EW NLO corrections to pair production of top-squarks at the LHC

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Abstract. Presented are complete electroweak (EW) corrections at $O(\alpha\alpha_s^2)$ to top-squark pair production at the Large Hadron Collider (LHC) within the framework of the Minimal Supersymmetric Standard Model (MSSM). At this order, effects from the interference of EW and QCD contributions have to be taken into account. Also photon-induced top-squark production is considered as additional partonic channel which arises from the non-zero photon density in the proton. Furthermore, the impact of MSSM parameters on the EW corrections is analyzed.

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1 Introduction

The lighter top-squark is as a candidate for the lightest squark within many supersymmetric models \cite{1}, for mainly two reasons based on the large top Yukawa coupling. Evolving the scalar masses from the GUT scale to low scales leads to a low value of the top-squark mass, and, moreover, a large mixing in the top-squark sector induces a substantial splitting between the two mass eigenstates \cite{2}. Top squarks are therefore of particular interest, especially for hadron colliders.

In hadronic collisions, top-squarks are primarily produced in pairs via the strong interaction. Present experimental limits from the Tevatron RUN II data, dependent on the lightest neutralino mass, are provided by the CDF and DØ collaborations \cite{3}. Concerning the theoretical predictions, Born-level cross sections calculated in \cite{4}, have been improved by including the next-to-leading (NLO) corrections in supersymmetric QCD (SUSY-QCD). These were worked out in \cite{5} with the restriction to final state squarks of the first two generations. The analysis for the stop sector, performed in \cite{6}, shows that the SUSY-QCD corrections significantly modify the LO cross section.

At lowest order in QCD as well as at $O(\alpha_3^2)$, only diagonal top-squark pairs can be produced. The non-diagonal production is suppressed as the cross section becomes non-zero only at $O(\alpha_4^2)$. The production of non-diagonal top-squark pairs can also proceed at $O(\alpha_2^4)$ via $Z$-exchange in $e^+e^-$ annihilation \cite{7}, or $q\bar{q}$ annihilation \cite{8}. The LO cross section for the diagonal pair production depends only on the mass of the produced squarks. As a consequence, bounds on the cross section can easily be translated into lower bounds on the lightest top-squark mass. At NLO, the cross section is not only considerably changed, but also other supersymmetric parameters, like mixing angle, gluino mass and other sparticle masses, enter through higher order corrections. On the other hand, once the top-squarks are discovered, their masses could be directly determined from the cross section measurement.

In the following, we study the NLO EW-like corrections to the top-squark pair production within the Minimal Supersymmetric Standard Model (MSSM). We assume the MSSM with real parameters, R-parity conservation and minimal flavor violation.

2 EW NLO Contributions

As a subset of the complete set of EW virtual corrections, photonic contributions are present. These contain IR singularities, which cancel when also the real photonic corrections are taken into account. In addition, at NLO a photon-induced subclass of contributions appears as an independent production channel.

2.1 Virtual Corrections

The virtual corrections can be classified according to self-energy, vertex, box, and counter-term contributions dressing the Born-level partonic amplitudes of $q\bar{q}$ annihilation and gluon fusion. Getting an UV finite result requires renormalization of the involved quarks and top-squarks. The counterterms for self-energies, quark and squark vertices and the squark quartic interaction at one-loop order are determined in the on-shell renormalization scheme. It is not necessary to renormalize the gluon field and the strong coupling constant.

Loop diagrams involving virtual photons generate IR singularities. According to Bloch-Nordsieck \cite{9}, IR-singular terms cancel against their counterparts in the

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real photon corrections. To regularize the IR singularities we introduce a fictitious photon mass $\lambda$. In case of external light quarks, also collinear singularities occur if a photon is radiated off a massless quark in the collinear limit. We therefore keep non-zero initial-state quark masses $m_q$ in the loop integrals, which give rise to single and double logarithmic contributions of quark masses. The double logarithms cancel in the sum of virtual and real corrections, single logarithms, however, survive and have to be treated by means of the factorization.

