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# Signatures of New Physics Versus the Ridge Phenomenon in Hadron–Hadron Collisions at the LHC

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**Abstract:** In this paper, we consider the possibility that a new stage of matter stemming from hidden/dark sectors beyond the Standard Model, to be formed in $pp$ collisions at the LHC (Large Hadron Collider), can significantly modify the correlations among final-state particles. In particular, two-particle azimuthal correlations are studied by means of a Fourier series sensitive to the near-side ridge effect while assuming that hidden/dark particles decay on top of the conventional parton shower. Then, new (fractional) harmonic terms should be included in the Fourier analysis of the azimuthal anisotropies, encoding the hypothetical new physics contribution and enabling its detection in a complementary way to other signatures.

**Keywords:** $pp$ interactions at LHC; models beyond the Standard Model; Hidden Valley models; Ridge phenomenon; two-particle azimuthal correlations

## 1. Introduction

The interest in discovering new physics (NP) beyond the Standard Model (SM) at the Large Hadron Collider (LHC) is beyond doubt. Within the last decades, many distinct strategies have been put forward, most of them based on signatures in the transverse plane with respect to the beam's axis, such mono-jets, missing transverse energy, displaced vertices, and so on. On the other hand, other kinds of rather "diffuse" signals have been examined in the literature (e.g., [1,2]), featuring the whole event (multiplicity distribution and moments, event shape variables, underlying event, etc.) as a key signature of NP. For instance, the so-called "soft bomb" scenario [3] is characterized by high multiplicity events with nearly spherically distributed soft SM particles and a large amount of missing transverse energy. In particular, a strongly coupled hidden/dark sector could lead to a large angle emission of partons carrying a non-negligible amount of momentum and yielding a rather isotropic distribution of final-state particles all sharing a similar amount of energy. Note, however, that a likely complicated hidden sector (HS) beyond the SM may have limited observable effects at colliders, making detection from an SM background, and especially the discrimination between different models, difficult [4,5]. Therefore, alternative signatures, as proposed in this work, should be considered as complementary to other search strategies, as discussed in [3].

Indeed, as is well known, (pseudo)rapidity and azimuthal particle correlations provide a crucial insight into the underlying mechanism of particle production (see [6] for a review). Moreover, from general arguments based on causality, long-range correlations should have the origin at very early times after the collision. Therefore, if the parton shower were to be altered by the presence of a non-conventional state of matter, final-state particle correlations should be sensitive to it [7,8].

The two-particle correlation function is often defined in pseudorapidity and azimuthal space as [9–11]

$$C(\Delta\eta, \Delta\phi) = \frac{S(\Delta\eta, \Delta\phi)}{B(\Delta\eta, \Delta\phi)} \; . \tag{1}$$

Here, $S$ denotes the signal distribution built with particle pairs from the same event, while $B$ denotes the background distribution constructed by particle pairs taken from different events. $\Delta\eta = \eta_1 - \eta_2$ and $\Delta\phi = \phi_1 - \phi_2$ denote, respectively, the pseudorapidity and azimuthal differences of particles 1 and 2—the indexes labeling the trigger and associate particles, respectively.

Typically, a complex structure of the correlation function is observed. In particular, an enhancement of the two-particle correlations is found at $\Delta\phi \simeq 0$ in heavy-ion collisions [12]. Because of its extended longitudinal (pseudorapidity) shape, as seen in the $\Delta\eta$–$\Delta\phi$ plot, it is referred to as the (near-side) ridge. One-dimensional correlation functions $C(\Delta\phi)$ are obtained from Equation (1) by integration over pseudorapidity along the range $2 < |\Delta\eta| < 5$ to focus on long-range correlations.

The observed azimuthal anisotropy in heavy-ion collisions is commonly analyzed by means of a Fourier decomposition:

$$C(\Delta\phi) \; \sim 1 + 2\sum_{n=1}^{\infty} V_n \cos\left(n\Delta\phi\right) , \tag{2}$$

where the coefficients $V_n$ are supposed to factorize as the product of the coefficients of the equivalent Fourier expansion of two single-particle densities. When applied to heavy-ion collisions, the different terms in the series of Equation (2) find a "natural" interpretation according to a hydrodynamical model describing the very hot and dense matter resulting from the collision. In practice, up to five or six Fourier terms are taken into account in the analysis of the experimental data.

Remarkably, similar long-range ridge structures show up in proton–nucleus [9–11,13] and even proton–proton [13,14] collisions, under several conditions on events such as high multiplicity and a given transverse momentum range of charged particles. The interpretation of a positive $V_2$ in these small systems is currently highly debated, and different observables have been proposed to probe new dynamical effects related to large hadronic densities [15].

