

Multiboson splashes at future colliders from electroweak compositeness

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We propose a new collider signature for the composite origin of the electroweak symmetry breaking of the standard model. The Higgs sector consists of new fundamental fermions (hyperquarks), which confine at a hadronization scale $\Lambda_{\text{HC}} \sim \text{few TeV}$. At energies above Λ_{HC} , the Drell-Yan production of the hyperquarks leads to the production of a few electroweak bosons, in analogy with hadron production in QCD at $e^+e^- \rightarrow q\bar{q}$ around a few GeV. We show that this regime can be probed at future colliders, namely the proposed 100 TeV hadron collider (FCC-hh) and a 10 TeV muon collider. Together with the direct discovery of electroweak resonances, the multi-electroweak boson signature provides a smoking gun for Higgs compositeness.

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The origin of the electroweak (EW) symmetry breaking in the Standard Model (SM) remains unresolved. A class of models that aims at providing a dynamical explanation poses the Higgs boson as a bound state within a new composite sector akin to QCD, where spontaneous symmetry breaking arises. A scaled-up version of QCD, dubbed Technicolor (TC), was the first concrete realization [1,2]. A generic TC-like model consists of a new fundamental fermionic sector (made of hyperquarks, q_{HC}), charged under the EW group, and a new confining hypercolor (HC) group G_{HC} . Similarly to QCD, the new dynamics is characterized by a new physics scale $\Lambda_{\text{HC}} \sim \mathcal{O}(\text{few}) \text{ TeV}$, where q_{HC} bound states are present. In this setup, the longitudinal polarization of the EW bosons and the Higgs emerge as light resonances below Λ_{HC} .

If the q_{HC} condensate breaks the EW symmetry, then one would naturally expect $\Lambda_{\text{HC}} \sim 1 - 3 \text{ TeV}$. There are models where the condensate also features an EW-preserving

direction, and the EW symmetry breaking is due to misalignment [3], hence allowing for larger Λ_{HC} up to tens of TeV. In those models, the Higgs boson emerges as a pseudo-Goldstone, while a TC-like direction can always be reached continuously [4]. The scale Λ_{HC} serves as an indicator beyond which the composite theories can be treated in terms of the fundamental hyperquarks and hypergluons and beyond the chiral approximation. Investigations for compositeness at past and current colliders, such as the Large Electron-Positron (LEP) and the Large Hadron (LHC) colliders, have been focused either on precision measurements in the EW sector (gauge and Higgs couplings) or on searches for individual resonances. This strategy was mainly due to the limited energies in the individual collision, reaching up to a few TeV at partonic level. This work sketches out a novel strategy for the exploration of TC-like theories at future higher energy colliders, where large multiplicities of composite resonances are produced.

The exploration of strongly-interacting theories at colliders can be classified into regimes that depend on the available collision energy, as parametrized by partonic Mandelstam variable $\hat{s}$. For $\sqrt{\hat{s}} < \Lambda_{\text{HC}}$, chiral expansion is used to study the direct production of a small (one or two) number of light resonances. For $\sqrt{\hat{s}} > \Lambda_{\text{HC}}$, instead, the production of resonances can be parametrized in terms of perturbative matrix elements involving hyperquarks and hypergluons. Hence, irrespective of the theory, whether QCD or TC-like, the corresponding regimes can be conveniently quantified by the ratio $\sqrt{\hat{s}}/\Lambda$. In the case

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of QCD, the inclusive measurement for $e^+e^- \rightarrow$ multi-mesons is consistent with the evaluations from the perturbative matrix element $\mathcal{M}(e^+e^- \rightarrow q\bar{q})$ at energies above ~ 2 GeV. The mesons are formed from the outgoing quarks by a process of fragmentation and hadronization [5,6]. Depending on the number of produced mesons, the value of $\sqrt{\hat{s}}/\Lambda_{\text{QCD}}$ can further classify the perturbative regime into two broad categories:

- (i) $\sqrt{\hat{s}}/\Lambda_{\text{QCD}} \sim \mathcal{O}(1-10)$ leads to the production of a small number of mesons (process $2 \rightarrow \text{few}$). In this regime, data is described in terms of R ratios [7–9].
- (ii) $\sqrt{\hat{s}}/\Lambda_{\text{QCD}} \gg \mathcal{O}(10)$ leads to $2 \rightarrow$ many mesons, with the final states characterized in terms of QCD jets rather than explicit meson multiplicities. An example is collisions at the Z pole at LEP [10,11].

