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The measurement of the 4-jet cross section at LHC as a probe of new physics

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Abstract

We investigate the possibility to look for new physics by the measurement of the 4-jet cross section at the LHC. In particular, we consider a model with scalar colour octet and a supersymmetric model with $R-$parity violation. In both models pair produced new particles decay into 2 jets, thus leading to 4-jet events. Therefore, a detailed analysis of 4-jet events might discover new physics. The main background comes from standard QCD 4-jet events. We have found that an integrated luminosity $L = 10^4 pb^{-1}$ allows to discover scalar octets(squarks) with a mass up to 900 GeV(1100 GeV). To keep backgrounds under control and eventually to separate new physics signal a good dijet mass resolution is essential.

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1 Introduction

Many extensions of the standard model predict the existence of new massive objects (excited quarks, axigluons, colour octet technirhos, new gauge bosons $W^{'}$, $Z^{'}$, scalar diquarks, etc.) [1] - [3] that couple to quarks and gluons, and result in resonant structures in the dijet mass spectrum. These new particles are singly produced in hadron-hadron interactions. Each object will give resonant type contribution to the QCD dijet cross section. In ref. [4] experimental bounds on new particles decaying to dijets have been obtained. There are examples of new particles (scalar colour octets, squarks in a model with $R-$parity violation etc.) that are produced mainly in pairs and decay to dijets so their decays lead to the resonant structure for the 4-jet differential cross section. The main background comes from the standard QCD 4-jet (or more) events.

In this paper we study the possibility to search for scalar colour octets and squarks in a model with $R-$parity violation by the measurement of the 4-jet cross section at the LHC. In section 2 we describe the phenomenology of scalar octets. In section 3 we describe a model with $R-$parity violation. Section 4 is devoted to the discussion of QCD background. In section 5 we discuss the LHC discovery potential of new physics by the measurement of the four-jet cross section. Section 6 contains concluding remarks.

2 Phenomenology of scalar colour octets

Relatively light $M \leq O(1)TeV$ scalar colour octets are predicted in some non-supersymmetric and supersymmetric GUTs. [5]. Namely, an account of light colour octet in the evolution of QCD running coupling constant increases the value of grand unification scale M_{GUT} and leads to successful prediction for Weinberg angle θ_W [6] The phenomenology of light scalar octets has been discussed in ref. [7]. In this paper we consider colour light scalar octets neutral under $SU(2) \otimes U(1)$ electroweak gauge group. Such particles are described by the self-conjugate scalar field $\Phi^{\alpha}_{\beta}(x)$ $((\Phi^{\alpha}_{\beta}(x))^{+} = \Phi^{\beta}_{\alpha}(x),\ \Phi^{\alpha}_{\alpha}(x) = 0)$ and interact only with gluons. Here $\alpha = 1,2,3$; $\beta = 1,2,3$ are $SU(3)$ indices. The scalar potential for the scalar octet field $\Phi^{\alpha}_{\beta}(x)$ has the form

$$V(\Phi) = \frac{M^2}{2}Tr(\Phi^2) + \frac{\lambda_1 M}{6}Tr(\Phi^3) + \frac{\lambda_2}{12}Tr(\Phi^4) + \frac{\lambda_3}{12}(Tr\Phi^2)^2 \qquad (1)$$

The term $\frac{\lambda_1 M}{6}Tr(\Phi^3)$ in the scalar potential (1) breaks the discrete symmetry $\Phi \to -\Phi$. The existence of such term in the lagrangian leads to the decay of the scalar octet mainly into two gluons through one-loop diagrams similar to the corresponding one-loop diagrams describing the Higgs boson decay into two photons. The decay width of the scalar octet has been determined to be [7]

$$\Gamma(\Phi \to g\,g) = \frac{15}{4096\pi^3}\alpha_s^2 c^2 \lambda_1^2 M\,, \qquad (2)$$

where

$$c = \int_0^1 \int_0^{1-w} \frac{wu}{1-u-w}\, du\, dw = 0.048 \quad (3)$$

and α_s is the effective strong coupling constant at some normalization point $\mu \sim M$. Numerically for $\alpha_s = 0.12$ we find that