In this paper, we furthermore consider that hidden particles and states, stemming from Hidden Valley (HV) models [16], can be formed at primary interactions in very high energy $pp$ collisions. Generically, an HV model consists of three sectors: (i) a HS containing v-particles charged under a valley group $G_{\rm v}$ but blind to the SM interactions, (ii) a visible sector including SM particles charged under the SM group $G_{\rm SM}$ but neutral under $G_{\rm v}$, and (iii) mediators connecting both visible and hidden sectors. Usually, the masses of the hidden sector particles are assumed to lie below the electroweak scale, while the mediators may have TeV-scale masses. The simplest possibility for $G_{\rm v}$ is a QCD-like scenario, with a strong (running) coupling constant $\alpha_{\rm v}$ and confinement scale $\Lambda_{\rm v}$. The SM sector could feebly couple to the HS (and the equivalent hadronic v-particles and states) via a neutral $Z'$ or via heavy particles bearing both $G_{\rm SM}$ and $G_{\rm v}$ charges. Here, we consider the latter possibility along the lines of the Monte Carlo (MC) study using PYTHIA [17], where the hidden shower is basically controlled by two parameters: the coupling strength $\alpha_{\rm v}$, assumed to be a constant (i.e., no running is considered), and the lower cut-off scale set equal to 0.4 GeV as by default in QCD showers, consistent with a low hidden confinement scale $\Lambda_{\rm v}$. Such a simplified picture is compatible with the expected walking behavior requiring a strong coupling over a large energy window along the showering before reaching $\Lambda_{\rm v}$, thereby yielding a large number of hidden partons and final-state particles. At the end, the energy from the primary interaction is democratically shared by soft final-state SM particles, while no classical jet structure is expected, thereby adapting quite well to a soft-bomb scenario. As previously mentioned, the ultimate goal in this paper is to show that long-range azimuthal correlations among final-state particles should emerge as a consequence of such a scenario.

## 2. Hidden Valley Scenario

Focusing only on the particle content relevant to the study presented here, we collectively denote by $Q_v$ the (spin 1/2) hidden partners of the SM quarks, charged under both $G_v$ and $G_{SM}$, while $g_v$ and $q_v$ stand for the v-gluon and (spin 0) v-quark only charged under the $G_v$ hidden group, respectively (the notation used follows that of [17] for the HS in the PYTHIA 8 MC generator).

The unparticle scenario, which can be viewed as a special case of HV models, deserves special mention. Let us recall that, from a phenomenological point of view, an unparticle [18] does not have a fixed invariant mass squared, but instead a continuous mass spectrum. As pointed out in the literature (see e.g., [19]), direct detection of unparticle stuff at colliders should rely on peculiar missing energy distributions. The influence of unparticle production on particle correlations would become another useful tool to study such a scenario, as shown in this work.

For some parameter values of HV models, hidden particles could promptly decay back into SM particles, altering the subsequent conventional parton shower [20] and yielding (among others [4]) observable consequences, e.g., extremely long-range correlations, especially in azimuthal space [21]. In this paper, we do not enter into details about specific models but limit ourselves to general features associated with the production of very massive objects on top of the parton shower and their observable consequences, mainly from kinematic constraints.

Our analysis focuses on $Q_v$ pair production via $gg$ or $q\bar{q}$ fusion (see Figure 1) subsequently decaying into a v-quark and an SM quark: $Q_v \to q_v + q + X$, where $X$ stands for an ensemble of radiated gluons and v-gluons which, in turn, will originate visible and hidden parton cascades. Note that a very massive $Q_v$ would be produced at a rather low velocity during the primary parton–parton interaction in $pp$ collisions at the LHC. In fact, assuming that the center-of-mass subenergy of the parton–parton interaction is of the order of or higher than twice the magnitude of the mediator mass ($\sqrt{\hat{s}} \geq 2M_{Q_v}$), then $Q_v$ states can be on-shell pair-produced. Moreover, all (either SM or hidden) particles stemming from its decay should have access to a limited energy due to v-gluon radiation. In sum, final particles would "democratically" share the center-of-mass energy released in the primary collision, and rather soft and diffuse signatures are expected.

Below, we consider very heavy hidden sources moving non-relativistically for kinematic estimates involving angular distributions. Then, velocity may become a well-defined physical and meaningful quantity when dealing with heavy particles [22]. Moreover, we assume an isotropic parton emission in the hidden particle rest frame, coming out from the primary interaction and slightly boosted in the laboratory reference frame due to a non-relativistic velocity of the above-mentioned very massive hidden source. Both assumptions provide the essential framework for our estimates and conclusions.

