Flesh and Blood, or Merely Ghosts?
Some Comments on the Multi-Muon Study at CDF

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Abstract

A recent CDF paper suggests (but does not claim) an anomalous event sample containing muons produced with large impact parameter, often with high multiplicity and at small angles from one another. This curious hint of a signal is potentially consistent with the hidden valley scenario, as well as with some other classes of models. Despite its tenuous nature, this hint highlights the experimental difficulties raised by such signals, and merits some consideration. Some of the simplest interpretations of the data, such as a light neutral particle decaying to muon and/or tau pairs, are largely disfavored; three-body decays to $\tau^+\tau^-\nu$ appear slightly better. An alternative speculative possibility — a “micro-cascade decay” — might be consistent with the data. It is suggested that the experimentalists involved provide additional plots showing invariant mass distributions of same- and opposite-sign dimuon pairs, invariant masses of various classes of displaced vertices, and spatial correlations among vertices within a cone.
I. INTRODUCTION

A recent CDF paper [1] attempts to study a class of unidentified processes, called “ghost events”, which it fails to explain through known detector or physical effects. Among these events [1] finds indications or suggestions (not called “evidence”) of a new long-lived particle, with a lifetime of order 20 picoseconds (see Figure 25). Other plots in [1], such as Figures 30 and 36, are intended to suggest that multiple such particles are produced at the same time within a narrow cone.

No one would be happier than the author of the present note if this “suggestion of evidence” were to hold up under scrutiny. The hidden valley scenario [2, 3, 4], in which a new hidden sector with a mass gap is added to the standard model and coupled to it at or below the TeV scale, naturally predicts high-multiplicity production of new neutral states, which are typically very light, and are typically long-lived, possibly decaying with macroscopically displaced vertices. (The scenario has some overlap with the more recent “unparticle” scenario [8]; in fact unparticle models with mass gaps are examples of hidden valleys [6]. A recent model of dark matter [9] is also a hidden valley and has an interesting variant of the standard hidden valley signatures [10].) Indeed, the point of developing the scenario was to highlight the fact that such models are theoretically reasonable, are allowed by all known data, and pose significant experimental difficulties.

Unfortunately, although the paper [1] is long, it is far too short given its potential importance, and many critical plots that could support the case are absent. Nevertheless, it is interesting and hopefully useful to consider the implications of its “suggestion of evidence”. Such is the limited goal of this note. The aim is to explore a few possible explanations, and to identify analysis strategies that could be used to clarify the situation, eliminating certain phenomenological options. No serious attempt is made to interpret the data. This exercise may well be helpful for forthcoming searches at the Tevatron and the LHC, even if the specific results of [1] (and a related attempt at an interpretation by the experimentalists involved [11]) are eventually discredited.

II. PRELIMINARY COMMENTS

We begin with two important observations relevant to the discussion below.
First, although the cross-section for “ghost events” in [1] seems at first glance very large, about 75 pb, the number of new physics events, if any, is significantly lower, by an unknown amount. The number of ghost events, given in Table II of [1], requires determination of the efficiency for “QCD” effects (that is, QCD heavy flavor processes), the expected sources of multi-muon events. This efficiency is inferred in an intricate way from Table I and Figure 2a of [1], and its value, $24.4 \pm 0.2$ percent, implies that of the $743006$ events passing the dimuon trigger and other preliminary requirements, $589111 \pm 4829$ are from “QCD” sources. (This is determined by taking those $143743$ events that pass a tight silicon vertex tracking requirement and dividing by 24.4 percent.) Subtracting, one finds $153895$ “ghost” events. But if the efficiency estimate were in error for a subclass of events, and the efficiency were only, say, 23.4 percent, then the number of “ghost” events would drop by $1/5$, to only about $128000$ events. Thus the number of “ghost” events is very sensitive to the correctness of the efficiency estimate.

Later in [1], about 69000 events are attributed to known detector effects — and again, by subtraction, one concludes that only 83000 events are unexplained. Any errors in estimating the detector effects could also have a drastic effect on the number of events requiring a new explanation. For these two reasons, we must view the number of unexplained ghost events as highly uncertain.

Second, most of the “ghost” events, and most of the known backgrounds quoted in [1], involve the minimal number of muons (the two trigger muons), and perhaps one additional muon. Events with at least two muons in each of two independent cones provide a cleaner subsample. If “ghost” events with many muons are due to detector backgrounds, severe failures in tracking or in the muon system might be imagined as a cause. But an important correlation is noted in [1]: for those $27990$ events in which one cone of $36.8^\circ$ ($\cos \theta < 0.8$) around one of the trigger muons contains an additional muon, over 10 percent have an additional muon in the cone around the second trigger muon. In these $3000$ “2-dimuon-cone” events, the second cone is generally in a rather different region of the detector. To explain this requires an event-wide fluctuation that can provide correlated fakes in both cones, or a substantial failure of the modeling of heavy flavor physics, which is claimed in [1] to be well under control. Backgrounds such as decays-in-flight, punch-through and secondary interactions are not likely to contribute to both cones. In short, this subsample is unexpectedly large, and much cleaner than the full ghost sample. If there is new flesh-
and-blood physics hiding among the ghosts, this subsample seems like a good place to look for it. To explain these events may require a new process with a cross section closer to $5 \text{–} 10 \text{ pb}$, rather than $100 \text{ pb}$.

