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Collider Tests of the Non-Commutative Standard Model

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We discuss the non-commutative extension of the standard model constructed with the Seiberg-Witten maps for $\mathrm{SU}(3)_C \otimes \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y$. Using the first-order approximation in the non-commutative parameters $\theta^{\mu\nu}$, we estimate the sensitivity of $Z\gamma$-production at the Tevatron and LHC from Monte Carlo simulation.

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1. Gauge Theory on Non-Commutative Space-Time

Ever since it was shown that quantum field theory on a non-commutative (NC) space-time arises naturally in the low energy limit of string theory [1], there has been a lot of interest in building realistic models, working out the phenomenology and testing the predictions by experiment.

NC space-time is characterized by a nonvanishing commutator among coordinates,

$$[\hat{x}^\mu, \hat{x}^\nu] = \mathrm{i}\theta^{\mu\nu} = \mathrm{i}\frac{C^{\mu\nu}}{\Lambda_{\mathrm{NC}}^2}\,, \tag{1.1}$$

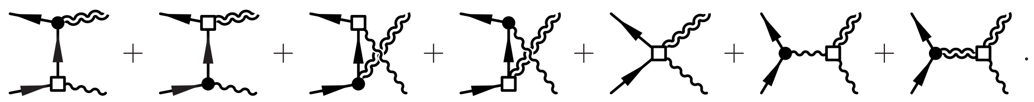
with a typical energy or inverse length scale Λ_{NC}. The current bounds on Λ_{NC} are strongly model dependent, ranging from 141 GeV in collider experiments up to 10^{14} GeV from rotation invariance tests in atomic physics and astrophysics [2]. In the following, we will assume the matrix $C^{\mu\nu}$ to be constant and realize the commutator (1.1) by replacing the product of functions of the NC coordinates $f(\hat{x}) \cdot g(\hat{x})$ by the Moyal-Weyl $\star$-product of functions of the ordinary space-time coordinates:

$$(f \star g)(x) = f(x)\exp(\frac{\mathrm{i}}{2}\overleftarrow{\partial_\mu}\theta^{\mu\nu}\overrightarrow{\partial_\nu})g(x)\,. \tag{1.2}$$

In the case of gauge theories, this approach is only consistent for $\mathrm{U}(N)$ gauge groups and only a single eigenvalue is allowed for the charge operator of each $\mathrm{U}(1)$ factor. For a NC extension of the standard model (SM), the construction must therefore be amended. A minimal solution is provided by the Seiberg-Witten maps (SWM) [1], that express the NC gauge and matter fields as non-linear functions of ordinary gauge and matter fields, such that the gauge transformations of the non-commutative fields are realized by the gauge transformations of the ordinary fields: $\hat{A}'(A) = \hat{A}(A')$ and $\hat{\psi}'(\psi, A) = \hat{\psi}(\psi', A')$. The SWM can be determined from these conditions order by order in $\theta^{\mu\nu}$ for arbitrary gauge groups and representations. In [3] the NC generalisation of the $\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$ standard model (NCSM) has been constructed in first order in $\theta^{\mu\nu}$.

2. Cross Section for $f\bar{f} \to Z\gamma$

Starting from the Lagrangian in [3], we determined the relevant Feynman rules in the NCSM (cf. [4]). Interaction vertices that are already present in the SM acquire momentum dependent corrections and new vertices like contact terms and couplings among neutral gauge boson appear. All these effects are present in $f\bar{f} \to Z\gamma$, the amplitude of which is given by $A = A^{\mathrm{SM}} + A^{\mathrm{NC}}$, where, at $O(\theta^{\mu\nu})$,

$A^{\mathrm{NC}} =$ 

The new and modified vertices have been marked by an open box in the Feynman diagrams above. The coupling strength of the contact term is fixed by gauge invariance, while the s-channel diagrams depend on two new coupling constants $K_{Z\gamma\gamma}$ and $K_{ZZ\gamma}$ that are only constrained by the matching to the SM in the limit $\theta^{\mu\nu} \to 0$ and can vary independently in a finite range [3].

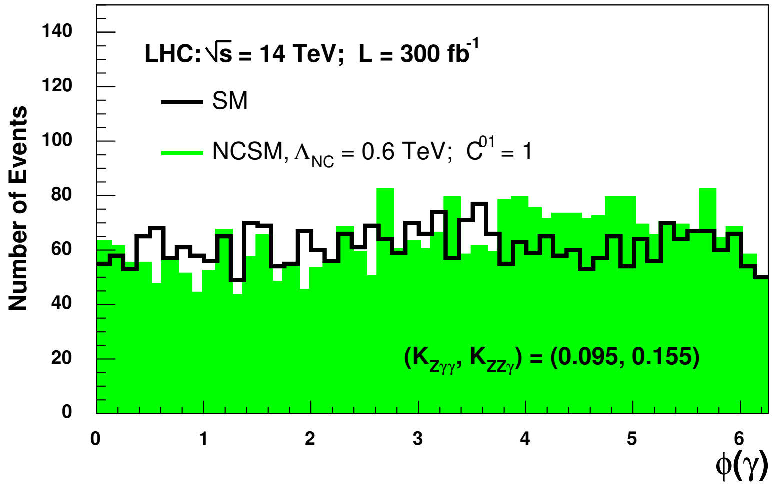


Figure 1: Azimuthal distribution of the photon in $pp \to e^+e^-\gamma$ at the LHC, applying the cuts $\cos\theta_{e^+e^-} > 0$, $\cos\theta_\gamma > 0$ and $0 < \cos\theta^*_\gamma < 0.9$.

