Radiative Corrections to Deep-Inelastic Neutrino–Nucleon Scattering in the MSSM

O. BREIN[1 a], B. KOCH[2,3] and W. HOLLIK[4]
[1] *Institut für Theoretische Physik E, RWTH Aachen, D-52056 Aachen, Germany*
[2] *Institut für Theoretische Physik, Johann Wolfgang Goethe-Universität,*
D-60054 Frankfurt am Main, Germany
[3] *Frankfurt International Graduate School for Science (FIGSS)*
D-60054 Frankfurt am Main, Germany
[4] *Max-Planck-Institut für Physik, Föhringer Ring 6, D-80805 München, Germany*

We discuss the radiative corrections to charged and neutral current deep-inelastic neutrino–nucleon scattering in the minimal supersymmetric standard model (MSSM). In particular, deviations from the Standard Model prediction for the ratios of neutral- to charged-current cross sections, R^{ν} and $R^{\bar{\nu}}$, are studied, and results of a scan over the MSSM parameter space are presented.

1 Introduction

In the Standard Model (SM), neutral (NC) and charged current (CC) neutrino–nucleon scattering are described in leading order by t-channel W and Z exchange, respectively (see Fig. 1). At the NuTeV experiment, ν_μ and $\bar{\nu}_\mu$ beams of a mean energy of 125 GeV were scattered off a target detector and the ratios $R^{\nu} = \sigma^{\nu}_{\rm NC}/\sigma^{\nu}_{\rm CC}$ and $R^{\bar{\nu}} = \sigma^{\bar{\nu}}_{\rm NC}/\sigma^{\bar{\nu}}_{\rm CC}$ were measured. The NuTeV collaboration also provided a determination of the on-shell weak mixing angle [1],

$$\sin^2\theta_w^{\text{on-shell}} = 0.2277 \pm 0.0013(stat.) \pm 0.0009(syst.)\ .$$

This value is about 3σ below the value derived from the residual set of precision observables [2]. The analysis makes use of the Paschos-Wolfenstein relation [3],

$$R^{-} = \frac{R^{\nu} - rR^{\bar{\nu}}}{1-r} = \frac{1}{2} - \sin^2\theta_w + \text{corrections}\ , \qquad\qquad r = \frac{\sigma^{\bar{\nu}}_{\rm CC}}{\sigma^{\nu}_{\rm CC}} \approx \frac{1}{2}\ ,$$

and the measurement of counting rates $R^{\nu}_{\rm exp}, R^{\bar{\nu}}_{\rm exp}$. From the theoretical ratios $R^{\nu}, R^{\bar{\nu}}$ for a fixed beam energy, one obtains the SM prediction for the experiment $R^{\nu}_{exp}(SM), R^{\bar{\nu}}_{exp}(SM)$ by a detailed Monte Carlo (MC) simulation. These predictions differ from the counting rates $R^{\nu}_{exp}, R^{\bar{\nu}}_{exp}$ by [4]

$$\Delta R^{\nu} = R^{\nu}_{\rm exp} - R^{\nu}_{\rm exp}(SM) = -0.0032 \pm 0.0013\ ,$$
$$\Delta R^{\bar{\nu}} = R^{\bar{\nu}}_{\rm exp} - R^{\bar{\nu}}_{\rm exp}(SM) = -0.0016 \pm 0.0028\ .$$

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[a] Speaker.

Figure 1: Tree-level Feynman graphs for neutral-current and charged-current scattering of muon-neutrino and quark.

Basically, there are three types of explanations of the observed anomaly.
(a) *There is no signal.* The result might be a statistical fluctuation or theoretical errors may have been underestimated. This line of thought lead to re-analyses of the electroweak radiative corrections to neutrino–nucleon DIS [5], which have been originally calculated almost 20 years ago [6].
(b) *The apparent signal is due to neglected but relevant SM effects.* An asymmetry between the distribution of the strange quark and its corresponding anti-quark in the nucleon ($s \neq \bar{s}$) could account for part of the deviation. The result of the measurement of the weak mixing angle could also be influenced by a violation of the usually assumed isospin symmetry ($u_p \neq d_n$), or nuclear effects which have not been taken into account. For a list of other sources see refs. [7,8] and references therein.
(c) *The signal is due to new physics.* Many suggestions have been made, like effects from modified gauge boson interactions (e.g. in extra dimensions), non-renormalizable operators, leptoquarks (e.g. R-parity violating SUSY) and SUSY loop effects (e.g. in the MSSM), just to name a few of them (see [7,9] and references therein for an overview).

Here we consider the effects of the radiative corrections to neutrino–nucleon DIS in the MSSM. Although the NuTeV anomaly is not settled as yet, it is interesting to check how far the MSSM could account for such a deviation. There are two earlier studies in the literature [7,9]. Both treat the loop effects in the limit of zero-momentum transfer of the neutrino to the hadron, neglecting kinematical cuts and potential effects from the parton distribution functions. They conclude that the radiative corrections in the MSSM cannot be made responsible for the NuTeV anomaly, owing to the wrong sign.