III. HIGH MULTIPLICITY OF NEW LIGHT NEUTRAL PARTICLES

Light neutral particles which can decay to standard model particles, possibly with long lifetimes, are very poorly constrained by existing data, as emphasized in [2, 3, 4, 5, 6]. Many classes of models within the hidden valley scenario can generate metastable particles of spin $\leq 2$, often produced with moderate to high multiplicity [2, 3, 6]. This includes a recent dark-matter-motivated context [10], where the possibility of spin-one particles with mass below 2 GeV was particularly highlighted. Other models can do the same [12]. However, the data pose a challenge for any attempt to explain the “ghost” events using a new light boson, notwithstanding the interpretation given by a small group of CDF experimentalists [11].

The data quickly excludes some options. A new light particle $X$ which produces muons via the decay $X \rightarrow \mu^+ \mu^-$, or the decay $X \rightarrow \mu^+ \mu^-$-plus-additional-particles, would generate a strong charge anti-correlation. Figure 22 of [1], which shows distributions of muon charges within narrow cones, is consistent with no muon charge correlations or anticorrelations, and strongly disfavors this interpretation. A rough estimate and simulated data both suggest that unless efficiency for muon detection is well below 20 percent or muon fake rates are very large — both inconsistent with naive expectations and with estimates given in [1] — new particles decaying directly to $\mu^+ \mu^-$ would give Figure 22 a very different appearance. (Also, a resonant decay $X \rightarrow \mu^+ \mu^-$ would appear in Figure 34 of [1]; see below.)

The simplest way to get uncorrelated muon charges is to have $X \rightarrow \tau^+ \tau^-$ followed by $\tau \rightarrow \mu \nu \bar{\nu}$. This then gives an efficiency for muon production and detection below 20 percent, and in a way consistent with the uncorrelated charge distribution given in Figure 22. This is the approach to the data suggested in [11]. But there are two disquieting — though not quite fatal — aspects of this interpretation, which we will now demonstrate. The first is that the distribution of the invariant masses of all muons in a cone, given in Figure 34, requires that the the ratio $Br(X \rightarrow \mu^+ \mu^-)/Br(X \rightarrow \tau^+ \tau^-)$ is well below $10^{-3}$, whereas theoretical expectations would suggest a ratio between 1 (for a typical spin-one particle)
and $m_{\mu}^2/m_{\tau}^2 = 0.0035$ (for a typical spin-zero particle, such as a scalar mixing with the Higgs boson.) The second is that the kinematics of the events shown in Figure 34 are squeezed into a corner with the minimal amount of available energy, where $m_X - 2m_{\tau}$ is very small, suppressing the phase space for $X \to \tau^+\tau^-$ and making it somewhat surprising that $Br(X \to \tau^+\tau^-)$ is large.

To check these statements, various simulations of a Higgs boson decaying to multiple $X$ bosons were conducted, and a plot analogous to Figure 34 was generated. Some models were similar to that of [11] though with a different mass spectrum. Efforts were made to match the trigger criteria and cuts to the extent possible in a theoretical simulation. A plot from one such simulation, with $m_X = 7.2$ GeV, and a branching fraction ratio of $m_{\mu}^2/m_{\tau}^2 = 0.0035$ for $X \to \mu^+\mu^-$ compared to $X \to \tau^+\tau^-$, is shown in Figure 1a.

The figure indicates that the resonance from $X \to \mu^+\mu^-$ should have easily been seen in Figure 34a and 34b, and thus the branching fraction for this mode must be much less than $10^{-3}$. This limit could most likely be improved: Figure 34 uses binning of 200 MeV, but the dimuon resolution at CDF should be better than this, perhaps by a factor of 2 or greater. This is suggested in Figure 1b above. One hopes that the experimentalists will update their result to put an upper bound on $Br(X \to \mu^+\mu^-)$ within the context of the hypothesis of a new light boson. Also, note that Figure 34 plots the invariant mass of all muons in a cone with $\geq 2$ muons. Figure 22 indicates the plot is dominated by dimuon cones, but only about half of these have opposite-sign dimuons. If instead the plot were limited to opposite-sign dimuons, the continuum background would drop and the limits might further improve.

In figure 1a one also sees a substantial tail, up to and beyond the $X$ mass, from the dominant $X \to \tau^+\tau^-$ decays. The absence of such a tail in Figure 34 of [11] implies the $X$ mass cannot be much more than 3 GeV. Of course, it must be heavier than $2m_{\tau} = 3.55$ GeV. Thus the kinematics from Figure 34 forces $m_X$ toward its lowest possible value. (While the low-mass end of Figure 1 also fails to match Figure 34 of [11], one should probably disregard this fact, since this region can more easily be affected by mismatches between the crude theoretical study and the details of the CDF detector.)