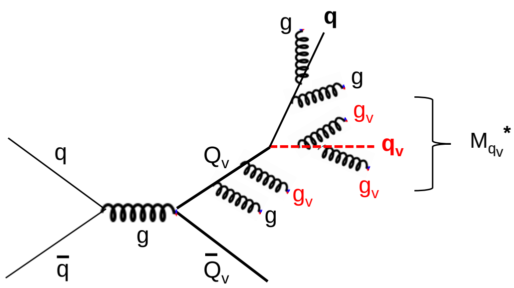


**Figure 1.** Pair production via $q\bar{q}$ fusion of a pair of mediators ($Q_v\bar{Q}_v$) bearing both Standard Model (SM) and hidden charges. The decay $Q_v \to q + q_v$ can originate SM and hidden cascades from gluon and v-gluon emission.

In the hidden source $Q_{\rm v}$ rest frame, the product of the velocity $v_{\rm h}$ and the Lorentz factor $\gamma_{\rm h} = \left(1 - v_{\rm h}^2\right)^{-1/2}$ of the fragmenting v-quark is roughly given by

$$v_{\rm h}\gamma_{\rm h} = \frac{M_{Q_{\rm v}}^2 - M_{q_{\rm v}}^{\rm eff\,2}}{2M_{Q_{\rm v}}M_{q_{\rm v}}^{\rm eff}}\ , \tag{3}$$

where the bare $q$-mass is set equal to zero. The effective v-quark invariant mass, denoted as $M_{q_{\rm v}}^{\rm eff}$, is defined in a similar way to conventional QCD jets, i.e.,

$$M_{q_{\rm v}}^{\rm eff} = \sqrt{(\sum_j E_j)^2 - (\sum_j \vec{p}_j)^2}\ , \tag{4}$$

where $E_j$ and $\vec{p}_j$ stand for the energy and three-momentum of the v-gluons emitted by the fragmenting v-quark, respectively, and the sum on $j$ runs over all emitted v-gluons. Even though the bare $q_{\rm v}$-mass could be as light as 10 GeV, $M_{q_{\rm v}}^{\rm eff}$ can reach values close to $M_{Q_{\rm v}}$ because of radiation, as happens in QCD jets [17]. This would especially be the case for a strongly interacting hidden/dark sector, i.e., at large $\alpha_{\rm v}$. We look upon expression (3) as providing an order of magnitude estimate of the v-quark velocity. Of course, large variations of the $v_{\rm h}\gamma_{\rm h}$ factor will occur event by event because of the wide spread of $M_{q_{\rm v}}^{\rm eff}$.

In their turn, bound v-states can be formed as v-gluons create new v-quark-antiquark pairs, as happens with gluons in a conventional QCD shower. In HV models with v-hadrons promptly decaying back into SM partons, a new SM parton cascade would be originated (coexisting with invisible particles), eventually leading to final-state SM particles as well. Furthermore, as the $q_{\rm v}$ radiates more and more v-gluons and the mean value of its effective mass $M_{Q_{\rm v}}^{\rm eff}$ distribution shifts from $M_{q_{\rm v}}$ towards $M_{Q_{\rm v}}$, more and more energy is subtracted from the visible quark and its associated system of emitted gluons. In sum, a strong coupling $\alpha_{\rm v}$ should lead to small velocities of both SM and hidden particles.

Indeed, under a Lorentz boost of velocity $v_{\rm h}$, the angular distribution of the final-state particles in the laboratory reference frame (LRF), with the latter almost coinciding with the fragmenting $q_{\rm v}$ reference frame, is given by [23]

$$w(\phi - \phi_{\rm h}) = \frac{1}{\gamma_{\rm h}[1 - v_{\rm h}^2\cos^2(\phi - \phi_{\rm h})]}\ f(\phi, g)\ . \tag{5}$$

Here, $f(\phi, g) = (g \pm \sqrt{D})/\pm\sqrt{D}$ with $D = 1 + \gamma_{\rm h}^2(1 - g^2)\tan^2(\phi - \phi_{\rm h})$, and $g = v_{\rm h}/v$ with the final-state particle velocity $v$ in the $q_{\rm v}$ rest frame. For $g \ll 1$, one can roughly set $f(\phi, g) \approx 1$. A massive hidden object of spin zero, as assumed for the fragmenting v-quark in this work (leading to a nearly spherical distribution in the $q_{\rm v}$-quark reference frame), with $v_{\rm h}$ being non-relativistic, plainly justifies such an approximation.