3. Sensitivity of the channel $q\bar{q} \to e^+e^-\gamma$ at the Tevatron and LHC

We have performed a phenomenological analysis of the NC effects at hadron colliders in the process $q\bar{q} \to e^+e^-\gamma$, which includes the resonant $Z\gamma$ contribution. The complete $q\bar{q} \to e^+e^-\gamma$ cross section was calculated numerically using an unpublished extension of the libraries of O'Mega [5]. The Monte Carlo simulations were performed with WHiZard [6].

Cross sections in the NCSM show a characteristic dependence on the azimuthal angle ϕ, which can be used to search for NC signals and to discriminate against other new physics effects. However, this effect is linear in the partonic $\cos\theta^*$ and cancels at the LHC due to the symmetric initial state pp, even if we require $\cos\theta^* > 0$. Nevertheless, since the average momentum fraction of quarks in the proton is much higher than the average momentum fraction of antiquarks, one can select either $q\bar{q} \to Z\gamma$ or $\bar{q}q \to Z\gamma$ events at the LHC, by requiring a minimal boost of the partonic center of mass system in the direction of the quark. A simple and efficient cut is to require both the γ and the e^+e^--pair to be produced in the same hemisphere. The resulting distribution at the LHC is depicted in fig. 1. At the Tevatron, the corresponding events with a high partonic $\sqrt{\hat{s}}$ are mostly $q\bar{q} \to Z\gamma$ without additional cuts. However, the NC effect is much weaker [7].

Using the azimuthal dependence of the cross section in first order in $\theta^{\mu\nu}$ plotted in fig. 1, we have estimated the sensitivity on the scale Λ_{NC} from fitting the quadratic dependence of χ^2 on $\theta^{\mu\nu}$. The resulting error ellipses for $C^{\mu\nu}$ at fixed $\Lambda_{NC} = 500\,\text{GeV}$ are shown in fig. 2. The correlations between (C^{01}, C^{13}) and (C^{02}, C^{23}), respectively, are expected from kinematics. In the center of mass system, the partonic cross sections show a much stronger dependence on the time-like components C^{0i} than on the space-like components C^{ij}. However, in the laboratory frame, the time-like and space-like components are mixed by Lorentz boosts, e. g. $C^{01} \to \gamma(C^{01} - \beta C^{13})$, leading to the strong correlations observed in fig. 2. Analytically, the corresponding contours would be straight diagonal lines. The depicted stretched ellipse and hyperbola are the result of fluctuations of the vanishing eigenvalues of the quadratic form for χ^2, fitted from the simulated event samples.

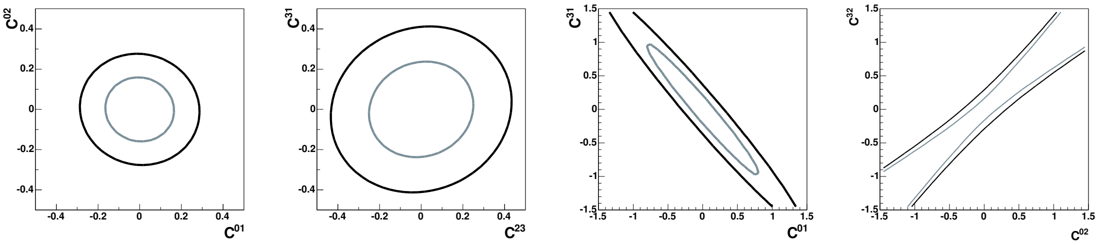


Figure 2: Sensitivity on $C^{\mu\nu}$ at the LHC for an integrated luminosity of $100\,\mathrm{fb}^{-1}$ assuming $\Lambda_{\mathrm{NC}} = 500\,\mathrm{GeV}$ and applying the kinematical cuts given in fig. 1.

From the error ellipses in fig. 2, we derive the following sensitivity limits on the NC scale at the LHC for an integrated luminosity of $100\,\mathrm{fb}^{-1}$:

$$\Lambda_{\mathrm{NC}} \geq 1.2 \text{ TeV for } C^{0i} = 1, \quad \Lambda_{\mathrm{NC}} \geq 1.0 \text{ TeV for } C^{3i} = 1, \quad i = 1,2. \tag{3.1}$$

Such a measurement would improve the current collider bounds by an order of magnitude. A similar analysis for the Tevatron shows that the sensitivity on the NC scale remains below $100\,\mathrm{GeV}$ there [7].

Our analysis is based on the scattering amplitude $A = A^{\mathrm{SM}} + A^{\mathrm{NC}}$ to first order in the non-commutativity $\theta^{\mu\nu}$. Therefore the NC effects arise only from the SM/NC interference term which scales with $\hat{s}/\Lambda_{\mathrm{NC}}{}^2$. It turns out that values of Λ_{NC} that are observable in events with typical values of $\sqrt{\hat{s}}$ can correspond to an unphysical cross section at the highest $\sqrt{\hat{s}}$ available. We have eliminated this problem by assuming that higher orders in $\theta^{\mu\nu}$ will cancel the large negative interference contributions. Preliminary results for the calculation in second order in $\theta^{\mu\nu}$ support this prejudice [7]. We also find that the second order contributions to the unpolarized cross section do not cancel for symmetric final states such as $\gamma\gamma$ as they did in first order [4]. This could provide signatures for the NCSM also in $pp \to \gamma\gamma$, a process which will be studied in great detail for Higgs searches at the LHC.

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