Indeed, to fit the data, the interpretation [11] actually requires $m_X \approx 3.6$ GeV. This reduces the phase space for $X \to \tau^+\tau^-$ by a factor of 30 or more compared to naive estimates, and thus would increase the branching ratio for $X \to \mu^+\mu^-$ (or anything else) by a corresponding factor. To get a sufficiently small branching fraction for $X \to \mu^+\mu^-$ then...
FIG. 1: Analogous to Figure 34a of [1], the invariant mass of all muons within cones that contain two or more muons for the toy model described in the text, with a 7.2 GeV particle $X$. (a) 200 MeV bins, as in Figure 34a of [1]; (b) 100 MeV bins, highlighting the $\mu^+\mu^-$ resonance at $m_X = 7.2$ GeV.

implies that the $X$ coupling to muons must be smaller than expected for a typical scalar by at least a factor of 10. Similarly, any decay to hadrons, such as $X \rightarrow K^+K^-$, would also be relatively enhanced due to the small $X \rightarrow \tau^+\tau^-$ phase space, so $X$ couplings to quarks must be very small.

Thus an $X \rightarrow \tau^+\tau^-$ interpretation of [1] forces on us a new particle that couples to $\tau^+\tau^-$ only. Since tau-number is violated by the mixing of tau and muon neutrinos, adding such a particle risks introducing unobserved flavor-changing-neutral-current tau decays.

Here are three additional comments on the specific interpretation suggested in [11].

- The long lifetime of the $X$ (called $h_3$ in [11]) could arise in a number of ways. But it cannot arise from the small splitting between $m_X$ and $2m_\tau$. In the limit $m_X \rightarrow 2m_\tau$, the tau-loop-induced decay $X \rightarrow \gamma\gamma$, which cannot be forbidden, will always come to dominate, eliminating the muon signal.

- To avoid the unseen high-side tail in Figure 34, [11] is forced to take not only the mass of $h_3$ to be close to $2m_\tau$, but also $m_{h_2} \approx 2m_{h_3}$ and $m_{h_1} \approx 2m_{h_2}$. In short, to fit Figure 34 requires a triple fine-tuning into the kinematic corner with the minimal visible energy. While possible, it hardly seems likely.
The fact that the model lies in this kinematic corner should make it relatively easy to verify or falsify with the existing data. In the cascade decay \( h_1 \rightarrow 2h_2 \rightarrow 4h_3 \) suggested in [11] to explain the multi-muon cones in [1], the small energy available in the cascade decay implies the relative velocity of the four \( h_3 \) particles in their shared center-of-mass frame will be small. However, their velocities in the lab frame must be large to generate a 3 GeV trigger muon. Therefore, the four \( h_3 \) particles will be tightly collimated, which predicts that all four displaced vertices from the \( h_3 \) decays will lie approximately on a line pointing back to the collision point.

If the data does not support four highly collinear decay vertices, or we simply find the fine-tuning of [11] akin to epicycles, what else might be responsible for the data? There are certainly other options, the simplest being a fermion \( X \) instead of a boson, so that it might decay to \( \tau^+\tau^-\nu \) and \( \mu^+\mu^-\nu \). (For example, this could happen in non-minimal supersymmetry with R-parity violation.) This eliminates the resonance feature of Figure 1 (turning it into an unmeasurable enhancement of the continuum) and pushes the continuum of Figure 1 down to lower values. In this case, theoretical studies suggest that \( m_X \) could perhaps be raised to as much as 4.5 or 5 GeV, so the kinematic fine-tuning required for the models of [11] to fit the data is certainly not quite as severe. On the other hand, a problem pointed out by the authors of [11] is the inability of their simplest models to obtain the large track-\( p_T \) seen in Figure 32 of [1]. If neutrinos carry off even more of the energy, it potentially makes this worse.

One should also consider the skeptic’s interpretation of Figures 22 and 34. The uncorrelated muon charges are consistent with random hadronic tracks being misidentified as muons, random tracking errors, etc. Also, Figure 34 is potentially consistent with a random distribution shaped mainly by triggering and cuts. A trigger muon (with \( p_T \geq 3 \text{ GeV} \)) combined at random with a non-trigger muon (with \( p_T \geq 2 \text{ GeV} \)) within a cone of \( \cos \theta < 0.8 \) will have an invariant mass of order or below 1.5 GeV, potentially consistent with the distribution in Figure 34. This observation might motivate raising the \( p_T \) cuts to see whether the low-invariant-mass region entirely disappears.

There would seem to be a natural check of the whole story (beyond the specific interpretation of [11].) If there were a physics signal from new light particles, then the dimuon-invariant-mass distribution in dimuon cones would show two components: (I) from opposite-sign dimuons from the same \( X \) decay, and (II) from opposite- or same-sign-dimuons from
different $X$ decays. By restricting the plots in Figure 34 to dimuon cones, and separating them into same- and opposite-sign dimuons, one could measure (I) and (II), determine whether in fact (I) is present, and estimate the $X$ mass directly from the data. (If in fact there were no signal one would expect no evidence for the component (I); opposite- and same-sign distributions would look the same.) Armed with this information, one could then perform a critical cross-check. Opposite-sign muon pairs with low masses (below $m_X$) would be much more likely to stem from a two-muon displaced vertex than either same-sign pairs of any mass or opposite-sign pairs with higher invariant mass. It is not clear why these checks were not performed in [1].

