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

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We present 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. For these quantities we present results of a scan over the MSSM parameter space.

1 Introduction

NuTeV's $\sin^2\theta_w$ measurement in ν-N deep-inelastic scattering (DIS)
In the Standard Model neutral (NC) and charged current (CC) neutrino-nucleon scattering is described in leading order by t-channel W and Z exchange (see fig. 1), respectively. 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 measurement 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 smaller than the SM prediction [2]. But the measurement is indirect, making use of the Paschos-Wolfenstein relation [3]:

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

and the measurement of ratios of counting rates $R^\nu_{\rm exp} \approx R^\nu, R^{\bar\nu}_{\rm exp} \approx R^{\bar\nu}$, which are related to $R^\nu, R^{\bar\nu}$ by a detailed Monte Carlo (MC) physics simulation. The deviation from the SM in terms of $R^\nu_{\rm exp}, R^{\bar\nu}_{\rm exp}$ are [4]:

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

[a] Speaker.

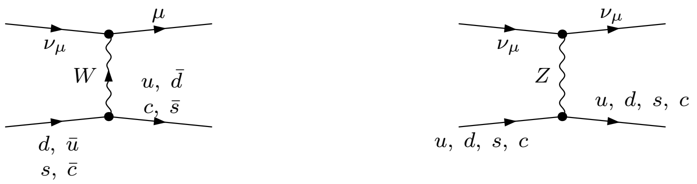

Figure 1: Tree-level Feynman graphs for neutral-current and charged-current scattering of muon-neutrino and quark.

For the MSSM to be able to explain the deviations $\Delta R^{\nu(\bar{\nu})}$ the radiative corrections $\delta R^{\nu(\bar{\nu})}$ to the quantities $R^{\nu(\bar{\nu})}$ should be of the same order as $\Delta R^{\nu(\bar{\nu})}$. But, a precise answer calls for a detailed MC simulation, which is beyond the scope of this study.

Possible explanations of the NuTeV anomaly
Basically, there are three types of explanations.
(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 and a list of other sources (see [7,8] and refs. therein for an overview).
(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 (see [7,9] and refs. therein for an overview).

We are interested in the radiative corrections to neutrino nucleon DIS in the MSSM. Although the NuTeV anomaly is far from being settled, it is interesting, if the MSSM *could* account for such a deviation. A negative answer would also have interesting consequences for the MSSM, if the anomaly was established. There are two earlier studies in the literature. Davidson et al. [7] present a rough study of the MSSM radiative corrections in terms of oblique parameters. They study only one special MSSM parameter scenario. Kurylov et al. [9] study the MSSM parameter dependence. But, both papers neglect kinematical effects present in the NuTeV experiment. They work in the limit of zero momentum transfer of the neutrino to the hadron, neglect kinematical cuts and effects of the parton distribution functions. Both conclude that the radiative corrections in the MSSM are not responsible for the NuTeV anomaly. It seems that the magnitude of the corrections fits, but the sign is opposite to what would be needed to explain the deviation.

Our calculation includes several kinematic effects and attempts to make a thorough parameter scan of the radiative corrections $\delta R^{\nu(\bar{\nu})}$ over the relevant MSSM parameter space. As for the kinematics, we include the full q^2 dependence of the one-loop amplitudes, evaluate hadronic cross sections using PDFs, and use NuTeV-inspired cuts on the hadronic energy in the final state ($20\,\mathrm{GeV} < E_{\mathrm{had.}} < 180\,\mathrm{GeV}$) and the mean neutrino beam energy of 125 GeV.

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

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

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

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 collapses to the genuine superpartner (SP) loops and the difference between the Higgs sector contributions, i.e. schematically

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

The second term in eq. (1) vanishes, if the MSSM Higgs sector is SM-like, which is the case for a CP-odd Higgs mass $m_A \gtrsim 250\,\mathrm{GeV}$. The superpartner loop corrections 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. 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 [10].

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

We make use of a technique described in [11] which allows to perform parameter scans with emphasis on certain features of the prediction. We perform two different parameter scans over the following set of MSSM parameters in the ranges given: $50\,\mathrm{GeV} \leq M_1, M_2, M_3, M_{\mathrm{Sf.}} \leq 1\,\mathrm{TeV}$, $1 \leq \tan\beta \leq 50$, $-2\,\mathrm{TeV} \leq \mu, A_t, A_b \leq 2\,\mathrm{TeV}$, where M_1, M_2, M_3 are gaugino mass parameters, $M_{\mathrm{Sf.}}$ 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 $m_A = 500\,\mathrm{GeV}$, such that the Higgs sector is SM-like and the superpartner loops determine $\delta R^{\nu(\bar{\nu})}$. First 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 $M_{\mathrm{Sf.}}$–X_t–plane ($X_t = A_t - \mu/\tan\beta$). There are large radiative corrections for a kind of "large-mixing" scenario ($|X_t| \approx 3M_{\mathrm{Sf.}}$). Interestingly, we obtain only positive values for δR^{ν} and $\delta R^{\bar{\nu}}$. Therefore, in a second scan we neglect all constraints and put an emphasis on negative values of $\delta R^{\nu(\bar{\nu})}$. This scan adaptively improves on sampling 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 $\approx 500\,\mathrm{GeV}$. Fig. 2(c) shows that negative values with a magnitude $> 10^{-4}$ only appear for $m_{\chi_1^0}, m_{\chi_1^\pm} < 80\,\mathrm{GeV}$. 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 in the MSSM are most likely not responsible for the NuTeV anomaly. The size can be right, but the sign is wrong. But, to make sure, a full analysis, including the MSSM-SM Higgs sector differences, is needed (and planned). Once the NuTeV anomaly is established, interesting restrictions on the MSSM

