Search for walking technipion in four-jet sample

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Abstract

We discuss how to search for a possible signal of the recently observed 750 GeV enhancement in the diphoton channel in the four-jet production. In the present studies we assume that the produced state is pseudoscalar. This fact, when combined with specificity of the corresponding amplitude, allows to improve the signal-to-background (S/B) ratio. We discuss in detail how to impose cuts on jets in rapidity and transverse momenta in order to find optimal S/B ratio and not to lose too much statistics. Our study suggest a measurement of two soft (low cut on $p_t$) large-rapidity jets and two hard (high cut on $p_t$) mid-rapidity jets. Azimuthal correlation between the soft external jets may be useful to further improve the situation. Several differential distributions in rapidities and transverse momenta of jets as well as dijet invariant mass are shown. The integrated cross sections corresponding to different cuts are collected in a table and number of events are presented.

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I. INTRODUCTION

Last year the ATLAS and CMS collaborations observed an enhancement of the cross section at 750 GeV in the diphoton channel at $\sqrt{s} = 13$ TeV \[1, 2\]. Very recently also data searching for the potential signal at $\sqrt{s} = 8$ TeV were released \[3, 4\]. Different models were discussed recently in the context of the newly observed enhancement. A short review on the topic can be found in Ref. \[5\]. If the signal is true we know that the new object decays (couples) to photons (the observation channel). The production mechanism is, however, not clear at present and we have no any clear hint for this. In some of the models considered recently the object is produced dominantly by the gluon-gluon fusion \[6\], in some models dominantly by the photon-photon fusion \[7, 8\]. If the gluon-gluon fusion dominates the resonance should have large width. In contrast, when photon-photon fusion dominates the resonance should be narrow, much narrower than experimental resolution in the diphoton invariant mass. The recent analysis \[3\] suggests that the gluon-gluon fusion may be preferred from the analysis of the ratio of the $\sqrt{s} = 8$ TeV and $\sqrt{s} = 13$ TeV cross sections.

In Ref. \[8\] one of us discussed production of the signal in a vector-like SU(2) technipion model as well as in a walking technipion model \[6\]. In the first case the signal is produced mainly via photon-photon fusion while in the second one dominantly via gluon-gluon fusion. If models with gluon-gluon fusion (like-walking technipion model) are right then the object could be also potentially observed (or at least could be searched for) in the digluon (dijet) final state. However, as shown in Ref. \[8\], the dijet background makes practically impossible such an observation in the dijet invariant mass. Possible specificity of the couplings involved in the amplitude may cause that the signal is in large fraction of cases produced in association with one or two jets \[8\].

FIG. 1: The mechanisms of four-jet production with one intermediate resonant state $R(750)$. 
Here we discuss how to search for the state in the four-jet sample (the relevant diagrams for the signal are shown in Fig. 1). In the present case we consider production of the pseudoscalar object ($f^\pi = 0^-$) discussed in detail in Ref. [8].

II. A SKETCH OF THE THEORETICAL FORMALISM

A. Signal in four-jet final state

When calculating signal we consider a simple $2 \rightarrow 3$ partonic subprocesses shown in Fig. 1. Here for example we discuss only the first diagram. The cross section for the partonic $qq' \rightarrow q\pi^0 q'$ process reads:

$$\sigma_{qq' \rightarrow q\pi^0 q'} = \frac{1}{2s} |\mathcal{M}_{qq' \rightarrow q\pi^0 q'}|^2 \int d\xi_1 d\xi_2 dy_{\pi^0} d\phi_{12}, \quad (2.1)$$

where $\phi_{12}$ is the relative azimuthal angle between $q$ and $q'$, $\xi_1 = \log_{10}(p_{1t})$ and $\xi_2 = \log_{10}(p_{2t})$, where $p_{1t}$ and $p_{2t}$ are transverse momenta of outgoing $q$ and $q'$, respectively.

