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A SEARCH FOR QUARK COMPOSITENESS AT THE LHC. DIJET ANGULAR DISTRIBUTIONS

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The existence of an underlying substructure will be good key for understanding of the unresolved problems of Standard Model such as the presence of few generations of quarks and leptons, the fundamental properties of particles.

The quark substructure would appear as an excess of the high P_T jets compared to the level predicted by QCD or with dijet angular distributions more isotropic than what is expected from a point-like quark theory. Dijet angular distributions have been studied by the CDF[1] and $D0$[2] experiments at a center-of-mass(CM) energy of $1.8\,TeV$. The highest E_T reached so far at the $Tevatron$, $440\,GeV$, corresponds to a distance scale $10^{-17}\,cm$. The experimental data have been compared with QCD predictions including compositeness. No evidence of quark substructure was found. Previous studies of dijet invariant mass spectrum reported by $UA1$[3], $UA2$[4] at $\sqrt{s} = 630\,GeV$ and by CDF[5] have also shown the data that were consistent with QCD predictions. The CDF[6] and D0[7] results on high-mass Drell-Yan cross-section measurement sets lower limit on the quark-electron compositeness scale about $5.5\,TeV$. From the ratio of charged current to neutral current cross-section measurement in the CCFR fixed target neutrino experiment[8] at Tevatron limit on $\Lambda \sim 8\,TeV$ was achieved.

In future hadron colliders, the search for quark substructure will continue. Here we investigate the effect of quark compositeness in dijet angular distribution as would be seen by $ATLAS$[14] at the LHC. The same problem for high E_T jet spectrum was pointed out earlier[9]. To simulate a scenario with quark substructure the event generator $PYTHIA$-5.7[10] has been used. This has allowed to use a simple phenomenological approch of contact interactions between quark constituents with a compositeness scale Λ[11], where the sign of the $effective\ Lagrangian$ for a flavor diagonal definite chirality current is positive (destructive interference) or negative (constructive interference). The data simulated in the framework of $Standart\ Model\,(SM)$ are compared with those obtained assuming quark compositeness. The analysis is based on a samples of $\sim$ 280800 pp-interactions at $\sqrt{s} = 14\,TeV$ which corresponds to the sample of dijet events expected after one month of LHC operation at a luminosity $\mathcal{L} = 10^{33}\,cm^{-2}s^{-1}$. The simulated event sample included the following hard-scattering subprocesses: qq, qg, gg, $g\gamma$, $q\gamma$, $\gamma\gamma$. The γ^*/Z, W, tt production subprocesses also enabled. To get a sufficiently large number of events with high P_T jets in a reasonnable CPU time, a cut on the transverse momentum of the hard scattering subprocess was set to $600\,GeV$. Under these conditions, the contributions from the qq, qg and gg process represent 97.5% of the total cross section $3.370 \cdot 10^{-7}\,mb$. Initial and final state QCD and QED radiation, fragmentation and decay of partons and particles, multiple interactions were enabled. First-order running α_S calculations were applied. The Λ_{QCD} value is chosen according to the parton distribution functions (pdf) parametrizations, used in $PYTHIA$. For the Q^2 scale in the hard scattering $2 \to 2$ process, $Q^2 = (m_{T1}^2 + m_{T2}^2)/2$ was used. The detector performance was simulated using the $ATLFAST$[12] package which provides a reliable estimate of the detector response to hadronic jets. Jets were reconstructed with $ATLFAST$ using the standard procedure of summing the energy deposited in a cone of radius $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.7$. All calorimeter cells with $E_T > 1.5\,GeV$ are taken as possible initiators of clusters. The total E_T summed over all cells in a cone ΔR should be larger than $15\,GeV$. Jets are reconstructed down to $|\eta| \leq 5.0$.