Although the boundary between $2 \rightarrow \text{few}$ and $2 \rightarrow$ many regimes is not well defined, this classification helps define the final state. A similar framework can be used in TC-like theories. The analog of QCD-mesons (π 's etc.) are “EW bosons,” i.e., the lightest bound states of the hyperquarks. They are identified as (pseudo)scalars that are not charged under QCD's $SU(3)$ and have masses around the EW scale. The “EW bosons” include the longitudinal components of the massive gauge bosons and the Higgs, together with other spin-0 states, whose number and properties depend on the global symmetry of the specific TC-like model. If we consider a benchmark $\Lambda_{\text{HC}} = 2$ TeV, the regime $2 \rightarrow \text{few}$ would occur if $\sqrt{\hat{s}} \sim 10$ TeV. On the other hand, $\sqrt{\hat{s}} \gtrsim 50$ TeV would be necessary for the realization of the $2 \rightarrow$ many regime. While the latter is beyond the reach of any foreseeable terrestrial accelerator, the former regime with $\sqrt{\hat{s}} \sim 10$ TeV can be reached at the proposed 100 TeV hadron collider (FCC-hh) [12] and at a high-energy muon collider [13].

In this paper, we present a proof-of-principle study of $2 \rightarrow \text{few}$ EW-boson process in TC-like theories at future high energy colliders. The pair production $pp(q\bar{q}')/\mu^+\mu^- \rightarrow q_{\text{HC}}\bar{q}'_{\text{HC}}$, followed by fragmentation and hadronization under G_{HC} , is treated as the analog of $e^+e^- \rightarrow q\bar{q}$ in QCD at low-energy colliders. In both cases, the hadronizing quarks are produced via their EW interactions. We show that such a multi EW-boson final state yields characteristic kinematic properties, which allow for a clear distinction from purely SM processes. This signature, together with the direct discovery of light resonances (produced singly or in pairs), provides a smoking gun for the discovery of composite dynamics in the Higgs sector.

For concreteness, we consider a strong dynamics as close as possible to that of QCD, hence $G_{\text{HC}} = SU(N)_{\text{HC}}$ with q_{HC} in the fundamental representation.¹ In the most minimal

model, the hyperquarks are organized into doublets under the global flavor symmetry $G_F \equiv SU(2)_L \times SU(2)_R$:

$$q_{\text{HC}} \equiv \begin{pmatrix} U \\ D \end{pmatrix}_L \oplus \begin{pmatrix} U \\ D \end{pmatrix}_R. \quad (1)$$

The flavor symmetry is partly gauged by the EW symmetry $G_{\text{EW}} = SU(2)_L \times U(1)_Y$. These fields transform under $SU(N)_{\text{HC}} \times G_{\text{EW}}$ as follows:

$$\begin{pmatrix} U \\ D \end{pmatrix}_L \equiv (N, 2, y), \quad U_R \equiv \left(N, 1, y + \frac{1}{2}\right), \\ D_R \equiv \left(N, 1, y - \frac{1}{2}\right).$$

At a scale Λ_{HC} , the formation of a hyperquark condensate,

$$\langle \bar{U}_L U_R \rangle = \langle \bar{D}_L D_R \rangle \neq 0, \quad (2)$$