An additional source of IR singularities originates from the gluonic insertions to the box contributions in the $q\bar{q}$ channel. These appear in combination with photons or $Z$-bosons. The similarity between gluon and photon in the box contributions allows us to treat the gluonic IR singularities in analogy to the photon case.

### 2.2 Real Corrections

To compensate IR singularities in the virtual EW corrections, real photonic and gluonic contributions are required. In case of $gg$ fusion, only photon bremsstrahlung is needed, whereas in the $q\bar{q}$ annihilation channel, also gluon bremsstrahlung of the appropriate order of $\mathcal{O}(\alpha_s^2)$, shown in Fig. 1, has to be taken into account. The necessary contributions originate from the interference of QCD and EW tree level diagrams which vanishes at LO. Not all of the interference terms contribute, however. Owing to the color structure, only the interference between initial and final state gluon radiation is non-zero.

Including the EW–QCD interference in the real corrections does not yet lead to an IR-finite result. Also the IR-singular QCD-mediated box corrections interfering with the $\mathcal{O}(\alpha)$ photon and $Z$-boson tree-level diagrams are needed. Besides the gluonic corrections there are also IR-finite QCD-mediated box corrections, which contain gluinos in the loop. Interfered with the $\mathcal{O}(\alpha)$ tree-level diagrams, these also give contributions of the respective order of $\mathcal{O}(\alpha_s^2)$.

We encounter also IR-finite bremsstrahlung contributions, which are, however, suppressed by more than a factor of ten and therefore not included in our numerical studies. For similar reasons we also neglect contributions coming from the interference of IR-singular and IR-finite terms.

The treatment of IR-singular bremsstrahlung is done using the phase space slicing method. The photonic (gluonic) phase space is split into soft and collinear parts, which contain singularities and into non-collinear hard part, which is free of singularities and can be integrated numerically. In the singular regions, the squared matrix elements for the radiative process factorize into lowest-order matrix elements and universal factors containing the singularities.

The soft-photon part of the radiative cross section in the $q\bar{q}$ annihilation channel, which is similar to that in $e^+e^-\rightarrow t\bar{t}$

$$d\hat{\sigma}^{q\bar{q}}_{soft,\gamma}(s) = \frac{\alpha}{\pi} \left( e_q^2 \delta_{soft}^{fin} + e_t^2 \delta_{soft}^{fin} + 2e_qe_t \delta_{soft}^{int} \right) \times d\hat{\sigma}^{q\bar{q}}_{0}(s) \quad (1)$$

and for the radiative cross section in the $gg$ fusion channel,

$$d\hat{\sigma}^{gg}_{soft,\gamma}(s) = \frac{2}{\pi} e_q^2 \delta_{soft}^{fin} d\hat{\sigma}^{gg}_{0}(s) \quad (2)$$

can be expressed using universal factors, $\delta_{soft}^{fin,int}$, which refer to initial state radiation, final state radiation, or interference of initial and final state radiation, respectively, with $e_q$ and $e_t$ denoting the electric charges of the initial-state quark and of the top-squark, respectively. $d\hat{\sigma}^{q\bar{q},gg}_{0}$ denote the corresponding partonic lowest order cross sections.

The soft-gluon part for the $q\bar{q}$ channel can be written in a way similar to (1), but with a different arrangement of the color matrices,

$$d\hat{\sigma}^{q\bar{q}}_{soft,g}(s) = \frac{\alpha_s}{\pi} \delta_{soft}^{int} \left[ T_{ij} T_{lm} \tau^b_{ji} \tau^b_{ml} \right] \times 2\text{Re} \sum \left( \tilde{M}^{q\bar{q}}_{0,g,\gamma/Z} \tilde{M}^{q\bar{q}}_{0,\gamma/Z} \right) \frac{d\hat{\sigma}}{16\pi s^2} \quad (3)$$

with $\tilde{M}$ denoting the “Born” matrix elements for $q, \gamma$ and $Z$ exchange where the color matrices are factorized off.