The analysis was made in terms of an angular variable $\chi \equiv e^{(|\eta_1 - \eta_2|)}$, where $\eta_{1,2}$ are the pseudorapidities of the two leading jets. For the case of $2 \to 2$ parton scattering, it is related to the CM scattering angle Θ^* as follows:

$$\chi = \frac{1 + |cos\Theta^*|}{1 - |cos\Theta^*|} \qquad (1)$$

This definition makes the comparison with theory more straightforward[13]. The investigation of the dijet angular distribution, $(1/N)\,(dN/d\chi)$, was made in four dijet invariant mass bins. The dijet invariant mass is defined as

$$M_{jj} = \sqrt{(E_1 + E_2)^2 - (P_1 + P_2)^2}, \qquad (2)$$

where $(E_{1,2}, P_{1,2})$ are the 4-vector of the two leading jets. For all dijet invariant mass bins the E_T-threshold for the highest E_T jet was $400\,GeV$. *Table*1 shows the selection cuts for the highest E_T jet for the various invariant dijet mass bins, together with the average M_{jj} and the number of events per bin.

The dijet angular distributions for these dijet mass bins are shown in *Figure* 1, and *Figure* 2 for destructive and constructive interference, respectively. From the figures, one can see that quark compositeness leads to an enhancement in the distribution at low values of χ in comparision to the SM prediction. The dijet mass range above $3400\,GeV$ is good for the determination of isotropic contributions to the dijet angular distribution in pp-interactions at $\sqrt{s} = 14\,TeV$ for Λ up to $8\,TeV$. One can see as well that the sensitivity is greater for a constructive interference than for destructive one.

$Mass\,bins(GeV)$	2000-2300	2300-2800	2800-3400	>3400
$E_T tresholds(GeV)$	400	400	400	400
N_{ev}	18562	15781	7722	5228
$Average\ M_{jj}\,(GeV)$	2136	2512	3050	4048

Table 1: Characteristics of the invariant mass bins for the high E_T jets.

To estimate the limits on the quark compositness scale the CDF-group used the variable R_χ which is the ratio of the number of events with $\chi < \chi_0$ to the number with $\chi > \chi_0$. In our case a value of $\chi_0 = 5$ was used. *Figure* 3 shows the R_χ as a function of the dijet mass for different values of the compositeness scale Λ, in the constructive case, when two, and all quarks are composite. The data are plotted at the average mass for each mass bin. In the case that all quarks are composite and for a compositeness scale $\Lambda = 16\,TeV$ the data differ from the SM predictions by $1.5\,\sigma$ and $3.5\,\sigma$, for destructive and constructive interference, respectively.

In *Figure* 4 the dependence of R_χ on the scale Λ, for the constructive and destructive cases, and when two and all quarks are composite are compared. It is clear, that there is not enough sensitivity to distinguish the cases of two or all quarks compositeness.

R_χ is not very sensitive to the pdf as illustrated in *Figure* 5, where the values of R_χ are shown for the mass bin of M_{jj} above $3400\,GeV$. These predictions have been obtained for $\Lambda^-_{ud,all} = 8000\,GeV$ for the cases when two or all quarks are composite. Note that in the rest of the analysis, $PYTHIA$ was used with the default structure function $CTEQ2L$.

R_χ is also insensitive to the jet cone radius ΔR.

The sensitivity to the calorimeter resolution has been studied[15]. In $ATLFAST$, the jet energy is smeared according to $\sigma_E/E \sim 50\%/\sqrt{E} + 2\%$ in the central region ($|\eta| < 3$) and $\sigma_E/E \sim 100\%/\sqrt(E) + 7\%$ in the forward calorimeters ($3 < |\eta| < 5$).

In order to investigate the influence of a change of the constant term on $(1/N)\,(dN/d\chi)$, we simple multiplied and divided the constant term by two. Changes in the stochastic were also considered. There is no significant impact of those changes on the dijet angular distribution.

The non-linear response of the hadron calorimeter can affect the observed difference between the SM and compositeness scenario, or fake a compositeness signal. To study this effect, we considered a non-linearity of the jet E_T scale according the relation[16]:

$$E_T(meas) = E_T \cdot \frac{1.}{c(1. + (e/h - 1.) \cdot 0.11 \cdot lnE_T)} \qquad (3)$$

where $E_T(meas)$ and E_T are measured and true jet transverse energy; $e/h = 1.36$ and c is adjusted such that at $50\,GeV$ the scale is unchanged. Such a dependence on E_T leads to a deviation from linearity of 6.5, 9.3 and 12.3% for 400, 1000 and $3000\,GeV$, respectively. In $Figure\,6$ we compare the SM and composite quarks predictions with and without non-linearity effects. For this choice of dijet mass bin intervals and jet E_T, we see that no fake signal is created and that the angular distribution is quite insensitive to effects of non-linearity.

