Experimental verification of two types of gluon jets in QCD

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The Abelian decomposition of QCD tells that there are two types of gluons, the color neutral neurons and colored chromons. We propose to confirm the Abelian decomposition testing the existence of two types of gluon jets experimentally. We predict that one quarter of the gluon jet is made of the neurons which has the color factor $3/4$ and the sharpest jet radius and smallest charged particle multiplicity, while the three quarters of the gluon jet are made of the chromons with the color factor $9/4$, which have the broadest jet radius (broader than the quark jet). Moreover, we argue that the neuron jet has a distinct color flow which forms an ideal color dipole, while the quark and chromon jets have distorted dipole pattern. To test the plausibility of this proposal, we suggest to analyze the gluon distribution against the jet shape (the sphericity) and/or particle multiplicity from the existing gluon jet events and look for two distinct peaks in the distribution.

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I. INTRODUCTION

A common misunderstanding on QCD is that the non-Abelian color gauge symmetry is so tight that it defines the theory almost uniquely and thus, does not allow any simplification. This is not true. The Abelian decomposition of QCD tells that we can construct the restricted QCD (RCD), which inherits the full non-Abelian color gauge symmetry with the restricted potential obtained by the Abelian projection. This tells that QCD has a nontrivial core, RCD, which describes the Abelian subdynamics of QCD but has the full color gauge symmetry. Moreover, it tells that QCD can be viewed as RCD which has the gauge covariant valence gluons as the colored source [1,2]. This is because the Abelian decomposition decomposes the color gauge potential to the restricted potential made of the color neutral gluon potential, the topological monopole potential, and the gauge covariant valence potential, which describes the colored gluon gauge independently.

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There are ample motivations for the Abelian decomposition. Consider the proton made of three quarks. Obviously, we need the gluons to bind the quarks in the proton. However, the quark model tells that the proton has no valence gluon. If so, what is the binding gluon that bind the quarks in proton, and how do we distinguish it from the valence gluon?

Moreover, the simple group theory tells that the color gauge group has the Abelian subgroup generated by the diagonal generators and that the gauge potential, which corresponds to these generators, must be color neutral, while the potential which corresponds to the off diagonal generators must carry the color. This strongly implies that there are two types of gluon, the color neutral ones and colored ones. And they should behave differently, because they have different color charges. If so, how can we distinguish them?

Another motivation is the color confinement in QCD. Two popular proposals for the confinement are the monopole condensation [2,3] and the Abelian dominance [4,5]. To prove the monopole condensation, we first have to separate the monopole potential gauge independently. Similarly, to prove the Abelian dominance, we have to know what is the Abelian part and how to separate it.

The Abelian decomposition tells how to do this. It decomposes the non-Abelian gauge potential to two parts, the restricted Abelian part, which has the full non-Abelian gauge symmetry and the gauge covariant valence part, which describes the colored gluons. Moreover, it separates the restricted potential to the nontopological Maxwell part, which describes the colorless binding gluons and the topological Dirac part, which describes the non-Abelian monopole [1,2].

This has deep consequences. It tells us that QCD has two types of gluons, the color neutral binding gluons (the neurons) and the colored valence gluons (the chromons), which play totally different roles. The neurons, just like the photon in QED, play the role of the binding gluon. On the other hand, the chromons, like the quarks, play the role of the constituent gluon. This has a deep impact in hadron spectroscopy, replacing the quark and gluon model by the quark and chromon model.

Moreover, this allows us to decompose the QCD Feynman diagrams made of the gluon propagators in terms of the neuron and chromon propagators, in such a way that the conservation of color is made explicit.

As importantly, this allows us to prove the Abelian dominance, that RCD is responsible for the confinement [4,5]. This is because the chromons, being colored, have to be confined. So it can not play any role in the confinement. Furthermore, this provides us an ideal platform for us to prove the monopole condensation. Indeed, integrating out the chromons under the monopole background gauge invariantly, we can demonstrate that the true QCD vacuum is given by stable monopole condensation [6,7].

This makes the experimental verification of the Abelian decomposition an urgent issue [8]. The prediction and subsequent confirmation of the gluon jet was a great success of QCD [9,10]. It proved that QCD is indeed the right theory of strong interaction. Moreover, it justified the asymptotic freedom and extended our understanding of QCD greatly [11]. Certainly, the experimental confirmation of the existence of two types of gluons will extend our understanding of QCD to a totally new level. The purpose of this paper is to show how to do this with the existing data on a gluon jet.

