Phenomenological interpretation of the multi-muon events reported by the CDF collaboration

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Abstract

We present a phenomenological conjecture of new physics that is suggested by the topology and kinematic properties of the multi-muon events recently reported by the CDF collaboration. We show that the salient features of the data can be accounted for by postulating the pair production of three new states, respectively. The heavier states cascade-decay into the lighter ones, whereas the lightest state decays into a τ pair with a lifetime of the order of 20 ps.

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The Higgs mechanism provides a scheme for the electroweak symmetry breaking (EWSB). Electroweak precision tests (EWPT) indicate that the standard model (SM) Higgs boson is light, \( m_H < 186 \, \text{GeV}/c^2 \), with a central value considerably below the lower bound of 114 GeV. While it is possible that one is misled in interpreting the EWPT data in terms of a light Higgs mass, the EWSB sector in the SM Lagrangian appears to be the most elusive and the one most likely to provide experimental surprises.

In Refs. [7, 8], the CDF collaboration presents a set of studies of multi-muon events. Reference [7] uses multi-muon events to measure the correlated \( b \bar{b} \) production cross section. That study is extended in Ref. [8] to additional properties of multi-muon events. Based on the properties of these events, this paper explores a possible conjecture of new physics that might relate the results of Ref. [8] to the EWSB mechanism.

The data set used in Refs. [7, 8] has been acquired with a dedicated dimuon trigger, and consists of events containing two central (|η| < 0.7) muons, each with transverse momentum \( p_T \geq 3 \, \text{GeV}/c \), and with invariant mass larger than 5 GeV/c². References [7, 8] show that, when both trigger (initial) muons arise from particles that have decayed within the beam pipe of radius 1.5 cm, their number and kinematic properties are correctly predicted by a SM simulation. According to the simulation, approximately 96% of the known sources of dimuons, such as Drell-Yan, \( \Upsilon \), \( Z^0 \), and heavy flavor production, satisfy this condition. The sum of these contributions (1131090 events) is for simplicity referred to as QCD production. Reference [8] also reports the observation of 295481 events, referred to as ghost events, in which at least one muon originates beyond the beam pipe. A large fraction of these events is attributed to muons arising from \( \pi, K, K^0_S \), and hyperon decays as well as to secondary interactions in the detector volume. However, a small but significant fraction of these events has characteristics that cannot be explained by known processes in conjunction with the current understanding of the CDF II detector, trigger, and event reconstruction.

Reference [8] has investigated the rate and kinematic properties of tracks and muons contained in a 36° cone around the direction of each trigger muon in ghost events. The nature of these events is characterized by four main features. The impact parameter [9] distribution of initial muon pairs is markedly different from that of QCD events. In 36° (cos \( \theta \geq 0.8 \)) cones around the initial muon direction, the rate of additional muons and charged tracks is significantly higher than that of QCD events. The invariant mass of the initial and additional muons distributes differently from that expected from sequential semileptonic decays of hadrons with heavy flavor.

The distributions of the impact parameter of additional muons, and of the distance between the \( pp \) collision point and secondary vertices reconstructed using pairs of tracks contained in a cone, do not correspond to the lifetime of any known particle.

Although it is not excluded that the features of these events can be later explained in terms of known sources, this paper presents a phenomenological conjecture of new physics that shows that it is possible to account for the various features of these events, and also suggests additional observations that are further tested with the published data. In this conjecture, a fraction of the ghost events is attributed to pair production of three new states \( h_1, h_2, \) and \( h_3 \) with masses in the range of 15, 7.3, and 3.6 \( \text{GeV}/c^2 \), respectively. The heavier states cascade-decay into the lighter ones, whereas the lightest state decays into a τ pair with a lifetime of the order of 20 ps.

