The search for new physics by the measurement of the
4-jet cross section at LHC and FNAL.

S.I.Bityukov
IHEP, Protvino RU-142284, Russia
and
N.V.Krasnikov
INR, Moscow 117312, Russia

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Abstract

We investigate the possibility to look for new physics by the measurement of the
4-jet cross section at LHC and FNAL. In particular, we consider the model with
scalar colour octet and the supersymmetric model with R-parity violation. In both
models pair produced new particles decay into 2 jets thus leading to 4-jet events.
Therefore, the measurement of the distributions of 4-jet differential cross section on
on the invariant dijet masses allows to look for new physics. The main background
comes from standard QCD 4-jet events. We find that at LHC it would be possible
to discover scalar colour octet particles with a mass $\leq 900$ Gev and for FNAL the
corresponding bound is 175 Gev.
1 Introduction

Many extensions of the standard model predict the existence of new massive objects that couple to quarks and gluons, and result in resonant structures in the two-jet mass spectrum. Usually such new objects (excited quarks, axigluons, colour octet technirhos, new gauge bosons $W'$, $Z'$, scalar diquarks, etc.) are singly produced in hadron-hadron interactions. So such new particle will give new resonant type contribution to the QCD two-jet cross section. In ref.[1] experimental bounds on new particles decaying to dijets have been obtained. However there are examples of new particles (scalar colour octets, squarks in model with R-parity violation etc.) that produced mainly in pairs and decay to dijets so their decays lead to the resonant structure for the four-jet differential cross section. The main background comes from the standard QCD 4-jet events. Therefore it is very interesting to answer the question: is it possible to discover new physics at hadron-hadron colliders by the measurement of the 4-jet differential cross section?

In this paper we study the possibility to search for scalar colour octets and squarks with R-parity violation by the measurement of the 4-jet cross section at LHC and FNAL. We find that at LHC it would be possible to discover the scalar colour octets with the mass $\leq 900$ Gev and at FNAL the corresponding bound is 175 Gev. Analogous bounds take place for the squarks in model with R-parity violation.

In section 2 we describe the phenomenology of scalar octets. In section 3 we describe the model with R-parity violation. Section 4 is devoted to the discussion of QCD background. In section 5 we discuss the LHC and FNAL 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

The relatively light ($M \leq O(1)\text{TeV}$) scalar colour octets are predicted in some nonsupersymmetric and supersymmetric GUTs [2, 3]. The phenomenology of light scalar octets has been discussed in ref.[4]. To be precise, 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 selfconjugate scalar field $\Phi^\alpha_\beta(x) ((\Phi^\alpha_\beta(x))^+ = \Phi^\beta_\alpha(x), \Phi^\alpha_\alpha(x) = 0)$ interacting 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

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

The term $\frac{\lambda_1 M}{6} Tr(\Phi^3)$ in the scalar potential (1) breaks the discrete symmetry $\Phi \rightarrow -\Phi$. 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. One can find that the decay width of the scalar octet is determined by the formula

$$\Gamma(\Phi \rightarrow gg) = \frac{15}{4096 \pi^3} \alpha_s^2 \lambda_1^2 M,$$ (2)

where

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

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

$$\Gamma(\Phi \rightarrow gg) = 0.39 \cdot 10^{-8} \lambda_1^2 M$$ (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 $\lambda_2, \lambda_3$ don’t have Landau pole singularities up to the energy $M_0 = 100 \cdot M$ we find that $\lambda_1 \leq O(1)$. Therefore the decay width of the scalar coloured octet is less than $O(1) ev, O(100) ev, O(1) KeV, O(10) KeV$ for the octet masses $M = 1, 10, 100, 1000$ Gev correspondingly. It means that new hadrons composed from scalar octet $\Phi$, quarks and gluons ($\overline{\Phi}q, \Phi g, ggg\Phi$) are longlived even for very high scalar octet mass. 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 extremly small and that the search for the scalar octets in dijet events is hopeless.
Consider pair production of scalar octets at FNAL and LHC. The corresponding lowest order formulae for the parton cross sections have the form

\[
\frac{d\sigma}{dt}(\bar{q}q \rightarrow \Phi \Phi) = \frac{4\pi \alpha_s^2}{3s^4}(tu - M^4),
\]