For practical purposes, the azimuthal distribution $w(\phi - \phi_{\rm h})$ can then be approximated by a Gaussian distribution for small $\phi - \phi_{\rm h}$ angles, namely

$$w(\phi - \phi_{\rm h})\ \approx\ \exp\left[-\frac{(\phi - \phi_{\rm h})^2}{2\delta_{{\rm h}\phi}^2}\right]\ ,\ \delta_{{\rm h}\phi}\ \simeq\ \frac{1}{\sqrt{2}\,v_{\rm h}\gamma_{\rm h}}\ , \tag{6}$$

where $\delta_{\rm h Œ}$ was interpreted as an azimuthal cluster "width" in [24,25]. As we are focusing on azimuthal angles, the particle trajectories are projected onto the transverse plane, hence the velocities $v_{\rm h}$ and $v$ and the Lorentz factor $\gamma_{\rm h}$ actually correspond to transverse velocities. Large hidden source velocities lead to small $\delta_{{\rm h}\phi}$ and thereby a more pronounced peak at $\phi \simeq \phi_{\rm h}$, in accordance with Equation (5). Conversely, small velocities of the hidden source lead to flatter azimuthal distributions.

## 3. Results on Two-Particle Azimuthal Correlations

Substituting Equation (3) into Equation (6) for $\delta_{h\phi}$, one gets

$$\delta_{h\phi} \simeq \frac{\sqrt{2}M_{Q_v}M_{q_v}^{\text{eff}}}{M_{Q_v}^2 - M_{q_v}^{\text{eff}2}} , \quad (7)$$

where $M_{q_v}^{\text{eff}}$ stands for the effective mass resulting from v-gluon radiation, as mentioned above.

Next, by Taylor expanding the exponential, we can identify the above expression with a cosine function such that $1/\delta_{h\phi}$ determines the leading Fourier component of the NP contribution from a given range of the effective v-quark mass. As reference values, we set $M_{Q_v} = 1000$ GeV and $M_{q_v}^{\text{eff}} = 700$ GeV [17], yielding the closest fractional number

$$\frac{1}{\text{Integer}[\delta_{h\phi}]} = \frac{1}{2} . \quad (8)$$

This estimate can be extended to the mass interval of the v-quark invariant mass $M_{q_v}^{\text{eff}} \in [630, 760]$ GeV, leading to the NP contribution

$$w(\phi - \phi_h) \approx \cos[(\phi - \phi_h)/2] \quad (9)$$

from this $M_{q_v}^{\text{eff}}$ mass "slice".

By integration of the product of the two single particle azimuthal distributions, one gets

$$C(\Delta\phi) \approx \frac{1}{2\pi}\int_0^{2\pi} \cos[(\phi_1 - \phi_h)/2] \cos[(\phi_2 - \phi_h)/2] \, d\phi_h = 2 \cos[(\phi_1 - \phi_2)/2] . \quad (10)$$

In Figure 2 we show the expected angular dependence of the corresponding Fourier term in the correlation function $C(\Delta\phi)$ for two reference benchmarks: *(a)* $M_{Q_v} = 300$ GeV and $M_{q_v}^{\text{eff}} = 200$ GeV, and *(b)* $M_{Q_v} = 1000$ GeV and $M_{q_v}^{\text{eff}} = 700$ GeV. All hidden initial sources from the primary collision originating the subsequent visible/invisible shower are assumed to be non-relativistic ($g$ is taken of the order of 0.1 in Equation (5)). A comparison with the $\cos(\Delta\phi/2)$ modulation, shown in the same plot, indicates that the HS contribution should yield a Fourier component dominated by this term (not yet considered so far in any analysis to our knowledge).

