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Discovery Mass Reach for Excited Quarks at Hadron Colliders

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ABSTRACT

If quarks are composite particles then excited states are expected. We estimate the discovery mass reach as a function of integrated luminosity for excited quarks decaying to dijets at the Tevatron, LHC, and a Very Large Hadron Collider (VLHC). At the Tevatron the mass reach is 0.94 TeV for Run II (2 fb^{-1}) and 1.1 TeV for TeV33 (30 fb^{-1}). At the LHC the mass reach is 6.3 TeV for 100 fb^{-1}. At a VLHC with a center of mass energy ,$\sqrt{s}$, of 50 TeV (200 TeV) the mass reach is 25 TeV (78 TeV) for an integrated luminosity of 10^4 fb^{-1}. However, an excited quark with a mass of 25 TeV would be discovered at a hadron collider with $\sqrt{s} = 100$ TeV and an integrated luminosity of 13 fb $^{-1}$, illustrating a physics example where a factor of 2 in machine energy is worth a factor of 1000 in luminosity.

I. EXCITED QUARKS

We consider a model of composite quarks with excited states that have spin 1/2 and weak isospin 1/2. The effective Lagrangian for chromomagnetic transitions between excited quarks (q^*) of mass M and common quarks (q) is constrained by gauge invariance to be [1]:

$$\mathcal{L} = \frac{g_s f_s}{4M}\bar{q}^*_R \sigma^{\mu\nu}\lambda_a G^a_{\mu\nu} q_L + h.c. \tag{1}$$

where G^a are gluon fields, λ_a are $SU(3)$ structure constants, and g_s is the strong coupling. Here we have chose the compositeness scale to be $\Lambda = M$, by writing M in the denominator in Eq. 1, because the excited quark mass should be close to the energy scale of quark compositeness. The constant f_s depends on the unknown dynamics of the quark consituents, and is generally assumed to be equal to 1, thereby giving standard model couplings. Excited quarks decay to common quarks via the emission of a gluon in approximately 83% of all decays. Excited quarks can also decay to common quarks by emitting a W, Z, or photon, through an effective Lagrangian similar to Eq. 1.

We consider the process $qg \rightarrow q^* \rightarrow qg$ for discovering an excited quark at a hadron collider. The signal is two high energy jets, resulting from hadronization of the final state quark and gluon, which form a peak in the dijet invarian mass distribution. The subprocess differential cross section is a Breit-Wigner:

$$\frac{d\hat{\sigma}}{d\hat{t}} = \frac{2\pi\alpha_s^2}{9M^4}\frac{\hat{s}}{(\hat{s} - M^2)^2 + \Gamma^2 M^2} \tag{2}$$

where α_s is the strong coupling, $\hat{s}$ and $\hat{t}$ are subprocess Mandelstam variables, and Γ is the width of the excited quark. The sum of the partial widths in the gluon, W, Z, and photon channels, gives a half width at half maximum of $\Gamma/2 \approx 0.02M$.

In Eq. 2 we have already averaged over the angular distribution in the center of mass frame, $dN/d\cos\theta^* \sim 1 + \cos\theta^*$, where θ^* is the angle between the initial state and final state quark in the subprocess center of mass frame. In hadron collisions this subprocess angular distribution results in an isotropic dijet angular distribtion $dN/d\cos\theta^* \sim 1$. This is because for every quark in hadron 1 that becomes an excited quark and emerges in the final state at a fixed $\cos\theta^*$, with rate proportonal to $1 + \cos\theta^*$, there is a quark in hadron 2 which is headed in the opposite direction, and emerges at the same value of $\cos\theta^*$ with rate proportional to $1 - \cos\theta^*$. The sum of the two angular distributions is isotropic.