(5)

\[
\frac{d\sigma}{dt}(gg \rightarrow \Phi \Phi) = \frac{\pi \alpha_s^2}{s^2} \left( \frac{27}{32} + \frac{9(u - t)^2}{32s^2} \right)(1 + \frac{2M^2}{u - M^2} + \frac{2M^2}{t - M^2} + \frac{2M^4}{(u - M^2)^2} + \frac{2M^4}{(t - M^2)^2} + \frac{4M^4}{(t - M^2)(u - M^2)}),
\]

(6)

\[
\sigma(\bar{q}q \rightarrow \Phi \Phi) = \frac{2\pi \alpha_s^2}{9s} k^3,
\]

(7)

\[
\sigma(gg \rightarrow \Phi \Phi) = \frac{\pi \alpha_s^2}{s} \left( \frac{15k}{16} + \frac{51kM^2}{8s} + \frac{9M^2}{2s^2} \right) (s - M^2) \ln \left( \frac{1 - k}{1 + k} \right),
\]

(8)

where \( k = (1 - \frac{4M^2}{s})^{\frac{1}{2}} \). We have calculated the cross sections for the production of scalar octets at FNAL and LHC using the results for the parton distributions of ref.\[5\], namely, in our calculations we have used set 1 of the parton distributions of ref.\[5\] at the renormalization point \( \mu = 2M \). We have found that at LHC the main contribution (\( \geq 95\% \)) comes from the gluon annihilation into two scalar octets \( gg \rightarrow \Phi \Phi \), whereas at FNAL gluon-gluon and quark-antiquark annihilation cross sections are comparable. The results of our calculations for the total cross sections are presented in tables 1, 2 and in figures 1, 3.

For light scalar octets two gluon and quark-antiquark annihilations into two scalar octets give additional contribution to the two-jet cross section. However, this additional contribution is rather small. For instance, the cross section for gluon-gluon scattering is

\[
\frac{d\sigma}{dt}(gg \rightarrow gg) = \frac{9\pi \alpha_s^2}{2s^2} \left[ 3 - \frac{tu}{s^2} - \frac{su}{t^2} - \frac{st}{u^2} \right].
\]

(9)

Even for the most favorable case \( t = u = -\frac{s}{2} \) the cross section (12) is 20 times less than gluon-gluon cross section (15). So the perspective to detect light scalar octets by the measurement of the two-jet cross sections looks hopeless. For rather big values of the scalar octet mass \( M \geq O(50)\text{Gev} \) the scalar octets decay into two gluons that leads to the four-jet events.
3 Squarks in model with R-parity violation

The minimal supersymmetric standard model (MSSM) is considered as a leading candidate for supersymmetric generalization of Standard Model [7]. 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-violating superpotential using only MSSM superfields is [8]

\[ W = \lambda_{ij}^k L_i L_j \tilde{E}_k + \lambda_{ijk,1} L_i Q_j \tilde{D}_k + \lambda_{ijk,2} \tilde{U}_i \tilde{D}_j \tilde{D}_k. \] (10)

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

In this section we consider R-parity violating model with \( \lambda_{ij,k}^2 \) different from zero. The constraints on \( \lambda_{ij,k}^2 \) couplings have been discussed in refs. [9]. It should be noted that existing bounds on the R-parity violating couplings \( \lambda_{sd,2}^l, \lambda_{bd,2}^c, \lambda_{us}^u \) depend on some unknown soft supersymmetry breaking parameters of the theory and are not very stringent. The existence of R-parity violating interaction (10) leads to the decay of righthanded squarks into two antiquarks, so each of pair produced righthanded squarks will decay into two jets resulting in 4-jet signature. 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. So the typical signature for such scenario is the existence of additional 4-jet events arising due to squarks decays into two jets. We have calculated the squark cross section in the assumption that gluino mass is much heavier than the righthanded squarks and all righthanded squarks are degenerated in mass. In our calculations we have used ISASUSY program [10]. The results of our calculations are presented in tables 3, 4 and in figures 2, 4. Note that due to nonzero R-parity violating interaction we shall have the single squark production at supercolliders. At present we don’t interested in the single squark particle.
production (it is possible to imagine the situation when all $\lambda_{ij,2}^k$ coupling constants are small so the single squark production is negligible and the righthanded squarks are the lightest sparticles so they decay only into two antiquarks).