There are a number of other plots whose presence, or absence, in Appendix B of [1] is very surprising. In particular, though obviously presented so as to support the interpretation of [11], the plots of Appendix B do not actually appear to do so.

As far as can be discerned from the text of [1] and the captions of Figure 45 and 46, it appears that locations and invariant masses of three-track combinations are presented in order to support the idea that the events are rich in taus. But this seems odd: if the interpretation given in [11] is correct, any three-prong tau is emitted in an $h_3$ decay that has at least one more track. Therefore, any three-track vertex (if real) is actually a four-track vertex where one track has been lost or otherwise not included. At best, the combinatoric background for the search is therefore 3 to 1. At worst, since tracks in three-prong tau decays are softer than in one-prong decays, the probability that the three tracks observed actually come from a single tau is much less than 1/4. Finally, there is the issue of cuts sculpting the distribution. If one selects three tracks with $p_T > 1$ GeV from within a cone of $\cos \theta < 0.8$, the invariant mass of those tracks will typically be of order 1.1 GeV, close to the expectation for 3 tracks from a three-prong decay, and at the peak of the observed distribution. The evidence that this sculpting effect is unimportant seems insufficient. Clarifying comments from the authors of [11] would be welcome.

Conversely, the interpretation of [11] would imply that opposite-sign dimuon vertices should be quite common (appearing in 3 percent of vertices and 12 percent of cones), should have relatively low backgrounds, and should have a very distinctive invariant mass distribution. The location of such vertices is shown in Figure 44 of [1], but inexplicably the invariant mass distribution is not given. Clearly these plots could have potentially supported the case that a signal is present in [1], and perhaps even the interpretation of [11]. Similar plots for
same-sign dimuon vertices and for muon-plus-track vertices would also be instructive.

For the study in Appendix B, the \( p_T \) cuts are taken very low, presumably to obtain high statistics. But would it not have been better to focus on higher-\( p_T \) tracks in events with 2-dimuon-cones, obtaining a much cleaner sample with much lower detector backgrounds? The advantage of interpretability would seem likely to outweigh the cost in statistics.

More generally (as we will see below) there is every reason to consider vertices with \( k \) tracks, \( k \) any integer. To choose a particular \( k \) in advance is to risk biasing the study toward a particular interpretation, rather than allowing the data to speak for itself. It would be helpful to have a much more systematic, and less targeted, study of the vertices in these events.

A final issue with this analysis, not entirely robust but still worth mentioning, arises if the \( X \) particle can sometimes be produced at low multiplicity \( n_X \). (This issue would not arise in the interpretation \[11\].) In a low \( X \)-multiplicity cone, there is a certain probability that only one \( X \) will have significant \( p_T \); the others (if any) may be semirelativistic, with \( p_T \) or order \( m_X \). In this case the decay products of the slow \( X \) bosons may be so soft or at such large angles that they will not affect the isolation criteria of the daughters of the hard \( X \). A search for a single isolated well-displaced \( \mu^+\mu^- \) pair, with 380 pb\(^{-1} \) of data, was carried out by DZero in \[14\]. No candidate events were observed. This should strongly constrain the number of \( n_X = 1 \) cones, and probably even \( n_X = 2 \) cones, within the “ghost” sample.

In summary, the data seem to exclude high-multiplicity production of several types of light particles.

- Particles decaying often to \( \mu^+\mu^- \) are very strongly disfavored, by Figures 22 and 34.
- Particles decaying often to \( \mu^+\mu^-\nu \) are strongly disfavored, by Figure 22.
- Particles decaying to \( \tau^+\tau^- \) and to \( \mu^+\mu^- \) are strongly disfavored for \( Br(X \rightarrow \mu^+\mu^-) > 0.001 \), by Figure 34.
- Particles decaying to \( \tau^+\tau^- \) and not to \( \mu^+\mu^- \) are disfavored by Figure 34 unless \( m_X \) is uncomfortably close to \( 2m_{\tau} \).
- Particles decaying to \( \tau^+\tau^-\nu \), and possibly \( \mu^+\mu^-\nu \) with a small branching fraction, may be allowed by the data if \( m_X \) is not too far above \( 2m_{\tau} \).
In any case, it remains to explain the $p_T$ distribution implied by Figure 32 of [1].

Of course more complicated decays (such as direct four-body decays, or an intricate and non-minimal spectrum of $X$ particles) might also be allowed by the data. But to proceed any further, more experimental information is needed.