$$\Gamma(\Phi \to gg) = 0.39 \cdot 10^{-8} \lambda_1^2 M \quad (4)$$

From the requirements that colour $SU(3)$ symmetry is unbroken (the minimum $\Phi^{\alpha}_{\beta}(x) = 0$ is the deepest one) and the effective coupling constants $\overline{\lambda}_2$, $\overline{\lambda}_3$ haven't Landau pole singularities up to the energy $M_0 = 100 \cdot M$ we find that $\lambda_1 \le O(1)$. Therefore the decay width of the scalar coloure octet is less than $O(10)eV$, $O(100)eV$, $O(1)KeV$, $O(10)KeV$ for the octet masses $M = 1,\ 10,\ 100,\ 1000$ GeV correspondingly. Thus for $\lambda_1 = 0.1$ and $M = 100\, GeV$ the decay width is $\Gamma(\Phi \to gg) \approx 4\, eV$. Other consequence of the smallness of the scalar octet decay width into gluons is that the cross section of the scalar octet single production is very small and the search for the scalar octets in dijet events is hopeless.

However pair production of scalar octets has higher cross section. The corresponding lowest order formulae for the parton cross sections have the form

$$\frac{d\sigma}{dt}(\overline{q}q \to \Phi\, \Phi) = \frac{4\pi\alpha_s^2}{3s^4}(tu - M^4)\,, \quad (5)$$

$$\begin{aligned} \frac{d\sigma}{dt}(gg \to \Phi\Phi) \quad = \quad & \frac{\pi\alpha_s^2}{s^2}(\frac{27}{32} + \frac{9(u-t)^2}{32s^2})(1 + \frac{2M^2}{u-M^2} + \frac{2M^2}{t-M^2} + \\ & \frac{2M^4}{(u-M^2)^2} + \frac{2M^4}{(t-M^2)^2} + \frac{4M^4}{(t-M^2)(u-M^2)})\,, \end{aligned} \quad (6)$$

$$\sigma(\overline{q}q \to \Phi\Phi) = \frac{2\pi\alpha_s^2}{9s}k^3\,, \quad (7)$$

$$\sigma(gg \to \Phi\Phi) = \frac{\pi\alpha_s^2}{s}(\frac{15k}{16} + \frac{51kM^2}{8s} + \frac{9M^2}{2s^2}(s - M^2)ln(\frac{1-k}{1+k}))\,, \quad (8)$$

where $k = (1 - \frac{4M^2}{s})^{\frac{1}{2}}$. We have calculated the cross sections for the production of scalar octets at the LHC using the set 1 of the parton distributions of ref. [8] at the renormalization point $\mu = 2M$. The results of our calculations for the total cross sections are presented in table 1 and in figure 1.

Table 1: The cross section $\sigma(pp \to \Phi\Phi\, +\, ...)$ in pb for different values of octet masses at LHC.

M(TeV)	0.2	0.3	0.4	0.5	0.7	0.9	1.1
σ	701	84	20	7.4	1.1	0.18	0.055

Scalar colour octets decay mainly into two gluons, therefore the main signature for the search for scalar octets are four-jet events.

3 Squarks in a model with $R-$parity violation

The minimal supersymmetric standard model(MSSM) [9] is considered as a leading candidate for supersymmetric generalization of the Standard Model. In MSSM additional symmetry, called $R-$parity has to be imposed in order to avoid renormalizable interactions which violate lepton and baryon numbers. However the conservation of $R-$parity is an ad hoc postulate without deep theoretical justification.

The most general renormalizable $R-$parity violating superpotential using only MSSM superfields is [10]

$$W = \lambda^k_{ij} L_i L_j \bar{E}_k + \lambda_{ijk,1} L_i Q_j \bar{D}_k + \lambda^i_{jk,2} \bar{U}_i \bar{D}_j \bar{D}_k \,. \tag{9}$$

Here i, j, k are generation indices. The couplings λ^k_{ij} are antisymmetric in flavour, $\lambda^k_{ij} = -\lambda^k_{ji}$. Similarly, $\lambda^i_{jk,2} = -\lambda^i_{kj,2}$. There are 36 lepton number nonconserving couplings and 9 baryon number non-conserving couplings $\lambda^i_{jk,2}$. To avoid rapid proton decay it is necessary to put $\lambda^k_{ij} = \lambda_{kij,1} = 0$ or to put $\lambda^i_{jk,2} = 0$.