4 QCD background estimates

The main background comes from QCD jets. To estimate QCD background we have used PYTHIA 5.7 program [11]. We have used standard UA1 definition of jet and took the jet cone equal to $R = 0.4$ and $R = 1$. We have used the the transverse momentum cut on jets $p_{T0}$ equal to 100 Gev, 150 Gev, 200 Gev, 300 Gev for LHC and 50 Gev, 100 Gev for FNAL. We selected 4-jet events such that the invariant dijet masses fulfil the conditions

$$|M_{ij,\text{jet}} - M| \leq \delta, \quad (11)$$

$$|M_{kl,\text{jet}} - M| \leq \delta, \quad (12)$$

and moreover the jets have to satisfy the conditions:

a. $p_{T\text{jet}} \geq p_{T0}$

b. $|\eta_{\text{jet}}| \leq \eta_0$

Here $i, j, k, l = 1, 2, 3, 4$ label the jet number and $i \neq j, i \neq k, i \neq l, j \neq k, j \neq l, k \neq i, k \neq j, k \neq l$. For LHC we took $\eta_0 = 2.5$ and for FNAL we have used $\eta_0 = 0.5$.

The parameter $\delta$ determines the accuracy of the dijet invariant mass determination. In our analysis for LHC we have used $\delta = 50$ Gev (optimistic variant) and $\delta = 100$ Gev (realistic variant). For FNAL we have used $\delta = 25$ Gev. Both CMS and ATLAS detectors will be able to measure the dijet invariant mass with the accuracy 10 percent or even better for the case of big invariant dijet masses [12, 13]. Our realistic variant for $\delta$ corresponds to approximately 10 percent dijet invariant mass resolution and optimistic variant corresponds approximately to 5 percent accuracy in the dijet mass determination.

For FNAL $\delta = 25$ Gev corresponds to $\approx 10$ percent dijet mass determination for $M_{\text{dijet}} \leq 225$ Gev. We have generated one million QCD events for each value of $P_{T0}$ and $R$ to find 4-jet QCD background satisfying mass cuts (11,12) both for LHC and FNAL. As
for FNAL typical accuracy in the determination of dijet invariant mass is 10 percent. The results of our QCD background calculations are presented in tables 5 - 11 and in figures 5 - 10. In our calculations we took the LHC total luminosity equal to $L_t = 10^4 pb^{-1}$ and for FNAL we have used $L_t = 100 pb^{-1}$. In tables 5 - 11 $\sigma(4\text{jets, back.})$ denotes the QCD background 4-jet cross section satisfying the conditions (11,12) and with the cut on $p_T$ and $\eta$. For LHC we have used in tables 5 - 9 $\delta = 100$ Gev (realistic variant). For FNAL we have used $\delta = 25$ Gev ($\approx$ 10 percent dijet mass accuracy determination). For instance, the value $\sigma(4\text{jets, back.})$ for the $M = 0.3$ Tev in table 5 means that both dijet invariant masses have to be between (300 - 100) Gev and (300 + 100) Gev. The value $\sigma(\text{sig.disc.})$ means the lower value of the acceptable cross section corresponding to new physics which can be detected at $5\sigma$ level. The value $\sigma^{ac}(\Phi \Phi)$ denotes the cross section $\sigma(pp \rightarrow (\Phi \rightarrow \text{jet}_1 + \text{jet}_2) + (\Phi \rightarrow \text{jet}_3 + \text{jet}_4) + ...)$, where jets 1,2,3,4 satisfy the $p_T$ and $\eta$ cuts. The value $\sigma^{ac}(\text{squarks})$ has the similar meaning.

5 LHC and FNAL discovery potentials

As it has been mentioned before in our concrete calculations we take the total LHC luminosity equal to $L_{t,LHC} = 10^4 pb^{-1}$ and the total FNAL luminosity $L_{t,FNAL} = 100 pb^{-1}$. According to standard folklore (unfortunately folklore $\neq$ theorem statement) we suppose that new physics will be discovered by the measurement of the 4-jet events provided that

$$Significance = \frac{N_{signal}}{\sqrt{N_{background}}} \geq 5,$$

(13)

