Glueballs from gluon jets at the LHC

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The existence of glueballs within QCD is uncontroversial but their experimental verification is still in doubt. We discuss the new possibilities for a search of glueballs as the leading object in gluon jets at the LHC. We summarize previous results from LEP which demonstrate a significant excess rate of electrically neutral leading clusters in comparison with MC models.

1 QCD expectations and search for glueballs

According to an early prediction of QCD the self-interacting gluons are able to bind themselves and to give rise to a new spectroscopy of gluonic matter or glueballs; specific scenarios for glueball phenomenology go back to 1975 [1], for recent reviews, see [2]. Today, quantitative predictions are derived from lattice QCD and from QCD sum rules. The lightest glueball is found to be a scalar with $J^{PC} = 0^{++}$ and a mass of 1.0-1.7 GeV.

There have been considerable efforts to identify glueballs experimentally. The aim is at first to establish the lightest $q\bar{q}$ nonets in the spectrum; then, the appearence of extra states could hint towards a glueball. More directly, one looks for an enhanced production of a glueball candidate in "gluon rich" processes but a suppression in $\gamma\gamma$ reactions [2].

Studies of production and decay of resonances along these lines have led to various scenarios for classification of the lightest scalar states

$$f_0(600),\ f_0(980),\ f_0(1370),\ f_0(1500),\ f_0(1710).$$

According to one approach (e.g. [3]), the glueball could be mixed into the three states above 1 GeV together with two members of the $q\bar{q}$ nonet. Alternatively, the glueball could be related to the broad $f_0(600)$ (e.g. [4,5]). A problem in constructing multiplets is the status of $f_0(1370)$ which is not seen in phase shift analyses of $\pi^+\pi^- \to \pi^+\pi^-, \pi^0\pi^0$ [6].

The production of resonances has been studied in a number of gluon-rich processes: "central production" $pp \to p\ gb\ p$ by double Pomeron exchange, $J/\psi \to \gamma\ gb$, $p\overline{p} \to \pi\ gb$, $B \to K\ gb$ (through $b \to sg$) and, finally, forward fragmentation of a gluon into glueballs.

Only in the last reaction involving a high energy gluon jet the gluon can be identified as a source, in the other processes the overall energy is low of Ø (few GeV) and the role of gluons is not obvious anymore. An interesting result on central production has been presented at this conference by ALICE at LHC [7]: in the double gap events the isoscalar states $f_0(980)$ and $f_2(1270)$ are enhanced in comparison to no-gap events. The enhanced production of the well known $q\overline{q}$ state $f_2(1270)$ demonstrates that the double Pomeron mechanism does not enhance exclusively glueballs. We also note that the Pomeron structure has been investigated at HERA [8]. Present results suggest a dominant fracton ($\sim$ 70%) of momentum to be carried by gluons, but the ratio $G(x)/S(x)$ of gluon over singlet quark densities at large momentum fractions $x \sim 1$ varies between $G/S \sim 0$ for ZEUS data according to [9] and $G/S \sim 1-2$ for H1. Then, the production of $q\overline{q}$ states in double Pomeron scattering could be a reflection of the sizable quark valence component of the Pomeron.

2 Leading particle systems in gluon jets

According to the well known concept of quark fragmentation the leading particles at large Feynman x are those which carry the initial quark of the jet as a valence quark

$$q \to \text{Meson } (q\overline{q}') + X,$$

for example, leading particles in a u-quark jet are a $\pi^+(u\overline{d})$ or a $\pi^0(\{u\overline{u}+d\overline{d}\}/\sqrt{2})$ with half strength, whereas $\pi^-(d\overline{u})$ is suppressed at large x. In analogy, one can consider the fragmentation of a gluon and suppose that the leading particle in the jet is the one with a gluonic valence component

$$g \to \text{Meson } (gg) + X.$$

Models of this kind with leading glueballs, but also with leading isoscalars like $\eta,\ \eta',\ \omega$ at large x have been suggested already long ago [10], for x-distributions, see also [11].

Studies of gluon jets at LEP did not establish a clear support of the model for isoscalar $q\overline{q}$ mesons [12]. While the L3 collaboration found for the jet of lowest momentum in $e^+e^- \to 3$ jets a considerable enhancement of η production by factor 2-3 beyond MC calculations for $x_p > 0.06$, where $x_p = p/p_{beam}$, ALEPH later reported agreement between data and revised MC versions (similarly also for η', but with low statistics). OPAL found an excess η rate over MC's at the higher momenta but did not separate quark and gluon jets in this range. No other isoscalar particles have been studied separately for quark and gluon jets.

The distributions of charge and mass of the leading cluster Q_{lead} and M_{lead} in gluon jets beyond a rapidity gap reflect the colour neutralisation mechanism [13]. In particular, the "color octet neutralisation" is a precondition for glueball production. In that case, two gluons, if separated beyond the confinement radius R_c, will create two other gluons to form colour neutral sub-systems. Alternatively, colour triplet neutralisation is possible with creation of two $q\overline{q}$ pairs, or both mechanisms with probablilities P_8 and P_3. For large rapidity gaps one expects the charge distribution to approach a limiting behaviour with charge $Q_{lead} = 0$ with P_8 and charges $Q_{lead} = 0, \pm 1$ with P_3,

		p_T	x_T	g in di-jet	q in γ+ jet
TEVATRON	1.8 TeV	50	0.056	60%	75 %
LHC	7 TeV	200	0.057	60%	80 %
		50	0.014	75%	90 %
		800	0.229	25%	75%

Table 1: Rates for gluon and quark jets at TEVATRON [15] and LHC [16].