IV. MICRO-CASCADES

While awaiting the improved experimental constraints on the $X \rightarrow \tau^+\tau^-(\nu)$ option, it is interesting to note a rather different approach to understanding the data: a “micro-cascade”. Consider a set of relatively heavy particles $P_i$, $i = 1,\ldots,n$, with small mass splittings; take $P_n$ to be the heaviest and $P_1$ the lightest. Imagine these decay one to the next by $P_i \rightarrow f f' P_{i-1}$, emitting a pair of standard model quarks or leptons. Experimentally, each decay would generate a pair of soft dileptons, or a soft lepton and a neutrino, or perhaps soft hadrons. This sequence of decays or “micro-cascade” is sketched in Figure 2. There are no theoretical obstructions to such a phenomenon, nor any existing data that could exclude it. Indeed it is possible to construct extensions of the standard model, and especially easy to build hidden valley models, that could give this signature.

While many details will vary from one model to the next, the most reliable prediction of such a phenomenon stems from the fact that the heavy particles do not suffer much of a change in their velocity as they decay one to the next. This means that the vertices from the decays are aligned, roughly, in a straight line (though possibly bent slightly by the magnetic field if the heavy particles are charged.) If multiple tracks are emitted at each vertex, this should be relatively easy to verify. If only one track is emitted (or, on average, reconstructed) at each vertex, then a novel track correlation study is needed to check whether the various displaced tracks in a cone all intersect a single line pointing back to the primary vertex.

However, as noted above, this same feature (multiple collinearly-aligned vertices) is also a property of the kinematically squeezed $h_1 \rightarrow 2h_2 \rightarrow 4h_3$ decays suggested in [11]. To distinguish the two requires a more careful study of the correlations of the radial location of the vertices. Thus both angular and radial correlations among vertices are key observables in any interpretation involving multiple nearby displaced vertices, and it would be useful for any analysis aimed at such a signal to consider these observables.
A. The various types of micro-cascade

There are three questions whose answers determine much of a micro-cascade’s phenomenology. (1) What are the standard-model charges of the heavy particles $P_i$? (2) What are the branching fractions for the decays $P_i \rightarrow f \bar{f'} P_{i-1}$ for various choices of $f \bar{f'}$? (We assume for simplicity that each $P_i$ decays predominantly to $P_{i-1}$ and not to lighter $P_j$.) (3) What is the fate of $P_1$? Let us address these in turn.

If the $P_n$ carry color, then (since the displaced vertices require they are long-lived) they will hadronize, generating occasional stray hadronic tracks (from fragmentation and hadronic decays) both at the primary vertex and at subsequent vertices. Otherwise, they will behave like heavy leptons or neutrinos. Meanwhile, if they form nontrivial electroweak $SU(2)$ multiplets, they can potentially decay, just as do standard model quarks and leptons, by $W$ boson emission. The decays occur at tree-level and, given the mass splittings and CKM-like mixing angles, are calculable. Branching fractions are determined by couplings to the $W$ and by kinematics. If instead the $P_i$ are $SU(2)$ singlets, then they must decay, perhaps through loop effects, by emission of neutral particles, such as off-shell $Z$ bosons or Higgs bosons, or a new unknown particle. (If photon emission is allowed, then it typically dominates, as in the case of $b \rightarrow s$ decays; given the signature suggested in [1], let us assume photon decays
are absent.) Decay rates tend to be highly model-dependent. So do branching fractions, though they are most likely to be either generationally-democratic (as for a Z or typical Z') or weighted by mass-squared (as for a Higgs or new scalar/pseudoscalar.)

Finally, there are four natural options for the fate of the $P_1$ at the end of the cascade:

- $P_1$ is neutral, weakly interacting, and stable on detector time-scales; it exits the detector unseen.
- $P_1$ is charged, electromagnetically interacting, and stable on detector time scales; at first glance it appears to be a muon.
- $P_1$ is colored and forms hadrons with light quarks; the stable or metastable hadrons formed may be neutral, escaping unnoticed until searched for, or may be charged, often masquerading as a muon, or both.
- $P_1$ is unstable and decays within the detector volume, providing one last vertex in the cascade, possibly with many tracks and/or considerable visible energy.

A stable $P_1$ will exit the detector typically within the cone around the nearest trigger muon. A stable neutral $P_1$ leaves some amount of missing transverse momentum, which unfortunately tends to cancel between the $P_1$ and $\bar{P}_1$ in an event. A stable charged particle will actually add to the muon count within the cone, and might show up through precise time-of-flight measurements. New hadrons, both neutral and charged (and even charge-flipping), might be observable through their unusual interactions with matter. Finally, a an unstable $P_1$ would provide the terminal vertex in a micro-cascade. Much or all of the energy from its decay would be recorded, in contrast to the other cases where the stable $P_1$ would leave little or no energy in the calorimeter.

All of the above options are interesting in that they could give challenging experimental signatures, and only some of them (mainly stable charged particles) are on the usual experimental analysis menu. In the case at hand, a first glance at [1] turns up nothing which directly suggests or disfavors any one of these phenomenological possibilities.