Figure 1, reproduced from Ref. [8], shows the sign-coded multiplicity distribution of additional muons contained in a 36° cone around the direction of an initial muon in ghost events. In the plot, an additional muon increases the multiplicity by 1 when of opposite sign and by
10 when of the same charge of the initial muon. Leaving aside the case in which no additional muons are found, an increase of one unit in the muon multiplicity corresponds in average to a population decrease of approximately a factor of seven. This factor happens to coincide with the inverse of the $\tau \rightarrow \mu$ branching fraction (0.174) multiplied by the 83% efficiency of the muon detector, and suggests that these muons might arise from $\tau$ decays with a kinematic acceptance close to unity. We use Monte Carlo pseudoexperiments to model the shape of the muon multiplicity distribution in Fig. I. The pseudoexperiments generate $4 \tau^- + 4 \tau^+$ leptons and decay them into muons with a 17.4% probability. In the pseudoexperiments, initial and additional muons are identified with the measured detector efficiencies of 50% and 83%, respectively. The pseudoexperiment result is shown in Fig. I in which the simulated distribution is normalized to the integral of the data for multiplicity bins higher than 10. The comparison of the muon multiplicity distribution in ghost events with the toy simulation suggests that approximately 12,000 events contain $8 \tau$ leptons inside a $\cos \theta \geq 0.8$ cone. One interpretation is that they are $8-\tau$ decays of objects $h_1$ that are relatively light with respect to the transverse momentum with which they are produced.

Next, we test the data for an obvious consequence of the $h_1 \rightarrow 8\tau$ conjecture. If the hypothesis is correct, one expects that, when the $h_1$ transverse momentum is very large, the $8\tau$ decays produce an average of 9.5 tracks with $p_T \geq 2 \text{ GeV}/c$ in a $36.8^\circ$ cone. We compare the data presented in Ref. [8] to simulated events which contain $h_1$ states produced with large transverse momenta. We use the PYTHIA Monte Carlo program [10] to generate fictitious $p\bar{p} \rightarrow H \rightarrow h_1 h_1$ events followed by $h_1 \rightarrow 8\tau$ decays [11]. We use this process for convenience, without implying that the $h_1$ states might be Higgs bosons or might arise from Higgs decays. Figure 2 compares the average track multiplicity in the data and in some of the simulations. In order to reject the QCD contribution, Reference [8] considers events that contain at least three muons in a $36.8^\circ$ cone. The figure shows the average number of tracks with $p_T \geq 2 \text{ GeV}/c$ contained in a $36.8^\circ$ cone around a primary muon as a function of the total transverse momentum of the tracks. The asymptotic value of the average track multiplicity in the data adds support to the conjecture of a $h_1 \rightarrow 8\tau$ decay initially suggested by the muon multiplicity distribution.

In the assumption that leptons and tracks contained in a $36.8^\circ$ cone around a primary muon arise from $h_1 \rightarrow 8\tau$ decays, the mass of the $h_1$ particle is determined by comparing data and simulations in the following invariants proportional to $m_{h_1}$: (a) the invariant mass of all muons in a cone when both cones contain at least two muons; (b) the invariant mass of all muons in a cone containing at least three muons; (c) the muon invariant mass for cones containing exactly three muons; (d) the invariant mass of muons and tracks for cones containing three or more muons and 5 to 6 tracks. Reference [8] shows that the request of a large number of muons suppresses the QCD contribution. In cases when fewer muons are requested, the QCD background is larger and has been subtracted in Ref. [8]. These invariant mass distributions are shown in Fig. 3. The data are compared to simulations of the process $H \rightarrow h_1 h_1$ with $m_H = 300 \text{ GeV}/c^2$, and $m_{h_1} = 15$ and $20 \text{ GeV}/c^2$, respectively. A mass of $15 \text{ GeV}/c^2$, close to the invariant mass of $8 \tau$ leptons, provides a fair modeling of the data, whereas a mass of $20 \text{ GeV}/c^2$ appears to be too high.

We investigate if the data are consistent with the hypothesis of $h_1$ pair production by studying the rate and properties of events in which two $36.8^\circ$ cones contain a muon multiplicity larger than that of QCD events. In the sample of ghost events isolated by the study in Ref. [8], there are $27990 \pm 761$ cones containing two or more muons, $4133 \pm 263$ cones containing three or more muons, and $3016 \pm 60$ events in which both cones contain two or more muons. Figure 3 plots two-dimensional distributions of the invariant mass of all muons and of
The transverse momentum distribution of the data is different from that of the simulations, but the average number of tracks has the same asymptotic value, as indicated by the straight line. The QCD prediction (●) is based on the few events predicted by the heavy flavor simulation, normalized to the number of initial muon pairs in the data and implemented with the probability that tracks mimic a muon signal.