In this section we consider $R-$parity violating model with $\lambda^k_{ij,2}$ different from zero. The constraints on $\lambda^k_{ij,2}$ couplings have been discussed in refs. [11]. It should be noted that existing bounds on the $R-$parity violating couplings $\lambda^t_{sd,2}, \lambda^c_{bd,2}, \lambda^u_{bs}$ depend on some unknown soft supersymmetry breaking parameters of the theory and are not very stringent. The existence of $R-$parity violating interaction (9) leads to the decay of right-handed squarks into two antiquarks. We suppose for simplicity that the parameters of the model are such that the branching ratios of right-handed squarks to two antiquarks are closed to unit. We have calculated the squark cross section in the assumption that the gluino is much heavier than the right-handed squarks and all right-handed squarks are degenerate in mass. In our calculations we have used the ISASUSY code [12]. The results of our calculations are presented in table 2 and in figure 1. Note that due to nonzero $R-$parity violating interaction we should have also the single squark production at the LHC. At present we are not interested in the single squark production (it is possible to imagine the situation when all $\lambda^k_{ij,2}$ coupling constants are small so the single squark production is negligible and the right-handed squarks are the lightest sparticles so they decay only into two antiquarks).

Table 2: The cross sections for the production of 6 right-handed squarks in pb at LHC for the case of very heavy gluino.

M(TeV)	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.1
σ	300	56	14	4.7	2.1	0.81	0.47	0.24	0.074

4 QCD background estimates

The main background comes from QCD jets. To estimate QCD background we have used PYTHIA 5.7 code [13]. QCD multijets production includes gluon and light quark production. We have used standard UA1 jet definition [17] and took the jet cone size equal to $R = 0.4$ or $R = 1$. Four different transverse momentum cuts on jets p_{T0} have been used : 100 GeV, 150 GeV, 200 GeV, 300 GeV. The selected 4-jet events satisfy the cuts for the invariant dijet masses

$$|M_{ij,jet} - M| \leq \delta, \tag{10}$$

$$|M_{kl,jet} - M| \leq \delta, \tag{11}$$

and moreover the jets have to satisfy the conditions:

a) $p_{Tjet} \geq p_{T0}$

b) $|\eta_{jet}| \leq \eta_0$

Here $i, j, k, l = 1, 2, 3, 4$ $(i \neq j,\ i \neq k,\ i \neq l,\ j \neq k,\ j \neq l,\ k \neq l)$ is the label of the jet number. We also took $\eta_0 = 2.5$. The parameter δ determines the accuracy of the dijet invariant mass determination. In our analysis we have used $\delta = 0.05M$ (optimistic variant) and $\delta = 0.1M$ (realistic variant). Both CMS and ATLAS detectors will be able to measure the dijet invariant mass with an accuracy 10 percent or better for the case of large invariant dijet masses [14, 15]. For our analysis we use δ values 10 and 5 percents. We have generated one million QCD events for each value of p_{T0} and R to find 4-jet QCD background satisfying mass cuts (10),(11). The results of our QCD background calculations for the case $\delta = 0.05M$ are presented in tables 3 - 7. In our calculations we took the LHC total luminosity equal to $L = 10^4 pb^{-1}$. In tables 3 - 7 $\sigma(4jets, back.)$ denotes the QCD background 4-jet cross section satisfying the conditions (10),(11) and with the cut on p_T and η. For instance, the value $\sigma(4jets, back.)$ for the $M = 0.3$ TeV in table 3 means that both dijet invariant masses have to be between 315 GeV and 330 GeV. As it follows from Table 11.7 [14] for CMS we can expect the dijet mass resolution for high p_t and high dijet mass to be between 5 and 10 percents. The value of $\sigma(4jets, back.)$ is approximately proportional to dijet mass resolution δ^2. So for $\delta = 0.1M$ the $\sigma(4jets, back.)$ and hence the number of background events is increased by factor ~ 4 compared to $\delta = 0.05M$ case. Therefore good dijet mass resolution is very important for the decrease of QCD background and hence for the search for new physics by the measurement of 4-jet events.

In tables 3-7 the value $\sigma^{ac}(\Phi\Phi)$ denotes the cross section $\sigma(pp \to (\Phi \to jet1 + jet2) + (\Phi \to jet3 + jet4) + ...)$, where jets $1, 2, 3, 4$ satisfy the p_T and η cuts. The value $\sigma^{ac}(squarks)$ has the similar meaning.