The matrix element for the $2 \rightarrow 3$ subprocess is calculated as:

$$\mathcal{M}_{qq' \rightarrow q\pi^0 q'}(\lambda_1, \lambda_2, \lambda_3, \lambda_4) = e^2 \bar{u}(p_3, \lambda_3) \gamma^\mu u(p_1, \lambda_1) \frac{-ig_{\mu\nu}}{t_1}$$

$$\times \epsilon^{\nu'\alpha'\beta} q_{1a} q_{2\beta} F_{g_g \rightarrow R} \frac{-ig_{\nu'\mu'}}{t_2} \bar{u}(p_4, \lambda_4) \gamma^{\nu'} u(p_2, \lambda_2). \quad (2.2)$$

The $F_{g_g \rightarrow R}$ effective coupling, except of normalization, is the same as the $F_{\gamma\gamma \rightarrow R}$ one discussed in detail in Ref. [8]. As in Ref. [8], the normalization is adjusted to experimental data on diphoton production using branching fractions as obtained in the walking technicolor model [6].

The matrix elements for the other processes in Fig. 1 can be obtained easily in the high-energy approximation by replacing appropriate coupling constants and color factors (see e.g. [9]). As in Ref. [8] for comparison, we also calculated the matrix element in the high-energy approximation:

$$\bar{u}(p', \lambda') \gamma^\mu u(p, \lambda) \rightarrow (p' + p)^\mu \delta_{\lambda', \lambda}. \quad (2.3)$$

We have also obtained a formula for matrix element squared with algebraic computer calculation and checked that it gives the same result as the calculation with explicit use of spinors.
In order to impose cuts on transverse momenta and rapidity of jets we calculate first the distribution
\[ \frac{d\sigma}{dy_R dp_{t,R}}(y_R, p_{t,R}; \text{with explicit cuts on spectator jets}). \] (2.4)

Then the decay of \( R \rightarrow gg \) is done in a separate simple Monte Carlo code (four-momenta of gluons are obtained) where cuts on gluons from the decay of the resonance are imposed in addition.

**B. Four-jet background**

Four-jet production via single-parton scattering (SPS) mechanism in proton-proton scattering at the LHC was discussed some time ago in the collinear factorization, both at leading-order (LO) and, for the first time, at next-to-leading order (NLO) in Ref. [10]. Then, very recently also first four-jet studies based on the tree-level \( k_T \)-factorization approach with two off-shell partons have been performed, including double-parton scattering (DPS) effects [11]. In the present paper we follow the LO collinear approach in order to make the background calculations consistent with the predictions for the signal, so the S/B ratio can be estimated more or less in a model independent way.

According to the LO collinear approach the elementary cross section for the SPS mechanism of four-jet production has the following generic form:
\[ d\hat{\sigma}_{ij \rightarrow klmn} = \frac{1}{2s} \left| \mathcal{M}_{ij \rightarrow klmn} \right|^2 d^4PS, \] (2.5)
where the invariant phase space reads:
\[ d^4PS = \frac{d^3p_1}{2E_1(2\pi)^3} \frac{d^3p_2}{2E_2(2\pi)^3} \frac{d^3p_3}{2E_3(2\pi)^3} \frac{d^3p_4}{2E_4(2\pi)^3} (2\pi)^4 \delta^4(p_1 + p_2 + p_3 + p_4). \] (2.6)

Above \( p_1, p_2, p_3, p_4 \) are four-momenta of outgoing partons (jets) and \( \mathcal{M}_{ij \rightarrow klmn} \) is the relevant \( 2 \rightarrow 4 \) tree-level on-shell matrix element.

The hadronic cross section is then given by the integral
\[ d\sigma = \int dx_1 dx_2 \sum_{ijklmn} f_i(x_1, \mu_F^2) f_j(x_2, \mu_F^2) d\sigma_{ij \rightarrow klmn}. \] (2.7)

Above \( f_i \) and \( f_j \) are the standard collinear parton distribution functions (PDFs).
Instead of explicitly using the formulae above we shall use its Monte Carlo version as implemented in the event generator ALPGEN \cite{13} that is dedicated to multi-parton production studies. In the numerical calculations here we are working in the $n_F = 3$ flavour scheme and use a running $\alpha_S$ as implemented in the ALPGEN code and the MSTW2008nlo68cl PDF sets \cite{12}. We set both the renormalization and factorization scales equal to the sum of the final state transverse momenta squared, $\mu_R = \mu_F = \sum_i p_{T,i}^2$. The LO results for the background are corrected in the last step by the relevant $K = 0.5$ factor, which is taken from the comparison of the LO and NLO collinear predictions with the multi-jet ATLAS data \cite{10}. Recently, the similar comparison has been done, but for the tree-level $k_T$-factorization calculations and CMS data, and it seems to confirm the importance of the $K$-factor in the case of four-jet studies \cite{14}.

