Odd Tracks at Hadron Colliders

Patrick Meade,[1] Michele Papucci,[2,3] and Tomer Volansky[3,4]

[1]*C. N. Yang Institute for Theoretical Physics, Stony Brook University, Stony Brook, New York 11794, USA*
[2]*CERN, PH-TH, CH-1211, Geneva 23, Switzerland*
[3]*Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[4]*Berkeley Center for Theoretical Physics, Department of Physics, University of California, Berkeley, California 94720, USA*
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New physics that exhibits irregular tracks such as kinks, intermittent hits, or decay in flight may easily be missed at hadron colliders. We demonstrate this by studying viable models of light, $\mathcal{O}(10\ \mathrm{GeV})$, colored particles that decay predominantly inside the tracker. Such particles can be produced at staggering rates, and yet, may not be identified or triggered on at the LHC, unless specifically searched for. In addition, the models we study provide an explanation for the original measurement of the anomalous charged track distribution by CDF. The presence of irregular tracks in these models reconcile that measurement with the subsequent reanalysis and the null results of ATLAS and CMS. Our study clearly illustrates the need for a comprehensive study of irregular tracks at the LHC.

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Introduction.—A large variety of new physics scenarios feature the presence of charged particles with peculiar properties, that can lead to a systematic misreconstruction of their tracks by the standard algorithms. These properties can induce mismeasurements of the transverse momentum (p_T) or even a failure to reconstruct tracks. One of the simplest examples is a particle decaying in flight inside the tracker. In the following, we list other possibilities and refer to them generically as new odd tracks (NOTs). The systematic misreconstruction of NOTs implies that such theories may evade detection, even if they are produced at surprisingly high rates. Consequently, particles of this kind can be very light, and may require dedicated studies for discovery. In this Letter, we argue that there are viable models with very light colored states that would have gone unnoticed. As a motivating example, we consider an anomaly in a recent measurement based on minimum bias events, and provide viable explanations using NOTs.

In Ref. [1], the single charged particle inclusive distribution was measured by the CDF Collaboration. The measurement was found to be inconsistent with the quantum chromodynamics (QCD) prediction at high p_T [2,3] by a factor of 10^4. Subsequent measurements [4] by the ATLAS and CMS Collaborations found no evidence for an anomaly at high p_T. Most recently, CDF released an erratum [5] where they changed their track selection to remove the high-p_T tracks they had previously measured. While the original result could in principle come from an experimental mismeasurement or unaccounted for background, there is an intriguing possibility that it was due to new physics that can also account for all subsequent findings.

The main difference between the original CDF analysis and the subsequent reanalysis lies in demanding a higher track quality. Unfortunately, the reanalysis does not quantitatively find a standard model (SM) explanation of the original excess tracks, which are simply removed by the quality cut. The measurements by ATLAS and CMS also require much more stringent track quality cuts than the original CDF measurement. To address the original anomaly, together with the null results, one is, therefore, required to introduce new particles, which appear fundamentally different in the tracker, i.e., NOTs. The more stringent cuts on the CDF data reconcile the apparent tension; however, they do so at the cost of losing the sensitivity to new physics of this kind.

The models presented are interesting in their own right. The take-home message, however, is not a specific model. Rather, we stress the existence of a large variety of theories that exhibit NOTs, which would be misinterpreted or missed at the LHC unless specifically searched for. Our work aims, in part, at motivating additional studies to ensure NOTs will not escape detection.

New odd tracks.—Before discussing specific models, we briefly discuss the spectrum of possibilities for theories that exhibit NOTs. It is useful to classify the effects of new physics on standard track signatures. Typically, a given model exhibits more than one signature, which may simplify its identification:

Kinks.—Tracks that appear to change direction, without a secondary vertex. Typically produced by one-prong decays.

Displaced vertices.—Tracks appearing to emanate not from the PV.

Anomalous dE/dx.—Tracks may have lower or higher ionization loss. Standard heavy stable charged particle searches typically look for the latter.

Anomalous timing.—Slowly moving tracks as measured via the timing module at the calorimeter, but not necessarily with a larger dE/dx.

Intermittent hits.—Otherwise normal tracks that leave fewer hits than expected.

Anomalous curvature.—Tracks that appear to bend anomalously in the tracker.

Stub tracks.—Tracks that seem to disappear inside the tracking volume. We note that it is possible to misidentify some of the signatures above. For instance, as we discuss below, tracks with kinks may be misinterpreted as tracks with anomalous curvature.