II. BACKGROUND AND CUTS

Normal parton-parton scattering via QCD produces a large background to the dijet decays of excited quarks. However, QCD is dominated by t-channel gluon exchange which gives a dijet angular distribution $dN/d\cos\theta^* \sim 1/(1-\cos\theta^*)^2$, where θ^* is the angle between the incoming parton and the jet in subprocess center of mass. In contrast excited quark production and decay results in an isotropic dijet angular distribution as discussed above. Therefore to suppress QCD backgrounds we require $|\cos\theta^*| < 2/3$ and we also require the pseudorapidity of each jet satisfy $|\eta| < 2$. We note that any dijet analysis will generally make a $|\cos\theta^*|$ cut to have uniform trigger acceptance as a function of dijet mass, and an $|\eta|$ cut is to stay within a defined region of the detector. We include all lowest order QCD subprocesses in our background calculation: $qq \rightarrow qq$, $q\bar{q} \rightarrow gg$, $qg \rightarrow qg$, $gg \rightarrow gg$ and $gg \rightarrow q\bar{q}$.

III. CROSS SECTION

For both the excited quark signal and the lowest order QCD background, we convolute the subprocess differential cross section with CTEQ2L parton distributions [2] of the colliding hadrons, within the above range of $\cos\theta^*$ and η. This gives the differential cross section as a function of dijet mass, $d\sigma/dm$, for both the excited quark signal and the lowest order QCD background. For the excited quark signal we consider only the first generation, u^* and d^*, and we assume they are degenerate in mass. The half width of the excited quark resonance remains $\Gamma/2 \approx 0.02M$. This is significantly more narrow than the dijet mass resolution at the Tevatron, which is roughly Gaussian with RMS deviation $\sigma \approx 0.1M$. If we assume a Gaussian dijet resolution of width $\sigma \approx 0.1M$ at all hadron colliders, then 90% of the dijet events from an excited quark will be inside a 16% mass window $0.84M < m < 1.16M$, where m is the dijet invariant mass. We integrate the differential cross section, $d\sigma/dm$, for both the excited quark signal and the QCD background within

