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Multiple Gluon Effects in $t\bar{t}$ Production At and Beyond FNAL Energies*

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ABSTRACT

We use the extension of the YFS exponentiated multiple photon Monte Carlo(MC) event generator SSCYFS2 for $q+^{(}\bar{q}^{)'} \rightarrow q''+^{(}\bar{q}^{)'''}+n(\gamma)$ to the process $q+^{(}\bar{q}^{)'} \rightarrow q''+^{(}\bar{q}^{)'''}+n(G)$, where G is a QCD gluon, to investigate the multiple gluon effects in $t\bar{t}$ production at the fundamental fermion (anti-)fermion scattering level at and beyond FNAL energies. Hard gluon residuals are treated at the Born level. We illustrate these effects with MC data and comment on their possible relevance to recent CDF/D0 observations.

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Recently, CDF [1] and D0 [2] have reported strong evidence for the long expected top quark, where preliminary signals corresponding respectively to $m_t = 0.176 \pm .008 \pm 0.01$ TeV, $\sigma(t\bar{t}) = 6.8^{+3.6}_{-2.4}$ pb, and $m_t = 0.199^{+.019}_{-.02} \pm .02$ TeV, $\sigma(t\bar{t}) = 6.4 \pm 2.2$ pb. In interpreting such data, the issue of radiative corrections has to be considered and, indeed, recent work by several authors [3], based on exact $\mathcal{O}(\alpha_s^3)$ and leading logarithmic methods, would suggest that the CDF and D0 cross section central values are respectively too large by factors of 1.4 and 2.7 relative to the central theoretical expectations (this is only a suggestion because the three sets of cross sections are within 3σ of one another). This raises in a direct way the question of higher-order QCD corrections to $t\bar{t}$ production at FNAL and higher energies. In this Letter, we present the first results of a new approach [4] to such corrections based on the extension to QCD of YFS [5] Monte Carlo methods [6] which two of us (S. J. and B. F. L. W.) have used in the theory of high precision Z^0 physics.

Specifically, in Ref. [4], we have shown that the soft gluons in QCD, where by soft we mean gluon energies $k_G^0 << \Lambda_{QCD}$, exponentiate in the YFS sense with an all-orders in α_s cancellation of infrared divergences in physical cross sections. In view of our results in Refs. [6] using the analogous exponentiation in QED, we may apply the entirely analogous Monte Carlo realization of the respective QCD exponentiation to represent the process $q + {}^{(}\bar{q}{}^{)\prime} \rightarrow q'' + {}^{(}\bar{q}{}^{)\prime\prime\prime} + n(G)$ via a Monte Carlo event generator in which the entire calculation is based on amplitudes in which all quantum correlations are properly taken into account.

In what follows, in view of the normalization discussed above, we shall explore the possible source of enhanced corrections not already calculated (properly) elsewhere. Thus, in this Letter we shall present our YFS MC analysis for the fundamental $q + {}^{(}\bar{q}{}^{)\prime} \rightarrow t + \bar{t} + n(G)$ processes to investigate the issue of the rôle of multiple gluon radiative effects on the cross-section normalization at the basic parton level. Any enhancement of the expected normalization should already manifest itself at this level. Of course, the detailed prediction of the actual $\sigma(t\bar{t})$ at FNAL and beyond will require convolution of the cross-section discussed in this paper with the standard structure functions (properly modified to account for our treatment of the infrared regime – here, we stress that in the paper of Laenen, *et al.* in Ref. [3], for example, the mass factorization scale is taken as $\mu \sim m_t$, with the consequence that most of the infrared corrections exponentiated in our approach are in fact absorbed into the bare parton distribution functions via the standard factorization practice; in this view, most of the effect of the normalization correction calculated by us below from YFS exponentiation should then apply as an overall factor to the cross-section quoted in Refs. [3] as well [7]; we also should stress that, unlike the work of Laenen, *et al.*, our treatment of the soft regime for gluon radiation here *does not* suffer from the appearance of an unknown non-perturbative parameter μ_0 – we actually have a definite prediction for the effect of the $n(G)$ radiation). Such convolutions will be presented elsewhere [7]. (Here, we need to emphasize that, following the methods of Lepage and Brodsky [8], it is also possible to treat the entire hadron-level calculation on an amplitude basis as well – such a treatment will also appear elsewhere [9].)

