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Constraining the intrinsic structure of top-quarks

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ABSTRACT

The basic structure of top-quarks as spin-1/2 particles is characterized by the radius R_t and the intrinsic magnetic dipole moment κ_t, both individually associated with gauge interactions. They are predicted to be zero in pointlike theories as the Standard Model. We derive upper limits of these parameters in the color sector from cross sections measured at Tevatron and LHC in top pair production $p\bar{p}/pp \to t\bar{t}$, and we predict improved limits expected from LHC in the future, especially for analyses exploiting boosted top final states. An additional method for measuring the intrinsic parameters is based on $t\bar{t} + jet$ final states.

1. Basic set-up

The top-quark is the heaviest particle in the Standard Model (SM), even if the Higgs particle is included as a contender. This observation led to many approaches in which the top-quark plays the role of portal to physics beyond the Standard Model, see *e.g.* Refs. [1,2]. Scales characterizing the novel interactions in which the top-quark is identified with the crucial source field, may be realized not far beyond the TeV size. As a consequence, the top-quark may be endowed with intrinsic structure at the TeV scale. This should be contrasted with the pointlike character of all fundamental fields within the Standard Model, extending up to scales close to the Planck scale for low Higgs mass.

The basic non-pointlike structure will manifest itself in a non-zero *radius* R_t and a non-zero *anomalous magnetic dipole moment* κ_t in CP-invariant scenarios, probed in interactions with gauge fields [3]. Due to the high energy available, the LHC will enable us to probe the intrinsic top-quark structure in the colored sector at an unprecedented level [4,5,7,8,6]. Non-pointlike interactions with the gluon field[1] modify the color quark current to [3]

$$\mathcal{J}_\mu = F_t \gamma_\mu + i\frac{\kappa_t}{2m_t}\sigma_{\mu\nu}Q^\nu. \tag{1.1}$$

The current incorporates the form factor

$$F_t = 1 + \frac{1}{6}R_t^2 Q^2, \tag{1.2}$$

with the top-quark radius R_t related by

$$R_t = \sqrt{6}/\Lambda_* \tag{1.3}$$

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[1] The massless gluon gauge field is assumed intrinsically pointlike in the present analysis. This assumption can be removed, see Ref. [9], at the expense of increasing complexity. Non-pointlike structures of the weak current remain non-effective as long as the top decay is treated inclusively with $BR(t \to bW)$ very close to unity.

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to the new scale parameter Λ_*, and the anomalous chromo-magnetic dipole moment κ_t [beyond the loop value [10]]. To protect fermion masses from acquiring large values, the theory is generally assumed chiral [11], and the breaking of the chiral symmetry by anomalous magnetic moments is suppressed by two powers of the scale Λ_*, in the simplest possible realization:

$$\kappa_t = \rho m_t^2/\Lambda_*^2, \tag{1.4}$$

where $|\rho|$ is an $\mathcal{O}(1)$ number. The quadratic Λ_* dependence of κ_t is effectively equivalent to the scaling of the form factor. The quadratic dependence in the heavy quark mass singles out the top-quark as unique particle for which κ_t may be accessible experimentally, in contrast to much less sensitive light quarks or leptons. Assuming Λ_* to be of order 1 TeV and beyond, compatible with bounds on contact interactions from Tevatron and LHC [12], κ_t could be expected at the level of several per-cent.

Both the anomalous parameters, color radius and color magnetic dipole moment, can be introduced through effective Lagrangians [13] in an $SU(3)_c$ gauge-invariant and parity-even form[2]:

$$\mathcal{L}_R = -g_s \frac{R_t^2}{6} \bar{t}\gamma^\mu \mathcal{G}_{\mu\nu} D^\nu t + \text{h.c.}, \tag{1.5}$$

$$\mathcal{L}_\kappa = g_s \frac{\kappa_t}{4m_t} \bar{t}\sigma^{\mu\nu} \mathcal{G}_{\mu\nu} t, \tag{1.6}$$

with the gluon field $\mathcal{G}_\mu$, in octet matrix notation, and the gluon field strength $\mathcal{G}_{\mu\nu} = D_\nu \mathcal{G}_\mu - D_\mu \mathcal{G}_\nu$, while $D^\nu = \partial^\nu + i g_s \mathcal{G}^\nu$ denotes the covariant derivative of QCD. Besides the components generating the anomalous top color current, the Lagrangians are complemented by additional two-gluon and three-gluon top interactions, as demanded by gauge invariance. The effective Lagrangians unambiguously translate the anomalous parameters from scattering to annihilation processes.

