Discovery Mass Reach for Topgluons Decaying to $t\bar{t}$ at the Tevatron

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ABSTRACT

In topcolor assisted technicolor, topgluons are massive gluons which couple mainly to top and bottom quarks. We estimate the mass reach for topgluons decaying to $t\bar{t}$ at the Tevatron as a function of integrated luminosity. The mass reach for topgluons decreases with increasing topgluon width, and is $1.0-1.1$ TeV for Run II (2 fb^{-1}) and $1.3-1.4$ TeV for TeV33 (30 fb^{-1}).

I. TOPCOLOR AND TOPGLUONS

Topcolor assisted technicolor [1] is a model of dynamical electroweak symmetry breaking in which the top quark is heavy because of a new dynamics. Topcolor replaces the $SU(3)_C$ of QCD with $SU(3)_1$ for the third quark generation and $SU(3)_2$ for the first two generations. The additional SU(3) symmetry produces a $<t\bar{t}>$ condensate which makes the top quark heavy, and gives rise to a color octet gauge boson, the topgluon B. The topgluon is expected to be wide ($\Gamma/M \approx 0.3-0.7$) and massive ($M \sim 0.5-2$ TeV). In hadron collisions it is produced through a small coupling to the first two generations, and then decays via a much larger coupling to the third generation: $q\bar{q} \to B \to b\bar{b}, t\bar{t}$. Here we estimate the mass reach for topgluons decaying to $t\bar{t}$ at the Tevatron.

II. SIGNAL AND BACKGROUND

The sub-process cross section for $q\bar{q} \to t\bar{t}$ from both QCD and topgluons is given by [2]

$$\frac{d\hat{\sigma}}{d\hat{t}} = \frac{2\pi\alpha_s^2\beta_t}{9\hat{s}^2}(2-\beta_t^2+\beta_t^2\cos^2\theta^*)\left|1-\frac{\hat{s}}{\hat{s}-M^2+i\sqrt{\hat{s}}\Gamma}\right|^2 \quad (1)$$

for a topgluon of mass M and width Γ given by

$$\Gamma = \frac{\alpha_s M}{6}\left[4\tan^2\theta + \cot^2\theta\left(1+\beta_t\left(1-\frac{m_t^2}{M^2}\right)\right)\right] \quad (2)$$

where α_s is the strong coupling evaluated at renormalization scale $\mu = m_t$, $\hat{s}$ and $\hat{t}$ are subprocess Mandelstam variables, θ is the mixing angle between $SU(3)_1$ and $SU(3)_2$, θ^* is the scattering angle between the top quark and the initial state quark in the center of mass frame, $\beta_t = \sqrt{1-4m_t^2/M^2}$, and m_t is the top quark mass. Topcolor requires $\cot^2\theta >> 1$ to make the top quark heavy. In Eq. 2, the first term in square brackets is for four light quarks, and the second term has two components, the first for the bottom quark and the second for massive top quarks. In Eq. 1, the 1 inside the absolute value brackets is for the normal QCD process $q\bar{q} \to g \to t\bar{t}$. The other term inside the brackets is the Breit-Wigner topgluon resonance term for the process $q\bar{q} \to B \to t\bar{t}$. The two processes interfere constructively to the left of the mass peak and destructively to the right of the mass peak.

In Fig. 1 we have convoluted Eq. 1 with CTEQ2L parton distributions [3] to calculate the QCD background and topgluon signal for the case of a 1000 GeV toplguon in $p\bar{p}$ collisions at $\sqrt{s} = 2.0$ TeV. Fig. 1 also includes the QCD process $gg \to t\bar{t}$ which is only significant at low mass. In Fig. 11a we plot the differential cross section $d\sigma/dm$, where m is the invariant mass of the $t\bar{t}$ system. A clear distortion of the QCD $t\bar{t}$ spectrum is caused by the presence of a topgluon in Fig. 1a. After subtraction of the QCD background, Fig. 1b shows that the signal has a very long high tail to low masses, caused by the combination of constructive interference and parton distributions that rise rapidly as the $t\bar{t}$ mass decreases. The tail is larger than the peak, as seen in Fig. 1b. Nevertheless, the ratio between the topgluon signal and the QCD background, displayed in Fig. 1c, displays a noticeable peak close to the topgluon mass. Similar calculations have been performed for the masses 600, 800, 1200, and 1400 GeV.