II. ABELIAN DECOMPOSITION: A REVIEW

To show QCD has two types of gluons, consider the SU (2) QCD first. Let $(\hat{n}_1, \hat{n}_2, \hat{n}_3 = \hat{n})$ be an arbitrary SU(2) basis and select $\hat{n}$ to be the Abelian direction. Project out the restricted potential $\hat{A}_\mu$, which parallelizes $\hat{n}$ [1,2],

$$
\begin{aligned}
&D_\mu \hat{n} = (\partial_\mu + g\vec{A}_\mu \times)\hat{n} = 0,\\
&\vec{A}_\mu \to \hat{A}_\mu = A_\mu \hat{n} - \frac{1}{g}\hat{n}\times\partial_\mu\hat{n} = \tilde{A}_\mu + \tilde{C}_\mu,\\
&\tilde{A}_\mu = A_\mu \hat{n}, \qquad \tilde{C}_\mu = -\frac{1}{g}\hat{n}\times\partial_\mu\hat{n}.
\end{aligned} \tag{1}
$$

The restricted potential is made of two parts, the nontopological (Maxwellian) $\tilde{A}_\mu$, which describes the colorless neuron and the topological (Diracian) $\tilde{C}_\mu$, which describes the non-Abelian monopole [12,13]. Moreover, it has the full SU(2) gauge degrees of freedom.

With this, we have

$$
\begin{aligned}
&\hat{F}_{\mu\nu} = (F_{\mu\nu} + H_{\mu\nu})\hat{n} = F'_{\mu\nu}\hat{n},\\
&F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu,\\
&H_{\mu\nu} = -\frac{1}{g}\hat{n}\cdot(\partial_\mu\hat{n}\times\partial_\nu\hat{n}) = \partial_\mu C_\nu - \partial_\nu C_\mu,\\
&C_\mu = -\frac{1}{g}\hat{n}_1\cdot\partial_\mu\hat{n}_2,\\
&F'_{\mu\nu} = \partial_\mu A'_\nu - \partial_\nu A'_\mu, \qquad A'_\mu = A_\mu + C_\mu.
\end{aligned} \tag{2}
$$

From this, we can construct RCD which has the full non-Abelian gauge symmetry,

$$
\begin{aligned}
\mathcal{L}_{RCD} &= -\frac{1}{4}\hat{F}^2_{\mu\nu} = -\frac{1}{4}F^2_{\mu\nu}\\
&\quad + \frac{1}{2g}F_{\mu\nu}\hat{n}\cdot(\partial_\mu\hat{n}\times\partial_\nu\hat{n}) - \frac{1}{4g^2}(\partial_\mu\hat{n}\times\partial_\nu\hat{n})^2,
\end{aligned} \tag{3}
$$

which describes the Abelian subdynamics of QCD.

We can express the full SU(2) gauge field adding the gauge covariant colored chromon $\vec{X}_\mu$ to $\hat{A}_\mu$ [1,2],

$$
\begin{aligned}
&\vec{A}_\mu = \hat{A}_\mu + \vec{X}_\mu,\\
&\hat{n}\cdot\vec{X}_\mu = 0, \vec{F}_{\mu\nu} = \hat{F}_{\mu\nu} + \hat{D}_\mu\vec{X}_\nu - \hat{D}_\nu\vec{X}_\mu + g\vec{X}_\mu\times\vec{X}_\nu.
\end{aligned} \tag{4}
$$

With this, we recover the full SU(2) QCD,

$$
\begin{aligned}
\mathcal{L}_{\mathrm{QCD}} &= -\frac{1}{4}\hat{F}^2_{\mu\nu} - \frac{1}{4}(\hat{D}_\mu\vec{X}_\nu - \hat{D}_\nu\vec{X}_\mu)^2\\
&\quad - \frac{g}{2}\hat{F}_{\mu\nu}\cdot(\vec{X}_\mu\times\vec{X}_\nu) - \frac{g^2}{4}(\vec{X}_\mu\times\vec{X}_\nu)^2.
\end{aligned} \tag{5}
$$

This shows that QCD can be viewed as RCD, which has the chromon as the colored source [1,2].

The Abelian decomposition of SU(3) QCD is more complicated but similar [6,7]. Let $\hat{n}_i (i = 1, 2, \ldots, 8)$ be the orthonormal SU(3) basis and choose $\hat{n}_3 = \hat{n}$ and $\hat{n}_8 = \hat{n}'$ to be the two Abelian directions, and make the Abelian projection imposing the condition,

$$
\begin{aligned}
&D_\mu \hat{n} = 0, \qquad D_\mu \hat{n}' = 0,\\
&\vec{A}_\mu \to \hat{A}_\mu = A_\mu \hat{n} + A'_\mu \hat{n}' - \frac{1}{g}\hat{n}\times\partial_\mu \hat{n} - \frac{1}{g}\hat{n}'\times\partial_\mu \hat{n}'\\
&\qquad = \sum_p \frac{2}{3}\hat{A}^p_\mu, \qquad (p = 1,2,3),\\
&\hat{A}^p_\mu = A^p_\mu \hat{n}^p - \frac{1}{g}\hat{n}^p \times \partial_\mu \hat{n}^p = \mathcal{A}^p_\mu + \mathcal{C}^p_\mu,\\
&A^1_\mu = A_\mu, \qquad A^2_\mu = -\frac{1}{2}A_\mu + \frac{\sqrt{3}}{2}A'_\mu,\\
&A^3_\mu = -\frac{1}{2}A_\mu - \frac{\sqrt{3}}{2}A'_\mu, \qquad \hat{n}^1 = \hat{n},\\
&\hat{n}^2 = -\frac{1}{2}\hat{n} + \frac{\sqrt{3}}{2}\hat{n}', \qquad \hat{n}^3 = -\frac{1}{2}\hat{n} - \frac{\sqrt{3}}{2}\hat{n}'. \qquad (6)
\end{aligned}
$$

