Sensitivity of potential future pp colliders to quark compositeness

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A study is presented of the sensitivity of potential future pp colliders to quark compositeness. The analysis uses normalized dijet angular distributions compared to expectations from leading-order contact interaction models.

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Though quarks are treated as fundamental particles in the standard model, facilities with sufficient center-of-mass energy may reveal substructure [1–4]. Quarks as bound states of more fundamental particles may explain current outstanding questions, such as the number of quark generations, the charges of the quarks, or the symmetry between the quark and lepton sectors.

A typical approach to the study of quark compositeness [5] is to search for evidence of new interactions between quarks at a large characteristic energy scale, Λ. At interaction energies below Λ, the details of the new interaction and potential mediating particles can be integrated out to form a four-fermion contact interaction model (see Fig. 1).

This is well-described by an effective field theory approach [6]:

\[ L_{qq} = \frac{2\pi}{\Lambda^2} \eta_{LL}(\bar{q}L\gamma^\mu qL)(\bar{q}L\gamma^\mu qL) + \eta_{RR}(\bar{q}R\gamma^\mu qR)(\bar{q}R\gamma^\mu qR) + 2\eta_{RL}(\bar{q}R\gamma^\mu qR)(\bar{q}L\gamma^\mu qL) \]  

where the quark fields have L and R chiral projections and the coefficients ηLL, ηRR, and ηRL turn on and off various interactions. In this study, we examine the cases of energy scales Λ+LL, Λ+RR, and Λ+VV-A with couplings (ηLL, ηRR, ηRL) = (1, 0, 0), (0, 1, 0) and (0, 0, 1), respectively, in order to demonstrate the center-of-mass dependence of the sensitivity of possible future pp facilities.

Evidence for contact interactions would appear in dijets with large values of dijet mass (mjj) and small values of θ∗, the center-of-mass angle relative to the beam axis. Dijets produced via quantum chromodynamics (QCD) are predominantly at small values of mjj and large values of θ∗, as they are peaked in the forward and backward directions.

Dijet angular distributions can also be used to search for a variety of new physics models, such as those hypothesized to mediate the interaction between the standard model sector and the dark matter sector [7], and extra spatial dimensions [8–12].

In this study, we generate events at leading-order with MADGRAPH [13], describe the showering and hadronization with PYTHIA [14] and the detector response with DELPHES [15] for the facilities described in Table I.

Following the approach of Ref. [5], we calculate \( \chi_{jj} = e^{i(y_1 - y_2)} \) where y1 and y2 are the rapidities of the two highest transverse momentum (leading) jets. The dis-

![FIG. 1: Diagrams for QCD mediation of quark-quark interactions (left) and a four-fermion contact interaction (right) describing an effective field theory for the mediation of a new interaction between quark constituents.](image)

![FIG. 2: Distributions of \( \chi_{jj} \) for QCD and contact interactions with two choices of Λ+LL,RR, and Λ+VV-A, for the four collider facilities considered.](image)
distribution for QCD interactions is slightly increasing with $\chi_{jj}$, while contact interaction models predict angular distributions that are strongly peaked at low values of $\chi_{jj}$, as can be seen in Fig. 2. Note that $LL$ and $RR$ models have no significant differences in their predicted distributions of $\chi_{jj}$. In this study, $|y_1|$ and $|y_2|$ are restricted to be less than 2.5 and $\chi_{jj}$ less than 16.

In the analysis of Ref. [5], the dominant uncertainties are statistical and theoretical, followed by experimental uncertainties such as jet energy resolution and calibration. Theoretical uncertainties are due primarily to variation in the predicted $\chi_{jj}$ shape with changes to the renormalization and factorization scales. We extract the approximate size and dependence on $\chi_{jj}$ of the theoretical uncertainty from Ref. [5] and apply it to the predictions from our simulated samples.

The statistical analysis is performed by evaluating the likelihood ratio

$$q = -2 \ln \frac{L(\Lambda + \text{QCD})}{L(\text{QCD})}$$

where nuisance parameters are fixed at the nominal values. The extraction of the limit is done using the CLs [16, 17] technique, where the null and alternate hypothesis $p$-values are evaluated from distributions of $q$ constructed using simulated experiments in which the nuisance parameters have been varied according to their prior probabilities.

The distortion of the $\chi_{jj}$ shape from new physics compared to QCD is most distinct at large $m_{jj}$; however, the cross section falls sharply with $m_{jj}$, reducing the statistical power of the data. These two effects are in tension, and there is an optimum lower threshold value of $m_{jj}$ which captures the distortions without sacrificing statistical power. Note that in Ref. [5] the analysis is done in the two highest bins of $m_{jj}$ and the lower bins are used to validate the QCD predictions. In our study, we use only the highest bin in $m_{jj}$, with modest loss of sensitivity. We are able to reproduce the sensitivity of Ref. [5] using our approximate approach.

If a deviation from QCD production is seen at the LHC with $\sqrt{s} = 14$ TeV, then a future facility may have the energy to directly probe the new physics process. If the deviation is due to quark substructure, then with sufficiently high energy and luminosity it is possible to observe the quark constituents and investigate their interactions.

### Conclusions

We have studied the sensitivity of future $pp$ collider facilities to quark compositeness via dijet angular distributions. As seen in Fig. 7, increases in center-of-mass 

| $\sqrt{s}$ (TeV) | $\mathcal{L}$ (fb$^{-1}$) | $m_{jj}$ threshold (TeV) | $p_T$ threshold (TeV) |
|------------------|-----------------|-----------------|-----------------|
| 7                | 2               | 3               | 0.3             |
| 14               | 300             | 5               | 1               |
| 14               | 3000            | 7.5             | 1               |
| 33               | 3000            | 16              | 2.5             |
| 100              | 3000            | 44              | 5               |

TABLE I: Details of compositeness studies for current and potential future $pp$ colliders, including center-of-mass energy ($\sqrt{s}$), total integrated luminosity ($\mathcal{L}$) and the minimum threshold in $m_{jj}$.
energy brings significant increases in sensitivity to the mass scale, \( \Lambda \), such that a collider with \( \sqrt{s} = 100 \) TeV would be expected to probe scales above \( \Lambda = 125 \) TeV.

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\[\text{FIG. 5: Distributions of } \chi_{jj} \text{ for QCD and contact interactions with a variety of choices of } \Lambda_{LL,RR} \text{ for the case of } pp \text{ interactions with with } \sqrt{s} = 33 \text{ TeV and } L = 3000 \text{ fb}^{-1}.\]

\[\text{FIG. 6: Distributions of } \chi_{jj} \text{ for QCD and contact interactions with a variety of choices of } \Lambda_{LL,RR} \text{ for the case of } pp \text{ interactions with with } \sqrt{s} = 100 \text{ TeV and } L = 3000 \text{ fb}^{-1}.\]

\[\text{FIG. 7: Summary of the threshold requirement on } m_{jj} \text{ and the expected limit on composite scale } \Lambda_{LL,RR} \text{ at each of the proposed facilities.}\]

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