III. DISCOVERY MASS REACH

For topgluons of width $\Gamma/M \geq .3$, the measured $t\bar{t}$ mass peak should have a resonance shape similar to the parton level distribution, since the detector mass resolution for $t\bar{t}$ (≈ 6% at $m = 800$ GeV) is significantly finer than the topgluon width. To calculate the discovery mass reach we integrate both the lowest order topgluon cross section and the qcd background within the range $0.75M < m < 1.25M$. The resulting total topgluon signal in the $t\bar{t}$ channel is shown in Fig. 2. The resulting background rate in this mass range 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. To obtain the discovery cross section we used both the luminosity and a 6.5% $t\bar{t}$ reconstruction efficiency at CDF in run II [4]. In Fig. 2 we compare the topgluon signal cross section to the 5 σ discovery cross section for two different luminosities: 2 fb^{-1} for Tevatron collider Run II and 30 fb^{-1} for TeV33. The topgluon discovery mass reach, defined as the mass at which a topgluon would be discovered with a 5σ signal, is tabulated in Table I as a function of integrated luminosity and topgluon width. The mass reach decreases with increasing width, caused by worsening signal to background within the search window. The width as a function of mixing angle, from Eq. 2, is shown in Figs. 1d and 2d. Also shown is the preferred theoretical range for the mixing angle $\cot^2\theta$, determined from the topcolor model and constraints from other data [6], which implies a width of the topgluon in the range $\Gamma/M \approx 0.3-0.7$.