More precisely, at FNAL energies, the dominant $t\bar{t}$ production process is $q\bar{q}$ annihilation. Thus, from our QCD exponentiation formula in Ref. [4], we have the YFS exponentiated cross-section (see Fig. 1 for an illustration of the kinematics)

$$d\sigma_{\text{exp}} = \exp[\text{SUM}_{\text{IR}}(\text{QCD})] \sum_{n=0}^{\infty} \int \prod_{j=1}^{n} \frac{d^3k_j}{k_j} \int \frac{d^4y}{(2\pi)^4} e^{iy\cdot(p_1+p_2-q_1-q_2-\sum k_j)+D_{\text{QCD}}}$$
$$* \bar{\beta}_n(k_1,\ldots,k_n) \frac{d^3q_1}{q_1^0}\frac{d^3q_2}{q_2^0} \tag{1}$$

with

$$SUM_{IR}(QCD) = 2\alpha_s ReB_{QCD} + 2\alpha_s \tilde{B}_{QCD}(K_{\max}),$$
$$2\alpha_s \tilde{B}_{QCD}(K_{\max}) = \int \frac{d^3k}{k^o} \tilde{S}_{\text{QCD}}(k)\theta(K_{\max}-k),$$
$$D_{\text{QCD}} = \int \frac{d^3k}{k} \tilde{S}_{\text{QCD}}(k) \left[e^{-iy\cdot k} - \theta(K_{\max}-k)\right], \tag{2}$$

$$\frac{1}{2}\bar{\beta}_0 = d\sigma^{(1-\text{loop})} - 2\alpha_s \text{Re}B_{\text{QCD}} d\sigma_B,$$
$$\frac{1}{2}\bar{\beta}_1 = d\sigma^{B1} - \tilde{S}_{\text{QCD}}(k) d\sigma_B, \quad \ldots \tag{3}$$

where the $\bar{\beta}_n$ are the QCD hard gluon residuals defined in complete analogy with the respective YFS hard photon residuals and we show explicitly the formulas for $\bar{\beta}_0$ and $\bar{\beta}_1$, which are relevant for exact $\mathcal{O}(\alpha_s)$ exponentiation, for illustration. Here, $d\sigma^{(1-\text{loop})}$ is the respective cross-section including virtual corrections(Figs. 1a,1b) [10], $d\sigma^{B1}$ is the $\mathcal{O}(\alpha_s)$ single bremsstrahlung cross-section(Fig. 1c) [10, 11], and the virtual and real QCD infrared functions $B_{\rm QCD}$ and $\tilde{S}_{\rm QCD}$, respectively, are given in Ref. [4]. It is the formula (1) which we have realized via Monte Carlo methods at FNAL and higher energies for the case $q + \bar{q} \rightarrow t\bar{t}$, where q is a light quark, and where in this paper we work to the $\bar{\beta}_0$ level; $\bar{\beta}_1$ level results will appear elsewhere [7]. We call the corresponding event generator TOPYFS and we will now illustrate its results.