Regarding the production of the $P_i$, there are several options, given the fairly large cross-sections needed to explain $\Pi$. For colored $P_i$ particles, ordinary pair production may be sufficient. However, pair production predominantly creates $P_i$ moving with rather low velocity, in which case the leptons and hadrons produced in the $P_i$ decays would go off in all
directions. To collimate these particles into narrow cones, as seems required to explain $P_1$, requires a boost of the parent $P_n$. For this reason, the data motivates consideration of models where the $P_i$ appear in the decay of a heavy resonance $R$. In this case the $P_i$ production rates are determined by their couplings to the resonance, allowing large cross-sections even for color-neutral $P_i$, and also the $P_i$ are somewhat boosted, if they are light compared to $m_R/2$. Still, pair production of colored $P_i$ is by no means excluded by the discussion below.

**B. Brief aside on model-building**

It should be stressed that there is nothing exceptionally natural about a micro-cascade. It could easily be the case that all $P_i$ directly decay to the lightest particle $P_1$. It might be that lifetimes are different by several orders of magnitude, implying that only one or two displaced vertices, with a high multiplicity of tracks, can actually be resolved. For this reason, detailed model-building seems premature; let us see if the data actually shows a signature. Still, for the interested reader, a few preliminary comments are in order.

Despite some risk of ruining perturbative unification of the standard model gauge couplings, it is straightforward to add several new Dirac fermions or scalars at the weak scale, charged in one way or other under the standard model gauge couplings, without violating experimental constraints. More precisely, this is true as long as these particles do not get their masses mainly from the Higgs boson (which would affect electroweak precision measurements) and are heavy enough to have avoided direct discovery at LEP. (Indeed this is what could happen in certain supersymmetric or extra-dimensional models if their mass spectrum were squeezed.) It is even simpler to add standard-model-neutral particles (as in a hidden valley); such particles could have any mass.

Near-degeneracies and long lifetimes can arise even in minimal supersymmetric models, as in the limit that $M_2 \ll M_1$ (e.g. anomaly mediation) or $\mu \ll M_2, M_1$ (light Higgsinos). In a non-minimal model of supersymmetry, one may obtain a richer near-degenerate spectrum. For instance, if gauginos are Dirac instead of Majorana, the spectrum is doubled, and small splittings are induced if the Majorana terms are small. Similar degeneracies could easily arise in extra-dimensional models, depending on the shape of the extra dimensions.

One easy way to obtain a near-degenerate spectrum with a micro-cascade is to obtain a large multiplet of a weakly-broken symmetry. For example, consider that in QCD, if the $b$
quark had a lifetime of seconds, then the $B_u, B_d, B_s, B_u^*, B_d^*, B_s^*$ system would form six near-degenerate states that could only decay through electroweak interactions. Were there no photon, all of their decays would all be through soft lepton emission. A new heavy vectorlike long-lived quark of QCD, added to the standard model, would have such a spectrum, but it would be too degenerate for present needs. However, a confining hidden valley with a similar structure of $v$-quark masses would have near-degenerate $v$-mesons that could only decay to standard model particles and that might be able to explain [12]. (If the heavy $v$-quark were in an antisymmetric tensor representation of hidden-color rather than in a fundamental, then the number of near-degenerate states would double.) A scalar that has hidden-flavor-changing couplings and mixes with the Higgs boson could then allow these hidden states to decay to one another. If the splittings all lie between $2m_\tau$ and $2m_b$, the dominant final state would be non-resonant $\tau^+\tau^-$ pairs.

In this example, the heavy $v$-quark inside the $v$-meson, and therefore the $v$-meson itself, could potentially carry standard model color. This would realize the option of colored $P_i$ particles, and allow naturally large cross-sections without a new resonance.

Another way to obtain a micro-cascade would involve a weakly-coupled hidden valley with an extra dimension of radius $R \equiv 1/\mu$. A massive five dimensional particle with a large mass $M$ would then have a tower of states $P_i$ with splittings of order $\mu^2/M$. (A similar model could be built using the spectrum of a string with massive ends.) If a scalar $S$ violates all conserved Kaluza-Klein charges, then particles in this tower can decay via off-shell $S$ emission. Mixing of $S$ with the Higgs boson would then allow $\tau^+\tau^-$ final states in a cascade.

One could and eventually should do a much better job of model-building than attempted here. Let us now return to the data and phenomenology.

C. Reducing the space of options: I

What if most of the displaced muons came from three-body $P_i \rightarrow \mu^+\mu^-P_{i-1}$ decays? As before, the lack of muon charge correlations in Figure 22 would be reasonable only if the efficiency for muon detection were implausibly low. We therefore set this option aside.

Consistency with Figure 22 would be much improved if the $P_i$ decay via off-shell $W$ bosons. A decay $P_i \rightarrow \mu^+\nu P_{i-1}$ is just as likely to be followed by $P_{i-1} \rightarrow e^-\bar{\nu}P_{i-2}$ or $P_{i-1} \rightarrow \rho^-P_{i-2}$ as $P_{i-1} \rightarrow \mu^-\nu P_{i-1}$; there is no correlation between the final states of the
first and second decay.