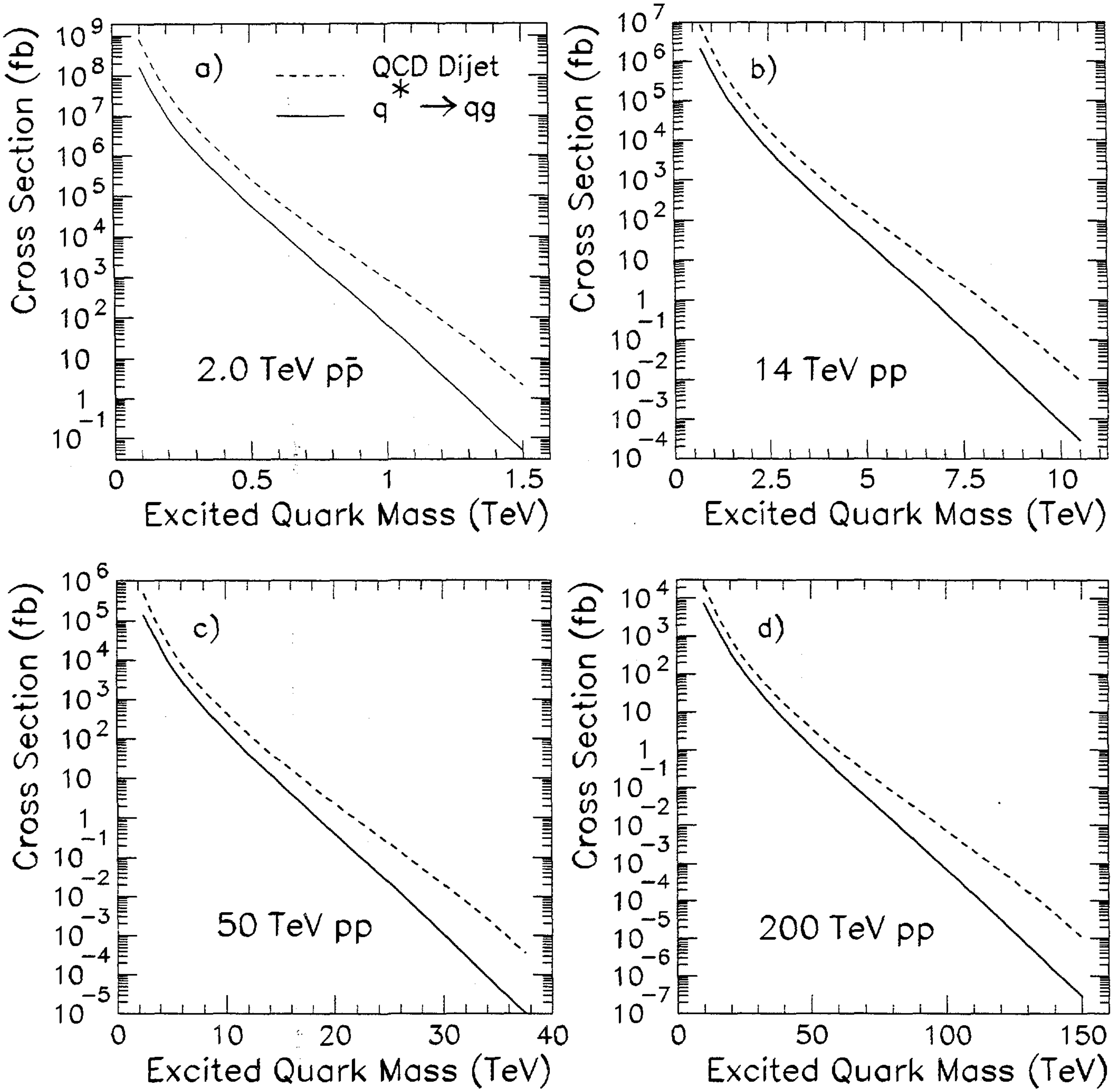

Figure 1: Lowest order parton level cross sections within a 16% wide search window for QCD dijets (dashed curve) and excited quarks decaying to dijets (solid curve) are shown as a function of excited quark mass at **a)** the future energy of the Tevatron, **b)** the LHC, **c)** a VLHC with center of mass energy 50 TeV, and **d)** 200 TeV. All cross sections are for dijets with $|\eta| < 2$, $|\cos\theta^*| < 2/3$.