Notice that, although SU(3) has only two Abelian directions, $\hat{A}_\mu$ can be expressed by three SU(2) restricted potential $\hat{A}^i_\mu$ $(i = 1,\ 2,\ 3)$ in Weyl symmetric way, symmetric under the permutation of three SU(2) subgroups (or equivalently, permutation of three Abelian directions $\hat{n}^i$). With this, we have the Weyl symmetric SU(3) RCD,

$$
\mathcal{L}_{RCD} = -\frac{1}{4}\hat{F}^2_{\mu\nu} = -\sum_p \frac{1}{6}(\hat{F}^p_{\mu\nu})^2, \qquad (7)
$$

which has the full SU(3) gauge symmetry.

Adding the valence part $\vec{X}_\mu$ to $\hat{A}_\mu$, we have the SU(3) Abelian decomposition,

$$
\begin{aligned}
&\vec{A}_\mu = \hat{A}_\mu + \vec{X}_\mu = \sum_p \left(\frac{2}{3}\hat{A}^p_\mu + \vec{W}^p_\mu\right),\\
&\vec{F}_{\mu\nu} = \hat{F}_{\mu\nu} + \hat{D}_\mu \vec{X}_\nu - \hat{D}_\nu \vec{X}_\mu + g\vec{X}_\mu \times \vec{X}_\nu = \sum_p \left[\frac{2}{3}\hat{F}^p_{\mu\nu} + (\hat{D}^p_\mu \vec{W}^p_\nu - \hat{D}^p_\mu \vec{W}^p_\nu)\right] + \sum_{p,q} \vec{W}^p_\mu \times \vec{W}^q_\nu,\\
&\vec{W}^1_\mu = X^1_\mu \hat{n}_1 + X^2_\mu \hat{n}_2, \qquad \vec{W}^2_\mu = X^6_\mu \hat{n}_6 + X^7_\mu \hat{n}_7, \vec{W}^3_\mu = X^4_\mu \hat{n}_4 + X^5_\mu \hat{n}_5, \qquad (8)
\end{aligned}
$$

where $\hat{D}^p_\mu = \partial_\mu + g\hat{A}^p_\mu \times$. Notice that $\vec{X}_\mu$ is decomposed to three (red, blue, and green) SU(2) chromons $(\vec{W}^1_\mu, \vec{W}^2_\mu, \vec{W}^3_\mu)$. Here again, $\vec{A}_\mu$ is expressed in a Weyl symmetric way, but unlike $\hat{A}^i_\mu$, the three chromons are completely independent.

From this, we obtain [6,7]

$$
\begin{aligned}
\mathcal{L}_{\mathrm{QCD}} = &\sum_p \left\{ -\frac{1}{6}(\hat{F}^p_{\mu\nu})^2 - \frac{1}{4}(\hat{D}^p_\mu \vec{W}^p_\nu - \hat{D}^p_\nu \vec{W}^p_\mu)^2 - \frac{g}{2}\hat{F}^p_{\mu\nu}\cdot(\vec{W}^p_\mu \times \vec{W}^p_\nu)\right\} - \sum_{p,q}\frac{g^2}{4}(\vec{W}^p_\mu \times \vec{W}^q_\mu)^2\\
&- \sum_{p,q,r}\frac{g}{2}(\hat{D}^p_\mu \vec{W}^p_\nu - \hat{D}^p_\nu \vec{W}^p_\mu)\cdot(\vec{W}^q_\mu \times \vec{W}^r_\mu) - \sum_{p\neq q}\frac{g^2}{4}[(\vec{W}^p_\mu \times \vec{W}^q_\nu)\cdot(\vec{W}^q_\mu \times \vec{W}^p_\nu) + (\vec{W}^p_\mu \times \vec{W}^p_\nu)\cdot(\vec{W}^q_\mu \times \vec{W}^q_\nu)]. \qquad (9)
\end{aligned}
$$

This is the Abelian decomposition of the Weyl symmetric SU(3) QCD.