The collinear part of the $2 \rightarrow 3$ cross section is proportional to the Born cross section of the hard process with reduced momentum of one of the partons. Assuming that parton $a$ with momentum $p_a$ radiates off a photon with $p_\gamma = (1-z)p_a$, the parton momentum available for the hard process is reduced to $z p_a$. Accordingly, the partonic energy of the total process inclusive photon radiation $\hat{s} = (p_a + p_\gamma)^2$, is reduced for the hard process to $\hat{s} = (z p_a + p_\gamma)^2$.

Using these variables, the partonic cross section in the collinear cones can be written as

$$d\hat{\sigma}_{coll}(\hat{s}) = \frac{\alpha_s}{\pi} \frac{\alpha}{\pi} \int_0^{1-z} dz \, d\hat{\sigma}_{q}(\hat{s}) \, \kappa_{coll}(z) \quad (4)$$

with

$$\kappa_{coll}(z) = \frac{1}{2} P_{qq}(z) \left[ \ln \left( \frac{\hat{s}}{m_q^2} \frac{\delta_0}{2} \right) - 1 \right] \quad (4)$$

$$+ \frac{1}{2} (1-z),$$

where $P_{qq}(z) = (1+z^2)/(1-z)$ is an Altarelli-Parisi splitting function and $\delta_0$ is the cut-off parameter to
define the collinear region by $\cos \theta > 1 - \delta s$. The Born cross section refers to the hard scale $s$, whereas in the collinear factor the total energy $\hat{s}$ is the scale needed. In order to avoid an overlap with the soft region, the upper limit on the $z$-integration in (4) is reduced from $z = 1$ to $z = 1 - \delta s$, where $\delta s = 2\Delta E/\sqrt{s}$.

As already mentioned, after adding virtual and real corrections, the mass singularity in (4) does not cancel and has to be absorbed into the (anti-)quark density functions (PDFs). This can be formally achieved by a redefinition at NLO QED as shown in [11,14,15].

### 2.3 Photon-Induced Top-Squark Pair Production

We also consider the photon-induced mechanism of top-squark pair production, which becomes non-zero at NLO in QED as a direct consequence of the non-zero photon density in the proton. Although the photon-induced processes are of different overall order, they contribute to the same hadronic final state and thus represent contributions at NLO QED. We consider only the photon–gluon process in our numerical analysis and neglect the quark–photon process, which gives contribution of higher order.

As the PDFs at NLO QED have become available only recently [16], the results shown here thus correspond to the first study of these effects on the top-squark pair production [17].

### 3 Numerical results

Here we present numerical results for the production of lighter top-squark pairs at LHC energies with EW contributions at one-loop level. We show in the integrated hadronic cross section $\sigma$ and the differential hadronic cross sections with respect to the invariant mass of the top-squark pair inclusive the photon ($d\sigma/dM_{inv}$) and to the transverse momentum ($d\sigma/dp_T$) of one of the final state top-squarks. All hadronic quantities are obtained by folding the partonic cross section with parton distributions and summing over all contributing partons.

Our Standard Model input parameters are chosen in correspondence with [19]. As described above, we use the MRST 2004 QED [16] PDF set with the choice of factorization and renormalization scales to equal the sum of the final state particles, $\mu_F = \mu_R = 2m_{\tilde{t}_1}$. $q\bar{q}$ denotes the sum of the $u\bar{u}$, $d\bar{d}$, $c\bar{c}$, and $s\bar{s}$ annihilation channels.

In Table 1 we show results for the total hadronic cross sections within four different SPS mSUGRA scenarios [18,19]. The total cross sections at leading order, $\sigma^{LO}$, the absolute size of the EW corrections, which corresponds to the difference between the LO and NLO cross sections, $\Delta\sigma^{NLO}$, and the relative corrections, $\delta$, given as the ratio of NLO corrections to the respective LO contributions, are presented for $gg$ fusion, $q\bar{q}$ annihilation, and $g\gamma$ fusion separately. The $g\gamma$ channel contributes only at NLO. The total amount of EW corrections is small in all SUSY scenarios.