is responsible for the breaking of the flavor symmetry to its diagonal subgroup, $G_F \rightarrow H \equiv SU(2)_V$. In this minimalist construction, the three Goldstone bosons are identified with the longitudinal components of the $W^\pm$ and Z gauge bosons, while the analog of the CP -even σ meson can be identified with the Higgs boson [16–19]. Instead of identifying individual bosons, we label all mesons as EW-gauge bosons to remain model agnostic. Note that, for $N = 2$ ($y = 0$), this model corresponds to the ultramiminal Technicolor of [20], which also allows one to embed the Higgs as a pseudo-Goldstone boson [4,21] thanks to an enhanced global symmetry. Instead, $N = 3$ ($y = 1/6$) leads to the old-school Technicolor [1,2], where a light σ -Higgs can be obtained via the addition of heavy TC-quark flavors [22,23]. Furthermore, top partial compositeness [24] can also be implemented by means of the same heavy flavors [25]. Finally, $N = 4$ models have also been considered within the framework of partial compositeness in [26,27]. Models with extended global symmetries can also be constructed, leading to the presence of additional light EW bosons [28,29] that will decay predominantly into pairs of EW gauge bosons or third generation fermions [27,30]. In some models, the EW bosons may include a dark matter candidate [31–35], hence leading to missing energy in the decay. In the following we only consider TC-like models, where Λ_{HC} is closely related to the EW scale via the meson decay constant $f_\pi \sim \frac{\sqrt{N}}{4\pi} \Lambda_{\text{HC}}$, with $f_\pi \equiv v = 2m_W/g$. In models where the Higgs emerges as a pseudo-Goldstone, a hierarchy between f_π and v is necessary, with typically $v/f_\pi \lesssim 0.1$ [36,37], hence leading to values of Λ_{HC} too large to be accessible at future colliders in the $2 \rightarrow \text{few}$ regime. Higgs coupling measurements to gauge bosons provide one of the strongest bound on Λ_{HC} . The existing constraints permit $\sim 3\%$ deviation with an improvement up to 1% expected at HL-LHC and consistent with $\Lambda_{\text{HC}} \sim 2$ TeV. Probing larger values of Λ_{HC} requires a

¹Our discussion is also applicable to larger number of flavors and colors, as long as the fermion multiplicity falls below the conformal windowsill [14]. Beyond this regime, simulating the so-called near-conformal theories needs new developments in PYTHIA [15].

subpercent sensitivity that is expected at muon colliders and the FCC-ee/hh facilities. The Supplementary Material [38] (see also Refs. [12,39–51] therein) offers a detailed insight on the different regimes of Λ_{HC} that can be probed by the current and future experiments.

For the collider signatures, we consider Drell-Yan production of hyperquark pairs for both the FCC-hh and muon colliders as follows:

(A) $pp \rightarrow q_{\text{HC}}\bar{q}_{\text{HC}}$ and

(B) $\mu^+\mu^- \rightarrow q_{\text{HC}}\bar{q}_{\text{HC}}$.

The processes are simulated using MADGRAPH [52] and PYTHIA [53] at 100 TeV and 10 TeV center-of-mass energy, respectively. The data was generated from the PYTHIA codes in [54]. The production is due to EW gauge bosons, following the quantum numbers specified above (for $y = 0$). After hadronization, the outgoing EW bosons are required to be in the central region of the detector, satisfying a pseudorapidity cut $|\eta| < 2.5$. In the minimal setup, the final state bosons will be composed of the longitudinal components of the gauge bosons, $W^\pm$ and Z . In the extended setups, other bosons in the electroweak coset G_F/H , will also be formed. Other heavy resonances, with masses around Λ_{HC} will also be produced during hadronization, such as spin-1 TC- ρ mesons.

Several parameters govern the properties of the signal in our model, e.g., the multiplicity, phase-space distributions of the EW bosons. They correspond to the process of fragmentation as well as hadronization, as implemented in the PYTHIA HV module [55,56]. Among those are ProbVector, $a_L, b_L, r_Q, \sigma_{m_q}$ —parameters that control the hadronization—and Λ_{HC} together with the order of running coupling—parameters that control fragmentation or shower [57]. We chose to investigate a subset of these parameters, which have the largest impact on the signal properties. ProbVector controls the probability for a formed meson to be a ρ , as it ranges from 0 to 1, and its value should be fitted from data. As we are close to the chiral limit, $m_\pi \ll m_\rho$, the value for this parameter cannot be easily fixed [58]. We use the QCD template value 0.3, while noting that its increase reduces the scalar mesons multiplicity in the final state. The decay $\rho \rightarrow \pi\pi$ could also further enrich the pion multiplicity; however, in realistic models, other decay channels are also open, rendering the final state model dependent, even in the most minimal model [59–61]. Hence, in our analysis, we conservatively ignore them and only count the scalar states directly produced via the hadronization. We also concentrate on a_L, b_L , which are two dimensionless parameters entering the Lund fragmentation function [62,63]. Given the absence of data for TC-like models, the values of the Lund parameters are chosen to be the same as the values recommended for QCD ($a_L = 0.3$, and $b_L = 0.087$) [58]. The constituent quark mass is set to Λ_{HC} . The Supplemental Material [38] provides further insights on the dependence of the results on these parameters.