The classical method for studying radius and anomalous magnetic dipole moment of the top quark is given by the elastic Rutherford-type scattering of a top quark t with a light quark q [taken pointlike in the present scenario], which is mediated by the exchange of a gluon in $qt \to qt$. Rutherford-type scattering is also embedded in the process $gq \to t\bar{t}q$. At very high energies, gluon partons in the protons split into beams of long-lived top-quark pairs traveling parallel to the gluon momentum. Thus, the events of the $t\bar{t}q$ process, characterized by a forward moving t-quark plus a $\bar{t}q$-pair, with the two partons in the pair balanced in transverse momentum, signal Rutherford qt scattering. [Elastic gluon-top scattering is independent of the radius R_t and cannot be exploited.]

2. Theoretical groundwork

We will analyze the total cross sections for the production of top-quark pairs

$$p\bar{p}/pp \to q\bar{q}, \qquad gg \to t\bar{t} \tag{2.1}$$

at Tevatron and LHC for deriving limits on the color radius R_t, the anomalous chromo-magnetic dipole moment κ_t and the Λ_* parameter in practice. Additional constraints can be derived from the angular dependence of the top-quarks, and the correlations between longitudinal spin components of t and $\bar{t}$ [14], which can be measured unperturbed by fragmentation due to the short top lifetime [15]. Related analyses have been discussed in Refs. [18,16,17].

We will assume that the non-pointlike contributions to the observables are small and, correspondingly, we will expand the observables linearly in the analytic formulae. In fact, anomalous chromo-magnetic dipole moment and chromo-radius are the first terms of a multipole expansion including scale parameters beyond the Standard Model. The systematic expansion would continue with higher-order moments the quadratic terms in R_t^2 and κ_t would compete with. An analysis of these contributions is beyond the scope of the present Letter.

The hadron cross sections are built up by the incoherent superposition of quark–antiquark annihilation and gluon fusion to top–antitop pairs. Quark–antiquark annihilation is mediated only by s-channel gluon exchange[3], gluon fusion by s-channel gluon and t, u-channel top exchanges.

The anomalous terms of the independent cross sections at the parton level can be summarized as follows [see also references quoted above], using $\beta = \sqrt{1 - 4m_t^2/s}$, where s is the partonic center-of-mass energy:

Quark-antiquark annihilation:

$$\frac{\Delta\sigma}{\sigma_B} = \frac{s}{3} R_t^2 + \frac{6\kappa_t}{3-\beta^2}, \tag{2.2}$$

$$\frac{\Delta d\sigma/d\cos\theta}{d\sigma_B/d\cos\theta} = \frac{s}{3} R_t^2 + \frac{4\kappa_t}{2-\beta^2(1-\cos^2\theta)}, \tag{2.3}$$

$$\frac{\{t_R\bar{t}_R + t_L\bar{t}_L\} - \{t_R\bar{t}_L + t_L\bar{t}_R\}}{\{t_R\bar{t}_R + t_L\bar{t}_L\} + \{t_R\bar{t}_L + t_L\bar{t}_R\}} = -\frac{1+\beta^2}{3-\beta^2} + \frac{8\beta^2}{(3-\beta^2)^2}\kappa_t. \tag{2.4}$$

Gluon fusion:

$$\frac{\Delta\sigma}{\sigma_B} = \frac{(36\beta - 64\tanh^{-1}\beta)\kappa_t}{\beta(59-31\beta^2) - 2(33-18\beta^2+\beta^4)\tanh^{-1}\beta}, \tag{2.5}$$

[2] Electroweak gauge invariance can be ensured by expanding the Lagrangians to the complete third generation and incorporating the Higgs field [13].
[3] We neglect electroweak interactions in the following.