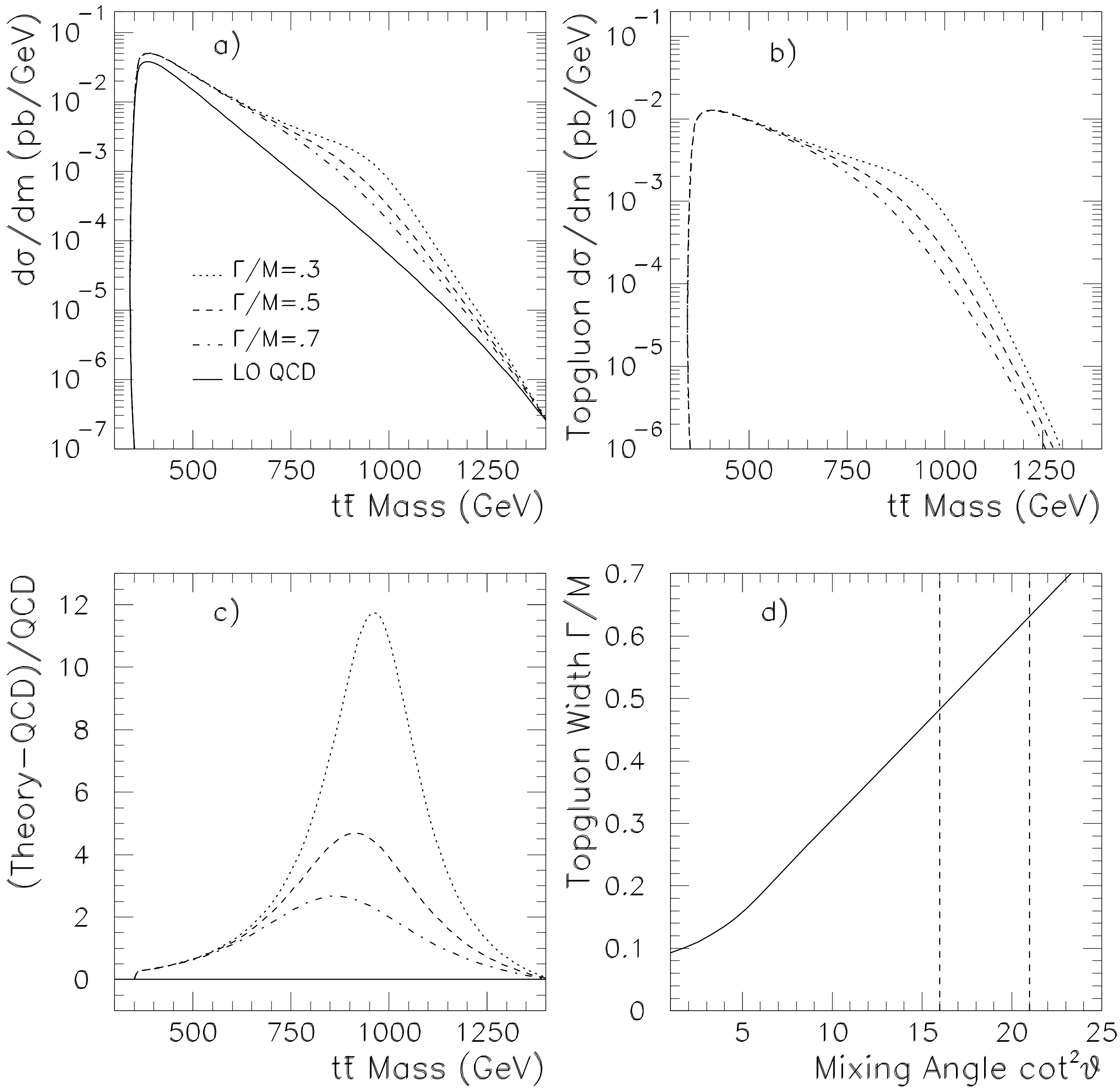

Figure 1: Lowest order parton level predictions for a 1000 GeV topgluon decaying to $t\bar{t}$ displayed as a function of $t\bar{t}$ mass. a) The cross section for the LO $t\bar{t}$ background from QCD (solid) is compared to the coherent sum of LO QCD and a topgluon of fractional width $\Gamma/M = 0.3$ (dots), 0.5 (dashes) and 0.7 (dotdash). In b) the QCD prediction has been subtracted leaving only the topgluon signal and the interference between QCD and topgluons (constructive beneath peak, destructive above peak). c) The fractional deviation above the QCD prediction produced by the presence of a topgluon. d) The solid curve relates the topgluon width and the mixing angle, θ, between $SU(3)_1$ and $SU(3)_2$ for a 1000 GeV topgluon. The vertical dashed lines indicate the theoretically preferred range of mixing angle [6].

