Electroweak Contributions to Squark Pair Production

Sascha Bornhausera, Manuel Drees, Herbi K. Dreiner and Jong Soo Kim

Physikalisches Institut, Universität Bonn, Nussallee 12, D53115 Bonn, Germany

Abstract. We compute electroweak contributions to the production of squark pairs at hadron colliders. Since in many cases interference with QCD amplitudes is possible, this yields contributions of $O(\alpha_s^2)$ as well as of $O(\alpha_s \alpha_W)$, where $\alpha_W$ is a weak gauge coupling. We find that these change the total cross section by only a few percent if at least one of the produced squarks is an $SU(2)$ singlet. On the other hand, the cross section for the production of two $SU(2)$ doublet squarks is changed by 10 to 20% in typical mSUGRA (or CMSSM) scenarios, but in more general scenarios they can vary between -40 and +55%, depending on size and sign of the $SU(2)$ gaugino mass. The electroweak contribution to the total squark pair production rate at the LHC is about 3.5 times smaller.

PACS. 12.60.Jv Supersymmetric models – 14.80.Ly Supersymmetric partners of known particles

1 Introduction

We compute the leading order electroweak contributions to squark pair production at hadron colliders. Since in many cases interference with QCD amplitudes is possible, this yields contributions of $O(\alpha_s^2)$ as well as of $O(\alpha_s \alpha_W)$, where $\alpha_W$ is a weak gauge coupling. We find that these change the total cross section by only a few percent if at least one of the produced squarks is an $SU(2)$ singlet. On the other hand, the cross section for the production of two $SU(2)$ doublet squarks is changed by 10 to 20% in typical mSUGRA (or CMSSM) scenarios, but in more general scenarios they can vary between -40 and +55%, depending on size and sign of the $SU(2)$ gaugino mass. The electroweak contribution to the total squark pair production rate at the LHC is about 3.5 times smaller.

This contribution is a short summary of Ref. [1], where detailed results for the leading–order partonic–level squared matrix elements for the production of two (anti–) squarks from two (anti–)quarks in the initial state and additional explanations for the following numerical results are given.

2 Numerical Results

We focus on $pp$ collisions at the LHC operating at $\sqrt{s} = 14$ TeV and squarks of the first and second generation, where mixing between $SU(2)$ doublets and singlets can be neglected. Third generation squarks are produced dominantly through gluon fusion or pure $s$–channel diagrams; the EW contributions to these cross sections will therefore be very small. Table 1 shows results for the total squark pair production cross sections at the LHC in six mSUGRA benchmark scenarios, taken from [4]. Here we sum over all squarks and anti–squarks of the first and second generation; results where both final state (anti–)squarks are $SU(2)$ doublets are shown separately. We only include contributions with (anti–)squarks in the initial state, since the gluon fusion contribution obviously does not receive electroweak contributions in leading order. We take equal factorization and renormalization scales, $\mu_F = \mu_R = m_\tilde{g}/2$; this choice leads to quite small NLO corrections to the pure QCD contribution.

Not surprisingly, the cross sections fall quickly with increasing squark mass. The partonic cross sections scale like $m_\tilde{g}^2$, if the ratios of sparticle masses are kept fixed and the running of $\alpha_s$ is ignored. In addition, the pdf factors decrease quickly with increasing squark mass. There is also some dependence on the gluino mass ($\simeq 2.5 m_{1/2}$), which appears in $t$– and $u$–channel propagators. Varying the ratio $m_\tilde{q}/m_\tilde{g}$ between 0.5 and 1.2, which is the range covered by the scenarios of Table 1, leads to 15 to 20% variation of the QCD prediction.

| SPS $m_0$ | $m_{1/2} m_\tilde{q}$ | QCD | QCD+EW | ratio |
|---------|------------------|-----|--------|-------|
| tot LL  | QCD tot LL       |     |        |       |
| 1a 10   | 25 56            | 12.1 3.09 | 12.6 3.50 | 1.04 1.13 |
| 1b 20   | 40 87            | 1.57 0.42 | 1.66 0.50 | 1.06 1.19 |
| 2 145   | 30 159           | 0.06 0.01 | 0.06 0.01 | 1.03 1.09 |
| 3 9     | 40 85            | 1.74 0.46 | 1.83 0.55 | 1.06 1.19 |
| 4 40    | 30 76            | 3.10 0.81 | 3.22 0.93 | 1.04 1.14 |
| 5 15    | 30 67            | 5.42 1.41 | 5.66 1.62 | 1.04 1.15 |