where $N_{signal} = \sigma_{signal} L_t$ and $N_{background} = \sigma_{background} L_t$. The results of our calculations are presented in tables 5 - 11 and in figures 11 - 15. It appears that the most promising cut for the search for scalar octets at LHC corresponds to $p_{T0} = 300$ Gev and the jet definition with the cone equal to $R = 0.4$ (table 8). As it follows from the table 8 it is possible to discover at $5\sigma$ level scalar octets with the mass up to 900 Gev and the squarks in the model with R-parity violation with the mass up to 1100 Gev. As for FNAL the most promising cut corresponds to $p_{T0} = 100$ Gev (Table 12). As it follows from the table 12 FNAL is able
to discover scalar octets and squarks with the masses lighter than 175 Gev. As we know up to now there was not analysis of dijet mass distributions for 4-jet events both in CDF and D0. It would be very interesting to perform such analysis. In our estimates we used PYTHIA 4-jets estimates. It is well known that PYTHIA underestimates the number of many jets events. Suppose that the real 4-jets background is 10 times bigger than the PYTHIA background. In this case for LHC the discovery potential of scalar octets and squarks will be for the masses up to \( \approx 700 \text{ Gev} \) and for FNAL up to \( \approx 150 \text{ Gev} \). However the increase of luminosity for LHC up to \( L_t = 10^5 \text{pb}^{-1} \) (the luminosity for a year after 2 first years of exploitation) and for FNAL up to \( L_t = 1000 \text{pb}^{-1} \) (upgraded TEVATRON) just will compensate the factor 10 in background cross section. More reliable estimates of the 4-jet cross section are necessary.

6 Conclusion

To conclude, in this paper we have studied the perspectives of the discovery of scalar octets and squarks in the model with R-parity violation at FNAL and LHC. We have found that scalar octets and squarks could be discovered at LHC and FNAL by the measurement of the distributions of the differential 4-jet cross section on the invariant two-jet masses with the mass up to 900 - 1100 Gev(LHC) and 175 - 200 Gev(FNAL). One of the main problems here is an accurate estimate of QCD background. We have used PYTHIA to estimate QCD background. In general PYTHIA gives the 4 jet cross section with the accuracy of factor 2 -5. Therefore more careful calculation of QCD background is necessary. Nevertheless our results are very encouraging. Moreover, it is necessary to estimate more carefully the accuracy of the dijet invariant mass determination at CMS and ATLAS. However we think that our numbers 5 percent and 10 percent (optimistic and realistic variants) for the estimation of the dijet invariant mass accuracy determination are reasonable.

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

| M(Tev) | 0.2 | 0.3 | 0.4 | 0.5 | 0.7 | 0.9 | 1.1 |
|--------|-----|-----|-----|-----|-----|-----|-----|
| $\sigma$ | 701 | 84  | 20  | 7.4 | 1.1 | 0.18| 0.055 |

Table 2. The cross section $\sigma(\bar{p}p \to \Phi\Phi + \ldots)$ in pb for different values of octet masses at FNAL.

| M(Gev) | 125 | 150 | 175 | 200 | 225 | 250 | 275 | 300 | 325 |
|--------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| $\sigma$ | 11  | 3.6 | 1.1 | 0.42| 0.21| 0.074| 0.030| 0.014| 0.0067|

Table 3. The cross sections for the production of 6 mass degenerate righthanded 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 |
|--------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| $\sigma$ | 300 | 56  | 14  | 4.7 | 2.1 | 0.81| 0.47 | 0.24 | 0.074 |

Table 4. The cross sections for the production of 6 mass degenerate righthanded squarks in pb at FNAL for the case of very heavy gluino.

| M(Gev) | 125 | 150 | 175 | 200 | 225 | 250 | 275 | 300 | 325 |
|--------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| $\sigma$ | 8.2 | 3.8 | 1.7 | 0.72| 0.37| 0.17| 0.083| 0.036| 0.017|

Table 5. The background and signal acceptance cross sections for LHC ($p_T \geq p_{T0} = 100$ Gev, $R = 0.4$, $L_t = 10^4 pb^{-1}$). All cross sections are in pb.

| M(Tev) | 0.3 | 0.5 | 0.7 | 0.9 | 1.1 |
|--------|-----|-----|-----|-----|-----|
| $\sigma(4jets,\backslash\text{back.})$ | 1200| 430 | 84  | 19  | 3.8 |
| $\sigma(sig.disc.)$ | 1.7 | 1.1 | 0.46 | 0.22| 0.1 |
| $\sigma^{ac}(\Phi\Phi)$ | 25  | 3.7 | 0.61| 0.12| 0.040|
| $\sigma^{ac}(\text{squarks})$ | 17  | 2.3 | 0.44| 0.13| 0.053|