The dependence of the $h_1$ pair production on the Mandelstam variable $\bar{s}$ is studied by comparing data to different simulations in the following distributions shown in Fig. 6: (a) the invariant mass, $M$, of all muons and (b) the total number of tracks contained in a 36.8° cone when both cones contain at least two muons. The data distributions fall less rapidly than in the $f \bar{f} \to h_1 h_1$ simulation, with a possible indication that the $h_1$ pair production is not mediated by a photon or a gluon. The $f \bar{f} \to h_1 h_1$ distribution shown in Fig. 6 corresponds to a production cross section of 3.4 nb. Events in which the $h_1$ pairs have larger invariant mass are modeled with a simulation of the process $p \bar{p} \to H \to h_1 h_1$. However, the data distributions fall less rapidly than in the $f \bar{f} \to h_1 h_1$ simulation, with a possible indication that the $h_1$ pair production is not mediated by a photon or a gluon. The $f \bar{f} \to h_1 h_1$ distribution shown in Fig. 6 corresponds to a production cross section of 3.4 nb. Events in which the $h_1$ pairs have larger invariant mass are modeled with a simulation of the process $p \bar{p} \to H \to h_1 h_1$. However, the data distributions fall less rapidly than in the $f \bar{f} \to h_1 h_1$ simulation, with a possible indication that the $h_1$ pair production is not mediated by a photon or a gluon. The $f \bar{f} \to h_1 h_1$ distribution shown in Fig. 6 corresponds to a production cross section of 3.4 nb. Events in which the $h_1$ pairs have larger invariant mass are modeled with a simulation of the process $p \bar{p} \to H \to h_1 h_1$.
FIG. 5: Distributions, reproduced from Ref. [8], of the invariant mass, $M$, of all muons contained in (a) the 27,990 36.8° cones with two or more muons and (b) the 3016 events in which both cones contain two or more muons. QCD and fake muon processes have been removed. Simulations of the pro-

FIG. 6: Invariant mass, $M$, distribution of (left) all muons and (right) all tracks with $p_T \geq 2$ GeV/$c$ for events in which both cones contain at least two muons. QCD and fake muon contributions have been removed. Simulations of the pro-

with $m_H = 150$ and 300 GeV/$c^2$. The results of these simulations, also shown in Fig. 6, correspond to a production cross section of 50 and 35 pb for $m_H = 150$ and 300 GeV/$c^2$, respectively. Using the acceptance measures with these different simulations we again estimate that approximately 5% of the 295,481 ghost events with two initial muons can be explained by pair production of $h_1$ particles.

In the assumption that ghost muons are produced in the decays of these states, the fits to the high impact parameter tail of additional muons in ghost events [8], where the distribution is well modeled by an exponential function, can be used to estimate their lifetime to be $21.4 \pm 0.5$ ps. If the $h_1$ states decay directly into 8 $\tau$ leptons with a lifetime of 20 ps, the impact parameters of muons due to ghost events would be highly correlated since the $\tau$ lifetime is negligible compared to that of the $h_1$ states. In contrast, the study in Ref. [8] finds a very weak correlation between the impact parameters of muons contained in the same cone. We compare data from Ref. [8] to simulations in order to test the more elegant conjecture of a three-stage decay $h_1 \rightarrow 2h_2 \rightarrow 4h_3$,