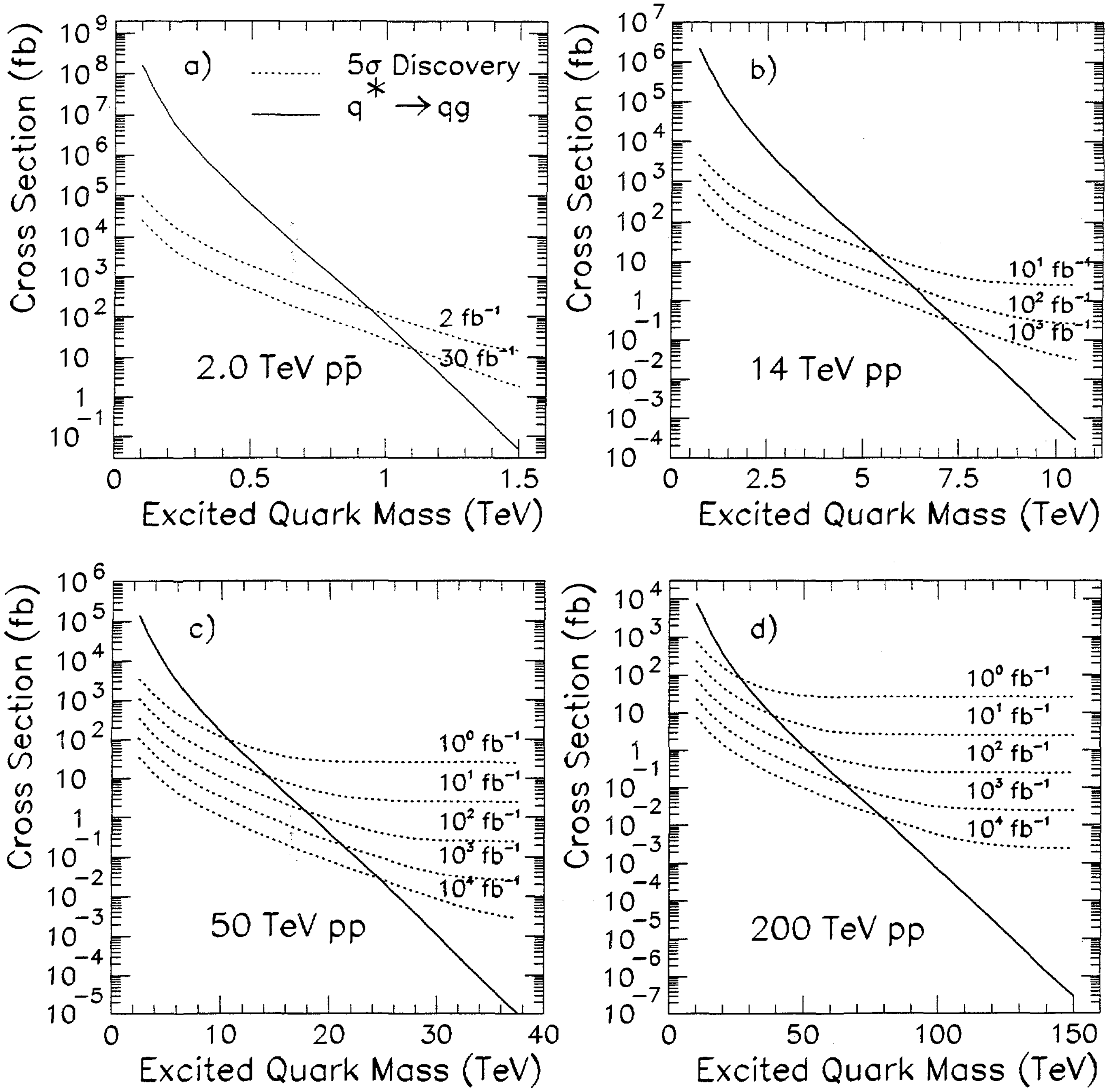

Figure 2: The predicted cross section for dijet decays of excited quarks (solid curve) is compared to the 5σ discovery reach (dotted curves) at various luminosities for **a)** the future energy of the Tevatron, **b)** the LHC, **c)** a VLHC with center of mass energy 50 TeV, and **d)** 200 TeV. All cross sections are for dijets with $|\eta| < 2$, $|\cos\theta^*| < 2/3$, and invariant mass within 16% of the excited quark peak assuming a 10% dijet mass resolution.

the 16% mass window to obtain an estimate of the signal and background cross section for a search. Figure 1 shows the resulting total signal and background cross section in the search window at the Tevatron, LHC and VLHC as a function of excited quark mass.

IV. DISCOVERY MASS REACH

The QCD background rate is used to find the 5 σ discovery cross section. This is conservatively defined as the cross section which is above the background by 5 σ, where σ is the statistical error on the measured cross section (not the background). For example, if the background were zero events the 5σ discovery rate would be 25 events. In Fig. 2 we compare the excited quark cross section to the 5 σ discovery cross section at various luminosities for the future Tevatron, the LHC, and the VLHC. The excited quark discovery mass reach, defined as the mass at which an excited quark would be discovered with a 5σ signal, is tabulated as a function of mass for the LHC and VLHC proton-proton colliders in Table I. We have also performed the calculation for VLHC proton-antiproton colliders, where the QCD background is slightly higher but the excited quark signal is exactly the same, which yields a 3% smaller mass reach. Because of space limitations, Figs. 1 and 2 do not display curves for a 100 TeV VLHC, but the mass reach of a 100 TeV VLHC tabulated in Table I was determined from curves similar to those in Fig. 2.

The mass reach at the future Tevatron is 0.94 TeV for collider run II (2 fb^{-1}) and 1.1 TeV for TeV33 (30 fb^{-1}). This can be compared to the published 95% CL limit of 570 GeV from CDF [3] and the the preliminary limits of 750 GeV from CDF and 720 GeV from D0 [4]. The mass reach at the LHC is 6.3 TeV for 100 fb^{-1}, which could be obtained by running for one year ($\sim 10^7$ seconds) at the design luminosity of 10^{34} cm^{-2} s^{-1}. Since the design luminosity may not be quickly achieved, we note that with only 10 fb^{-1} at the beginning of the LHC the mass reach is still 5.3 TeV. Ultimately, the LHC may be able to integrate 1000 fb^{-1}, which will provide a mass reach of 7.3 TeV. The mass reach at the VLHC varies widely depending on the energy of the machine and it's luminosity. A 50 TeV machine with only 1 fb^{-1} of integrated luminosity has a mass reach of 10.5 TeV, significantly better than LHC with any conceivable luminosity. At the other extreme, a 200 TeV machine with 10^4 fb^{-1} would have a mass reach of 78 TeV.