We can add quarks in the Abelian decomposition,

$$
\begin{aligned}
\mathcal{L}_q &= \bar{\Psi}(i\gamma^\mu D_\mu - m)\Psi\\
&= \bar{\Psi}(i\gamma^\mu \hat{D}_\mu - m)\Psi + \frac{g}{2}\vec{X}_\mu \cdot \bar{\Psi}(\gamma^\mu \vec{t})\Psi\\
&= \sum_p \left[\bar{\Psi}^p(i\gamma^\mu \hat{D}^p_\mu - m)\Psi^p + \frac{g}{2}\vec{W}^p_\mu \cdot \bar{\Psi}^p(\gamma^\mu \vec{\tau}^p)\Psi^p\right],\\
\hat{D}_\mu &= \partial_\mu + \frac{g}{2i}\vec{t}\cdot\hat{A}_\mu, \qquad \hat{D}^p_\mu = \partial_\mu + \frac{g}{2i}\vec{\tau}^p \cdot \hat{A}^p_\mu, \qquad (10)
\end{aligned}
$$

where m is the mass, p denotes the color of the quarks, and Ψ^p represents the three SU(2) quark doublets ([i.e., (r,b), (b,g), and (g,r) doublets] of the (r,b,g) quark triplet. Notice that here we have suppressed the flavor degrees [6,7].

The Abelian decomposition is expressed graphically in Fig. 1. Although the decomposition does not change QCD, it reveals the important hidden structures of QCD. In particular, it shows the existence of two types of gluons, the neuron and chromon. In the literature, the Abelian

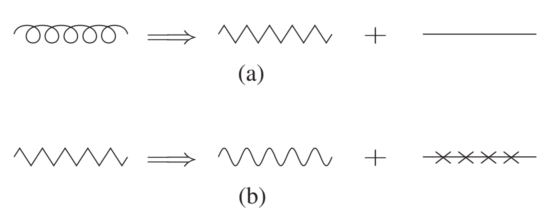

FIG. 1. The Abelian decomposition of the gauge potential. In (a), it is decomposed to the restricted potential (kinked line) and the chromon (straight line). In (b), the restricted potential is further decomposed to the neuron (wiggly line) and the monopole (spiked line).

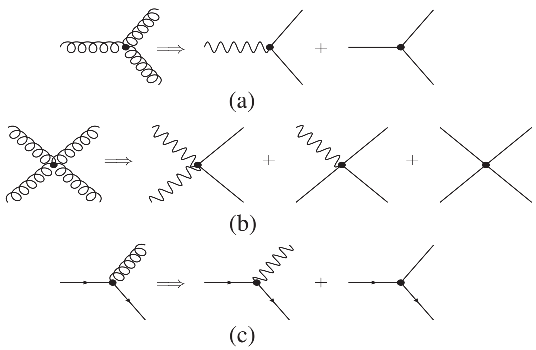

FIG. 2. The decomposition of the Feynman diagrams in SU(3) QCD. In (a) and (b), the three-point and four-point gluon vertices are decomposed, and in (c), the quark-gluon vertices are decomposed. Notice that the monopole does not appear in the Feynman diagrams because it describes topological degree, not dynamical degree.

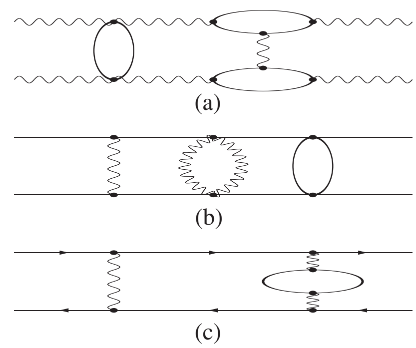

FIG. 3. The possible Feynman diagrams of the neurons and chromons. Two neuron interaction is shown in (a), chromon-antichromon interaction is shown in (b), and quark-antiquark interaction is shown in (c).

decomposition is known as the Cho decomposition, Cho-Duan-Ge (CDG) decomposition, or Cho-Faddeev-Niemi (CFN) decomposition [14–17].

The Abelian decomposition has deep implications. In the perturbative regime, this tells that the Feynman diagram can be decomposed in such a way that the color conservation is explicit. This is graphically shown in Fig. 2. Notice that here the monopole does not appear in the Feynman diagram, because it is not a dynamical degree. Moreover, it makes the condensation so that it has no role in the perturbative regime.

A remarkable feature of the decomposition of the Feynman diagram is that the color conservation is explicit in the decomposition. There are no three-point vertex made of two or three neuron legs, and no four-point vertex made of three or four neuron legs. This is because the color conservation forbids them.

As importantly, this shows that neurons and chromons play totally different roles. The neuron, just like the photon in QED, provides the binding. But the chromons, just like the quarks, become the colored source. This could be shown graphically by the Feynman diagrams of two neuron binding and chromon-antichromon binding shown in Fig. 3.

Notice that the two neuron binding in Fig. 3(a) looks totally different from the other two bindings. The leading order of this binding is of the order of $O(g^4)$, while the leading order of the other two in 3(b) and 3(c) is of the order of $O(g^2)$. Moreover, the neuron binding looks very much like two photon binding in QED, while the chromon-antichromon binding look just like the quark-antiquark binding in QCD.

This strongly implies that the neurons may not be viewed as the constituent of hadrons. In contrast, the chromon binding strongly implies that they, just like the quarks, become the constituent of hadrons. This changes the quark and gluon model to the quark and chromon model, which provides a new picture of hadrons [18,19].