5 LHC discovery potential

As it has been mentioned above, in our concrete calculations we take the total LHC luminosity equal to $L = 10^4 pb^{-1}$. We suppose that new physics will be discovered by the measurement of the 4-jet events provided that

$$S = \frac{N_{signal}}{\sqrt{N_{background}}} \geq 5, \tag{12}$$

where $N_{signal} = \sigma_{signal} L$ and $N_{background} = \sigma(4jets, back.)L$ [14, 15]. The results of our calculations are presented in tables 3 - 7 and in figure 2 . It appears that the most promising cut for the search for scalar octets and squarks at LHC corresponds to $p_{T0} = 300$ GeV and the jet definition with the cone equal to $R = 0.4$ (table 6). In tables (3-7) the value $\sigma^{ac}(\Phi\Phi)$ denotes the cross section $\sigma(pp \to (\Phi \to jet1 + jet2) + (\Phi jet3 + jet4)$, where jets 1,2,3.4 satisfy the p_T and η cuts. The value $\sigma^{ac}(squarks)$ has the similar meaning. The value $S(\Phi\Phi)$ (S(squarks)) in tables (3-7) denotes the significance (see formula (12)) for a model with scalar octets (squarks). The value of σ_{signal} in formulae (13) is $\sigma_{signal} = (0.67)^2\sigma^{ac}(..)$. Here the factor $(0.67)^2$ takes into account intrinsic detector resolution. For $L = 10^4 pb^{-1}$ and for $\delta = 0.05M$ it is possible to discover scalar octets (squarks) with a mass up to 900 GeV(1100 GeV).

The value of $\sigma(4jets, back)$ and hence the number of background events is approximately proportional to the square of the dijet mass resolution, whereas the significance S is inversely proportional to the dijet mass resolution δ. For 10 percent dijet mass resolution ($\delta = 0.1M$) the significance is decreased by factor 2 compared to $\delta = 0.05M$. Therefore good dijet mass resolution is very important for the search for new physics by the measurement of the 4-jet events.

In our estimates we have used PYTHIA 4-jets estimates. It is known [16] that PYTHIA underestimates the number of multi jet events. Suppose, as an extreme example, that the real 4-jets background is 10 times higher than the PYTHIA background. In this case the LHC discovery potential of scalar octets and squarks will be limited to the masses of ≈ 700 GeV. However the increase of luminosity for LHC up to $L = 10^5 pb^{-1}$ will just compensate the factor 10 in background cross section. In any case more reliable estimates of the 4-jet cross section are necessary.

6 Conclusion

To conclude, in this paper we have studied the possibility to discover scalar octets and squarks in a model with $R-$parity violation at the LHC. We have found that scalar octets (squarks) could be discovered at the LHC by the measurement of the distributions of the differential 4-jet cross section on the invariant dijet masses with a mass up to 900 GeV(1100 GeV). To estimate QCD background cross section we have used PYTHIA 5.7 code. In general PYTHIA gives the 4-jet cross section with the accuracy up to factor 2 - 5 [16]. Therefore, more careful calculation of QCD background is necessary. The accurate dijet invariant mass determination is very important for the search for new physics at LHC since QCD background is proportional to the square of the dijet mass resolution and the significance is inversely proportional to δ. Hence the accurate dijet mass determination allows to suppress background. Our values 5 percent and 10 percent for the dijet invariant mass accuracy determination come the optimistic and realistic mass resolutions estimates.

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Table 3: The background and signal acceptance cross sections for LHC ($p_T \geq p_{T0} = 100$ GeV, $R = 0.4$, $L = 10^4 pb^{-1}$). All cross sections are in pb.

M(TeV)	0.3	0.5	0.7	0.9	1.1
$\sigma(4jets, back.)$ $(M \pm 0.05M)$	27.	26.9	10.3	3.8	1.2
$\sigma^{ac}(\Phi\Phi)$	25	3.7	0.61	0.12	0.040
$S(\Phi\Phi)$	217	32	8.6	2.8	1.6
$\sigma^{ac}(squarks)$	17	2.3	0.44	0.13	0.053
$S(squarks)$	147	20	6.2	3.0	2.2

Table 4: The background and signal acceptance cross sections for LHC ($p_T \geq p_{T0} = 150$ GeV, $R = 1$, $L = 10^4 pb^{-1}$). All cross sections are in pb.