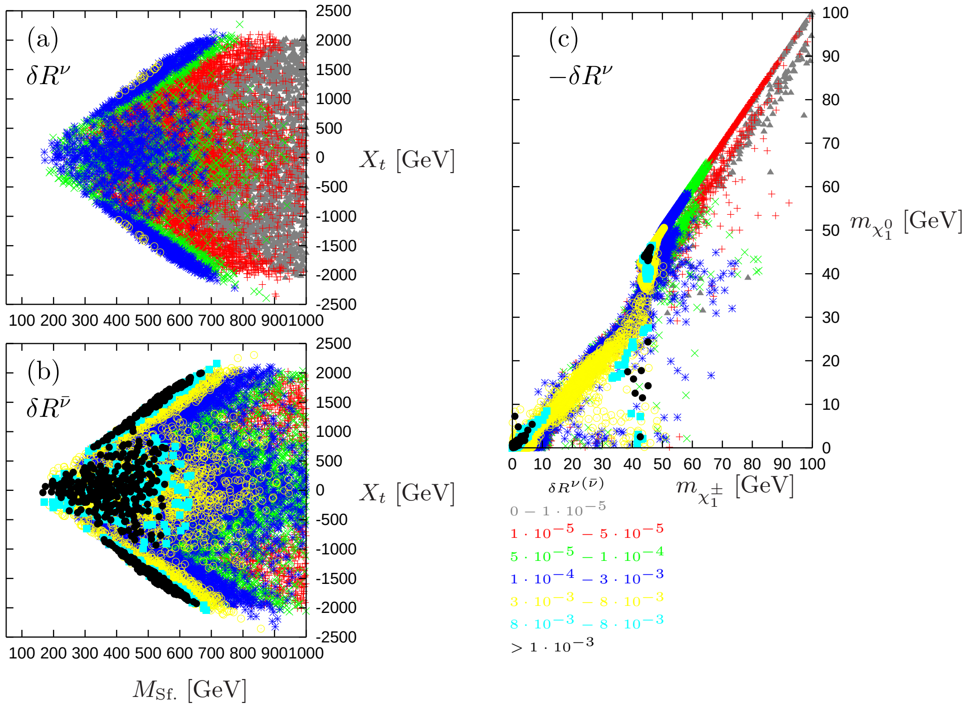

Figure 2: Results of the first parameter scan (see text) for (a) δR^{ν} and (b) $\delta R^{\bar{\nu}}$ in the $M_{\rm Sf.}$–X_t–plane. Panel (c) shows $-\delta R^{\nu}$ of all results with $\delta R^{\nu} < 0$ of the second scan in the $m_{\chi_1^\pm}$–$m_{\chi_1^0}$–plane. The color code for the displayed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

parameters arise.

References

1. G. P. Zeller *et al.* [NuTeV Collaboration], Phys. Rev. Lett. **88** (2002) 091802 [Erratum-ibid. **90** (2003) 239902].
2. M. W. Grünewald, hep-ex/0304023.
3. E. A. Paschos and L. Wolfenstein, Phys. Rev. D **7** (1973) 91.
4. G. P. Zeller *et al.* [NuTeV Collaboration], in hep-ex/0207052.
5. K.-P. O. Diener, S. Dittmaier and W. Hollik, Phys. Rev. D **69** (2004) 073005; Talk by A. B. Arbuzov, these proceedings; A. B. Arbuzov, D. Y. Bardin and L. V. Kalinovskaya, hep-ph/0407203.
6. D. Y. Bardin and V. A. Dokuchaeva, JINR-E2-86-260
7. S. Davidson, et al. JHEP **0202** (2002) 037.
8. S. A. Kulagin, Phys. Rev. D **67** (2003) 091301; K. S. McFarland and

S. O. Moch, hep-ph/0306052; S. Kretzer, et al. Phys. Rev. Lett. **93** (2004) 041802.

9. A. Kurylov, M. J. Ramsey-Musolf and S. Su, Nucl. Phys. B **667** (2003) 321.
10. J. Küblbeck, M. Böhm and A. Denner, Comput. Phys. Commun. **60** (1990) 165; H. Eck, Ph.D. thesis, University of Würzburg (1995); T. Hahn and M. Perez-Victoria, Comput. Phys. Commun. **118** (1999) 153; T. Hahn, ibid. **140** (2001) 418; T. Hahn and C. Schappacher, ibid. **143** (2002) 54; see also: www.feynarts.de.
11. O. Brein, hep-ph/0407340.