*a Speaker*
Since QCD contributions dominate even after inclusion of the electroweak diagrams, the overall behavior of the total cross sections does not change much. These contributions are clearly more important for the production of $SU(2)$ doublet squarks than for the total cross section summed over all final states. This is not surprising: the cross sections for all other combinations of squarks only receive electroweak contributions due to hypercharge interactions, and the squared $SU(2)$ gauge coupling exceeds the squared $U(1)_Y$ coupling by a factor $\cot^2 \theta_W \approx 3.3$

However, the weakness of the $U(1)_Y$ coupling by itself is not sufficient to explain the small size of electroweak contributions to final states involving at least one $SU(2)$ singlet (anti-)squark. For example, we can infer from the first line of Table 1 that in scenario SPS 1a, electroweak contributions increase the cross section for the production of two $L$-type squarks by 0.41 pb, whereas they only contribute 0.03 pb to all other squark pair production channels combined. We also note that the importance of the EW contributions seems to depend much more strongly on the ratio $m_{1/2}/m_0$ than the QCD prediction does. Finally, the EW contributions evidently become more important for heavier squarks if the ratio $m_0/m_{1/2}$ remains roughly the same.

In order to understand these features it is helpful to consider all 24 different processes involving only (s)quarks and anti–(s)quarks from the first generation which add up to the total cross section, cf. Table 2. These processes can be grouped into three categories having different weighting of the electroweak contributions with respect to the pure QCD cross section and positive or negative interference between $s-$, $t-$ and $u-$ channel diagrams, respectively.

The first category consists of seven reactions with interference between $t-$ and $u-$ channel diagrams, where in all but the last case there are both strong and electroweak contributions from both $t-$ and $u-$ channel diagrams. The next class of seven processes allows interference between $s-$ and $t-$channel diagrams. In the first four cases there are both QCD and electroweak contributions to both the $t-$ and $s-$channel, while in the last three cases only one QCD diagram contributes. For the third class of ten processes, no interference between electroweak and strong contributions is possible; two of these processes only proceed via $s-$channel diagrams, whereas the remaining eight are pure $t-$channel reactions.

The total cross section depends on a complex interplay of the pdf’s of the squarks, the mass and hypercharge of the squarks, a possible helicity flip of the exchanged $t-$ or $u-$channel fermion and whether the produced squarks are $SU(2)$ singlets or doublets and have to be a $S-$ or $P-$wave, respectively. For an extensive analysis we refer again to our paper [1].

By looking at Table 1 we see that the relative importance of the electroweak contributions increases with increasing gaugino to squark mass ratio. This can be explained from the observation that the most important EW contributions involve the interference of $t-$ and $u-$channel amplitudes [1]. The amplitudes for all processes of this kind that receive contributions from $SU(2)$ interactions are proportional to a gaugino mass. These contributions are therefore sensitive to the ratio of gaugino and squark masses. In mSUGRA the relative importance of the EW contributions becomes largely insensitive to $m_{1/2}$ (for fixed squark mass) once $m_{1/2} \gtrsim m_0$. The physical squark masses are then essentially independent of $m_0$, i.e. $m_{\tilde{q}} \propto m_{1/2}$, so that the ratios of gaugino and squark masses become independent of $m_{1/2}$.

Finally, Table 1 also shows that the electroweak contributions become relatively more important with increasing squark mass scale, although for scenario SPS 2 this effect is over–compensated by the small center–of–mass $\sqrt{s}$ velocity. We pointed out in Ref. [1] that the dominant EW contributions come from the interference of $t-$ and $u-$channel diagrams with QCD diagrams. Since in mSUGRA the electroweak gauginos are about three and six times lighter than the gluino, one expects the EW contributions to be most prominent for small transverse momenta of the produced squarks. This is borne out by Fig. [1] which shows the ratio of the tree–level differential cross section with and without EW contributions. Here, and in the subsequent figures, we concentrate on the production of two $SU(2)$ doublet (anti–) squarks, where the EW contributions are largest. The observed behavior can be understood from the interplay of several effects. For simplicity assuming equal squark masses in the final state, the relation between the partonic cm’s energy and squark transverse momentum can be written as

$$\hat{s} = 4 \left( m_{\tilde{q}}^2 + \frac{p_T^2}{\sin^2 \theta} \right),$$

where $\theta$ is the cm’s scattering angle. The parton flux in the initial state is largest for smallest $\hat{s}$.

