagram

$$\begin{aligned} A_0^{\text{fin}}\left((m_{\tilde{t}_{L,R}}^{\overline{\text{MDR}}})^2\right) = \\ &= A_0^{\text{fin}}\left((m_{\tilde{t}_{L,R}}^{\overline{\text{DR}}})^2\right) - (m_{\tilde{t}_{L,R}}^{\overline{\text{DR}}})^2\left(\xi_{L,R}\ln\frac{(m_{\tilde{t}_{L,R}}^{\overline{\text{DR}}})^2}{\mu_R^2} - \frac{1}{2}\xi_{L,R}^2 + \frac{1}{6}\xi_{L,R}^3 + \dots\right) \\ &= A_0^{\text{fin}}\left((m_{\tilde{t}_{L,R}}^{\overline{\text{DR}}})^2\right) - (m_{\tilde{t}_{L,R}}^{\overline{\text{DR}}})^2\left(\xi_{L,R}^2\ln\frac{(m_{\tilde{t}_{L,R}}^{\overline{\text{DR}}})^2}{\mu_R^2} + \sum_{k=2}^{\infty}\frac{\xi_{L,R}^k}{k(k-1)}\right) \\ &= A_0^{\text{fin}}\left((m_{\tilde{t}_{L,R}}^{\overline{\text{DR}}})^2\right) - (m_{\tilde{t}_{L,R}}^{\overline{\text{DR}}})^2\left(\xi_{L,R}\ln\frac{(m_{\tilde{t}_{L,R}}^{\overline{\text{DR}}})^2}{\mu_R^2} + (1-\xi_{L,R})\ln(1-\xi_{L,R})\right), \end{aligned} \tag{7}$$

recovering the resummation in Eq. (10) of [39].[4]

The right diagram of Fig. 1 in [39] corresponds to a B_0 Passarino–Veltman loop function. Analogously to the A_0 loop function above, we obtain for the special case where $m_{\tilde{t}_L}^{\overline{\text{MDR}}} = m_{\tilde{t}_R}^{\overline{\text{MDR}}}$.

$$\begin{aligned}
B_0\left(0, (m_{\tilde{t}_L}^{\overline{\text{MDR}}})^2, (m_{\tilde{t}_R}^{\overline{\text{MDR}}})^2\right) = \\
&= B_0\left(0, (m_{\tilde{t}_L}^{\overline{\text{DR}}})^2, (m_{\tilde{t}_R}^{\overline{\text{DR}}})^2\right) - \xi_{L,R} + \frac{1}{2}\xi_{L,R}^2 - \frac{1}{3}\xi_{L,R}^3 + \dots \\
&= B_0\left(0, (m_{\tilde{t}_L}^{\overline{\text{DR}}})^2, (m_{\tilde{t}_R}^{\overline{\text{DR}}})^2\right) - \sum_{k=1}^{\infty} \frac{\xi_{L,R}^k}{k} \\
&= B_0\left(0, (m_{\tilde{t}_L}^{\overline{\text{DR}}})^2, (m_{\tilde{t}_R}^{\overline{\text{DR}}})^2\right) + \ln(1 - \xi_{L,R}),
\end{aligned} \tag{8}$$

recovering the expression given in Eq. (12) of [39].

[4] The additional two-loop terms found in [39] originate from the matching of the soft SUSY-breaking Higgs mass parameter m_{22} and are not related to the matching of the soft SUSY-breaking stop masses. This additional contribution, however, does not affect the calculation of the SM-like Higgs mass at the considered order.

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