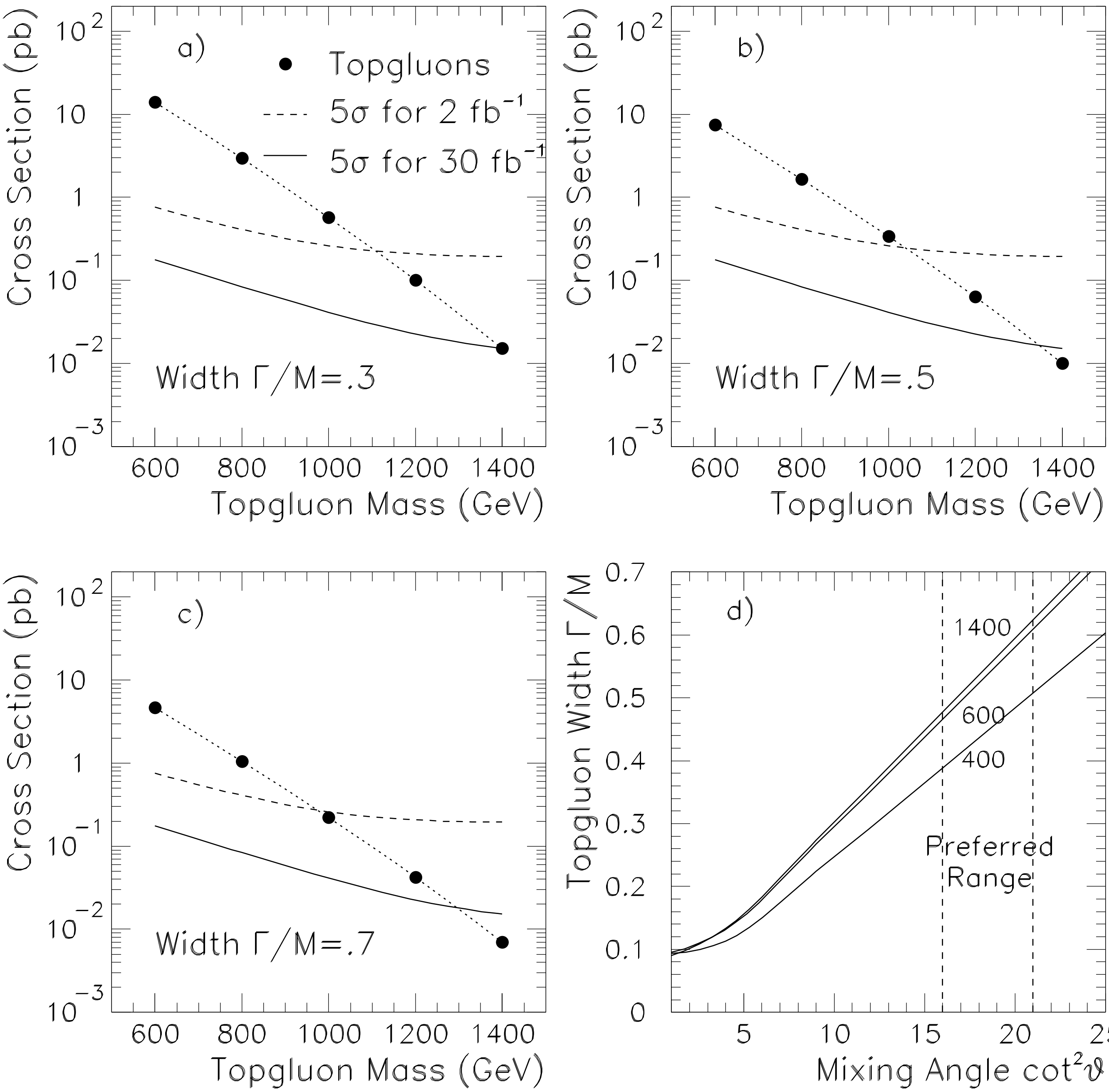

Figure 2: The mass reach for $b\bar{b}$ decays of topgluons of width a) 0.3 M, b) 0.5 M, and c) 0.7 M. The predicted cross section for topgluons (points) is compared to the 5σ discovery reach of the Tevatron with a luminosity of 2 fb^{-1} (dashed) and 30 fb^{-1} (solid). All cross sections are for $t\bar{t}$ with invariant mass within 25% of the topgluon peak. In d) the solid curves relate topgluon width and the mixing angle, θ, between $SU(3)_1$ and $SU(3)_2$ for 3 different topgluon masses. The vertical dashed lines indicate the theoretically preferred range of mixing angle [6].

Table I: The 5σ discovery mass reach of the Tevatron in Run II (2 fb^{-1}) and TeV33 (30 fb^{-1}) for a toplguon decaying to $t\bar{t}$ as a function of its fractional width (Γ/M).

Width	Mass Reach	
Γ/M	2 fb^{-1}	30 fb^{-1}
0.3	1.11 TeV	1.40 TeV
0.5	1.04 TeV	1.35 TeV
0.7	0.97 TeV	1.29 TeV

IV. SYSTEMATICS

In the discovery mass reach estimate we have not included any systematic uncertainties on the measured signal, and we have assumed that the shape and magnitude of the QCD $t\bar{t}$ spectrum will be well understood. We have not included any other sources of background, such as QCD W + jets. Also, our efficiency and resolution values are for reconstructing $t\bar{t}$ decaying into W + four jets where two of the jets are b-tagged. This efficiency and resolution may degrade at very high $t\bar{t}$ mass values, because the byproducts from high P_t top decay will be closer together, and modifications to the reconstruction technique may be necessary to preserve the efficiency and resolution. Adding systematics on the signal and the background will decrease the mass reach of a real search.