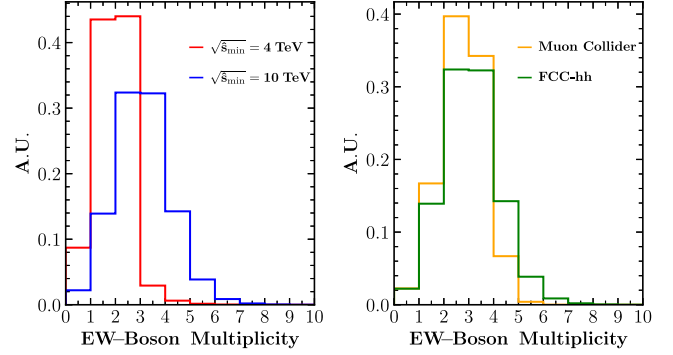


FIG. 1. Final state EW boson multiplicity. *Left*: Distribution at FCC-hh for $\sqrt{s_{\text{min}}} = 4$ TeV (red) and $\sqrt{s_{\text{min}}} = 10$ TeV (blue). *Right*: Comparison between the FCC-hh at $\sqrt{s_{\text{min}}} = 10$ TeV (green) and a muon collider at fixed $\sqrt{s} = 10$ TeV (orange).

The length of shower is controlled by the ratio $\sqrt{s}/\Lambda_{\text{HC}}$, and thus, it is an important parameter in determining the final-state EW boson multiplicity. This is illustrated in the left plot of Fig. 1, where the meson multiplicity for a minimum partonic collision energy $\sqrt{s_{\text{min}}} = 4(10)$ TeV (red, blue curves) is shown for fixed $\Lambda_{\text{HC}} = 2$ TeV. As the constituent quark mass is set to Λ_{HC} , the kinematics for the Drell-Yan production automatically ensures that the minimum invariant mass is $\sqrt{s_{\text{min}}} = 4$ TeV. At this point, no shower is initiated, and hence, the corresponding distribution (red curve) peaks at two bosons. On the other hand, $\sqrt{s_{\text{min}}} = 10$ TeV allows for a perturbative $q_{\text{HC}}\bar{q}_{\text{HC}}$ production process, followed by shower and hadronization, resulting in larger multiplicities. This is reflected in the blue curve where the boson multiplicity peaks at three. The tail of the distribution as seen in Fig. 1 results from variation of partonic center-of-mass energy $\sqrt{s} > \sqrt{s_{\text{min}}}$, in a pp system. The corresponding plot for the muon collider, operating at a fixed $\sqrt{s}$, has a significantly suppressed tail. The right plot of Fig. 1 quantifies this statement by comparing the expected EW boson multiplicity for FCC-hh and muon colliders.

The signal, with a desired multiplicity of final state bosons, has an irreducible SM background of the form $pp(\mu\mu) \rightarrow XY, XYZ$, where $X, Y, Z \equiv \text{EW bosons } (W^\pm, Z)$. The higher multiplicity final states in the background are primarily due to pair production of off-shell EW bosons and their eventual decay into multibody final states. The background cross sections are evaluated at leading order from MADGRAPH [52] and PYTHIA [53] by requiring that each of the EW boson in the final state satisfies $|\eta| < 2.5$. The signal cross sections are estimated by factoring the Drell-Yan cross section [$\sigma(pp/\mu\mu \rightarrow q_{\text{HC}}\bar{q}_{\text{HC}})$] with the corresponding efficiency for the three and four body final state. These cross sections can be estimated for different multiplicity of final states. For illustration, we consider $\Lambda_{\text{HC}} = 2$. For three boson EW bosons final state, signal cross sections are ~ 64 ab at FCC-hh with $\sqrt{s_{\text{min}}}/\Lambda_{\text{HC}} = 5$

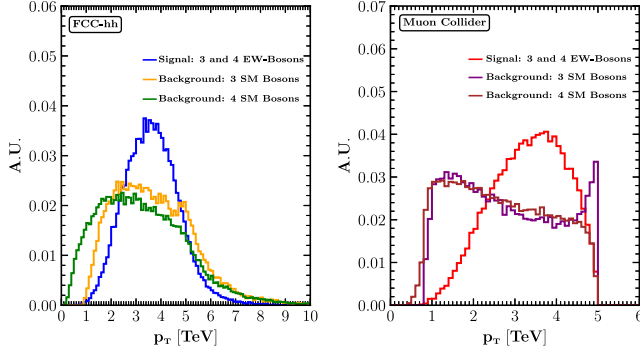


FIG. 2. Leading p_T distribution of the EW bosons (signal), and the three and four SM bosons for FCC-hh (left) and muon collider (right).

and ~ 758 ab at the muon collider with $\sqrt{\hat{s}}/\Lambda_{\text{HC}} = 5$. The corresponding values for the background are ~ 422 and ~ 4701 ab, respectively. The numbers for the four boson final state can also be similarly estimated and reflect similar patterns of hierarchy between the signal and the background.