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**Table 2. The 24 different squark pair production processes involving first generation (s)quarks.**

| No. | Process |
|-----|---------|
| 1   | $u\bar{u} \rightarrow \tilde{u}_L \tilde{u}_L$ |
| 2   | $u\bar{u} \rightarrow \tilde{u}_R \tilde{u}_R$ |
| 3   | $u\bar{u} \rightarrow \tilde{d}_L \tilde{d}_L$ |
| 4   | $d\bar{d} \rightarrow \tilde{d}_L \tilde{d}_L$ |
| 5   | $d\bar{d} \rightarrow \tilde{d}_R \tilde{d}_R$ |
| 6   | $d\bar{d} \rightarrow \tilde{d}_L \tilde{d}_L$ |
| 7   | $u\bar{u} \rightarrow \tilde{u}_L \tilde{u}_L$ |
| 8   | $u\bar{u} \rightarrow \tilde{u}_R \tilde{u}_R$ |
| 9   | $u\bar{u} \rightarrow \tilde{d}_L \tilde{d}_L$ |
| 10  | $d\bar{d} \rightarrow \tilde{d}_L \tilde{d}_L$ |
| 11  | $d\bar{d} \rightarrow \tilde{d}_R \tilde{d}_R$ |
| 12  | $u\bar{u} \rightarrow \tilde{d}_L \tilde{d}_L$ |

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shows that configurations where $\sin^2 \theta$ is maximal, i.e. where $\cos \theta$ is small, are preferred if $p_T$ is sizable.

On the other hand, the denominators of the $t-$channel propagators can be written as

$$ t - M_V^2 = m_q^2 - \frac{s}{2} (1 - \cos \theta) - M_W^2, $$

(2)

where $M_V$ is the mass of the exchanged gaugino; the expression for the $u-$channel propagators can be obtained by $\cos \theta \rightarrow -\cos \theta$. These propagators therefore prefer large $|\beta \cos \theta|$; however, $t-$ and $u-$channel propagators prefer different signs of $\cos \theta$.

The dominant EW contributions are due to the interference between $t-$ and $u-$channel diagrams. These cross sections are proportional to a single power of the threshold factor $\beta$. The steeply falling pdf’s imply that these processes therefore prefer rather small values of $\beta$ even for small $p_T$. As a first approximation we can therefore ignore terms $\propto \beta \cos \theta$ in the propagators.

The ratio of EW and QCD $t-$ or $u-$channel propagators then becomes

$$ \frac{\text{EW}}{\text{QCD}} = \frac{\hat{s}/2 - m_q^2 + M_W^2}{\hat{s}/2 - m_q^2 + M_W^2} \approx \frac{2p_T^2 + m_q^2 + M_W^2}{2p_T^2 + m_q^2 + M_W^2}, $$

(3)

where $M_W$ is the mass of the relevant chargino or neutralino. Most of the mSUGRA scenarios of Table 1 and Fig. 1 have $m_q^2 \sim M_Z^2 \gg M_W^2$. Eq. (3) shows that the interference term will then be enhanced by a factor $\sim 2$ at small $p_T$.

However, this enhancement disappears for $m_q^2 \gg M_Z^2$, as in SPS 2. Eq. (3) shows that the propagator enhancement of the EW contributions also disappears once $2p_T^2 \gg m_q^2$. However, at large $p_T$ one has two kinds of competing processes [I]: On the one hand constructive interference, where EW contributions enhance the cross section but are suppressed by an extra factor of $p_T^{-2}$ due to a necessary helicity flip. On the other hand destructive interference and without a helicity flip which are suppressed by more quickly falling PDFs. Eq. (4) shows that the latter suppression will be more relevant for larger squark masses. Indeed, at large $p_T$ we observe the largest (or least negative) EW contributions for scenarios with heaviest squarks. However, even in scenario SPS1a, which has the smallest squark masses, EW contributions only suppress the cross section by $\sim 3\%$ at large $p_T$.