Results from LEP on leading clusters have been obtained from OPAL, DELPHI and ALEPH [14]. All experiments agree upon a significantly enhanced rate for neutral clusters ($Q_{lead} = 0$) beyond a rapidity gap in gluon jets by 10-40% as compared to the JETSET MC, depending on the selection and purity of the jets. On the other hand, the corresponding distributions for quark jets or for gluon jets without gap agree well with MC's. In addition, DELPHI and OPAL find the excess of gluon jets with $Q_{lead} = 0$ with typically lower masses $M_{lead} \lesssim 2.5$ GeV. A natural explanation would be a leading gluonic system or glueball.

3 Proposal for LHC studies of gluonic systems

Studies of leading particle systems can be performed at the LHC with some advantages. Most importantly, gluon jets can be selected with higher energies in comparison to LEP and they are more copiously produced with good statistics. It is possible to compare quark and gluon jets with similar energies from different processes.
1. leading order processes to be calculated from $pdf's$ and parton-parton cross sections: Quark jets can be obtained from final states $pp \to \gamma + jet + X$ with subprocess $qg \to \gamma q$ dominating at the lower p_T. Gluon jets are found among di-jet events, also at low p_T. Examples are presented in Tab. 1.
A good purity of quark jets can be obtained in this way, but gluon jets with their steeper fragmentation need higher purity to reduce background.
2. gluon bremsstrahlung:
Using a trigger on total transverse energy one selects 3-jet events. Similar to the case at $e^+e^- \to 3\ jets$ the lowest momentum jet is most likely a gluon jet from QCD bremsstrahlung (qqg, qgg or ggg). The fraction of gluon jets can be derived within the DGLAP approximation for low k_T. For example, at small x_g one finds, given the ratio of gluon to quark production rate $R_g = \sigma_g/\sigma_q$ the fraction $F_g(x_g) = \frac{1}{1+4x_g/(8+18R_g)}$ which yields for $R_g = 1$, as example,

$$F_g \approx 95\% \text{ at } x_g = 0.2, \qquad F_g \approx 85\% \text{ at } x_g = 0.5.$$

Studies at LHC could be useful in two directions:
1. Leading clusters with larger rapidity gaps.
The new possibilities at LHC follow from the gluon jet energies larger by an order of magnitude as compareed to LEP (typically < 25 GeV). This allows for a better separation

of the leading cluster. The rapidity gaps could extend up to $\Delta y \sim 4$ (add $\ln 10 \approx 2.3$ to $\Delta y \approx 1.7$). With increasing rapidity gaps the leading charges should be closer to their asymptotic distribution with values $Q = 0, \pm 1$ allowing for a better estimate of probabilities P_3 and P_8.
2. Direct study of resonances in mass distributions.
The spectra of the invariant mass of leading particles beyond the gap are generally found quite smooth. There is some evidence in gluon jets for $f_0(980)$ in the $\pi\pi$ (DELPHI [14]) and for $f_0(1500)$ in the 4π spectrum (OPAL [14]). The rapidity gap cuts affect the angular decay distribution of the cluster and could reduce the resonance signal. This is avoided if the mass spectra are constructed first and then their x distribution is studied. Such resonance x spectra have not yet been determined for quark and gluon jets separately.

The distinguishing feature for identifying a glueball is its x distribution in comparison with the reference spectrum of a well defined $q\bar{q}$ resonance (examples ρ, $f_2(1270)$, $\phi(1020)$) of comparable mass in the quark and gluon jet resp. The glueball should be "suppressed" in a quark jet and should be "leading" in a gluon jet, i.e. above a $q\bar{q}$ reference resonance, according to the following scheme (for scalar f_0's):

meson	quark jet	gluon jet triplet neutr.	 octet neutr.
$q\bar{q} : f_0\ [ref : \rho, f_2, \phi \ldots]$	leading	suppressed	suppressed
$gb : f_0\ [ref : \rho, f_2 \ldots]$	suppressed	suppressed	leading
$q\bar{q} : f_0$, strongly mixed	leading	suppressed	leading (?)
$4q : f_0(600)/\sigma, f_0(980)$ (?)	suppressed	suppressed	suppressed

Table 2: Identifying glueballs through reference spectra in quark and gluon jets.

The last line in the table relies on the validity of particular models, here we refer to the quark counting approach [17]. To the extent, that the x-distribution of $f_0(980)$ almost coincides with the one of $f_2(1270)$ [18], there is no evidence for structure beyond $q\bar{q}$ of $f_0(980)$.

In principle, also mixed $gb - q\bar{q}$ states could be recognized by comparing with the appropriate superposition of two reference distributions. Gluonic components could appear in the spectra of $(\pi\pi)^0$ ($f_0(600)/''\sigma''$, $f_0(980)$, $f_0(1500)$), of $(4\pi)^0$ (($f_0(1370)(?)$, $f_0(1500)$) and $(K\overline{K})^0$, ($f_0(980)$, $f_0(1500)$, $f_0(1710)$).

4 Summary

1. The existence of glueballs is predicted since long, the clear evidence is still missing.

2. Lesson from LEP: evidence for a new fragmentation component:
excess of neutral clusters by up to 40% beyond expectation from MC's.
Gluon jets may not be built up from quark strings only.

3. There is a new chance of finding glueballs in gluon jets at LHC:
excess of neutral leading clusters with increasing gap size;
resonance x-spectra in quark and gluon jets in comparison with reference spectra.

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