To study the data sensitivity to the quark compositeness signal for higher scale Λ^-_{all}, a analysis was performed for integrated luminosity of $30\,fb^{-1}$ and $300 fb^{-1}$. $Figure\,7$ and $Figure\,8$ shows the difference between compositeness quark and SM predictions, divided by the SM predictions for dijet angular distributions.

In conclusion,the study based on $PYTHIA$-5.7 generated and processed through $ATLFAST$ shows that high mass dijet angular distribution has a good discovery capability for compositeness. Small sensitivity to the pdf choice, calorimeter energy resolution and non-linearity effects makes the dijet angular distribution a powerful tool for future high statistics data analyses. One month of LHC operation at $10^{33} cm^{-2} s^{-1}$ and $\sqrt{s} = 14\,TeV$ alows the discovery of quark substructure if the constituent interaction constant is of the order $14\,TeV$. To reach a lower limit of $25(40)\,TeV$ for interaction constant a data taking at integrated luminosity of $30(300)\ fb^{-1}$ is needed.

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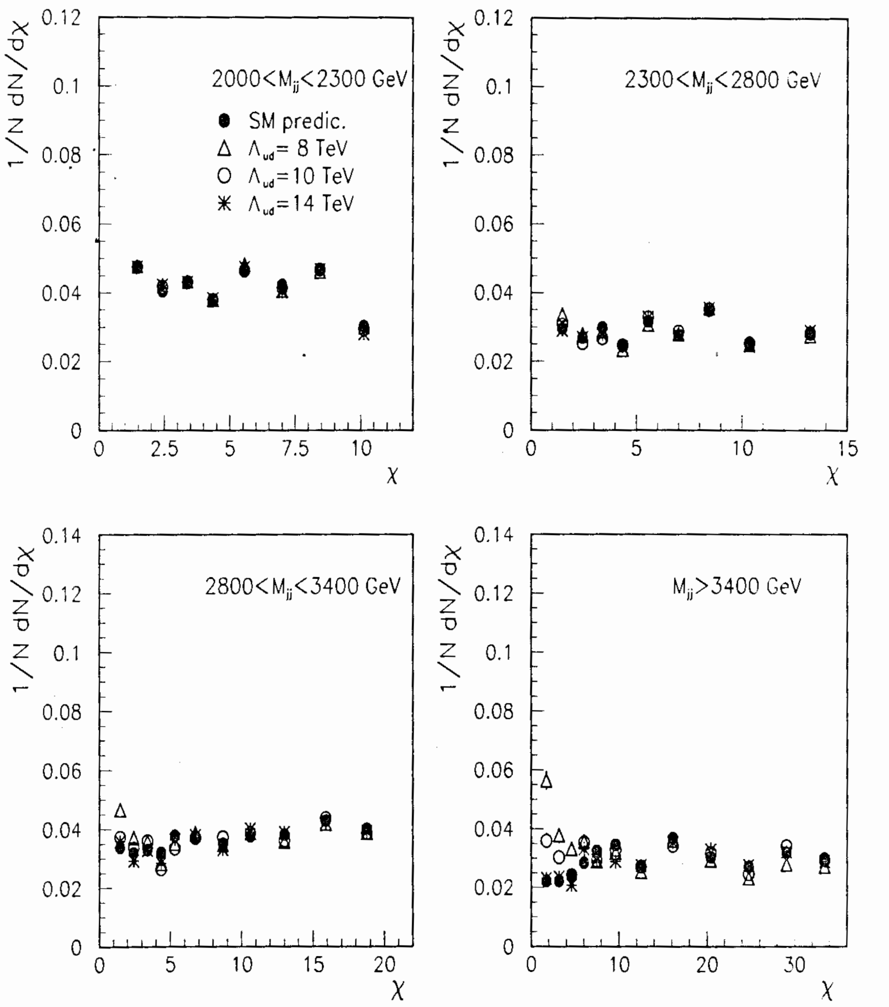

Figure 1: Dijet angular distributions for various mass bins in case of destructive interference.