where $h_3$ is the particle decaying into $\tau$ pairs. We use simulated samples of the processes $f \bar{f} \rightarrow h_1h_1$ and $p\bar{p} \rightarrow H \rightarrow h_1h_1$ with $m_H = 300$ GeV/$c^2$, in which the $h_1$ states decay into 8 $\tau$ leptons through a three-stage decay. We attribute in turn a 20 ps lifetime to only one of the $h_1$, $h_2$, and $h_3$ states. We measure the correlation between the impact parameters of muons contained in a 36.8° cone for the different cases. The correlation factor is $\rho_{dxdy} = 0.39$, 0.15, and 0.05 when the lifetime is attributed to the $h_1$, $h_2$, and $h_3$ states, respectively, whereas it is measured to be 0.03 in ghost events [8]. This indirect method provides evidence for the possible existence of two additional states, $h_2$ and $h_3$. The latter state is long-lived and decays into $\tau$ pairs. Following the assignment of a 15 GeV/$c^2$ mass to the $h_1$ state, one expects the $h_2$ mass to be in the range 7.1 – 7.5 GeV/$c^2$ and the $h_3$ mass $\approx 3.6$ GeV/$c^2$. The observed number and properties of the ghost events can accommodate the additional pair production of at least one of the $h_2$ and $h_3$ states. When the 20 ps lifetime is attributed to the $h_3$ state, only a few percent of the simulated events selected as in Ref. [8] survive the additional request that both initial muons originate inside the beam pipe. This models closely what happens in the data, as reported in Ref. [8].

Because the production mechanism of these hypothetical states is not understood, we cannot use the simulation to improve the measurement of the $h_3$ lifetime reported in Ref. [8]. However, we highlight one difficulty that arises if ghost events are due to mixed pair production of $h_1$, $h_2$, and $h_3$ states. In Ref. [8], the lifetime of the muon parent particle has been estimated by fitting with an exponential function the muon impact parameter distributions in the range 0.5 – 2.0 cm. We have produced simulated samples of $h_1$ pair production using the processes $f \bar{f} \rightarrow h_nh_n$ and $p\bar{p} \rightarrow H \rightarrow h_nh_n$ with $m_{h_n} = 300$ GeV/$c^2$ and $n = 1, 2, 3$. In these simulations, states heavier than the $h_3$ particles cascade-decay into them and ultimately produce events with 4, 8, and 16 $\tau$ leptons in the final state. We generated several samples with $h_3$ lifetimes ranging from 10 to 40 ps. For simulated events due to $h_3$ or $h_2$ pair production, analogous fits to the impact parameter distributions return the lifetime value used in the event generation. However, in the simulation of $h_1$ pair production, some of the $h_1$ cascade-decay products are not relativistic and the decay kinematics has greater complexity. As a consequence, the fits to the impact parameter distributions underestimate the lifetime by approximately 30%.

The identification of $\tau$ decays into three hadrons would provide additional support to the conjecture of new physics used to account for a fraction of the ghost events. This decay channel could also be used for a complementary measurement of the $h_3$ lifetime by using the $L_{xy}$ distribution of the three-track secondary vertices, where $L_{xy}$ is the distance between the secondary vertex and the $p\bar{p}$ collision point projected onto the transverse momentum
of the three-track system. Reference [8] has searched the data for such secondary vertices, and has verified the detector response by using identified $K^0_L \rightarrow \pi^+\pi^-$ decays. That study [8] reconstructs three-prong secondary vertices by using tracks with $p_T \geq 1.0$ GeV/c and $|\eta| \leq 1.1$ in a $36.8^\circ$ cone around the direction of each initial muon. Track systems with total charge of $\pm 1$ are constrained to arise from a common space point. In this study, we use similar criteria to search for hadronic $\tau$ decays in simulated events, and compare our result to the published data [8]. In a sample generated with the process $p\bar{p} \rightarrow H \rightarrow h_1 h_1$ with $m_H = 150$ GeV/c$^2$, there are in average two $\tau$ decays into three hadrons per event. Approximately 8% of these decays, or 0.16 $\tau$ hadronic decays per event, survive these selection criteria. Figure 7 shows the invariant mass and $L_{xy}$ distributions of the three-track systems that are also identified at generator level as $\tau$ decays into three hadrons.

