

# Searching for hidden matter with long-range angular correlations at $e^+e^-$ colliders

Redamy Pérez-Ramos<sup>a,†</sup>, Miguel-Angel Sanchis-Lozano<sup>b,‡</sup>, and Edward K. Sarkisyan-Grinbaum<sup>c,d,\*</sup>

<sup>a</sup> *DRII-IPSA, Bis, 63 Boulevard de Brandebourg, 94200 Ivry-sur-Seine France  
LPTHE, Sorbonne Université, UPMC Univ Paris 06, UMR 7589, F-75005, Paris, France*

<sup>b</sup> *Instituto de Física Corpuscular (IFIC) and Departamento de Física Teórica  
Centro Mixto Universitat de València-CSIC, Dr. Moliner 50, E-46100 Burjassot, Spain*

<sup>c</sup> *Experimental Physics Department, CERN, 1211 Geneva 23, Switzerland*

<sup>d</sup> *Department of Physics, The University of Texas at Arlington, Arlington, TX 76019, USA*

## Abstract

The analysis of azimuthal correlations in multiparticle production can be useful to uncover the existence of new physics beyond the Standard Model, e.g., Hidden Valley, in  $e^+e^-$  annihilation at high energies. In this paper, based on previous theoretical studies and using PYTHIA8 event generator, it is found that both azimuthal and rapidity long-range correlations are enhanced due to the presence of a new stage of matter on top of the QCD partonic cascade. Ridge structures, similar to those observed at the LHC, show up providing a possible signature of new physics at future  $e^+e^-$  colliders.

<sup>†</sup>E-mail address: redamy.perez-ramos@ipsa.fr

<sup>‡</sup>E-mail address: Miguel.Angel.Sanchis@ific.uv.es

\*E-mail address: Edward.Sarkisyan-Grinbaum@cern.ch

In a series of previous papers, particle correlations were used to extract information about intra-jet multiparticle dynamics [1], and for the search of new physics beyond the Standard Model (SM) in hadronic high-energy collisions [2, 3]. Indeed, the analysis of long-range particle correlations can provide useful information about the early stage of matter and shed light on the possible presence of new physics on top of the QCD parton shower. On the other hand,  $e^+e^-$  collisions should provide to this end a much cleaner environment than hadron colliders, as well as a definite (though adjustable) center-of-mass energy.

The analyses of 2-particle angular correlations in high-multiplicity proton-proton, proton-nucleus and heavy-ion collisions, have revealed a ridge structure of final state hadrons emitted almost collinearly within a broad rapidity difference [4–6]. Different theoretical explanations [7–9] have been put forward to explain this initially unexpected phenomenon, almost of all them requiring the existence of some unconventional state of matter at the beginning of the collision. Analogies can be found in the Cosmic Microwave Background [10] where the inflationary epoch plays the role of a hidden sector.

This paper mainly focuses on QCD-like hidden sectors within Hidden Valley (HV) models, where new types of particles, e.g.  $v$ -quarks, undergo new interactions mediated by HV photons ( $\gamma_v$ ) or HV gluons ( $g_v$ ) [11]. Production of HV matter will ultimately enhance and enlarge azimuthal correlations of final-state particles as, e.g., in heavy-ion collisions where the quark gluon plasma is assumed to be produced [12].

The simplest way of coupling the SM and the Hidden Sector (HS) occurs via a heavy  $Z_v$  of mass  $\gtrsim 1$  TeV. Another possibility involves mirror partners of the SM charged quarks and leptons (collectively denoted as  $F_v$ ) under both SM and HS, thereby with the capacity of connecting both sectors. Hence  $F_v$  can be pair-produced via the annihilation process  $e^+e^- \rightarrow \gamma/Z^0 \rightarrow F_v\bar{F}_v$  above energy threshold. The current paper only concerns the lightest and heaviest cases, namely  $D_v$  ( $\simeq 100$  GeV) and  $T_v$  (several 100 GeV). Intermediate masses lead to intermediate results and will not be explicitly reported.

Three kinds of partonic showers, ultimately yielding final-state SM particles, are distinguished here:

- (i)  $e^+e^- \rightarrow q\bar{q} \rightarrow$  hadrons, where  $q$  collectively denotes all quark flavors below the top ( $t$ ) mass. Using PYTHIA8 event generator [13, 14], all flavors are generated according to the respective production cross sections.
- (ii)  $e^+e^- \rightarrow t\bar{t} \rightarrow$  hadrons. Top quark possesses special interest because of its very large mass and the fact that it does not form bound states but promptly decays into lighter particles, mimicking the extra cascade due to an extra hidden sector.
- (iii)  $e^+e^- \rightarrow F_v\bar{F}_v \rightarrow$  hadrons [11], i.e. HV production, the main goal of this study. Let us stress that decay modes like  $g_v \rightarrow g_v\bar{g}_v$ ,  $g_v \rightarrow q_v\bar{q}_v$  and  $\gamma_v \rightarrow q_v\bar{q}_v$  are similar to SM processes along the partonic cascade before hadronization.