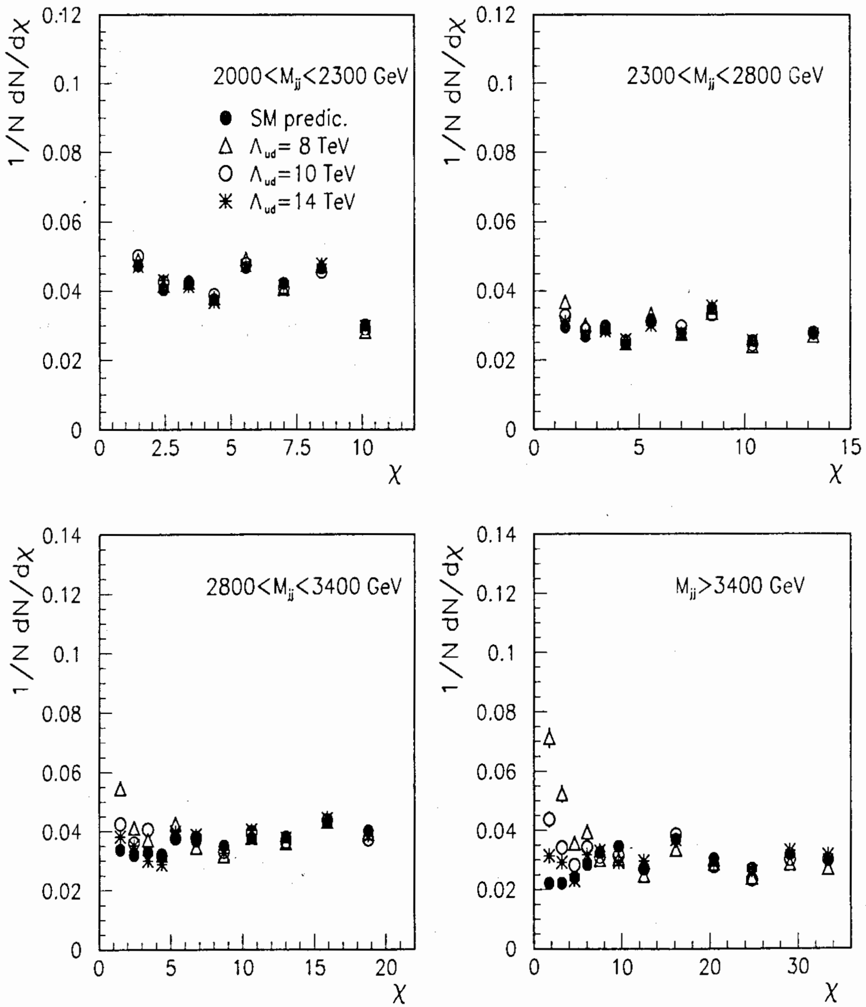

Figure 2: Dijet angular distributions for various mass bins in case of constructive interference.