| Scenario | Channel | $\sigma^{LO}$ (fb) | $\Delta\sigma^{NLO}$ (fb) | $\delta^{NLO}$ [%] |
|----------|---------|--------------------|--------------------------|------------------|
| SPS1a    | $q\bar{q}$ | 1444 | -15.4 | -1.1 % |
|          | $g\gamma$ | 29.0 | 0.155 | 0.116 |
|          | total     | 1664 | 3.95 | 0.24% |
| SPS1a’   | $q\bar{q}$ | 34830 | -10.0 | -0.56% |
|          | $g\gamma$ | 891 | 0.46% | 0.116 |
|          | total     | 35721 | 3.45 | 0.87% |
| SPS2     | $q\bar{q}$ | 3728 | -7.7 | -0.44% |
|          | gg        | 2479 | -1.0 | -0.08% |
|          | total     | 4137 | 3.45 | 0.84% |
| SPS5     | $q\bar{q}$ | 2870 | -13.2 | -0.46% |
|          | gg        | 31960 | 499 | 1.6 % |
|          | total     | 34830 | 891 | 2.6 % |

Fig. 2. Overall relative corrections $\delta_{tot}$ with respect to $p_T$ and $\sqrt{s}$ at the LHC within the SPS1a scenario.

In order to illustrate the numerical impact of the EW corrections on the LO cross section, in Fig. 2 we show the overall relative corrections $\delta_{tot} = \Delta\sigma^{NLO}/\sigma^{LO}$ as distributions with respect to $p_T$ and $\sqrt{s}$ (which corresponds to $M_{inv}$). In the $p_T$-distribution, the corrections grow in size with increasing $p_T$ and reach about $-20\%$ for $p_T \gtrsim 2500$ GeV. Similar effects are visible.
in the $M_{nn}$ distribution. Although smaller in size, the corrections raise up to $-15\%$ level for $\sqrt{s} \gtrsim 5000$ GeV. These ranges of $p_T$ and $\sqrt{s}$ are still within the reach of the LHC.

The behavior of EW corrections at high scales is dominated by the massive gauge boson contributions, which consist of double logarithms of $W$ and $Z$ masses. The double logarithms are not canceled by the real gauge boson corrections, since these correspond to different hadronic final states. As a result, large negative contributions show up in the $p_T$ and $\sqrt{s}$ distributions.

It is obvious that although small for the total cross sections, the EW corrections cannot be neglected in the differential distributions, since in the high-$p_T$ and high-$\sqrt{s}$ ranges they are of the same order of magnitude as the SUSY-QCD corrections.

We have also studied the dependence of the EW contributions on various SUSY parameters. We have focused on the parameters that affect the top-squark mass, since here the effects are expected to be strongest. Following parameters have been varied: $m_{\tilde{Q}_3}$, $m_{\tilde{t}_3}$, $\tan\beta$, $A_t$, and $\mu$ around the SPS 1a’ value, while keeping all other parameters fixed. As an example, in Fig. 3 we show the dependence of the overall EW corrections on $m_{\tilde{Q}_3}$ for each production channel separately.

The $gg$ corrections grow up to 2% with increasing $m_{\tilde{t}_3}$ in the considered range. The $g\gamma$ fusion channel is as important as the $q\gamma$ and $gg$ channels and should be taken into account for a reliable cross section prediction. The $g\gamma$ corrections involve many different SUSY particles in the loops, however the relative corrections change only little between different scenarios, varying between 0% and $-1\%$. The $gg$ contributions are more sensible to variations of the considered SUSY parameters. The general behavior is similar to the $q\gamma$ case, the decrease with increasing $m_{\tilde{t}_3}$ is, however, stronger. The $gg$ plot is dominated by striking (negative) peaks, some of them are (although much weaker) also visible in the $q\gamma$ corrections.

The peaks originate from two sources of threshold effects. One of them is the Higgs boson $H^0$ threshold, $m(H^0) = 2m_{\tilde{t}_1}$, which affects only the $gg$ channel. Second source of the threshold effects enhances the corrections in scenarios where $m_{\tilde{t}_1}$ equals the sum of masses of a neutralino and the top-quark or of a chargino and the bottom-quark. The parameter regions with large EW corrections due to the threshold effects are small and over the wide range of SUSY parameter space, the EW corrections to the top-squark pair production are smaller than 1%.

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