The current study rests on two bases: (a) a previous theoretical study of 2- and 3-particle correlations developed by two authors [3, 15, 16], where the possible HV contribution beyond the SM is incorporated on top of the parton shower, and (b) a Monte Carlo study using PYTHIA8 [13, 14] with different HV sectors incorporated.

The Monte Carlo study here explores different HV scenarios for the  $v$ -partners of the SM fermions with  $m_{q_v} = 100$  GeV. The corresponding coupling constant  $\alpha_v$  was set to the (default) value  $\alpha_v = 0.1$  since correlations prove to be quite insensitive to higher values. Correlation

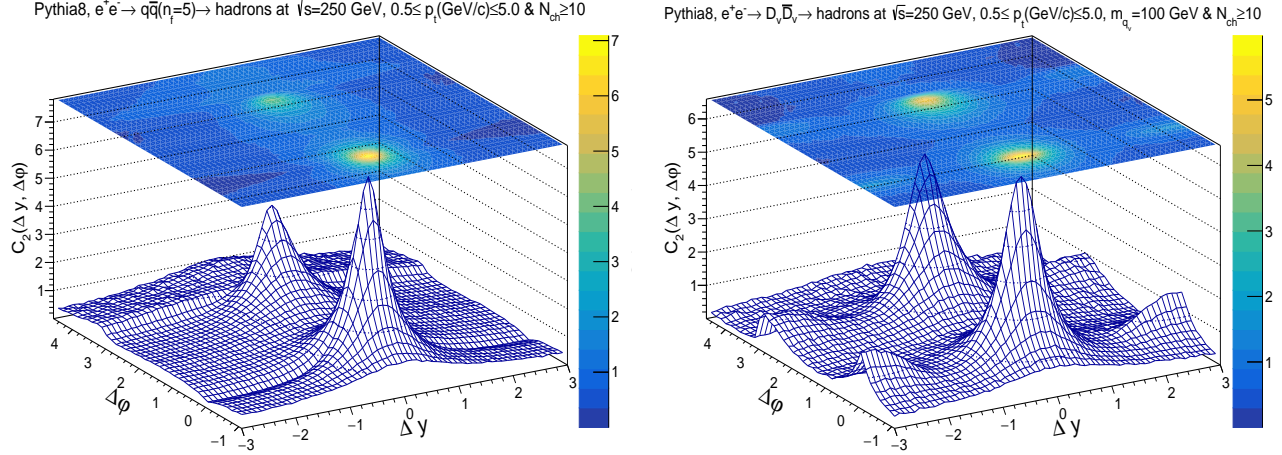


Figure 1: Two-particle correlation function,  $C_2(\Delta y, \Delta\phi)$  (in rapidity and azimuthal angle differences), obtained in the SM (left panel) and the HV scenario with the  $v$ -quark mass  $m_{q_v} = 100$  GeV (right panel) in the  $e^+e^-$  annihilation generated with PYTHIA8 at center-of-mass energy  $\sqrt{s} = 250$  GeV. Here,  $n_f$  is the number of SM flavours,  $q$  denotes all quarks except the top quark,  $D_v$  is the HV mirror partner to the SM down quark,  $N_{\text{ch}}$  is the number of the charged particles, and  $p_t$  is the transverse momentum of the produced particles in the sphericity frame.

functions are studied as a function of (pseudo)rapidity and azimuthal angle in  $e^+e^-$  collisions at center-of-mass energy 250 GeV using the sphericity frame. This choice is especially suitable in  $e^+e^-$  colliders [17, 18] since the sphericity axis coincides with the averaged outgoing direction of the back-to-back  $q\bar{q}$  jets produced in the annihilation process.