V. TOTAL CROSS SECTION MASS REACH

Another method of searching for topgluons is simply to measure the total $t\bar{t}$ cross section and compare it with QCD. In Fig. 3 we show the fractional effect of a topgluon on the total $t\bar{t}$ cross section: (topgluon - QCD)/QCD. This is compared with the total $t\bar{t}$ cross section measurements from CDF ($7.6\ ^{+1.9}_{-1.6}$ pb [7]). and D0 (5.2 ± 1.8 pb [4]), both of which are compatible with QCD (5 pb [5]) within errors. In Fig. 3 the location of the CDF and D0 points on the horizontal axis is arbitrary; the measured cross section and error give a location on the vertical axis only. The TeV2000 group projected the 1σ uncertainty on the top quark cross section measurement will be 11% with 1 fb^{-1}, 5.9% with 10 fb^{-1}, and 5.1% with 100 fb^{-1} [4]. This estimate included systematic uncertainties. In Fig 3 we multiply these numbers by a factor of 1.64 to obtain 95% CL upper bounds, and multiply them by a factor of 5 to obtain 5σ discovery cross sections, shown as horizontal dashed lines for luminosities of 1, 10 and 100 fb^{-1}. We interpolate between these luminosity values to estimate the 5σ discovery cross section for 2 fb^{-1} in Run II is 50% of the QCD cross section, and the 5σ discovery cross section for 30 fb^{-1} at TeV33 is 28% of the QCD cross section. These fractional deviations in the QCD cross section correspond to a topgluon mass reach of $1.05 - 1.1$ TeV for 2 fb^{-1}, depending on the topgluon width, and about 1.35 TeV for 30 fb^{-1}. This assumes we understand the total QCD cross section for $t\bar{t}$ production to much better than 50% in Run II and much better than 28% at TeV33. This may not be unreasonable, considering the theoretical systematic uncertainties on the $t\bar{t}$ cross section prediction are currently around 10-20% [5]. Finally we note that the estimate of the topgluon mass reach using the total $t\bar{t}$ cross section agrees with our estimate of the mass reach from the bump search in a 25% mass window. This increases our confidence that the estimated mass reach is reasonable.

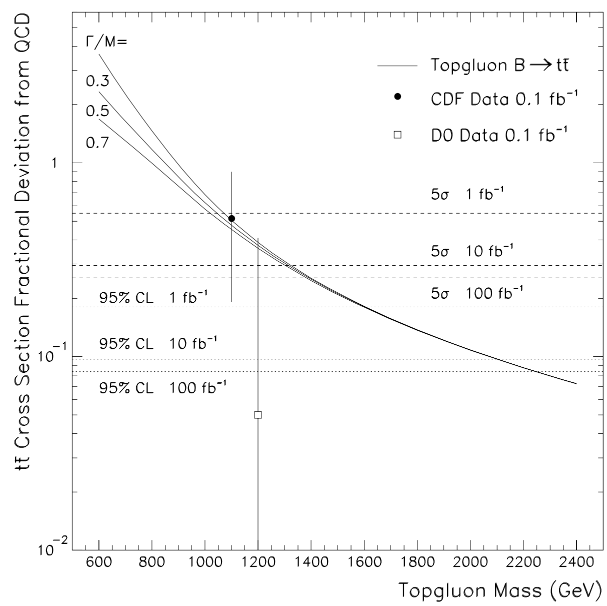

Figure 3: The fractional difference between the $t\bar{t}$ cross section and the QCD prediction is shown for topgluons (solid curves), CDF data (solid circle), and D0 data (open box). The projected 5σ uncertainty (dashed lines) and 95% CL (dotted lines) on the measured $t\bar{t}$ cross section can be compared with the topgluon prediction to determine the discovery reach and exclusion reach of the Tevatron at the luminosities of 1, 10 and 100 fb^{-1}.

VI. SUMMARY AND CONCLUSIONS

We have used a parton level prediction for $t\bar{t}$ production from QCD and topgluons, together with the projected experimental efficiency for reconstructing $t\bar{t}$, to estimate the topgluon discovery mass reach in a $t\bar{t}$ resonance search. The topgluon discovery mass reach, $1.0 - 1.1$ TeV for Run II and $1.3 - 1.4$ TeV for TeV33, covers a significant part of the expected mass range ($\sim 0.5 - 2$ TeV). The mass reach estimated using the total $t\bar{t}$ cross section is similar to that for the resonance search, providing an important check. For comparison, the mass reach in the $b\bar{b}$ channel is estimated to be $0.77 - 0.95$ TeV for Run II and $1.0 - 1.2$ TeV for TeV33 [8]. This is less than the mass reach in the $t\bar{t}$ channel primarily because of larger $b\bar{b}$ backgrounds. If topgluons exist, there is a good chance we will find them at the Tevatron, beginning the investigation into the origins of electroweak symmetry breaking.

VII. REFERENCES

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