Our calculation includes various kinematical effects. In particular, we include the full q^2 dependence of the one-loop amplitudes, evaluate hadronic cross sections using PDFs [10] cuts on the hadronic energy in the final state ($20\,\text{GeV} < E_{\text{had.}} < 180\,\text{GeV}$) at the mean neutrino beam energy of 125 GeV. Moreover, we perform a thorough parameter scan for the radiative corrections $\delta R^{\nu(\bar{\nu})}$ over the relevant MSSM parameter space.

2 MSSM radiative corrections to $\nu_\mu N$ DIS

The difference between the MSSM and SM predictions, $\delta R^n = R^n_{\text{MSSM}} - R^n_{\text{SM}}$ with $R^n = \sigma^n_{\text{NC}}/\sigma^n_{\text{CC}}$, with $(\sigma^n_{\text{XC}})_{\text{NLO}} = (\sigma^n_{\text{XC}})_{\text{LO}} + \delta\sigma^n_{\text{XC}}$ (X = N,C; $n = \nu, \bar{\nu}$), can be expanded as follows,

$$\delta R^n = \left(\frac{\sigma^n_{\rm NC}}{\sigma^n_{\rm CC}}\right)_{\rm LO}\left(\frac{(\delta\sigma^n_{\rm NC})_{\rm MSSM}-(\delta\sigma^n_{\rm NC})_{\rm SM}}{(\sigma^n_{\rm NC})_{\rm LO}}-\frac{(\delta\sigma^n_{\rm CC})_{\rm MSSM}-(\delta\sigma^n_{\rm CC})_{\rm SM}}{(\sigma^n_{\rm CC})_{\rm LO}}\right).$$

Thus, only differences between MSSM and SM radiative corrections and leading-order (LO) cross-section expressions appear. R-parity conservation in the MSSM makes the Born cross section the same as in the SM (up to a negligible extra contribution involving a virtual charged Higgs boson). Consequently, contributions from real photon emission and all SM-like radiative corrections without virtual Higgs bosons are equal in the MSSM and the SM. Therefore, the difference between the MSSM and SM prediction for the quantity R^n at one-loop order in the electroweak corrections boils down to the genuine superpartner (SP) loops and the difference between the Higgs-sector contributions, i.e. schematically given by

$$\delta R^n \propto \big(\ [\text{SP loops}] + [\text{Higgs graphs MSSM} - \text{Higgs graphs SM}]\ \big)\ . \tag{1}$$

The second term in eq. (1) vanishes when the MSSM Higgs sector is SM-like, which is the case for a CP-odd Higgs mass $m_A \gtrsim 250\,\text{GeV}$. The superpartner-loop contributions for CC (anti-)neutrino–quark scattering consist of W-boson selfenergy insertions, loop contributions to the $Wq\bar{q}'$- and $W\nu_\mu\mu^-(W\bar{\nu}_\mu\mu^+)$-vertex, and box-graphs with double gauge-boson exchange. Analogous contributions appear in the NC case with W replaced by Z and $\mu^-(\mu^+)$ by $\nu_\mu(\bar{\nu}_\mu)$. Additionally, there are SP-loop contributions to the photon–Z mixing selfenergy. The partonic processes were calculated using the computer programs FeynArts and FormCalc[11].

3 MSSM parameter scan for $\delta R^{\nu(\bar{\nu})}$

We make use of a technique described in[12] which allows us to perform parameter scans with emphasis on specific features of the prediction. We perform two different parameter scans over the following set of MSSM parameters in the ranges given: $50\,\text{GeV} \leq M_1, M_2, M_3, M_{\rm Sf.} \leq 1\,\text{TeV}$, $1 \leq \tan\beta \leq 50$, $-2\,\text{TeV} \leq \mu, A_t, A_b \leq 2\,\text{TeV}$, where M_1, M_2, M_3 are gaugino mass parameters, $M_{\rm Sf.}$ is a common sfermion mass scale, $\tan\beta$ is the ratio of the two Higgs vacuum expectation values in the MSSM, μ is the supersymmetric Higgs mass term, A_t and A_b are soft-breaking trilinear couplings. We choose $m_A = 500\,\text{GeV}$, such that the Higgs sector is SM-like and the superpartner loops determine $\delta R^{\nu(\bar{\nu})}$. In a first step (i), we scan the quantities $\delta R^{\nu(\bar{\nu})}$ with an emphasis on large deviations from the SM and neglect all points in parameter space which violate mass exclusion limits for Higgs bosons or for superpartners or the $\Delta\rho$-constraint on sfermion mixing. Fig. 2(a) and 2(b) show the values δR^{ν} and $\delta R^{\bar{\nu}}$, respectively, resulting from our parameter scan in the $M_{\rm Sf.}$–X_t–plane ($X_t = A_t - \mu/\tan\beta$). There are large radiative corrections for a kind of "large-mixing" scenario ($|X_t| \approx 3M_{\rm Sf.}$). Interestingly, we obtain only positive values for δR^{ν} and $\delta R^{\bar{\nu}}$. Therefore, in a second scan (ii) we neglect all constraints and put an emphasis on negative values of $\delta R^{\nu(\bar{\nu})}$. This scan adaptively improves on sampling