Figure 1 shows 3-dimensional plot of the 2-particle correlation function  $C_2(\Delta y, \Delta\phi)$  for the SM  $e^+e^- \rightarrow \gamma^*/Z^0 \rightarrow q\bar{q} \rightarrow \text{hadrons}$  and the HV  $e^+e^- \rightarrow \gamma^*/Z^* \rightarrow D_v\bar{D}_v \rightarrow \text{hadrons}$  scenarios, where the products of the decay  $D_v \rightarrow d + q_v$  initiate a parton shower. The 2-particle correlation function represents the ratio of the number of charged particle pairs from the same event (signal), and that from different events (background),  $C_2(\Delta y, \Delta\phi) = S_2(\Delta y, \Delta\phi)/B_2(\Delta y, \Delta\phi)$ , with the differences on rapidity and azimuthal angles of particles 1 and 2,  $\Delta y \equiv \Delta y_{12} = y_1 - y_2$  and  $\Delta\phi \equiv \Delta\phi_{12} = \phi_1 - \phi_2$  as used in experiments [4–6, 19, 20]. A nearside ridge can be expected in such a 3-dimensional plot of  $C_2$  function, very much like the one appearing in hadronic collisions.

One can see the narrow peak for  $\Delta\eta \approx 0$  and  $\Delta\phi \approx 0$  arising from particle pairs inside the same events, and the away-side ridge (at  $\Delta\phi \approx \pi$ ) typically due to back-to back jet production as a consequence of energy-momentum conservation. It is worth mentioning that the latter clearly exhibits stronger correlations in the HV sector than those in the SM, as visible from the plots. Note that the essential features of the equivalent plot, obtained by ALEPH [19] and Belle [20] experiments are reproduced while using the thrust axis.

Meantime, the most striking difference between both scenarios lies on the existence of long-range, nearside angular correlations (ridge [4]) within  $2 < |\Delta y| < 4$  at  $\Delta\phi \approx 0$  for the HV scenario. This structure was checked to hold to different extends for all  $F_v$  cases, while only the  $D_v$  is plotted. Such a ridge is not obtained from the SM cascade, so it becomes particularly suggestive to interpret the ridge phenomenon as a consequence of the presence of a new stage of matter on top of the QCD parton cascade. This is one of the main assumptions of this study,

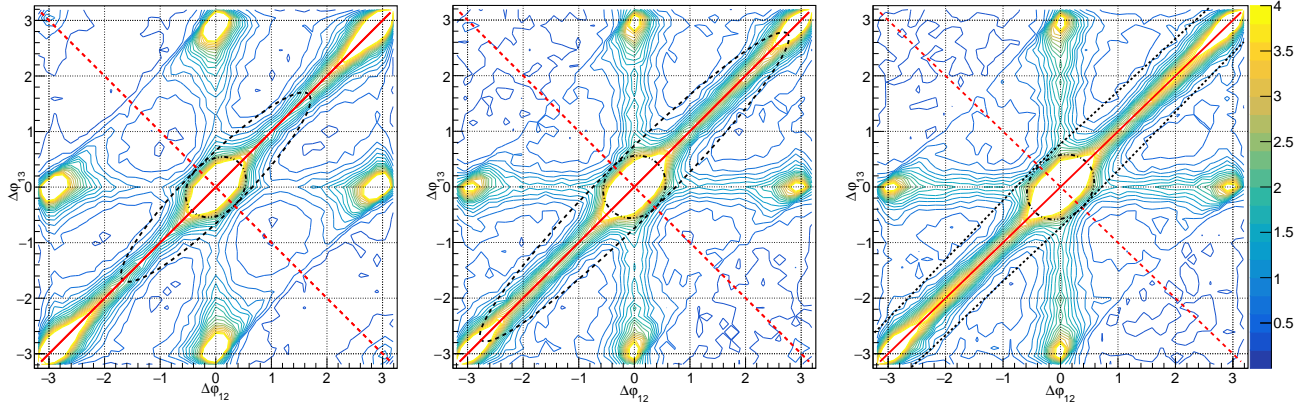


Figure 2: Contourplot of 3-particle azimuthal correlations  $C^{(3)}(\Delta\phi_{12}, \Delta\phi_{13})$  of charged hadrons in light quark (left panel),  $t\bar{t}$  (middle panel) and  $T_v\bar{T}_v$  (right panel) events in  $e^+e^-$  collisions generated with PYTHIA8 at  $\sqrt{s} = 800$  GeV. The solid and dotted red lines represent the on-diagonal ( $\Delta\phi_{12} = \Delta\phi_{13}$ ) and off-diagonal ( $\Delta\phi_{12} = -\Delta\phi_{13}$ ) projections, respectively. Ellipses indicate long-range correlations (major axis) and middle-range correlations (minor axis). Long-range correlations increase from left to right while short-range and middle-range correlations remain as eccentricities increase. The central peak from jet correlations is cut off by the horizontal plane  $C^{(3)}(\Delta\phi_{12}, \Delta\phi_{13}) = 4$ , to better illustrate the correlation structure outside that region.

which is examined below using 3-particle correlations.