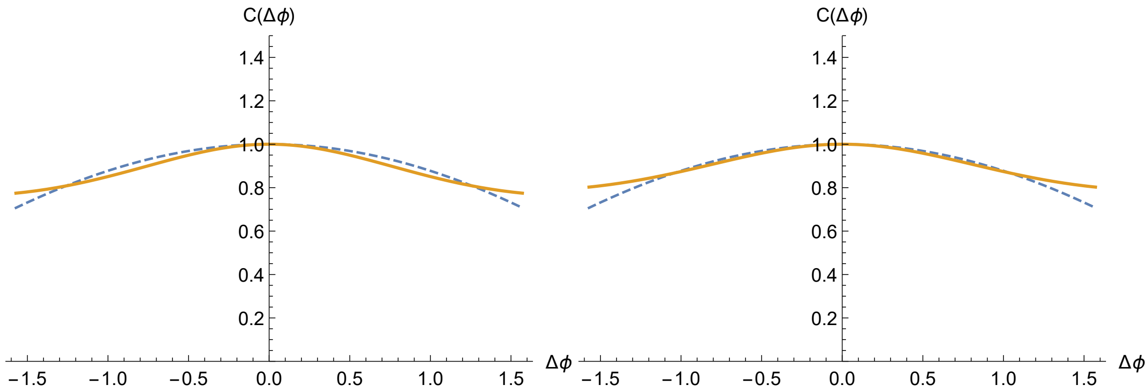


**Figure 2.** Expected contribution to the azimuthal dependence of the correlation function $C(\Delta\phi)$ from a massive hidden/dark sector (solid orange line). **Left panel**: $M_{Q_v} = 300$ GeV and $M_{q_v}^{\text{eff}} = 200$ GeV. **Right panel**: $M_{Q_v} = 1000$ GeV and $M_{q_v}^{\text{eff}} = 700$ GeV. Non-relativistic hidden sources are considered in both cases. The correlation function is normalized to unity at $\Delta\phi = 0$, to be compared with a $\cos(\Delta\phi/2)$ modulation function (dotted blue line), indicating the existence of long-range azimuthal correlations.

Actually, more fractional harmonic terms should be considered as the whole mass range of the effective mass $M_{q_v}^{\text{eff}}$ (up to $M_{Q_v}$) is taken into account in the expected continuous spectrum obtained from radiation [17]. Hence, the Fourier series should be more generally written as

$$C(\Delta\phi) \sim 1 + 2\sum_{n=1}^{\infty} V_n \cos(n\Delta\phi) + 2\sum_{m=1}^{\infty} V'_{1/m} \cos(\Delta\phi/m) \,, \tag{11}$$

where the extra $\cos(\Delta\phi/m)$ harmonic terms encode the angular anisotropies associated with massive hidden states modifying the parton shower and thereby correlations among final-state particles. The $V'_{1/2}$ term should be the leading component in these fractional harmonic terms. Note that the $\cos(\Delta\phi)$ term now has two contributions: a negative one ($V_1 < 0$) from the conventional series of Equation (2) and another positive one ($V'_1 > 0$) expected from a HS.

## 4. Discussion and Conclusions

Of course, the Fourier analysis using Equation (11) will contain contributions from both the conventional partonic cascade and from the hidden sector. In order to enhance such a hypothetical NP contribution, extra selection cuts beyond high multiplicity and usual $p_T$ ranges of charged hadrons should be applied on events, in particular high $p_T$ leptons and/or missing transverse energy/momentum.

Indeed, multi-lepton signatures have already been used in the search of NP at the LHC (see e.g., [26,27]) as they are predicted by many models beyond the SM. For example, a cascade of partons/particles initiated by the decay of a heavy hidden particle can proceed though intermediate states, yielding electrons, muons, or tau leptons in the final state. Realistic requirements would imply an electron or muon with $p_T > 20$ GeV and $|\eta| < 2.5$, a second electron or muon with slightly looser requirements, and a third electron, muon, or hadronically decaying tau. Moreover, lepton combinations of the same electric charge can be used to enhance the NP signature. Additional cuts can be large missing $E_T$ since the hidden/conventional cascade can result in invisible particles at the end of the decay chain. Lastly, as the decay of hidden particles to bottom quarks can be significantly enhanced in many hidden models, *b*-tagging would be another technique to enrich the sample with NP events.

Note that such proposed cuts (aside from a common high-multiplicity cut) could hardly be attributed to the formation of QGP or glass condensates, but are associated with the presence of NP.

Thereby, the sample would be enriched with NP events enhancing the ridge effect due to this non-standard mechanism. Then, the non-vanishing values of $V'_{1/2}$, $V'_{1/3}$ and so on, resulting in a better fit than the conventional Fourier analysis, provide a hint of NP, complementary to other kinds of searches.

Let us finally remark that, based on the observation of a near-side ridge effect in hadronic collisions, an integrated luminosity on the order of tens of pb$^{-1}$ would be needed to observe any possible NP emergent effect, provided that the HS production cross-section turns out to be large enough, which crucially depend on the $Q_v$ mass [17]. In order to avoid pile-up effects, a dedicated low-luminosity run would be desirable at the LHC.

Summarizing, hidden/dark sector production on top of the parton shower in *pp* collisions can considerably alter final-state particle correlations, becoming a signature of NP. This conclusion bears a resemblance to the finding of the ridge phenomenon in heavy ion collisions. Specifically, more fractional $\cos(\Delta\phi/m)$ harmonic terms should be included in the Fourier series when carrying out the analysis of the azimuthal correlation function $C(\Delta\phi)$, once appropriate NP selection cuts are applied to events. These extra fractional harmonic terms would capture the existence of very long range correlations.

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