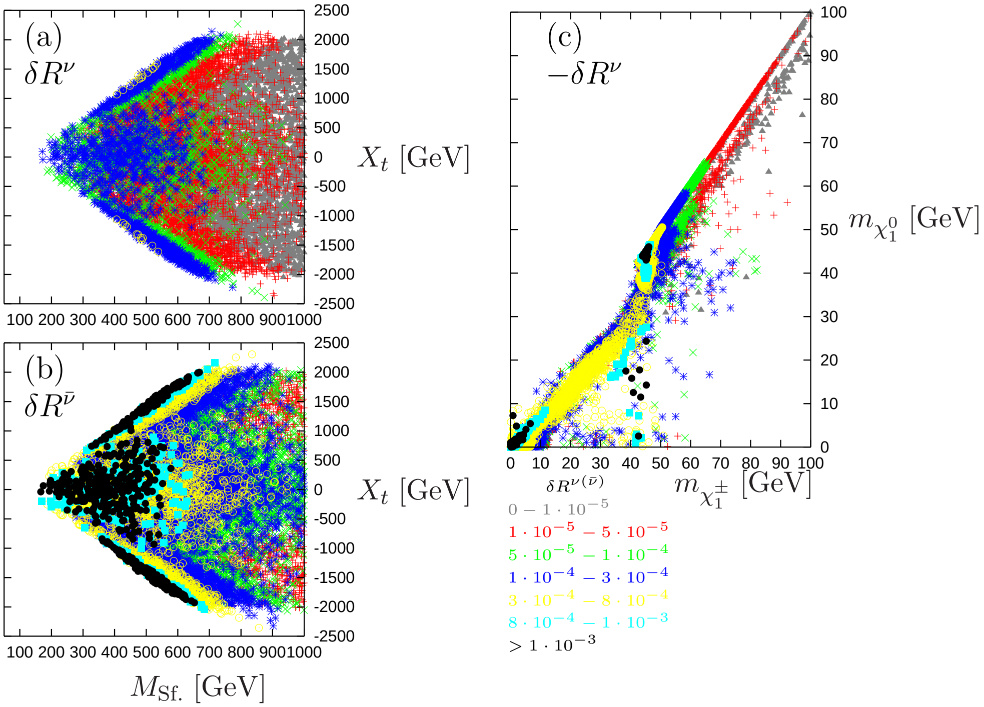

Figure 2: Results of the parameter scan (i) (see text) for (a) δR^{ν} and (b) $\delta R^{\bar\nu}$ in the $M_{\rm Sf.}$–X_t–plane. Panel (c) shows $-\delta R^{\nu}$ of all results with $\delta R^{\nu} < 0$ of the scan (ii) in the $m_{\chi_1^\pm}$–$m_{\chi_1^0}$–plane. The color code for the displayed values applies to all three panels.

parameter points where $\delta R^{\nu(\bar\nu)}$ is negative, as it is suggested by the NuTeV result, and finds indeed such points. But, all of them violate at least one of the above-mentioned constraints and are thus excluded. Fig. 2(c) shows only parameter points with $\delta R^{\nu} < 0$ resulting from the second scan in the plane of the lightest neutralino and chargino mass $(m_{\chi_1^0}, m_{\chi_1^\pm})$, which proves to be decisive for the sign of $\delta R^{\nu(\bar\nu)}$. Not shown in Fig. 2(c) is a narrow area of negative values with $|\delta R^{\nu}| < 10^{-5}$ around $m_{\chi_1^0} \approx m_{\chi_1^\pm}$ extending up to $\approx 500\,$GeV. Fig. 2(c) shows that negative values with a magnitude $> 10^{-4}$ only appear for $m_{\chi_1^0}, m_{\chi_1^\pm} < 80\,$GeV. From this analysis we conclude that the NuTeV result for R^{ν} and $R^{\bar\nu}$ cannot be explained by MSSM radiative corrections in parameter regions where the superpartner loops dominate.

4 Summary

The NuTeV measurement of $\sin^2\theta_w$ is intriguing but has to be further established. Especially, confirmation by other experiments is desirable. Loop effects from the non-standard particles in the MSSM do not provide aviable explanation of the deviation observed by NuTeV in the electroweak $\sin^2\theta_w$. The size of the deviation could be of the right order, but it either appears with the wrong sign or violates other electroweak constraints. For a final detailed analysis, also the differences between the Higgs sectors of the SM and the MSSM have to be incorporated. In any case, interesting restrictions on the MSSM parameters can be obtained.

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