The simulation also contains 5.5 three-track combinations per event that pass the same selection criteria, and the signal of the 3-hadron $\tau$ decays is swamped by the combinatorial background. However, this signal is comparable to the combinatorial background in a simulated sample of $h_3$ pair production in which a $36.8^\circ$ cone contains sometimes one muon and three tracks from the two $\tau$ decays. In this case, the vertices of the three-track systems identify correctly the $h_3$ decay vertex and generate an excess of events at positive $L_{xy}$ distances. Reference [8] presents a subsample of ghost events in which a $36.8^\circ$ cone around the direction of an initial muon contains only three tracks with $p_T \geq 1$ GeV/c. Three-track systems with total charge of $\pm 1$ are constrained to arise from a common space point. Figure 8 shows the $L_{xy}$ distribution for ghost and QCD events [8]. Ghost events show an excess at positive $L_{xy}$ that is, however, not as large as that of QCD events in which most of the muon plus the three-track combinations arise from single $b$-quark decays. Figure 8 compares the invariant mass of the three-track systems for positive and negative $L_{xy}$ values [8]. In the case of ghost events, the invariant mass of three-track systems with positive $L_{xy}$ exhibits an excess of events consistent with the shape of $\tau$ decays into three hadrons shown in Fig. 7.

In conclusion, we suggest one possible phenomenological interpretation of the multi-muon events recently reported by the CDF collaboration. As shown by the comparisons between the published data and simulations based on our conjecture, the most interesting features of these events can be accounted for by postulating the pair production of three new states $h_1, h_2,$ and $h_3$ with masses in the range of 15, 7.3, and 3.6 GeV/c$^2$, respectively. The heavier states cascade-decay into the lighter ones, whereas the lightest state decays into a $\tau$ pair with a lifetime of the order of 20 ps. The mechanism that produces $h_1$ pairs is completely obscure. It does not appear to be resonant nor mediated by a photon or gluon exchange. The observed pair production cross section ($\sim 100$ ab) is a few orders of magnitude larger than what is predicted if the $h_n$ states belonged to the Higgs sector [3, 6].

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[1] The ALEPH, DELPHI, L3, and OPAL Collaborations and the LEP Electroweak Working Group, A Combination of preliminary electroweak measurements and constraints on the standard model, arXiv:hep-ex/0612034.

[2] The ALEPH, DELPHI, L3, and OPAL Collaborations, Phys. Lett. B 565, 61 (2003).

[3] R. Dermisek and J. F. Gunion, Phys. Rev. D 76, 095006 (2003).

[4] E. Fullana et al., Phys. Lett. B 563, 67 (2007).

[5] S. Chang et al., arXiv:0801.455v2.

[6] M. J. Stressler et al., Phys. Lett. B 651, 374 (2007).

[7] T. Aaltonen et al., Phys. Rev. D 77, 072004 (2008).

[8] T. Aaltonen et al., arXiv:0810.5357.

[9] The impact parameter is the distance of closest approach of a track to the primary event vertex in the plane transverse to the beam direction.

[10] T. Sjöstrand and M. Bengtsson, Comp. Phys. Commun. 43, 367 (1987); H. Bengtsson and T. Sjöstrand, Comp. Phys. Commun. 46, 43 (1987); T. Sjöstrand et al., Comp. Phys. Commun. 135, 238 (2001).

[11] We have generated several simulated samples with a Higgs mass, $m_H$, ranging from 115 to 300 GeV/c^2 using the option isub=151 of the version 6.4 of the PYTHIA Monte Carlo program. We have also generated pair production of Higgs bosons ($f\bar{f} \rightarrow h_nh_n$) with the option isub=300. The $h_n$ widths are set to be negligible with respect to the detector resolution. We use the interface PYSLHA.F and decay Higgs bosons according to phase space. The $\tau$ decays are simulated with the TAUOLA program [12]

[12] S. Jadach et al., Comp. Phys. Commun. 76, 361 (1993). We use TAUOLA Library version 2.6.

[13] In a different simulation, that uses the process $p\bar{p} \rightarrow H \rightarrow h_1h_1$ with $m_H = 300$ GeV/c^2, this ratio is a factor of two higher than in the data because heavy resonant states are decayed by the PYTHIA generator program into $h_1$ pairs with well balanced transverse momenta.