Several of these possibilities have been explored before in the context of models of new physics. In various supersymmetry breaking mediation scenarios [6], or in models with R-parity violation (RPV), one can have kinks, anomalously high dE/dx, anomalous timing, stub tracks or displaced vertices. In other models of new physics, it is possible to find tracks with anomalous curvature. While many examples of new physics models with NOTs can be discovered via other means, it could prove to be significantly harder to identify the model without studying some of the above signatures. For instance, even if supersymmetry is discovered, identifying the breaking mechanism may require the study of kinks.

Other interesting possibilities for NOTs remain altogether unexplored at the Tevatron and LHC. In particular, intermittent hits and anomalously low dE/dx have not been investigated. One reason is that such signatures are caused by particles leaving less energy than a minimally ionizing particle (MIP) in the tracking system, thereby, deteriorating their reconstruction efficiency. Similarly, models with kinked tracks may not be reconstructed, albeit having regular dE/dx signature, or may present significant backgrounds from detector material effects.

In this Letter, we will give examples of some theories of NOTs that can explain the original CDF anomaly. These models may serve as benchmarks for classes of models that will not be found through standard tracking algorithms. Our hope is that the models presented here will serve, in addition to explaining the CDF data, as motivating examples to study irregular tracking at the LHC.

The CDF anomaly.—It is useful to recall why the original CDF results are difficult to explain with new physics. In Ref. [1], CDF looked at the p_T distribution of all charged tracks in minimum bias events. The dominant contribution to this distribution at high p_T is the single jet inclusive channel. The latter was found to be saturated above 100 GeV by the single charged particle distribution [3], thereby, signaling the breakdown of QCD factorization. On the other hand, the high-p_T tracks may come from new massive particles of mass, M. Since on average, $p_T \lesssim M$, to account for the high-p_T spectrum, one requires particles with a mass on the order of 100 GeV. In turn, the production rate for a particle of that mass is typically too low to explain the data, even if charged under QCD. This conflict between the p_T scale and the cross section represents the inherent difficulty in explaining this data with new physics.

Even if a scenario predicting high p_T tracks with a large enough rate were possible, additional constraints must be satisfied. In particular, the new physics: (i). Must not substantially affect the inclusive jet cross section which is well measured [7]. (i). Can not be a new resonance that decays only into a pair of charged tracks or jets [8]. (i). Must not have collider-stable particles [9]. With these basic restrictions, the difficulty to describe the measurement with NP is understood [3].

The tension described above can be ameliorated if the p_T of new particles is mismeasured. The presence of NOTs found in a variety of models, may thus, provide an explanation to the anomaly. A first example which would account for a systematic mismeasurement of p_T is a fractionally charged particle. Indeed, the analysis [1] assumes that the tracks have charge one and therefore, a particle of charge q would have its p_T measured as p_T/q. A sufficiently light new particle of this kind, interacting with QCD strength, could have a large cross section and *still* produce high p_T tracks which would account for the CDF data.

Another example of a NOT that may cause a systematic mismeasurement of p_T is a track with a kink. An attractive possibility is a light mass sparticle such as a light sbottom that decays via an RPV operator. Such a particle can be produced with a large cross section without being detected due to the kink or the displaced vertex. In a standard reconstruction algorithm, these tracks *could* in principle, be reconstructed as a single track with a high or low p_T and large χ^2. Only those tracks that are reconstructed with a high p_T would rise above the background, thereby, addressing the measurement. Much like the fractionally charged particles, a model of the above kind could escape detection unless specifically searched for.

Whether or not the original CDF data turn out to be attributed to new physics, it is important that the LHC looks for NOTs so that this window into new physics is not missed. In fact, since the examples above cause systematic mismeasurements in the tracker, they may not even be triggered on at the LHC. If the CDF data are indeed a measurement of NOTs, the looser track quality selection criteria together with the minimum bias triggering path, may be the only reason that these particles were observed.

Light colored particles.—As discussed above, a light colored particle would have a large enough cross section to reproduce the CDF anomaly, if the p_T of the resulting tracks were mismeasured. As an example, we now describe a viable and concrete model which exhibits fractionally charged particles. The possibility of light sbottoms with RPV previously discussed, will be presented elsewhere.