Specifically, using the prototypical $u + \bar{u} \rightarrow t + \bar{t} + n(G)$ case at $\sqrt{s} = 1.8$ TeV as an example, and imposing the relatively loose cuts $|\eta| \leq 3$ and $k_G \geq 3$ GeV for illustration, we get the MC data illustrated in Figs.2-4 for the expected gluon multiplicity, v-distribution, and total transverse momentum distribution, respectively. At FNAL energies, we find, for $m_t = 176$ GeV, and 199 GeV, respectively,

$$\langle n_G \rangle = \begin{cases} 23.5 \pm 4.6 \; , \quad m_t = 176 \; GeV \\ \\ 23.5 \pm 4.5 \; , \quad m_t = 199 \; GeV \end{cases} \tag{4}$$

$$\langle v \rangle = \begin{cases} 0.80 \pm 0.16 \; , \quad m_t = 176 \; GeV \\ \\ 0.77 \pm 0.17 \; , \quad m_t = 199 \; GeV \end{cases} \tag{5}$$

$$\langle p_{\perp,tot} \rangle \equiv \langle | \sum k_{i\perp} | \rangle = \begin{cases} (93.3 \pm 113.0) \; GeV \; , \quad m_t = 176 \; GeV \\ \\ (91.6 \pm 112.1) \; GeV \; , \quad m_t = 199 \; GeV \end{cases} \tag{6}$$

so that indeed, multiple gluon effects are important in the detailed profiles of top events at FNAL energies. On the important question of the overall normalization, we get the basic results

$$\sigma / \sigma_B = \begin{cases} 2.02 \pm 0.07 \; , \quad m_t = 176 \; GeV \\ \\ 1.76 \pm 0.04 \; , \quad m_t = 199 \; GeV \end{cases} \tag{7}$$

so that soft YFS radiation must be taken into account to understand the expected $\sigma(t\bar{t})$ normalization at FNAL energies. Similar results hold at higher energies (at the LHC energy, 15.4 TeV, for example). Of course, to translate the results (7) into a prediction for $\sigma(t\bar{t})$ will require the convolutionary analysis discussed above. That will appear elsewhere [7].

We note that a semi-analytical analysis of (1) for $t\bar{t}$ production in $q\bar{q}$ annihilation at FNAL energies has been presented in Ref. [12] for initial state radiation at the $\bar{\beta}_0$ level. The latter analysis is in agreement with the results presented herein.

In conclusion, we have shown that there are potentially important soft $n(G)$ effects in the $t\bar{t}$ production distributions and cross-sections at and beyond FNAL energies. We have illustrated these effects and found a potential source of enhancement of the expected $t\bar{t}$ cross-section at and beyond FNAL energies. We look forward with excitement to the detailed analysis of these potentially enhanced corrections in the actual hadron-level discussion [7].

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Figure Captions

1. The process $q + \bar{q} \to t + \bar{t} + n(G)$ to $\mathcal{O}(\alpha_s)$: (a) Born approximation; (b) $\mathcal{O}(\alpha_s)$ virtual correction; (c) bremsstrahlung process. Here, f.s.e. represents the fermion self-energies and G represents the QCD gluon, with $q = u, d, s$.

2. Gluon multiplicity for $u + \bar{u} \to t + \bar{t} + n(G)$ at the FNAL energy $\sqrt{s} = 1.8$ TeV. The cuts $|\eta| < 3$ and $k_G \geq 3GeV$ are imposed, where k_G is the gluon energy in the $u\bar{u}$ cms system.

3. v-distribution for $u + \bar{u} \to t + \bar{t} + n(G)$ at the FNAL energy $\sqrt{s} = 1.8$ TeV. The cuts are the same as those in Fig. 2.

4. Total transverse momentum distribution of the gluons in $u + \bar{u} \to t + \bar{t} + n(G)$ at the FNAL energy $\sqrt{s} = 1.8$ TeV. The cuts are the same as those in Fig. 3.