The mass reach in table I appears to be a smooth function of the proton-proton center of mass energy, $\sqrt{s}$, and integrated luminosity, L. The following analytic function exactly reproduces the VLHC mass reach in Table I for the energy range $50 < \sqrt{s} < 200$ TeV and the luminosity range $1 < L < 10^4$ fb^{-1}:

$$M = 7 + 3\log_2\left(\frac{\sqrt{s}}{50}\right) + k(1 + \log_{10} L) \tag{3}$$

where k depends on the energy of the machine according to

$$k = \frac{7}{2} + \frac{11}{3}\left(\frac{\sqrt{s}}{50} - 1\right) - \frac{1}{6}\left(\frac{\sqrt{s}}{50} - 1\right)^2 \tag{4}$$

Although Eq. 3 and 4 reproduces the VLHC mass reach, at LHC these equations give a mass reach that is 40% lower than the numbers in Table I. We provide Eq. 3 and 4 for interpolation among the VLHC entries in Table I only. We do not recommend these equations be used for extrapolation outside the energy range $50 < \sqrt{s} < 200$ TeV and the luminosity range $1 < L < 10^4$ fb^{-1}.

Table I: The 5σ discovery mass reach for excited quarks of a proton-proton collider as a function of integrated luminosity is tabulated for the LHC with a center of mass energy of 14 TeV and the VLHC with a center of mass energy of 50, 100 and 200 TeV.

	Excited Quark Mass Reach			
Integrated Luminosity (fb^{-1})	LHC 14 (TeV)	VLHC 50 (TeV)	VLHC 100 (TeV)	VLHC 200 (TeV)
1	–	10.5	17	26
10	5.3	14.0	24	39
100	6.3	17.5	31	52
10^3	7.3	21	38	65
10^4	–	24.5	45	78

V. ENERGY VS. LUMINOSITY

To clarify the superior gains obtained by increasing the energy of a machine, as opposed to increasing the luminosity, we show in Fig. 3 the mass reach for the VLHC which is also tabulated in Table I. Note that the mass reach is proportional to the logarithm of the luminosity, but is almost directly proportional to the energy of the machine. To clarify the energy vs. luminosity tradeoff consider the following hypothetical case.

A. Discovery of New Scale at LHC

Suppose the LHC sees a classic signal of new physics: an excess of high transverse energy jets which also have an angular distribution that is significantly more isotropic than predicted by QCD, an effect that cannot be due to parton distributions within the proton. Suppose further that this measurement corresponds to a scale of new physics $\Lambda \sim 15$ TeV, which is roughly the largest contact interaction that the LHC could see in the jet channel. We would have strong evidence of new physics, and the angular distribution might begin to separate between compositeness and other sources of new physics. But, we would probably not know for certain which source of new physics the scale $\Lambda \approx 15$ TeV corresponded too, and we would need an independent experimental confirmation that quarks were composite. If the source of new physics were quark compositeness, we would expect to see excited quarks with mass close to the compositeness scale. To be safe, we suppose the excited quark mass could be as high as 25 TeV, and we want to decide which machine to build to find the excited quark and confirm that the new physics is quark compositeness.

B. Discovery of 25 TeV q^* at VLHC

In Fig. 3 the horizontal dashed line at 25 TeV intersects the VLHC excited quark mass reach at an integrated luminosity of about 1.3×10^4 fb^{-1} for a 50 TeV machine, 13 fb^{-1} for a 100 TeV machine, and 0.9 fb^{-1} for a 200 TeV machine. Clearly, to find a 25 TeV excited quark, one would build either the 100 TeV or possible even the 200 TeV machine and quickly accumulate the relatively low integrated luminosities of 1-10 fb^{-1}, rather than build a 50 TeV machine and have to integrate between 3 and 4 orders of magnitude more luminosity. Note that the common accelerator wisdom that a factor of 2 in energy is worth a factor of 10 in luminosity is only roughly right for comparing the 100 TeV and 200 TeV machines; when comparing the 50 TeV and 100 TeV machines discovery potential for a 25 TeV excited quark, a factor of 2 in energy is worth a factor of 1000 in luminosity!