A Model.—While fundamental particles with fractional electric charges are very constrained, composite fractionally charged particles can more easily escape detection. For instance, let us introduce vector-like fermionic fields, $X + \bar{X}$, charged under the SM as $(\mathbf{3}, \mathbf{1})_{\mathbf{0}} + (\bar{\mathbf{3}}, \mathbf{1})_{\mathbf{0}}$ and with a mass, $m_X \simeq \mathcal{O}(10\text{ GeV})$. Once produced, X,$\bar{X}$ hadronize to form mesons, M_X, and baryons, B_X, both carrying fractional charges. Since the probability of hadronizing into baryons is $\mathcal{O}(10\%)$ compared to that of mesons, below we consider only the meson case, with charges $\pm 1/3$ and $\pm 2/3$. If X, $\bar{X}$ were stable, they would be excluded in charged massive long-lived particle (CHAMP) searches [9] by many orders of magnitude. Consequently, X must decay sufficiently fast and we are, therefore, led to introduce additional scalar fields, $Y + \bar{Y}$, with quantum numbers $(\mathbf{1},\mathbf{1})_{-1/9} + (\mathbf{1},\mathbf{1})_{1/9}$, mass $m_Y < m_X$ and nonrenormalizable couplings,

$$\frac{1}{\Lambda^2}\bar{d}_R X Y^3. \quad (1)$$

Here, $\bar{d}_R$ is the SM right handed down quark. Different charge assignments for Y can be accommodated, implying a corresponding dimension in the operator above.

The virtue of the above setup is that the colored X particles are produced copiously at hadron colliders but have suppressed production rate at e^+e^- colliders. On the other hand, the production rate of the fractionally charged Y particles are suppressed in both colliders due to their small EM charge. Furthermore, such particles are invisible at the Tevatron since they rarely leave ionization signals in the detectors.

Constraints.—New light strongly interacting particles with a fractional charge are potentially bounded by many different experiments. Here, we identify the most stringent bounds on these new states. We find that the model above, while only marginally in some cases, evades all experimental bounds. This is astonishing, given the lightness and strong coupling of these new states to SM particles. This example demonstrates the need to carefully search for NOTs as they can easily go unnoticed.

CHAMPs.—Heavy quasistable states have been searched for in studies such as Ref. [9], where events with isolated muon candidates can be compared to the SM prediction. This study excludes the possibility of a stable X. As a consequence, the lifetime for the X decays induced by Eq. (1) is strongly constrained. For the above X mass, we find the proper lifetime to be $c\tau_X \lesssim 25$ cm, corresponding to the cutoff scale, $\Lambda \simeq 3$ TeV in Eq. (1). Interestingly, it follows that X produced in colliders with mass $O(10\text{ GeV})$ and thus, $\langle\gamma\rangle \sim 1.4$, would typically decay inside the tracker.

Monojets.—Since the Y's do not significantly ionize, they will be registered as missing energy in events. Consequently, one can produce a monojet by having an X particle decay and its byproducts, subsequently, depositing much more visible energy than the other or by recoiling the $X\bar{X}$ pair against a gluon. The effects are comparable but slightly larger than the 95% C.L. for Tevatron monojet limits [10]. Since some cuts depend on the analysis response to the presence of the in-flight decays, one cannot asses whether the model is ruled out by these searches without a proper simulation.

LEP and e^+e^- colliders.—Since X couples to the SM through strong interactions, its production rate at a large electron positron (LEP) collider is suppressed. The only relevant production comes through a radiated gluon splitting into X-particles and as such, it is not constrained [11]. Similarly virtual corrections to QCD observables are not constraining enough [12]. On the other hand, Y-particles couple to the Z boson and may, therefore, be constrained by the Z-invisible width measurement at LEP-I. Y's small charge implies a contribution to the invisible Z-width of 0.88 MeV which easily evades the bounds at 95% C.L. [13]. Finally, constraints from lower energy e^+e^- colliders based on dE/dx do not constrain the Y particles either [14].

Cosmology.—There are no cosmological constraints on X particles since they are unstable and decay almost promptly. However, for any stable fractionally charged relic, such as the Y particle, there are severe constraints on its present abundance coming from a number of searches. The strongest comes from liquid drop experiments with mineral and silicon oil (for a review see [15]), requiring concentrations smaller than $O(10^{-17})$. These limits do not directly translate into a relic density bound, due to large dilution uncertainties from Y's chemistry and star evolution [16]. A relic abundance directly compatible with terrestrial limits is hard to achieve in a standard thermal history. A reheating temperature as low as allowed by nucleosynthesis and having Y's to further decay into particles not directly coupled to the plasma lower the abundance to $10^{-11} - 10^{-12}$ [17], still not sufficient to respect the bound. To accommodate this constraint a low $T_{\max}$, the maximum temperature reached during the reheating era, far below m_Y, is also needed, gaining a further Boltzmann suppression at the price of an extremely unnatural shape of the inflaton potential. A second way is to allow Y to further decay to a lighter particle Z with an even smaller electric charge, further relaxing the bounds from liquid drop searches.