III. MONOPOLE CONDENSATION

In the nonperturbative regime, the Abelian decomposition allows us to proves the Abelian dominance, or more precisely, the monopole dominance, that the monopole plays the central role in color confinement. The logic for the monopole dominance is the following. First, the chromons (being colored) are destined to be confined, so that they can not be the confining agent. This is because the prisoners (who are confined in jail) can not play the role of the jailer (who confines the prisoners).

This means that only the restricted potential plays the important role in the confinement, which proves the Abelian dominance that ’tHooft proposed [1,2,4]. Indeed, theoretically, we can show rigorously that only the restricted potential contributes to the Wilson loop integral which produces the area law for the confinement [5].

But the restricted potential is made of two parts, the nontopological neuron and topological monopole. On the other hand, Fig. 3 tells that the neuron in QCD plays the role of the photon in QED. This implies that it can not play any role in the confinement. This tells that only the monopole can confine the color [6,7].

Indeed, with the decomposition, we can rigorously prove that only the restricted potential contributes to the area law in the Wilson loop integral [5]. This is the Abelian dominance. This can be confirmed numerically in lattice QCD. Implementing the Abelian decomposition on the lattice, we can calculate the Wilson loop integral with the full potential, the restricted potential, and the monopole potential separately, and show that all three potentials produce exactly the same linear confining force Fig. 4 [20,21]. The lattice result for SU(3) QCD is shown in Fig. 4. This tells that the monopole plays the crucial role in the confinement.

On the other hand, this lattice result does not tell how the monopole can confine the color. To show that the monopole confines the color by dual Meissner effect as Nambu

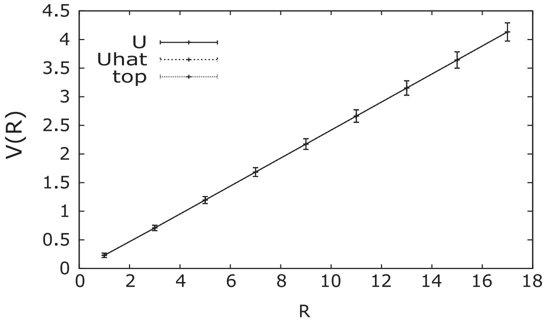

FIG. 4. The SU(3) lattice QCD calculation, which establishes the monopole dominance in the confining force in Wilson loop. Here, the confining forces shown in full, dashed, and dotted lines are obtained with the full potential, the Abelian potential, and the monopole potential, respectively.

and Mandelstam conjectured, we have to demonstrate the monopole condensation in QCD. The Abelian decomposition provides us an ideal platform to calculate the QCD effective potential and prove the monopole condensation gauge independently. This is because it puts QCD to the background field formalism, since we can treat the restricted part and the valence part as the slow varying classical background and the fast moving quantum fluctuation [22,23].

Indeed, choosing the monopole potential as the background and integrating out the chromons in (9) gauge invariantly, we can calculate the QCD effective potential, which has the Weyl symmetric unique minimum described by the monopole condensation. This prove that the true QCD vacuum is given by the gauge invariant monopole condensation [6,7].

IV. NEURON JET AND CHROMON JET

The Abelian decomposition is not just a theoretical proposition. There are many ways to test it experimentally. For example, we can test it by showing the quark and chromon model describes the correct hadron spectrum [18,19]. Or we can test it by demonstrating that the monopole condensation does describe the true QCD vacuum [6,7]. But these are indirect tests. If QCD really has two types of gluons, we should be able to confirm this directly by experiment.

During the last twenty years, there has been huge progress on jet structure in QCD. New ways to tag different jets have been developed [24–26]. Moreover, new features of the quark and gluon jet substructures have been known [27–30]. Now, we argue that these progresses could allow us to confirm the existence of two types of gluon jets experimentally.

Early experiments that established the existence of the gluon are based on planar three jet events made of two quark jets and one gluon jet [10]. So the problem here is to divide the gluon jets to neuron jet and chromon jet. For this, we have two questions. First, how many of them are the neuron jet? Second, how can we differentiate the neuron jet from the chromon jet to identify the existence of the neuorn jet?

The first question is easy. Since two of the eight gluons are neurons, one quarter of the gluon jet should be the neuron jet, and three quarters of them should be the chromon jet. The difficult problem is the second question. Actually, the problem here is not just how to separate the neuron jet from the chromon jet. Since we have the quark jet as well in QCD, we have to tell how to tag all three jets, the neuron jet, the chromon jet, and the quark jet, separately. So we have to know the difference of each jet from the other two.

To tell the difference, it is important to remember that the gluons and quarks emitted in the p-p collisions evolve into hadron jets in two steps, the soft gluon radiation of the hard partons described by the perturbative process and the hadronization described by the nonperturbative process. The hadronization in the second step is basically the same in all three jets. The difference comes from the parton shower (the soft gluon radiation) of the hard partons in the first step [8]. This is shown in Fig. 5 in the first order interaction.