As is known [21], 3-particle (and higher-order) correlations provide extra information on the formation and evolution of matter in high-energy collisions. In what follows, the function of four variables:  $C_3(\Delta y_{12}, \Delta y_{13}; \Delta\phi_{12}, \Delta\phi_{13}) = S_3(\Delta y_{12}, \Delta y_{13}; \Delta\phi_{12}, \Delta\phi_{13}) / B_3(\Delta y_{12}, \Delta y_{13}; \Delta\phi_{12}, \Delta\phi_{13})$  is used to study three-particle correlations. Again, the numerator represents the signal as it takes into account the number of particle triplets from the same event, while the denominator corresponds to the background, i.e. particle triplets from different events.

The present study is restricted to azimuthal correlations following the findings of [3] where we concluded that azimuthal distributions are more sensitive to the presence of hidden sectors than (pseudo)rapidity distributions. Therefore, and for the sake of simplicity, the rapidity difference is fixed here to the interval  $\Delta y_{12} = \Delta y_{13} = 0$ , that is, particles moving with similar longitudinal rapidity (along the sphericity axis of each event).

Figure 2 displays the contour plot of  $C_3(\Delta y_{12} = 0, \Delta y_{13} = 0; \Delta\phi_{12}, \Delta\phi_{13})$  for light quarks,  $t\bar{t}$  and  $T_v\bar{T}_v$  production with  $\alpha_v = 0.1$ . In all three cases, a rich structure can be observed on the  $(\Delta\phi_{12}, \Delta\phi_{13})$ -plane: a central high peak together with a set of “satellite” peaks linked by a set of ridges and valleys (i.e. higher or lower values of correlations) represented as contour line fluxes. Let us focus on the central  $(\Delta\phi_{12}, \Delta\phi_{13})$ -region, where the effects of the hidden sector mainly show up, while the other peaks can be interpreted as back-to-back correlations of particle pairs.

Examining all three patterns shown in Fig.2, one can immediately notice that long-range azimuthal correlations are stretched when passing from light quarks to top production and furthermore to the HV sector as areas of in-middle valleys shrink perceptively.

To investigate in more detail such a behaviour, one-dimensional distributions obtained from the on-diagonal ( $\Delta\phi_{12} = \Delta\phi_{13}$ ) and off-diagonal ( $\Delta\phi_{12} = -\Delta\phi_{13}$ ) projections of the 3-dimensional

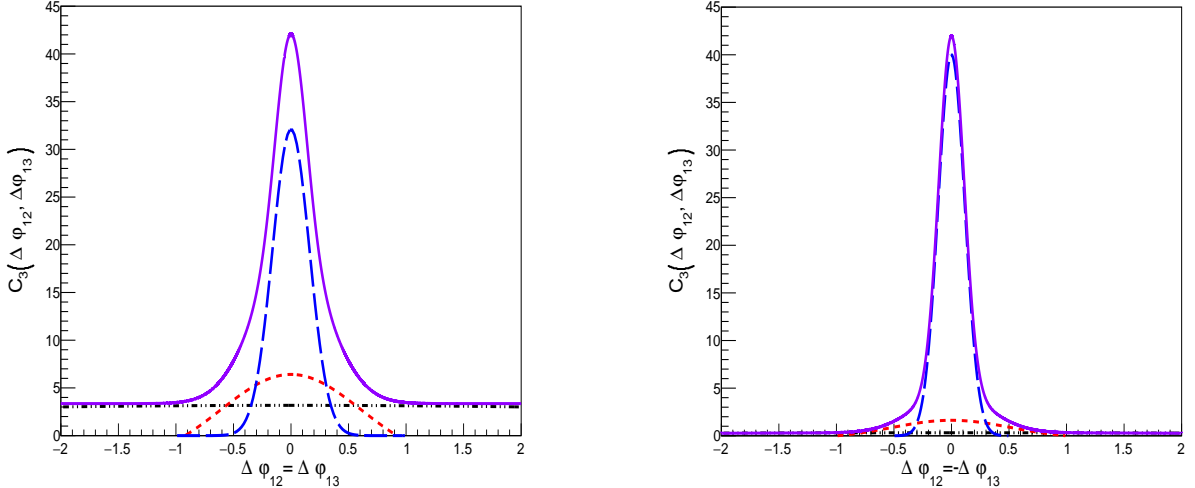


Figure 3: On-diagonal (left panel) and off-diagonal (right panel) projections of the azimuthal contour-plot of  $C_3$ -function in the HV scenario obtained from Fig.2. The solid violet line represents a global fit obtained from short-range correlations (long-dashed blue line), middle-range correlations (dashed red line) and long-range correlations (dotted black line).