M(TeV)	0.3	0.5	0.7	0.9	1.1
$\sigma(4jets, back.)$ $(M \pm 0.05M)$	1.3	10.3	6.6	4.5	1.5
$\sigma^{ac}(\Phi\Phi)$	18	2.2	0.50	0.090	0.037
$S(\Phi\Phi)$	710	31	8.8	1.9	1.4
$\sigma^{ac}(squarks)$	12	1.4	0.36	0.12	0.050
$S(squarks)$	474	20	6.3	2.5	1.8

Table 5: The background and signal acceptance cross sections for LHC ($p_T \geq p_{T0} = 200$ GeV, $R = 0.4$, $L = 10^4 pb^{-1}$). All cross sections are in pb.

M(TeV)	0.3	0.5	0.7	0.9	1.1
$\sigma(4jets, back.)$ $(M \pm 0.05M)$	0.09	0.88	1.47	0.81	0.54
$\sigma^{ac}(\Phi\Phi)$	12	1.9	0.44	0.081	0.028
$S(\Phi\Phi)$	1800	91	16	4.1	1.7
$\sigma^{ac}(squarks)$	7.8	1.2	0.32	0.11	0.038
$S(squarks)$	1170	58	12	5.5	2.3

Table 6: The background and signal acceptance cross sections at LHC ($p_T \geq p_{T0} = 300$ GeV, $R = 0.4$, $L = 10^4 pb^{-1}$). All cross sections are in pb.

M(TeV)	0.3	0.5	0.7	0.9	1.1
$\sigma(4jets, back.)$ $(M \pm 0.05M)$	0.005	0.008	0.089	0.182	0.103
$\sigma^{ac}(\Phi\Phi)$	6.7	1.2	0.33	0.068	0.024
$S(\Phi\Phi)$	4264	603	50	7.2	3.4
$\sigma^{ac}(squarks)$	4.5	0.74	0.24	0.092	0.033
$S(squarks)$	2860	372	37	9.8	4.7

Table 7: The background and signal acceptance 4 jet cross sections at LHC ($p_T \geq p_{T0} = 300$ GeV, $R = 1$, $L = 10^4 pb^{-1}$). All cross sections are in pb.

M(TeV)	0.3	0.5	0.7	0.9	1.1
$\sigma(4jets, back.)$ $(M \pm 0.05M)$	0.001	0.016	0.073	0.223	0.130
$\sigma^{ac}(\Phi\Phi)$	6.7	1.2	0.33	0.068	0.024
$S(\Phi\Phi)$	3015	427	55	6.5	3.0
$\sigma^{ac}(squarks)$	4.5	0.74	0.24	0.092	0.033
$S(squarks)$	2025	263	40	8.8	4.1

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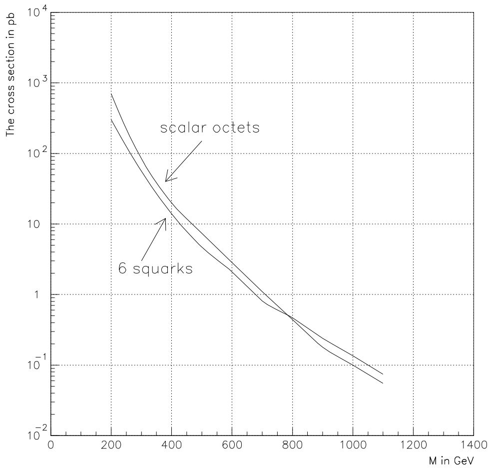

Figure 1: The scalar octet cross section production and the production cross section of 6 right-handed squarks at LHC.

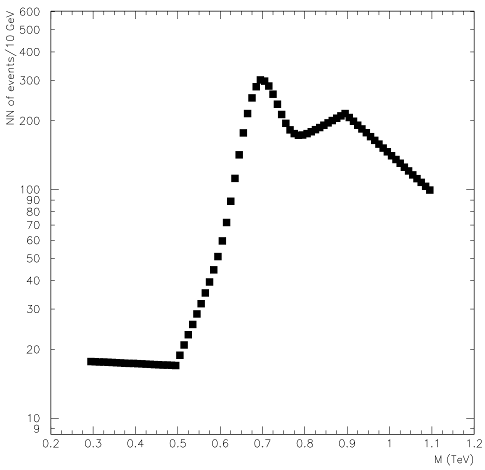

Figure 2: Background and signal dijet mass plot for $L = 10^4 pb^{-1}$ with signal for octet mass m_Φ = 700 GeV for p_T = 300 GeV and R = 0.4 cuts.