III. NUMERICAL FEASIBILITY STUDIES

The decay of (pseudo)scalar $R(750)$\footnote{This statement is universal, independent of the observed 750 GeV enhancement, however the measured signal for the 750 GeV enhancement is rather unnaturally large.} leads dominantly to not too soft (small transverse momentum) jets. On the other hand to improve statistics the other two jets can (should) be as soft as possible. As far as the signal is considered we shall call the jets from the decay of the $R(750)$ resonance as „internal” and the other two associated jets as „external”. These names are related to the position in diagrams and in rapidity space. As minimal set of cuts we select two leading jets with $p_T > 100$ GeV and the two other jets with $p_T > 20$ GeV. The leading jets are assumed to be within the main (CMS or ATLAS) detector and the subleading jets to be in the (CMS or ATLAS) calorimeters.

In Fig. 2 we show the corresponding cross sections in jet transverse momentum (left panel) and dijet invariant mass (right panel) of the hard jets (internal jets for the signal). Here we show both signal (solid, red on-line) and background (dashed) distributions. One can observe that with this minimal cut the signal is much below the four-jet background. The distribution in transverse momentum of the hard-internal jets suggests that they should be selected with transverse momenta arround $M_R/2$, where $M_R$ is the mass of the resonance (in the considered here case $M_R = 750$ GeV). Calculating invariant mass distribution we have assumed that the actual total decay width is smaller than experi-
mental dijet invariant mass resolution. For the experimental resolution we assumed here
Gaussian distribution with width $\sigma = 10$ GeV (see discussion in Ref. [8]).

![Graphs showing distributions in various physics quantities](image)

**FIG. 2:** Distribution in the transverse momentum of the hard-internal jets (left panel) and in the
invariant mass of the two hard-internal jets (right panel).

The distribution in transverse momentum of the hard-internal jets for the background
is a bit misleading because it cannot be directly compared with the signal. Therefore in
the left panel of Fig. 3 we show similar distribution but now in much narrower window
of dijet invariant mass ($700$ GeV < $M_{jj}$ < $800$ GeV). Now the signal-to-background (S/B)
ratio looks much better, especially for $p_T^{\text{int}}>350$ GeV. Therefore in the right panel of
Fig. 3 we show invariant mass distribution imposing extra cut on the internal jets $p_T^{\text{int}}>350$ GeV. Now the signal is still more than order of magnitude below the background.

Can we improve the situation even more? Below we shall try to include specific features
of the considered model amplitude for the signal.

So far we have taken only a rough choice of preferable cuts on jet rapidities as dictated
by pseudorapidity limitations of the tracker ($|y| < 2.5$) and calorimeters ($2.5 < |y| < 4.7$).
Can the S/B ratio be further improved by a better choice of the rapidity cuts? The situ-
ation is illustrated in the left panel of Fig. 4 The plot shows that the jets from the decay
of the R(750) resonance are centered at midrapidities. In addition, one could take larger
rapidity cuts for the soft-external jets. Our detailed study has shown that the rapidity
cuts $|y| < 1$ for the hard-internal and $3 < |y| < 4.7$ for the soft-external jets are optimal
as far as signal-to-background ratio and statistics is considered. Now the S/B ratio of
about 0.1 can be achieved that is already a significant improvement.

Can we use some specific features of the fact that the resonance is pseudoscalar? The
FIG. 3: Distribution in the transverse momentum of the hard jets with invariant mass window (specified in the figure legend) around the signal (left panel) and in the invariant mass of the two hard jets with the increased lower cut on transverse momenta of hard internal jets (right panel).