Cosmic Rays.—X and Y particles are regularly produced through cosmic ray (CR) interactions in the atmosphere. A flux of Y particles can then be searched for in underground experiments. The most stringent constraint, derived by the Monopole, Astrophysics and Cosmic Ray Observatory experiment, is only sensitive to a $1/6$ charge and therefore, irrelevant for the above model [18]. Fractionally charged particles produced by CRs accumulated on Earth. However, the produced density of Y particles is comfortably within current bounds of liquid drop searches.

Predictions.—The difficulty with making specific predictions for NOTs, is that it requires a detailed understanding of both the detector components and the algorithms used to reconstruct physics objects. For instance, it would be nearly impossible for us to quantify how often a moderately long-lived sbottom, that decays in the tracker, would be reconstructed as a single high p_T track. Nonetheless, for the case of a fractionally charged particle we can make a sensible set of estimates.

To make a prediction for CDF with the above model, we require that a measured track leaves at least 15 hits in the central outer tracker (COT) layers, and survives more than halfway through the COT before decaying. To estimate the number of hits in the COT, we use standard parametrizations for the tail of the energy loss of the fractionally charged mesons, and define a hit to occur when at least 15% of a MIPs energy loss is deposited within a layer. Using this minimal track definition, a prediction for the

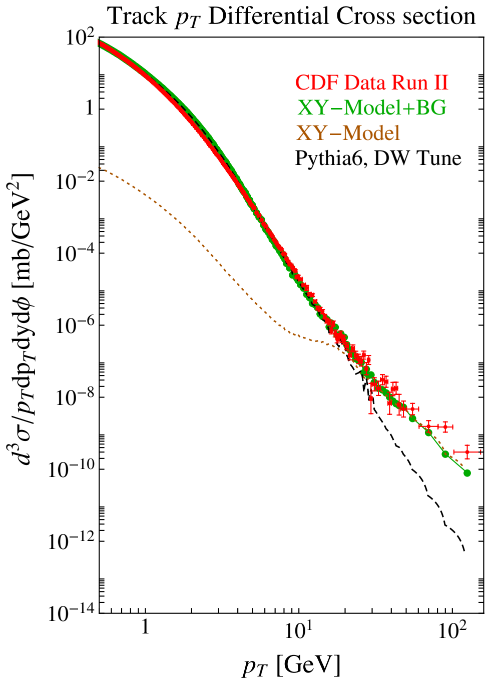

FIG. 1 (color online). Charged track p_T distribution. The QCD prediction is long dashed, while the prediction for X-Y model described in the text, with a best-fit value of $m_X = 7$ GeV and $m_Y = 1$ GeV is short dashed. The continuous curve is the total, to be compared with the CDF data with error bars.

p_T distribution of the X-Y model presented above, is compared to the data in Fig. 1.

Given that m_X sets the rate, by varying it we find a reasonable agreement with the original data published by CDF. Based on the nature of new physics, this model predicts that at high p_T, tracks have fewer hits with almost no hits in the silicon tracker, and very likely a bad χ^2 fit for the track. These tracks are precisely the types of tracks thrown out by CDF in their reanalysis [5]. It would, therefore, be very useful to analyze these tracks in more detail. We would also like to stress that a more accurate study of this signal is required, to take into account detector effects and the tracking algorithms. Nevertheless, it clearly shows that NOTs are an intriguing and viable possibility even in light of the errata [5].

The cross section at ATLAS and CMS will be even higher than at the Tevatron, $\mathcal{O}(10\ \mu b)$, so an investigation of how these NOTs could show up at the LHC would be useful. To date, in order to manage backgrounds, ATLAS and CMS searches have required stringent track quality cuts. Consequently, studies discussed in Ref. [4] would have missed NOTs of the type studied here. It seems advantageous, therefore, to expand the current searches by trying to loosen the track quality cuts. In particular, the nature of the silicon trackers at ATLAS and CMS allow for a lower hit thresholds and may be well suited for discovering NOTs with intermittent hits. While we have focused on the model parameters that could explain the original CDF data, there is a wide range of NOT phenomenology. In particular, the production rates may be significantly lower, thereby, easing the tension with existing constraints. Developing techniques to search for NOTs and expanding the benchmarks beyond those given in this Letter, provide important directions for future theoretical and experimental studies.

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