Note that even if $P_i \rightarrow P_{i-1} \ell \nu$ is the dominant decay mode, so that many steps in the micro-cascade produce only one track, it may still be the case that at least two tracks emerge at each displaced vertex. (The efficiency to detect these tracks is a separate issue.) This is because in this scenario there is some conflict between making the splittings between the $P_i$ large enough to generate triggerable muons in the decays while still permitting all the $P_i$ lifetimes to be of order a few ps or more. Instead there is a tendency, as in the decays of standard model quarks, for long lifetimes to require small off-diagonal mixings, in which case the diagonal decays are rapid. For example, a slow $P_3 \rightarrow \mu^+ \nu P_2$ decay might be likely to be followed by a faster $P_2 \rightarrow e^- \bar{\nu} P_1$ decay. Such a chain might be detected as a $\mu^+ e^-$ pair appearing at a single point. Note that $\mu^+ e^+$ vertices would not occur.

Thus, as a result of these overlapping decay steps in the micro-cascade, many of the muons may be produced at a composite decay vertex, with one or more additional tracks. (Note that if the $P_i$ are colored and form hadrons, sometimes unstable, in each decay, the number of tracks at each step may be further enhanced.) Consequently it would be helpful if an update of [1] would give more information about the vertices, including a histogram of the number of tracks that are present in vertices with 0, 1, or 2 muons, and how the number of vertices within a cone is correlated with the number of muons in that cone.

This phenomenological scenario may not work for [1], however. The particles $P_i$ must be fairly light, if they are to be produced abundantly and with a reasonable boost. But if they are $SU(2)$ non-singlets, some of them must be electrically charged, which presumably requires their masses to be close to or above 100 GeV (as some searches for displaced decays were carried out at LEP II). Pair production of heavy colorless particles has a low cross-section, while obtaining high enough rates from a new resonance well above 200 GeV might not be possible. This requires additional study.

D. Reducing the space of options: II

If instead the $P_i$ are colored and are all electrically neutral, the constraints on their masses are much weaker, since they would not be produced at LEP; masses of 50 GeV [13] are apparently allowed. (However such particles generally ruin coupling-constant unification.) If the $P_i$ are neutral under the entire standard model, as in hidden valleys, then there are
hardly any constraints.

As mentioned above, examples of hidden valleys with heavy neutral or colored particles $P_i$ decaying via a three-body decay to $f \bar{f} P_{i-1}$ can be obtained through multi-flavor generalizations of examples discussed in [2], and many other approaches. (Events from a similar model, with larger mass splittings than relevant here, were shown in [15].) Other types of models can also generate these phenomena.

Decays in this case must be of the form $P_i \rightarrow f \bar{f} P_j$, where $f$ and $f'$ have the same charge. We saw already that Figure 22 disfavors $P_i \rightarrow \mu^+ \mu^- P_{i-1}$ as an important source of muons, but it still allows $P_i \rightarrow \tau^+ \tau^- P_{i-1}$ to be the dominant source.

E. A toy example

Consider a toy example, which is intended to illustrate some simple observations (rather than as a serious attempt to fit the data.) Here a 200 GeV resonance decays to $P_5 \bar{P}_5$ is considered, where $P_5$ has mass 60 GeV; this then decays in a cascade $P_5 \rightarrow P_4 \rightarrow P_3 \rightarrow P_2 \rightarrow P_1$, where $m_4 = 53$ GeV, $m_3 = 45$ GeV, $m_4 = 38$ GeV, $m_1 = 31$ GeV. The $P_i$ are assumed all to be standard-model neutral. All decays are assumed to occur via $P_i \rightarrow \tau^+ \tau^- P_{i-1}$. The plot corresponding to Figure 34a in [1] is shown in Figure 3a. Because the decay is three-body, the result is closer to satisfactory than in Figure 1, and indeed is similar to the case $X \rightarrow \tau^+ \tau^- \nu$ described in the previous section. The plot suggests that a mass splitting among the $P_i$ of order 7 – 8 GeV is a bit too large, instead favoring a mass splitting closer to 4 – 5 GeV.

Given this moderate success, what fails? Again the $p_T$ distribution of the tracks is too low to match Figure 32 of [1]. This is no surprise, since a 200 GeV resonance will not often give cones with tracks that have $\sum p_T > 60$ GeV, especially if the $P_1$ is invisible and stable. But if instead the $P_1$ decays in flight, its decay products could both increase the observed $p_T$ and the observed number of tracks. However, the effect depends crucially on how many tracks $P_1$ decays to, and also on the $P_1$ lifetime, since sufficiently displaced or angled tracks might not all be reconstructed. To study this is beyond a theorist’s capability; a detailed understanding of the detector is needed.

For figure 3a, it was assumed that $P_i \rightarrow \mu^+ \mu^- P_{i-1}$ is disallowed. The effect of including this decay mode with a branching fraction of order $m_\mu^2/m_\tau^2$ is shown in Figure 3b. Comparing
with Figure 3a we see little change. Thus, as in the case \( X \rightarrow \tau^+\tau^-\nu \), Figure 34 of [1] can be matched without making the branching fraction to muons unnaturally small.

The toy model thus indicates that a micro-cascade is not obviously any worse at explaining the data than is high-multiplicity production of a light particle. In general, micro-cascades should be considered as an option whenever multiple long-lived particles are suspected.