It is interesting to note that the signal and SM cross sections are roughly of the same order of magnitude. This paints a highly optimistic scenario for a potential discovery of a multi-EW boson final state due to fragmentation. This situation is further bolstered by comparing the transverse momentum (p_T) distribution of all the EW bosons for both the signal, with $\Lambda_{\text{TC}} = 2$ TeV, and background. Choosing $\sqrt{\hat{s}_{\text{min}}}/\Lambda_{\text{HC}} = 5$ for FCC-hh and $\sqrt{\hat{s}}/\Lambda_{\text{HC}} = 5$ for the muon collider, the distribution is shown in Fig. 2. The top and bottom plots correspond to the FCC-hh and muon collider, respectively. All the EW bosons from the signal have consistently higher p_T , as they emerge from the fragmentation of the (heavy) hyperquarks and are predominantly produced in the transverse plane. On the other hand, the EW bosons from the background have a tendency to be in the forward direction, and typically only one of the total of three and four bosons in the final state is boosted. Thus, the signal event rate in the higher p_T bins is expected to be at least comparable with the background. The p_T distribution for the FCC-hh has a smoother longer tail as larger values of partonic center-of-mass energy is accessible. On the other hand, the distribution for the muon collider exhibits a sharp cutoff at 5 TeV as it is operated at a fixed center-of-mass energy of 10 TeV.

Hence, the ratio $\sqrt{\hat{s}}/\Lambda$ plays a crucial role in the ability to identify a signal over the background. While higher values of the ratio $\sqrt{\hat{s}}/\Lambda$ would lead to higher p_T bosons and higher multiplicity of final states for the signal, one would be limited by a falling cross section for the signal. As an illustration, Table I shows the cross sections at FCC-hh after cuts for $\Lambda_{\text{HC}} = 2$ TeV and three different values of the ratio, $\sqrt{\hat{s}_{\text{min}}}/\Lambda = 5, 10, 15$. We also remark that for fixed

TABLE I. Comparison of SM (σ_{SM}) and signal (σ_{sig}) cross sections for $\Lambda_{\text{HC}} = 2$ TeV at FCC-hh. Three and four boson final state are shown at three different $\sqrt{\hat{s}_{\text{min}}}$.

$\sqrt{\hat{s}_{\text{min}}}$ (TeV)	3 Bosons		4 Bosons	
	σ_{SM} (ab)	σ_{sig} (ab)	σ_{SM} (ab)	σ_{sig} (ab)
10	422.3	64.7	96.6	29.0
20	13.8	0.8	4.8	1.0
30	0.75	0.01	0.4	0.0

$\sqrt{\hat{s}_{\text{min}}}/\Lambda$, the cross sections decrease with increasing Λ_{HC} and grow linearly with N .

The extent in Λ_{HC} to which a given signal can be discriminated over the background can be quantified using the binned sensitivity [64] $Z = \sqrt{\sum_{i=1}^M (2(s_i + b_i) \log[1 + \frac{s_i}{b_i}] - 2s_i)}$, where the sum runs over the bins for a given discriminating variable, and $s_i(b_i)$ is the expected number of signal (background) events in the i th bin at a given luminosity. As p_T is identified as a useful variable to discriminate signal over background, we calculate the Z score using the p_T distributions with bins of size 20 GeV over the range $[0, 10]$ TeV. As the study is meant to be a proof of principle, the EW bosons for both the signal and background are considered as final-state objects. As a result, the Z value corresponds to the maximum possible sensitivity that can be achieved for a given Λ_{HC} . Figure 3 illustrates the sensitivity Z for three and four EW boson final state as a function of Λ_{HC} at FCC-hh, for three different $\sqrt{\hat{s}_{\text{min}}}/\Lambda$ settings/benchmarks. For a given value of Λ_{HC} , an interesting hierarchy in Z between the three different values of $\sqrt{\hat{s}_{\text{min}}}/\Lambda$ emerges. This is because $\sqrt{\hat{s}_{\text{min}}}/\Lambda = 4$ has the maximum cross section for three and four boson final state. For $\sqrt{\hat{s}_{\text{min}}}/\Lambda = 5$, on the other hand, a higher multiplicity of final states is preferred. The 2σ line illustrates the extent to which a bound on Λ_{HC} can be achieved using this methodology. The prospects for a muon collider are relatively less stringent, and only Λ_{HC} up to 3 TeV can be excluded at 95% with this method.