Clearly, the neuron jet (the soft gluon radiation of hard neuron) shown in Fig. 5(a) has only two chromon radiation with no other soft gluon radiation, which exists in both the chromon jet Fig. 5(b) and the quark jet Fig. 5(c). But the chromon and quark jets have the neuron and chromon radiations, and qualitatively look similar. The only difference is that the chromon jet has four point vertex, while the quark jet has only three point vertex. As importantly, the leading order of the soft gluon radiation of neuron shown in Fig. 5(a) is of $O(g^2)$, while that of the chromon and quark shown in Figs. 5(b) and 5(c) are of the order of $O(g)$. This is a direct consequence of the decomposition of the Feynman diagram shown in Fig. 2.

This tells that the neuron jet is almost like the photon jet, which is fundamentally different from the chromon and

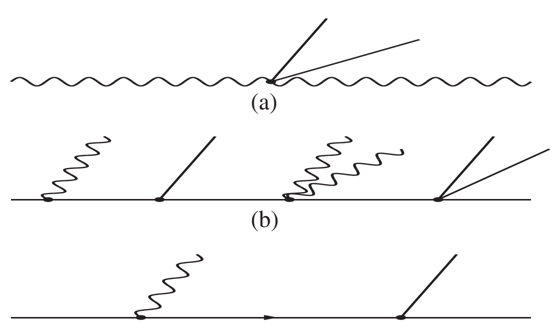

FIG. 5. The parton shower (the soft gluon radiation) of hard partons. The neuron jet shown in (a) is qualitatively different from the chromon jet and the quark jet shown in (b) and (c), while the chromon and quark jets are similar.

quark jets. This strongly suggests that the neuron jet must have different jet shape, different from the chromon and quark jets.

Intuitively, we could imagine that the neuron jet is sharp with relatively small jet radius compared to the chromon jet. This is because the neuron has only chromon-antichromon radiation, while the chromon has three more soft gluon radiations (as well as the chromon-antichromon radiation). And this could only broaden the jet. This is obvious from Fig. 5. This strongly implies that the neuron jet can not be broader than the chromon jet. But, of course, to find how much sharp the neuron jet is, we definitely need the numerical simulation.

Moreover, this also strongly implies that the neuron jet should have different (charged) particle multiplicity, considerably smaller than that of the quark and/or chromon jets. This must also be clear from Fig. 5, which shows that the neuron has weaker [of the order $O(g^2)$] soft gluon radiation than the chromon and quark.

Another important feature of the neuron jet is that it has different color flow. Clearly, the chromons and quarks carry color charge, but the neurons are color neutral. So the neuron jet must have different color flow. In fact, Fig. 5 tells that the color flow of the neuron jet generates an ideal color dipole pattern, but the other two jets have distorted dipole pattern.

The above observations show that the neuron jet must be quantitatively different from the chromon and quark jets, and that we should be able to confirm this experimentally. To quantify the differences, of course, we need more serious theoretical calculations and numerical simulations. For instance, we need to implement the Abelian decomposition in the existing PYTHIA and FastJet programs, and find how the numerical simulations predict the differences between the neuron and chromon jets.

For this, we have to know the color factors of the neuron and chromon jets, one of the most important quantities that determines the characters of the jet. It has been well known that the parton shower (the soft gluon radiation) of the quark and gluon jets are proportional to their color factors $C_F = 4/3$ and $C_A = 3$ in the eikonal approximation, and that the quark/gluon tagging performance crucially depends on their ratio C_A/C_F. This means that it is important to know the neuron and chromon color factors.

One might think that the neurons have no color factor, but this is not so. Although they are color neutral, they are not color singlet. So they have finite color factor. But at the moment, it appears unclear if one can calculate the neuron and chromon color factors from the first principle, because the color gauge symmetry is replaced to the 24-element color reflection symmetry after the Abelian decomposition [1,2,6,7]. On the other hand, from the fact that the gluon color factor is given by the trace of the quadratic Casimir invariant made of the eight gluon generators, we could assume the neuron color factor to be the trace of the quadratic Casimir invariant corresponding to the neuron generators. In this case, we can easily calculate the neuron and chromon color factors. Since each of the eight gluon generators contributes equally to the gluon color factor, we can deduce the neuron color factors to be $3/4$, one quarter of the gluon color factor 3. By the same reason, we can say that the chromon color factor must be $9/4$. A more intuitive way to understand this comes from the simple democracy of the gauge interaction. Since the neurons constitute one quarter of eight gluons, their color factor must be one quarter of the gluon color factor 3, that is $3/4$.

According to the above reasoning, the color factor ratio of the quark, chromon, and neuron jets should be $C_q\colon C_c\colon C_n = 4/3\colon 9/4\colon 3/4 \simeq 1.78\colon 3\colon 1$, since the quark color factor is given by $C_F = 4/3$. If this is so, the recent experiments that separated the quark jet from the gluon jet based on the color factor ratio $C_A/C_F = 9/4$ need to be completely reanalyzed [24–26].