**FIG. 3:** For the micro-cascade toy model, with mass splittings of order 7–8 GeV, a plot analogous to Figure 34a of [1]. (a) Decays via \( P_i \rightarrow \tau^+\tau^-P_{i-1} \) only. (b) Decays by \( P_i \rightarrow \tau^+\tau^-P_{i-1} \) and (with low branching fraction) \( P_i \rightarrow \mu^+\mu^-P_{i-1} \). (The lower statistics is a consequence only of the simulation and has no physical significance.)

**F. Summary on micro-cascades**

A summary of the signatures for a micro-cascade are the following:

- the model-independent signature of a chain of vertices, one after another (or of a common line that points back to the primary vertex and is crossed by all the displaced tracks);
- correlations in the radial positions of vertices due to the varying lifetimes of the new particles \( P_i \) that participate in the cascade
• possibly unexpected and widely varying combinations of particles emerging from the vertices (due to spatial overlap of multiple decay steps, and/or to hadronization effects from colored $P_i$ decays)

• possible “terminating vertices” at the end of the micro-cascade, where the last of the cascading particles decays with more energy and perhaps tracks than at any of the vertices within the micro-cascade;

• possible long-lived charged particles, weakly or strongly interacting, masquerading as muons and pointing back to the micro-cascade vertices;

• possible long-lived exotic hadrons, charged or neutral, pointing back to the micro-cascade vertices.

Of course, there are existing Tevatron studies looking for long-lived charged particles [16, 17]. These, along with the combination of mass constraints from LEP and the need for large cross-sections, may already have excluded the last two possibilities in the regime of interest. The other options lie somewhat outside the usual realm of particle physics analyses. It will be interesting to see whether they can be carried out successfully in any update of [1].

V. FINAL COMMENTS

While considerable skepticism is still in order, there is still some hope that [1] contains a hint of a new phenomenon. The considerations of this note suggest some additional plots that might be useful to include in any update of [1].

• A breakdown of Figures 34a and 34b into subcases: opposite-sign dimuon, same-sign-dimuon, and multi-muon.

• Figure 34 (and its subcases) with narrower binning, appropriate to the CDF mass resolution.

• Plots showing the correlation, within a single cone around a trigger muon, between the numbers of muons, numbers of non-muon tracks, and numbers of vertices.

• Plots showing the number of tracks and the invariant mass of all tracks within a cone, for cones with different numbers of muons.
• Plots similar to Figures 45 and 46 for a wider variety of vertex types, and plots comparing same-sign and opposite-sign di-track (or di-muon or muon-plus-track) vertices.

• Plots showing the number of tracks per vertex for vertices containing 0, 1 or 2 muons.

• Plots studying the radial and angular correlation between multiple vertices in a cone.

In each of these cases, it would be important to see these plots for the cleaner subsample of 3000 “ghost” 2-dimuon-cone events.

Separately, considerable light might be shed using those events where some muons pass the loose SVX criterion. For example, for the 3000 “ghost” 2-dimuon-cone events, how many have at least one pair of muons that pass the loose SVX criterion and form a dimuon vertex? how many have at least two muons passing the loose SVX criterion that each have a muon-plus-track vertex? A substantial number should be expected, if there really is a new particle of lifetime $\sim 20$ ps. According to the text of [1], the loose SVX criterion “accepts muons from parent particles with a decay length as long as 10 cm”. Since $c\tau \sim 0.6$ cm for $\tau = 20$ ps, even a substantial boost of order 10 for the decaying particles will still leave many decays at considerably shorter distances. If we crudely estimate that (a) 1/2 of the cones in Figure 34b have opposite-sign dimuons, and (b) 1/4 of these dimuons come from the same decay step, then accounting for both cones suggests hundreds of events have vertices built from loose-SVX muons. A careful study of this cleaner subsample, on its own merits, and also comparing it with the sample of events with no SVX requirement, would be most illuminating.

Then there is the issue of the electrons. While much more difficult to observe than non-isolated muons, and while suffering from large conversion backgrounds, the non-isolated electrons that almost any reasonable model of the new physics would predict must be identified. At least, an analysis of the electrons and positrons found in a small low-background sample of multi-muon events, such as the 2-dimuon-cone event sample, would be valuable. How many electrons there are, how their charges correlate or anticorrelate with the muon charges, how many vertices they participate in, etc., are crucial questions requiring experimental answers. Comparison of same-sign and opposite-sign $\mu e$ vertices — the latter being predicted by $X \rightarrow \tau^+\tau^- (\nu)$, most micro-cascades, and other physics signals, with a sign-uncorrelated background from secondary interactions of muons — would be especially valuable.
Finally, even if the hints in [1] turns out to be as ephemeral as a ghost, the challenges that this analysis faces are useful as a springboard for discussion. Clearly, if there were a signal of this type in the data, it would indeed be quite difficult to find it, and the approach used in [1] is far from optimal. Opening our minds regarding the possible signatures that nature might provide, and finding new techniques for expanding the range of reasonable searches at hadron colliders, is surely beneficial for the field.

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