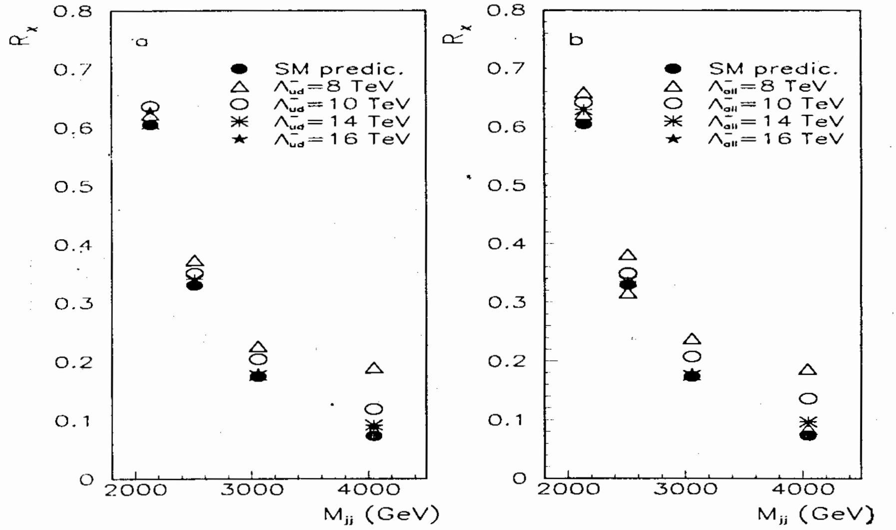

Figure 3: R_χ as a function of the dijet mass M for different values of the compositeness scale Λ when two (a) and all quarks (b) are composite. The data are plotted at the average mass for each mass bin.

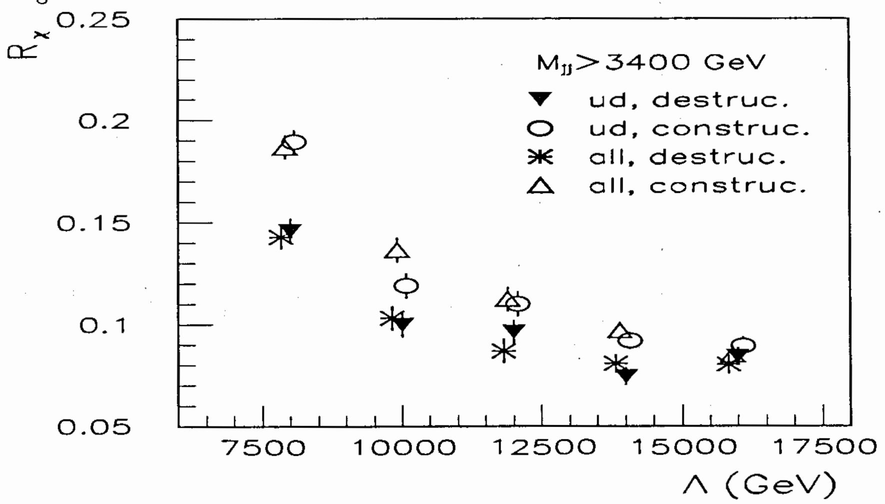

Figure 4: The dependence of R_χ on the scale Λ, for the constructive and destructive cases, when two and all quarks are composite.

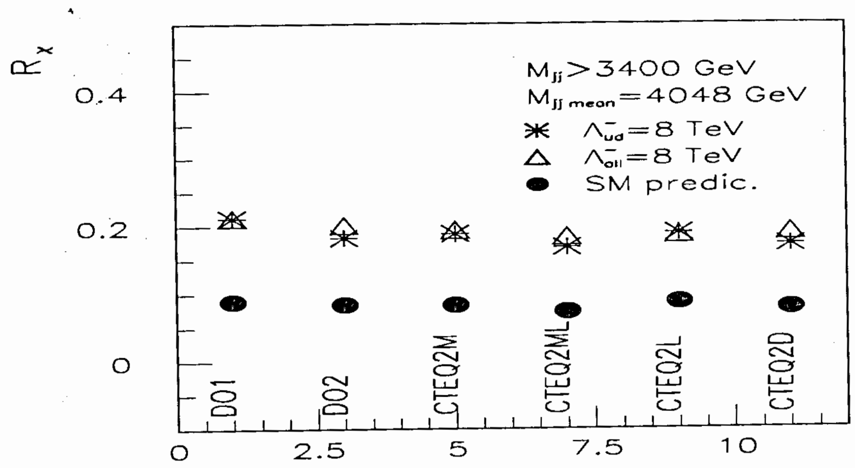

Figure 5: The dependence of R_χ on the parton distribution function.

