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Lorentz Violation in high-energy hadron collisions

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We present an overview of Lorentz violation in high energy collisions focusing on deep inelastic scattering and Drell-Yan at hadron-hadron colliders. We further discuss the bounds that can be attainable by sideral time studies of these processes at HERA, the planned Electron-Ion Collider and the LHC.

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Invariance of physical laws under Lorentz transformations is the most tested symmetry in Nature. Lorentz invariance constitutes the foundation of modern physics to such an extent that formulating consistent theories in which this symmetry is broken is a severe challenge. The Standard Model Extension [4–6] (SME) provides a model independent framework in which Lorentz violating effects can be described. The foundation of the SME lies in the preservation of invariance under observer Lorentz transformations. Every term in the SME Lagrangian is built out of standard building blocks (scalar, spinor and tensor fields, coupling constants and masses) and of coefficients for Lorentz violation which transform as tensors under observer transfomrations but are constant under particle Lorentz transformations. This set up can be thought as the result of a spontaneous breaking of the Lorentz symmetry, though this point of view is not necessary.

Bounds on Lorentz violating effects in stable or long lived particles (e.g. e, μ, γ, p, n) are extremely strong. The corresponding coefficients (which are fundamental parameters for the leptons and the photon and effective parameters for the nucleons) are very tightly constrained [7]. On the other hand constraints on coefficients in the quark sector are very weak due to the difficulty in relating quark and hadron properties (Attempts along these lines have been presented in Refs. [8,9].

In a series of recent papers [1–3, 10] we showed how to connect directly quark coefficients to observables in collisions at high energies. The presence of these coefficients induces a sidereal time variation. The irreducible background to this modulation is controlled by the fraction of the total experimental uncertainty which is uncorrelated with respect to time binning. The latter is usually statistical in origin. For this reason we focused on processes for which statistical errors are the smallest. Two prominent examples are deep inelastic scattering (DIS) at electron-proton colliders and Drell-Yan di-lepton pair production at hadron colliders. We refer to Ref. [3] for a detailed proof of factorization theorems for DIS and Drell-Yan within the SME. In the following we summarize the main results.

The SME coefficients that we consider are:

$$\mathscr{L} = \sum_{f=u,d} \left[\tfrac{1}{2} \bar{\psi}_f (\eta^{\mu\nu} + c_f^{\mu\nu}) \gamma_\mu i D_\nu \psi_f - a_f^{(5)\mu\alpha\beta} \bar{\psi}_f \gamma_\mu i D_{(\alpha} i D_{\beta)} \psi_f + \text{h.c.} \right] \tag{1}$$

where $c_f^{\mu\nu}$ are dimensionless coefficients which belong to the so-called minimal SME and $a_f^{(5)\mu\alpha\beta}$ are negative dimension non-renormalizable coefficients. The latter are interesting because their effects tend to be enhanced in very high energy interactions.

The prescription to calculate a generic lepton-hadron DIS cross section is relativelty simple [3]. First one needs to calculate the matrix element squared for the quark level transition and perform the phase space integration. In order to avoid complications associated with final state SME particles these steps are best achieved by employing the optical theorem: the integrated rate is obtained from the imaginary part of the forward lepton-hadron amplitude calculated using the standard Cutkosky rules. The final cross section is then obtained by multiplying by the proton flux factor (which depends only on the proton SME coefficients which are experimentally tiny [7]) and convoluting with the quark parton distribution functions (PDFs). An explicit expression for the latter, valid in presence of the minimal coefficients $c_f^{\mu\nu}$, is:

$$f_f(\xi, c_f^{pp}) = \int \frac{d\lambda}{2\pi} e^{-i\xi p\cdot n\lambda} \langle p|\bar{\psi}(\lambda \widetilde{n}_f) \frac{\not{n}}{2} \psi(0)|p\rangle \tag{2}$$

	HERA	EIC	LHC
$\lvert c_u^{XZ}\rvert$	63	0.23	7.3
$\lvert c_u^{YZ}\rvert$	65	0.23	7.1
$\lvert c_u^{XY}\rvert$	31	0.26	2.7
$\lvert c_u^{XX} - c_u^{YY}\rvert$	98	0.74	15
$\lvert a_u^{(5)TXZ}\rvert$	1.3	0.013	0.0031
$\lvert a_u^{(5)TYZ}\rvert$	1.3	0.013	0.0031
$\lvert a_u^{(5)TXY}\rvert$	0.65	0.036	0.0014
$\lvert a_u^{(5)TXX} - a_u^{(5)TYY}\rvert$	3.1	0.045	0.0064

Table 1: Bounds on selected u-quark coefficients at HERA, the EIC and the LHC. Bounds are reported in units of 10^{-5} and 10^{-5} GeV^{-1} for the c_f and $a_f^{(5)}$ coefficients, respectively.

where n and $\bar{n}$ are two light-cone vectors determined by the proton momentum $p^\mu = \bar{n}^\mu (n \cdot p)$, and $\widetilde{n}_f^\mu = (\eta^{\mu\nu} + c_f^{\mu\nu}) n_\nu$. This expression reduces to the standard definition of the PDFs in the $c_f \to 0$ limit. More importantly, it is possible to show that the n-th moment of this PDF is in one-to-one correspondence with the matrix element of the operator of dimension $n+3$ which appear in the Operator Product Expansion proof of the factorization theorem for DIS [7]. A similar result can be obtained for the non-minimal $a_f^{(5)}$ coefficients. In particular, this shows that the PDFs can only depend on contractions of the coefficients for Lorentz violation with the proton momentum: c_f^{pp} for the minimal case and $a_f^{(5)ppp}$, $a_f^{(5)p\mu}{}_\mu$ and $a_f^{(5)\mu p}{}_\mu$ for the non-minimal one. The dependence of the PDFs on the coefficients is non-perturbative and will be investigated in a forthcoming publication.

The calculation of the Drell-Yan cross section is very similar: the partonic squared matrix element calculated in the SME is convoluted with the *same* PDFs introduced above. The only additional complication is that we need to take into account that the di-lepton momentum is connected to the momenta of two partons which are on-shell in the SME: this leads to the appearence of an extra correction term in the final cross section [3].

All coefficients for Lorentz violation are defined in the sun-centric equatorial frame; therefore, in the lab frame most coefficients induce a sidereal time variation which depends on the location and orientation of the experiment.

We focus on DIS at HERA [11] and at the planned Electron Ion Collider (EIC) [12] and on Drell-Yan at CMS [13]. The expected bounds on the coefficients c_f and $a_f^{(5)}$ can be calculated by taking existing (or Monte Carlo generated) data and simulating the sidereal time binning by carefully considering what fraction of the experimental uncertainty is correlated in time (See Refs. [1,2] for details).

In table 1 we present bounds on selected coefficients which can be constrained by both DIS and Drell-Yan. We first note that expected bounds from EIC measurements are expected to place bounds which are more than an order of magnitude stronger than those from HERA. This is due to the much larger luminosity of the EIC. More importantly is the comparative advantage that LHC measurements have in the extraction of bounds on the coefficients $a_f^{(5)}$: while bounds from Drell-Yan on $c_f^{\mu\nu}$ are weaker than those attainable at the EIC, bounds on the non-minimal coefficients $a_f^{(5)}$ are an order of magnitude stronger than the EIC ones. The reason for this behavior is that the $a_f^{(5)}$ have negative mass dimension, implying that in physical observables they appear multiplied by the typical experimental energies which are much larger at the LHC. We conclude that both the EIC and the LHC have the potential to place strong constraints on various quark level coefficients for Lorentz violation.

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