In this respect, we notice two interesting reports that could support the above interpretation. The reanalysis of DELPHI e^+e^- three jet data at LEP strongly indicates that actual C_A/C_F could be around 1.74, much less than the popular value 2.25 but close to our prediction $C_c/C_q = 1.69$ [31,32]. Moreover, the $p\bar{p}$ DØ jets experiment at Fermilab Tevatron shows that the quark to gluon jets particle multiplicity ratio is around 1.84, again close to our prediction 1.69 [33]. They could be an indication that the observed gluon jets are indeed the chromon jets.

If this is true, one might ask what are the gluon jets identified by ATLAS and CMS. Probably they are the chromon jets, because the chromon jet has the characteristics of the known gluon jet. This is evident from Fig. 5. Perhaps a more interesting question is why they have not found the neuron jet. There could be two explanations. First, they have not searched for the neuron jet yet, because they had no motivation to do that. Or they might have misidentified some of the neuron jets as the quark jet. This is because the color factor of neuron and quark jets are not much different. This tells that we need a more careful analysis of quark and gluon jets.

A simple way to search for the neuron jet is to concentrate on the gluon jet production process like $H \to gg$ and to try to separate the neuron jet from the chromon jet. In an idealized setup with e^+e^- collision, we can have the quark and gluon jets separately [30],

$$\begin{aligned} &quark\ jet\colon\ e^+e^- \to \gamma/Z \to u\bar{u}, d\bar{d}, s\bar{s}, \\ &gluon\ jet\colon\ e^+e^- \to H \to gg, \end{aligned} \tag{11}$$

when we focus on the light quarks. Similarly, in the pp collision we have [30]

$$\begin{aligned} &quark\,enriched\,jet\colon\ pp \to Z + jet, \\ &gluon\,enriched\,jet\colon\ pp \to \text{dijet}. \end{aligned} \tag{12}$$

In this case, we could forget about the quark jet and concentrate on the gluon (enriched) jet, and try to separate the neuron jet from the chromon jet. In principle, this could be simpler for two reasons. First, the parton shower (the soft gluon radiation) of the neuron and chromon jets shown in Fig. 5 is totally different. Second, the ratio of the color factors of the neuron and chromon jets becomes bigger $C_c/C_n = 3$. This strongly implies that about one quarter of the gluon (enriched) jet must be the neuron jet, which has sharper shape than the other and has much less charged particle multiplicity and ideal color dipole pattern.

Independent of the details on the differences between the neuron and chromon jets, however, we like to emphasize that in principle there is a simple and straightforward way to confirm the existence of two types of gluon jets from the existing jet data. This is because, independent of what is the neuron jet and what is the chromon jet, one quarter of the existing gluon jets should actually have different jet shape (the sphericity), particle multiplicity, and color dipole pattern. If this is so, we can simply plot the jet shape (the solid angle) and/or charged particle multiplicity of all existing gluon jets, and find the gluon jet distribution made of two peaks populated by one quarter and three quarters of the jets.

The expected gluon jet distribution is shown in Fig. 6. In this figure we have assumed that the distribution of neuron and chromon is Gaussian, and plot the expected gluon jet distribution when the neuron peak is 1, 2, and 3 standard deviation away from the chromon peak. Notice that the shape of the overall gluon jet distribution crucially depends on the distance between the two peaks. For instance, when the distance between the two peaks becomes three standard deviation or more, the two peaks are well separated. But when the distance becomes two standard deviation or less, the neuron peak is submerged completely under the chromon peak as shown in Fig. 6. This strongly indicates that the neuron jet could easily be left unnoticed in the gluon jet analysis, when the distance between the neuron and chromon peaks becomes less than two standard deviation. The exact size (the solid angle) and particle

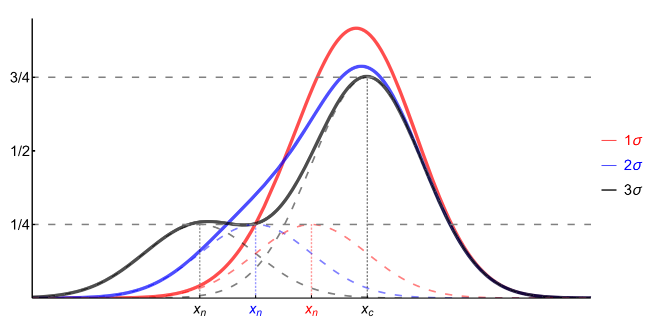

FIG. 6. The expected gluon jet distribution against the jet shape (the sphericity) and/or the particle multiplicity. Here we have assumed that the distribution is Gaussian, and plotted the overall gluon distribution when the distance between two peaks becomes 1, 2, and 3 standard deviations.

multiplicity (number of particles) of the neuron and chromon jets could be predicted implementing the Abelian decomposition in the PYTHIA and FastJet. But independent of the details the characteristic feature of the above gluon jet distribution is that it is asymmetric (tilted) against the peak axis. This tells that the asymmetry (tilt) of the gluon distribution against the peak axis is a strong indication that there are two gluon jets. This is the most important qualitative feature of the above analysis.