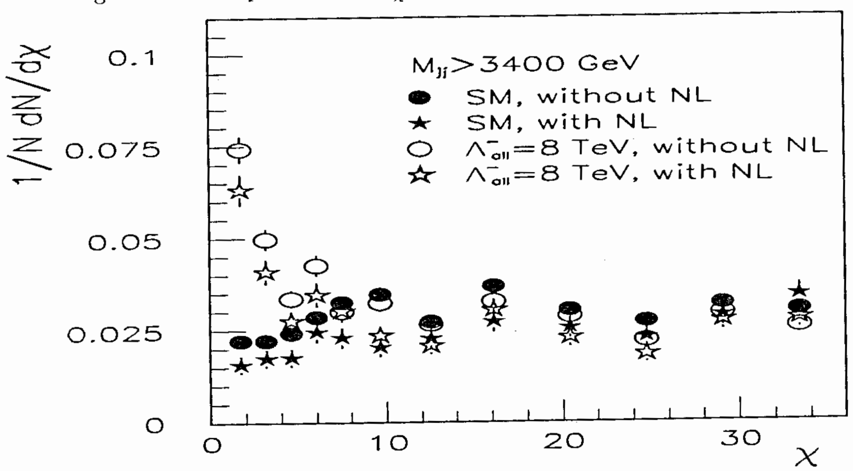

Figure 6: Standard Model and composite quark predictions with and without non-linearity effects.

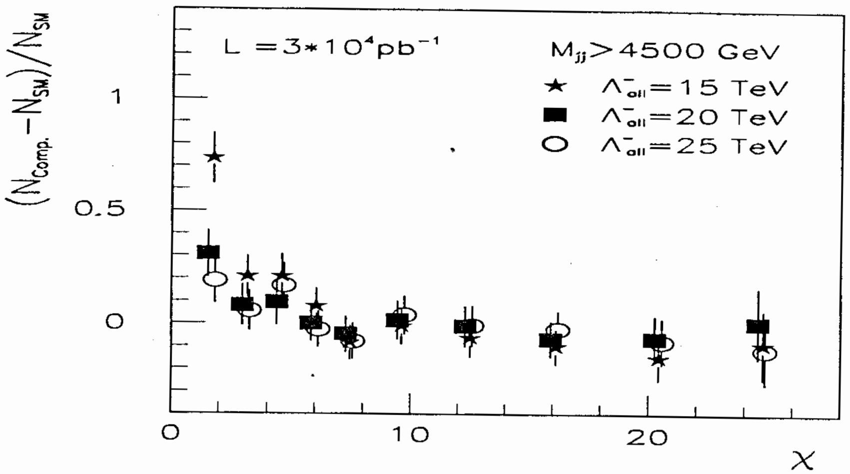

Figure 7: The difference between composite quark and Standard Model predictions, divided by the Standard Model for dijet angular distribution at integrated luminosity $L = 30\, fb^{-1}$.

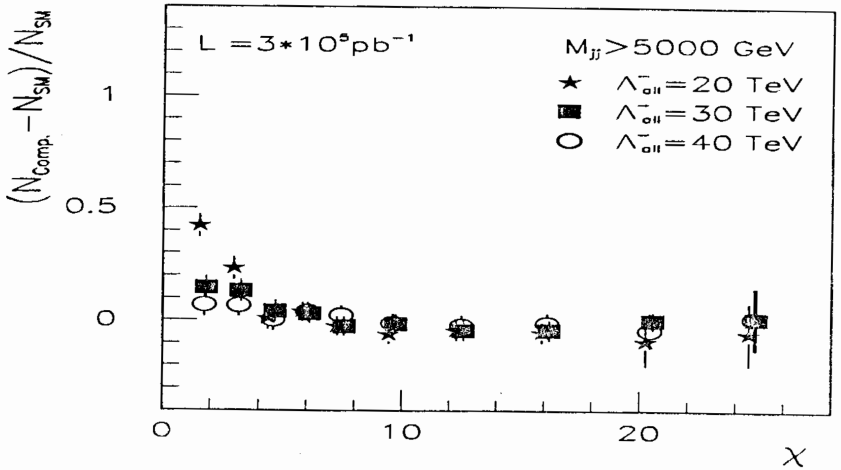

Figure 8: The same as in **Figure 7**, but for an $L = 300\, fb^{-1}$.

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