FIG. 4: Distribution in rapidities of internal and external jets with the selected invariant mass window around the signal and for increased lower cut on the transverse momenta of internal jets (left panel) and the corresponding distribution in internal dijet invariant mass with the optimized rapidity cuts specified in the figure legend (right panel).

answer is positive. Similar problem was studied e.g. in Ref. [8] for technipion and in Ref. [15] in the context of exclusive production of $\eta$ meson in the $pp \to pp\eta$ reaction. One typical example is azimuthal correlations between the external spectator jets. The corresponding angular distribution in azimuthal angle between the jets is shown in the left panel of Fig. 5. The signal has maximum at $\phi_{jj} \sim \pi/2$ (it would not be the case for scalar resonance, see e.g. Ref. [16]). The behaviour of the background is very different, it
peaks at $\phi_{jj}^{\text{ext}} \sim \pi$. Accepting only cases with $\phi_{jj}^{\text{ext}} \approx \pi/2$ would therefore improve the situation. An example is shown in the right panel (see the detailed figure legend). Now the signal-to-background ratio is about 0.2.

Combining the above cuts may further improve the situation but the statistics may be lowered too much. One could return to the issue when better statistics will be accessible.

The cross sections corresponding to different cuts are collected in Table I. If the resonance is really produced dominantly by the gluon-gluon fusion, these cross sections are larger than those for the diphoton channel. Therefore the four-jet study could be tried already with the so-far recorded data.

FIG. 5: Distribution in azimuthal angle between soft external jets for the selected dijet invariant mass window, increased lower cut on the transverse momenta of the internal jets and optimized rapidity cuts (left panel) and the dijet invariant mass distribution with the specified cuts with extra limitation on the $\phi_{jj}^{\text{ext}}$ variable (right panel).
TABLE I: The calculated cross sections for the signal in femtobarns together with signal-to-background ratios and number of events for the present integrated luminosity of 3.2 fb$^{-1}$ at $\sqrt{s} = 13$ TeV.

| Kinematical cuts | Cross section [fb] | S/B [%] | Event rate |
|------------------|--------------------|---------|------------|
| $p_T^{ext} > 20$ GeV; $2.5 < |y_{ext}| < 4.7$ | 69.00 | 0.3 | 220 |
| $p_T^{int} > 100$ GeV; $|y_{int}| < 2.5$ | 11.42 | 4 | 36 |
| $p_T^{ext} > 20$ GeV; $3.0 < |y_{ext}| < 4.7$ | 6.13 | 10 | 19 |
| $p_T^{int} > 350$ GeV; $|y_{int}| < 1.0$ | 4.92 | 20 | 15 |

IV. CONCLUSIONS

The recently observed enhancement of the cross section at 750 GeV in the diphoton channel may be produced by the gluon-gluon fusion. This would also mean that it decays not only into the diphotons but also into two gluons (dijets). As we have shown recently, the observation of the resonance in the dijet channel is practically not possible as the standard QCD background is fairly large compared to the signal.

As discussed recently, if the state is pseudoscalar then one can expect large fraction of events with one or even two associated jets. This could also mean that four-jet final state could be a better choice in independent (to the diphoton channel) searches for the signal of the so-far hypothetical 750 GeV state.

In the present studies we have focused on the analysis of the four-jet final state in the context of searches for the 750 GeV signal. Here, as an example, we have considered a walking technicolor model scenario. In the case of the pseudoscalar state the corresponding amplitude is very specific. Using its characteristic features we have analysed in detail how to enhance the signal-to-background ratio. The $gg \rightarrow R(750)$ coupling constant was adjusted to reproduce the enhancement in the diphoton channel. The four-jet back-
ground has been calculated with modern techniques implemented in the ALPGEN code. Imposing specific cuts on jet transverse momenta and rapidities as well as on azimuthal angle between external jets one can enhance the signal-to-background ratio up to about 20%. Unfortunately present statistics seems to be insufficient. Much better statistics will be available in a future. The study of four dijet production and investigating dependence on cuts may help in the future to assign a spin and parity to the new state, provided the signal is real.

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