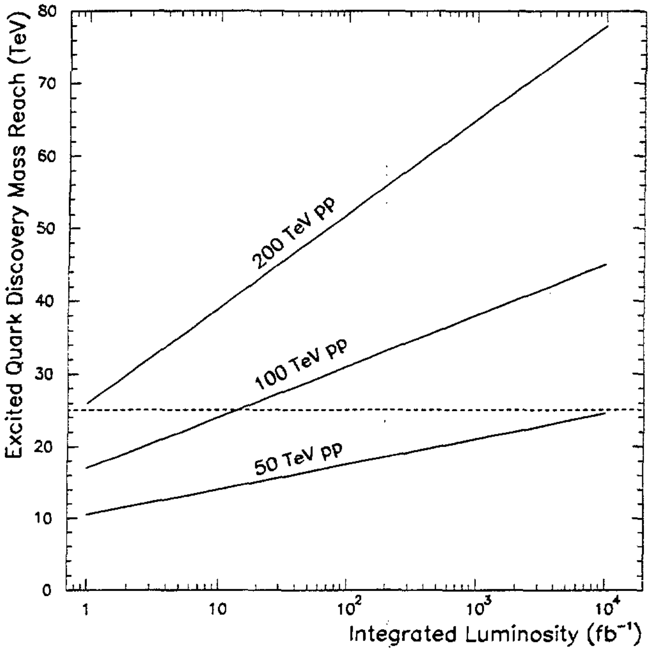

Figure 3: The discovery mass reach for dijet decays of excited quarks is shown as a function of integrated luminosity for a VLHC of energy 50 TeV, 100 TeV and 200 TeV (solid curves). The horizontal dashed line is for a hypothetical 25 TeV excited quark discussed in the text.

VI. SYSTEMATICS

In this analysis, we have not included any systematic uncertainties on the signal, and we have assumed that the shape and magnitude of the qcd background spectrum is reasonably approximated by lowest order QCD. We also assumed that the dijet mass resolution will be roughly 10% at all hadron colliders, ignoring a long tail to low mass caused by radiation. Adding systematics on the signal and the background will likely decrease the mass reach of a real search. To get a rough idea of the effect of systematics, we examine the TeV2000 report [5], which included systematics in the mass reach for excited quarks. Our discovery mass reach for the future Tevatron is about 10% better than the 95% CL mass reach quoted in the TeV2000 report, because ours is for $\sqrt{s} = 2.0$ TeV instead of 1.8 TeV and because ours does not include systematic uncertainties. If we increase the mass reach in the TeV2000 report by 10% to account for the increase in center of mass energy from 1.8 to 2.0 TeV, then the two results are roughly the same. From this we see that including systematic uncertainties would roughly change our 5σ result to merely a 95% CL result. However, the systematics in the TeV2000 report were likely overestimates, because they were based on previous dijet searches for excited quarks [3] in which there was no signal: if a signal is present the systematic uncertainties will likely be smaller.

VII. SUMMARY AND CONCLUSIONS

We have estimated the discovery mass reach for excited quarks at future hadron colliders. The mass reach at the Tevatron is 0.94 TeV for Run II (2 fb^{-1}) and 1.1 TeV for TeV33 (30 fb^{-1}). The mass reach at the LHC is 6.3 TeV for 100 fb^{-1}. At a VLHC with a center of mass energy of 50 TeV (200 TeV) the mass reach is 25 TeV (78 TeV) for an integrated luminosity of 10^4 fb^{-1}. However, an excited quark with a mass of 25 TeV would be discovered at a hadron collider with $\sqrt{s} = 100$ TeV and an integrated luminosity of only 13 fb^{-1}: here a factor of 2 increase in energy from a 50 TeV to a 100 TeV machine is worth a factor of 1000 increase in luminosity at a fixed machine energy of 50 TeV. When the goal is to discover new physics at high energy scales, even a modest increase in machine energy can be more desirable than a large increase in luminosity.

VIII. REFERENCES

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