Table 6. The background and signal acceptance cross sections for LHC ($p_T \geq p_{T0} = 150$ Gev, $R = 1$, $L_t = 10^4 pb^{-1}$). All cross sections are in pb.
Table 7. The background and signal acceptance cross sections for LHC ($p_T \geq p_{T_0} = 200$ Gev, $R = 0.4$, $L_t = 10^4 pb^{-1}$). All cross sections are in pb.

| M(Tev) | 0.3 | 0.5 | 0.7 | 0.9 | 1.1 |
|--------|-----|-----|-----|-----|-----|
| $\sigma(4jets, back.)$ | 58  | 165 | 54  | 22  | 4.8 |
| $\sigma(sig.disc.)$ | 0.38 | 0.64 | 0.37 | 0.23 | 0.11 |
| $\sigma^{ac}(\Phi\Phi)$ | 18  | 2.2 | 0.50 | 0.090 | 0.037 |
| $\sigma^{ac}(squarks)$ | 12  | 1.4 | 0.36 | 0.12 | 0.050 |

Table 8. The background and acceptance cross sections at LHC ($p_T \geq p_{T_0} = 300$ Gev, $R = 0.4$, $L_t = 10^4 pb^{-1}$). All cross sections are in pb.

| M(Tev) | 0.3 | 0.5 | 0.7 | 0.9 | 1.1 |
|--------|-----|-----|-----|-----|-----|
| $\sigma(4jets, back.)$ | 4   | 14  | 12  | 4   | 1.8 |
| $\sigma(sig.disc.)$ | 0.10 | 0.19 | 0.17 | 0.11 | 0.07 |
| $\sigma^{ac}(\Phi\Phi)$ | 12  | 1.9 | 0.44 | 0.081 | 0.028 |
| $\sigma^{ac}(squarks)$ | 7.8 | 1.2 | 0.32 | 0.11 | 0.038 |

Table 9. The background and acceptance 4 jet cross sections at LHC ($p_T \geq p_{T_0} = 300$ Gev, $R = 1$, $L_t = 10^4 pb^{-1}$). All cross sections are in pb.

| M(Tev) | 0.3 | 0.5 | 0.7 | 0.9 | 1.1 |
|--------|-----|-----|-----|-----|-----|
| $\sigma(4jets, back.)$ | 0.22 | 0.13 | 0.73 | 0.90 | 0.34 |
| $\sigma(sig.disc.)$ | 0.023 | 0.018 | 0.043 | 0.048 | 0.029 |
| $\sigma^{ac}(\Phi\Phi)$ | 6.7 | 1.2 | 0.33 | 0.068 | 0.024 |
| $\sigma^{ac}(squarks)$ | 4.5 | 0.74 | 0.24 | 0.092 | 0.033 |
Table 10. The background and accepted 4 jet cross sections at FNAL ($p_T \geq p_{T0} = 50 \text{ Gev}$, $R = 0.4$, $L_t = 10^2 \text{pb}^{-1}$). All cross sections are in pb.

| M(Gev) | 125 | 175 | 225 | 275 |
|--------|-----|-----|-----|-----|
| $\sigma(4\text{jets, back.})$ | 0.34 | 0.51 | 0.17 | 0.17 |
| $\sigma^{ac}(\text{sig.disc.})$ | 0.29 | 0.36 | 0.21 | $\leq 0.21$ |
| $\sigma^{ac}(\Phi\Phi)$ | 2.2 | 0.22 | 0.042 | 0.0061 |
| $\sigma^{ac}(\text{squarks})$ | 1.6 | 0.36 | 0.078 | 0.017 |

Table 11. The background and acceptance 4-jet cross sections at FNAL ($p_T \geq p_{T0} = 100 \text{ Gev}$, $R = 1$, $L_t = 10^2 \text{pb}^{-1}$). All cross sections are in pb.

| M(Gev) | 125 | 175 | 225 | 275 |
|--------|-----|-----|-----|-----|
| $\sigma(4\text{jets, back.})$ | $\leq 0.01$ | $\leq 0.01$ | $\leq 0.01$ | $\leq 0.01$ |
| $\sigma^{ac}(\text{sig.disc.})$ | $\geq 0.05$ | $\geq 0.05$ | $\geq 0.05$ | $\geq 0.05$ |
| $\sigma^{ac}(\Phi\Phi)$ | 1.2 | 0.103 | 0.025 | 0.0036 |
| $\sigma^{ac}(\text{squarks})$ | 0.90 | 0.20 | 0.044 | 0.011 |
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