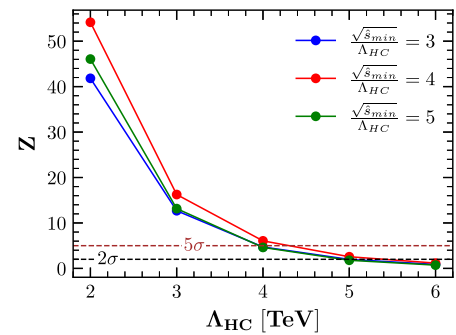


FIG. 3. Variation of Z (signal sensitivity) with Λ_{HC} for fixed $\sqrt{\hat{s}_{\text{min}}}/\Lambda_{\text{HC}}$ ratio.

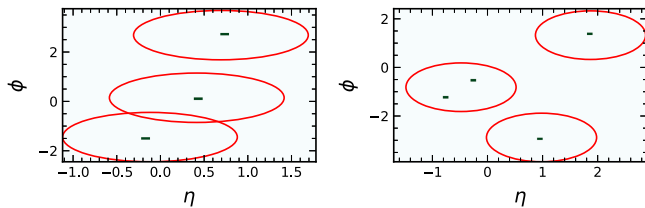


FIG. 4. Visualization of signal in the form of jets with $R = 1$ and represented by closed red contours.

In a complete analysis, the identification of each boson will be performed through its decay products. As the signal EW bosons are highly boosted, their decay products will likely be concentrated in a small angular region and hence can be classified as jets. Figure 4 illustrates the distributions of EW bosons (green dots) in the $\eta - \phi$ plane for two representative events for the signal with $\Lambda_{TC} = 2$ TeV. The region enclosed by the red boundary around each boson represents the circular disc with radius $R < 1$. This indicates the fact that the eventual decay products of the EW bosons will be distributed over a small region and hence identified as boosted jets. The right plot is particularly interesting as it suggests the clustering of two EW bosons in a single jet, which is extremely rare in the SM. The high values of Λ_{HC} and the available energies favor the exploitation of three and four EW boson final states. However, probing higher values of $\sqrt{s}_{\min}/\Lambda_{HC}$ may lead to higher multiplicities, particularly for relatively low values of Λ_{HC} . For example, $\Lambda_{HC} = 2$ TeV and $\sqrt{s}_{\min}/\Lambda_{HC} = 10$, can lead to about 25 signal events that contain five EW boson events. Although this does not seem significant, it must be remembered that it may be associated with negligible backgrounds. Higher multiplicities of EW bosons may also derive from nonminimal models, where the cosets contain additional light scalars in addition to longitudinal W , Z , and Higgs [29,30,65,66], and from the decays of the ρ mesons produced via hadronization. The new scalars could decay into a pair of EW gauge bosons (including the photon), hence providing a new handle into this process. A detailed analysis would crucially depend on the specific model, and it is left for future investigations.

Learning from QCD, we explored a novel regime for models of composite Higgs sectors, corresponding to energies a few times larger than the resonance scale Λ_{HC} . In this regime, the effects of the new strong dynamics can be described in terms of Drell-Yan production of the fundamental hyperquarks, followed by fragmentation and hadronization. We showed that for low values of Λ_{HC} in the few TeV range, a future 100 TeV hadron collider (FCC-hh) and a 10 TeV muon collider provide a picture similar to the one of a few GeV lepton collider for QCD. Higgs compositeness reveals itself by the production of few EW bosons (W , Z and Higgs), which can be kinematically distinguished from the pure standard model backgrounds. We provide a first proof of principle toward the discovery of this regime of TeV-scale strong interactions. This signature provides a clear proxy for the composite nature of the Higgs sector of the standard model and for the dynamical origin of the electroweak symmetry breaking, together with the further direct search for EW-resonances.

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Data availability. The data that support the findings of this article are openly available [54].

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