We saw in Table 1 that the EW contributions tend to become more important with increasing squark mass scale. This is further explored in Fig. 2 which shows the ratio of the total cross section for the production of SU(2) doublet squarks with and without EW contributions as function of the average doublet squark mass. These curves have been generated by keeping the ratios of the dimensionful mSUGRA input parameters $m_0, m_{1/2}$ and $A_0$ fixed, but varying the overall mass scale; this corresponds to the “benchmark slopes” of ref. [I]. We see that in a scenario with relatively large gaugino masses, as in SPS 1a (upper curve), the EW contribution can increase the cross section by more than $30\%$ for $m_q = 2$ TeV. A scenario with $m_0 = -A_0 = 4.5m_{1/2}$ (lower curve) shows the same trend; however, as noted earlier, the total EW contribution is much smaller in this case, only reaching $13\%$ for $m_q = 2$ TeV. The results of this Figure can therefore not be entirely due to the change of the relative weights of the various processes. On top of that, the importance of the EW contributions to single processes increases with increasing squark masses. This can be understood from the behavior of the $t-$ and $u-$channel propagators. Smaller squark masses allow larger values of $\beta$. The regions of phase space with large $|\cos \theta|$ will then favor the squared $t-$ or $u-$channel propagators of pure QCD contributions over the product of one $t-$ and one $u-$channel propagator of the interference terms. This implies that increasing $m_q$ will increase the relative importance of the interference terms relative to the squared $t-$ and $u-$channel diagrams. This reduces the pure QCD contribution, where the interference is destructive due to the negative color factor, see e.g. Eq. (4) of [I], and enhances the importance of the EW contributions. Comparison of the two

Fig. 1. The ratio of QCD+EW to pure QCD predictions as a function of the squark transverse momentum.

Fig. 2. The ratio of QCD+EW to pure QCD predictions as a function of the squark mass.
stratified in Fig. 3, where we vary the $SU(2)$ gaugino mass $M_2$ at the weak scale, keeping all other parameters fixed. We see that the electroweak contributions become maximal if $M_2 \approx m_\tilde{q}$. This can be understood from the observation that this choice maximizes $M_2/(t - M_2^2)$, see Eq. (2). In a scenario with $m_\tilde{g} \approx m_\tilde{q}$ and large squark mass (solid curve), this can lead to EW contributions in excess of 50%. In scenario SPS 2 (dashed curve) the contributions remain somewhat smaller, partly because of the reduced squark mass, and partly because the lower gluino mass reduces the importance of the interference terms. Not surprisingly, taking $m_\tilde{g} \approx m_\tilde{q}$ also maximizes the size of those pure QCD contributions that require a helicity flip.

Finally, in scenario SPS 1a with its relatively light squarks (dotted curve) the EW contribution never goes much beyond 20%. In this case processes with negative EW contributions contribute significantly. Since these EW contributions contribute significantly more than 50%, in scenarios with gaugino mass unification the EW contribution can still change the cross section for the production of two $SU(2)$ doublet squarks by more than a factor 1.3. Recall that $SU(2)$ doublet squarks often lead to different final states than singlet squarks do, allowing to distinguish these modes experimentally.

3 Summary and Conclusions

We analyzed electroweak (EW) contributions to the production of two squarks or anti–squarks at the LHC. Not surprisingly, corrections due to $SU(2)$ interactions are more important than those from $U(1)_Y$ interactions. In both cases the dominant effect is from the interference of electroweak and QCD interactions.

In conclusion the physical significance of our results are:

- The EW contributions can change the total cross section significantly. Focusing on the production of two $SU(2)$ doublet ($L-$type) squarks, we found the contributions with interference between $t-$ and $u-$channel diagrams to be dominant. For squark masses near the discovery reach of the LHC, EW effects can reduce or enhance the total cross section by more than a factor 1.5, if the absolute value of the $SU(2)$ gaugino soft breaking mass is near $m_\tilde{g}$; even in scenarios with gaugino mass unification the EW contribution can still change the cross section for the production of two $SU(2)$ doublet squarks by more than a factor 1.3. Recall that $SU(2)$ doublet squarks often lead to different final states than singlet squarks do, allowing to distinguish these modes experimentally.

- The EW contributions might give a new, independent handle on the gaugino mass parameters. In particular, we just saw that they are sensitive to relative signs between gaugino mass parameters, which might be difficult to determine using kinematical distributions only. For example, in anomaly–mediated supersymmetry breaking [9] the products of electroweak and QCD gaugino masses are negative. In order to realize this potential, both the experimental and the theoretical uncertainties should be reduced to the 10% level. This is certainly challenging, but should eventually be possible if squarks are not too heavy.

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