This tells that, without trying to identify the neuron jet from the chromon jet, we could tell the existence of the neuron jet in the gluon jet distribution checking if the gluon distribution is asymmetric against the peak axis or not, from the existing gluon jet data. This asymmetry could be an unmistakable indication that there are indeed two types of gluons, the neuron and chromon.

A straightforward way to do this is to use the existing 2071 gluon jet events of ALEPH data coming from $e\bar{e} \to Z \to b\bar{b}g$ three jet events [34], find out the distribution of the gluon jet on the sphericity and/or particle multiplicity, and see if the gluon jet has the predicted distribution shown in Fig. 6. In principle, this could be done without much difficulty.

One advantage in searching for the neuron jet is that we do not need any new experiment. LHC produces billions of hadron jets in a second, and ATLAS and CMS have already filed up huge data on jets. Moreover, DESY, LEP, ALEPH, and Tevatron have old data on three jet events (the gluon jets), which we could use to confirm the existence of the neuron jet. Here again, the simple number counting strongly suggests that one quarter of the gluon jets coming from the three jets events could actually be the neuron jets which do not fit to the conventional gluon jet category.

V. DISCUSSION

The gauge potential of QCD is thought to represent the gluons, but the role of gluons in QCD has been confusing. On the one hand, they are supposed to provide the binding of the (colored) quarks. But at the same time, they are supposed to play the role of the constituent of hadrons, because they are colored. The Abelian decomposition tells that there are two types of gluons, the binding gluons and the valence gluons, that play different roles.

As we have emphasized, the fact that there should be two types of gluons is evident from the simple group theory. Group theory tells that two of eight gluons must be color neutral. The question is how to separate the neutral gluons gauge independently. The Abelian decomposition does the job [1,2]. As importantly, it tells that the Abelian (restricted) potential contains not only the neurons but also the topological monopole part, which plays the crucial role to retain the full non-Abelian gauge degrees of freedom to the restricted potential.

This clarifies the role of gauge potential in QCD. The neurons and monopole potential together bind and confine the colored objects with the monopole condensation [6,7], but the chromons play the role of constituent of hadrons [18,19].

In this paper, we have argued that the existence of two types of gluon could actually be confirmed by experiment and proposed intuitive idea to verify this. Of course, to verify this experimentally, we need more concrete predictions and numerical simulations. But this is beyond the scope of this paper, because our aim here is to present the theoretical foundation why QCD must have two types of gluon, discuss the experimental plausibility of neuron and chromon jet tagging, and suggest basic idea how we can actually do this without ambiguity.

In fact, experimentally the quark/gluon tagging is a very complicated and ongoing issue that is not completely settled yet. It is well known that the gluon tagging has many unclear and unresolved problems [29,30]. In particular, the success rate of the gluon jet identification is known to be at best 70%. We believe that this could be, at least partly, due to the existence of two types of gluon jet. In fact, we interpret that this strongly implies that about 30% could actually be different jet, i.e., the neuron jet. To test the plausibility of this suggestion, we propose two step analysis. First, we could look at the existing gluon jet data and check if there are events which do not fit to the well known predicted characters of the gluon jet, in particular, the jets which have sharper radius. Second, if we confirm this, we could try to identify them as the neuron jet.

Our prediction tells that about one quarter of the gluon jets should actually be the neuron jets which have sharper jet shape, less charged particle multiplicity, and ideal color dipole pattern. This could be done without much difficulty. After we confirm this, we could try to do the neuron and chromon jets tagging. A nice thing about this proposal is that we do not need any new experiment. All that we have to do is to reanalyze the existing old data at LHC.

To do that, however, we have to have quantitative predictions based on the numerical simulations on the characteristic features of the neuron and chromon jets. For this, we have to modify the existing PYTHIA and/or FastJet programs implementing the Abelian decomposition and have new Monte Carlo simulations on the neuron and chromon jets based on the soft gluon radiations shown in Fig. 5 and the new color factors of the neuron and chromon jets. On this, the recent machine learning algorithm could also be very useful for us to find the characteristic features of the neuron and chromon jets [29,30]. But this could take time.

What one can do immediately is trying to confirm the existence of two types of gluon jet based on the gluon distribution against the jet shape (the sphericity) and/or particle multiplicity shown in Fig. 6, using the existing ALEPH data [34]. Currently we are working on this and expect to have the result soon [35]. The confirmation of the existence of two types of gluons could be a giant step forward that will help us to identify the existence of the neuron and chromon jets successfully.

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Note added.—Recently, it is suggested by the MIT high energy experimental group that the anomaly in gluon distribution observed in heavy ion collision at LHC could be explained by the existence of two types of gluons [36]. This is probably because neuron undergoes less gluon quenching than the chromon in the collision and thus, could escape the quark-gluon plasma fireball more easily. One of us (YMC) thanks Yen-Jie Lee for the constructive discussion.

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