plots of Fig.2 were plotted. Note that long-range correlations give rise to a kind of *spiderweb* structure developing in the contour plane of the 3-particle correlation function [15]. Fits were made using three Gaussian functions with widths,  $\delta_s$ ,  $\delta_m$  and  $\delta_l$  corresponding, respectively, to: short-range correlations mainly due to resonance decays; middle-range correlations mainly due to the parton shower; and long-range correlations, attributed to the HV sector on top of the conventional cascade. From these quantities, more general widths are defined to disentangle the possible existence of a hidden sector,  $\delta_M = \sqrt{\delta_s^2 + \delta_m^2}$  and  $\delta_L = \sqrt{\delta_s^2 + \delta_m^2 + \delta_l^2}$ , such that the former takes into account the “pure” QCD correlations while the latter embraces all QCD and HV correlations.

In Fig. 3, the fits for the  $T_v\bar{T}_v$  case are depicted with three Gaussian functions for short-range, middle-range and long-range correlations along the on-diagonal and off-diagonal projections. Note that off-diagonal long-range correlations drop off faster than the on-diagonal ones, in accordance with the results of [3]. The numerical values of the widths are given in Table 1 for all three cases, namely,  $q\bar{q}$ ,  $t\bar{t}$  and  $T_v\bar{T}_v$ , obtained from the Gaussian fits to the corresponding on-diagonal and off-diagonal projections of the  $C_3$ -function. Also, the mean sphericity values are given in Table 1 which are found to be the highest (“sphere-like” events) for the HV events and the lowest (“pencil-like” events) for the lightest quarks, while the top quark events stay in between. In other words, the back-to-back hadron jets produced from the HV sector reach the most sphere-like shape as particles are emitted more isotropically in the event. Then,  $\Delta\phi_{12} \approx \pi/2$  or  $\Delta\phi_{13} \approx \pi/2$ , assuming particle 1 has been emitted along the sphericity axis (for a recent study see [22]).

Notice the following hierarchy involving the long-range widths shown in Table 1:  $\delta_L(HV) > \delta_L(t\bar{t}) > \delta_L(q\bar{q})$ , highlighting the systematic enhancement of long-range correlations for non-standard HV-initiated cascade compared to a standard one. This difference also matches the highest mean sphericity obtained for HV events. In its turn,  $t\bar{t}$  production follows the same trend

Table 1: Widths (in rad) obtained from Gaussian fits of middle-range and long-range correlations contributing to  $C_3(\Delta y_{12} = 0, \Delta y_{13} = 0; \Delta\phi_{12}, \Delta\phi_{13})$  on-diagonal and off-diagonal projections (Fig.3), along with the mean sphericity values.

(v)-quark species:	light quarks	$t\bar{t}$	$T_v\bar{T}_v$
$\delta_L$ (on-diagonal)	2.2	3.9	6.2
$\delta_M$ (on-diagonal)	0.55	0.59	0.64
$\delta_M$ (off-diagonal)	0.44	0.53	0.53
mean sphericity	0.04	0.17	0.47

from  $q\bar{q}$  to HV events. This is actually not a surprise because as said above, top-quark behaves somehow like a new step from the correlation point of view.

It is also worthwhile mentioning the observed *universality* showing up for middle-range azimuthal correlations by comparing the values of  $\delta_M$  for all three channels, which are quite close. This can be understood since short-range and middle-range correlations are mainly due to a conventional QCD shower, common to all channels regardless of the existence of a hidden sector on top of it.

To illustrate pictorially all the above statements, the ellipses, whose minor/major axes numerically coincide with the  $\delta_M/\delta_L$  values, are drawn on the contour-plot plane in Fig.2. Indeed, the similar shape and size of the inner ellipses is a consequence of the universality of the conventional cascade, while longer correlations imply larger eccentricity ellipses revealing the existence of a hidden sector. All these results are in overall agreement with our previous theoretical findings developed for hadronic collisions [3].

To conclude, the analysis of long-range correlations in  $e^+e^- \rightarrow$  hadrons collisions using PYTHIA8 event generator provides potentially observable signals on the existence of a hidden sector decaying promptly back into SM particles. The proposed signatures, based on 2-particle and 3-particle (pseudo)rapidity/azimuthal correlations, are complementary tools in order to further contribute to the potential discovery of HV sectors at future  $e^+e^-$  colliders.

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