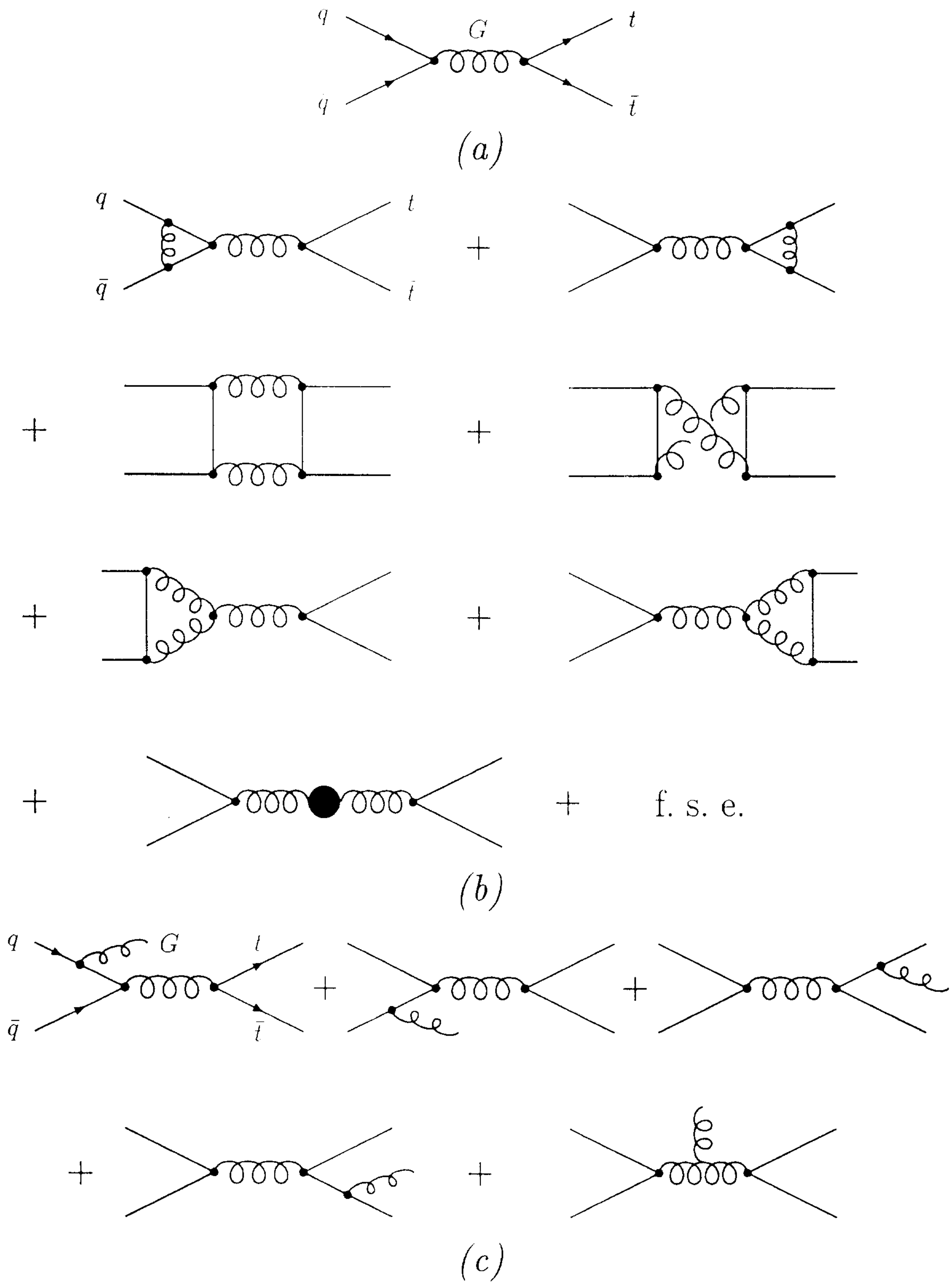


Fig. 1

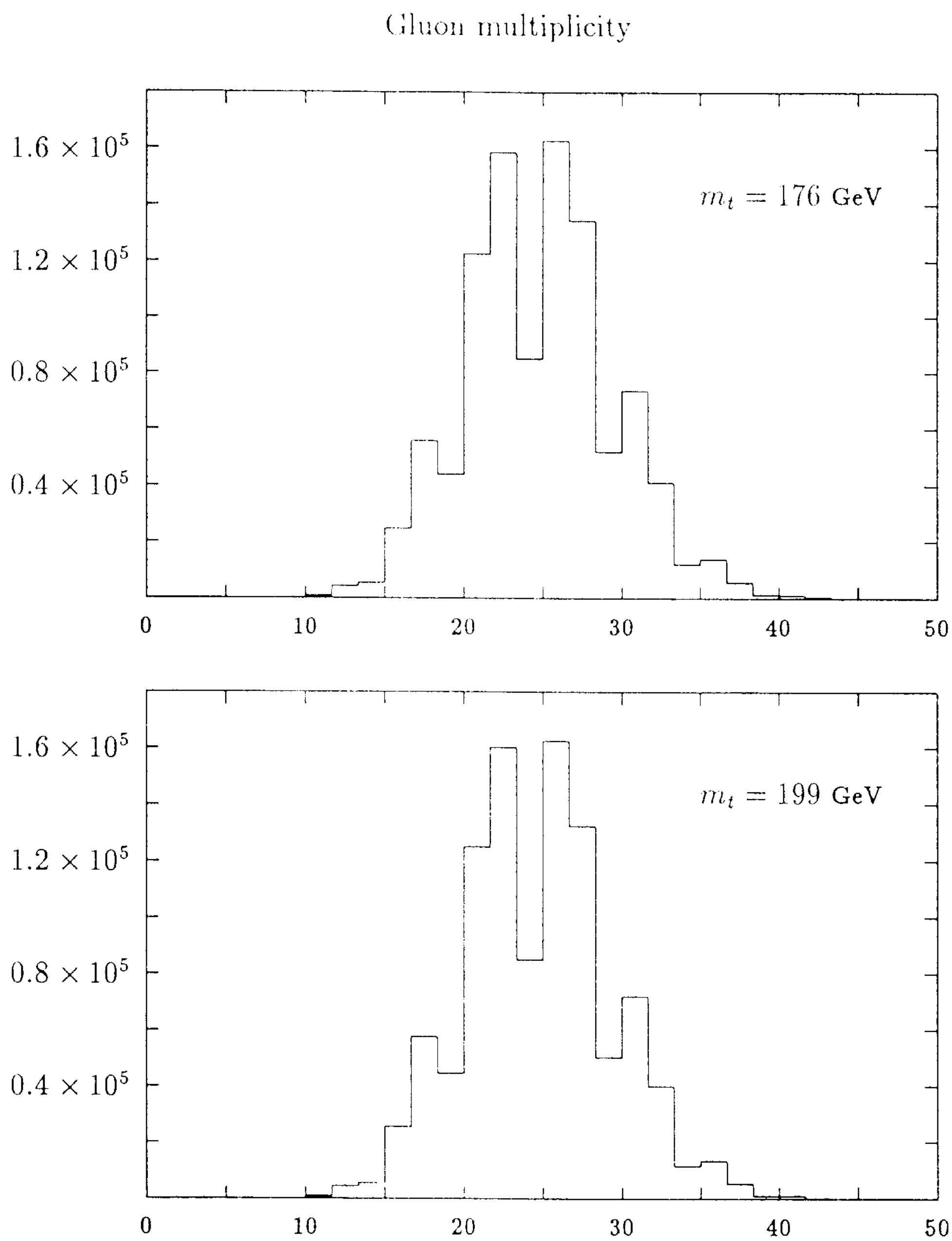
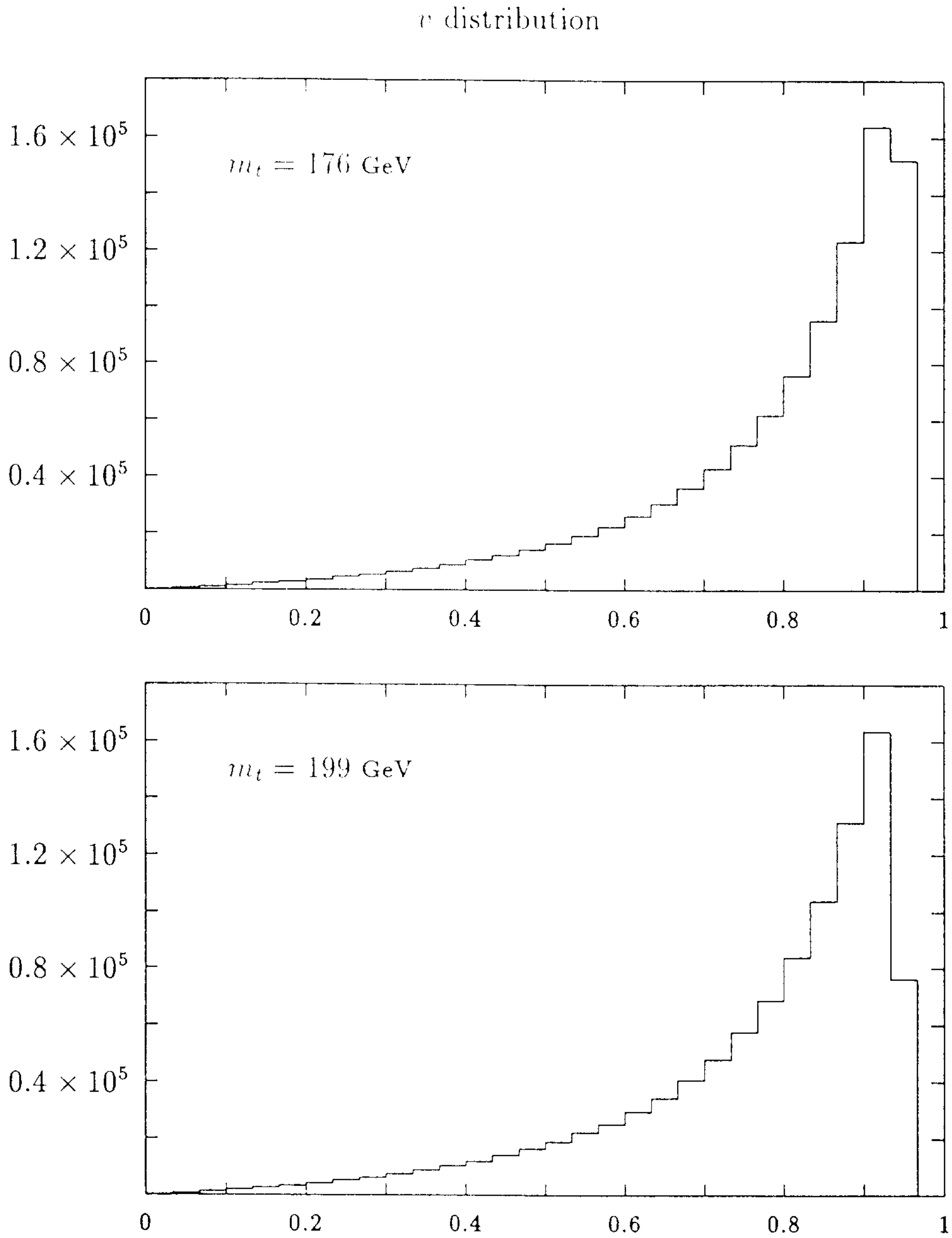

Gluon multiplicity
1.6 × 10^5
1.2 × 10^5
0.8 × 10^5
0.4 × 10^5
m_t = 176 GeV
0
10
20
30
40
50
1.6 × 10^5
1.2 × 10^5
0.8 × 10^5
0.4 × 10^5
m_t = 199 GeV
0
10
20
30
40
50

Fig. 2



v distribution
1.6×10^5
1.2×10^5
0.8×10^5
0.4×10^5
$m_t = 176$ GeV
0
0.2
0.4
0.6
0.8
1
1.6×10^5
1.2×10^5
0.8×10^5
0.4×10^5
$m_t = 199$ GeV
0
0.2
0.4
0.6
0.8
1

Fig. 3

Total gluon transverse momentum (TeV)

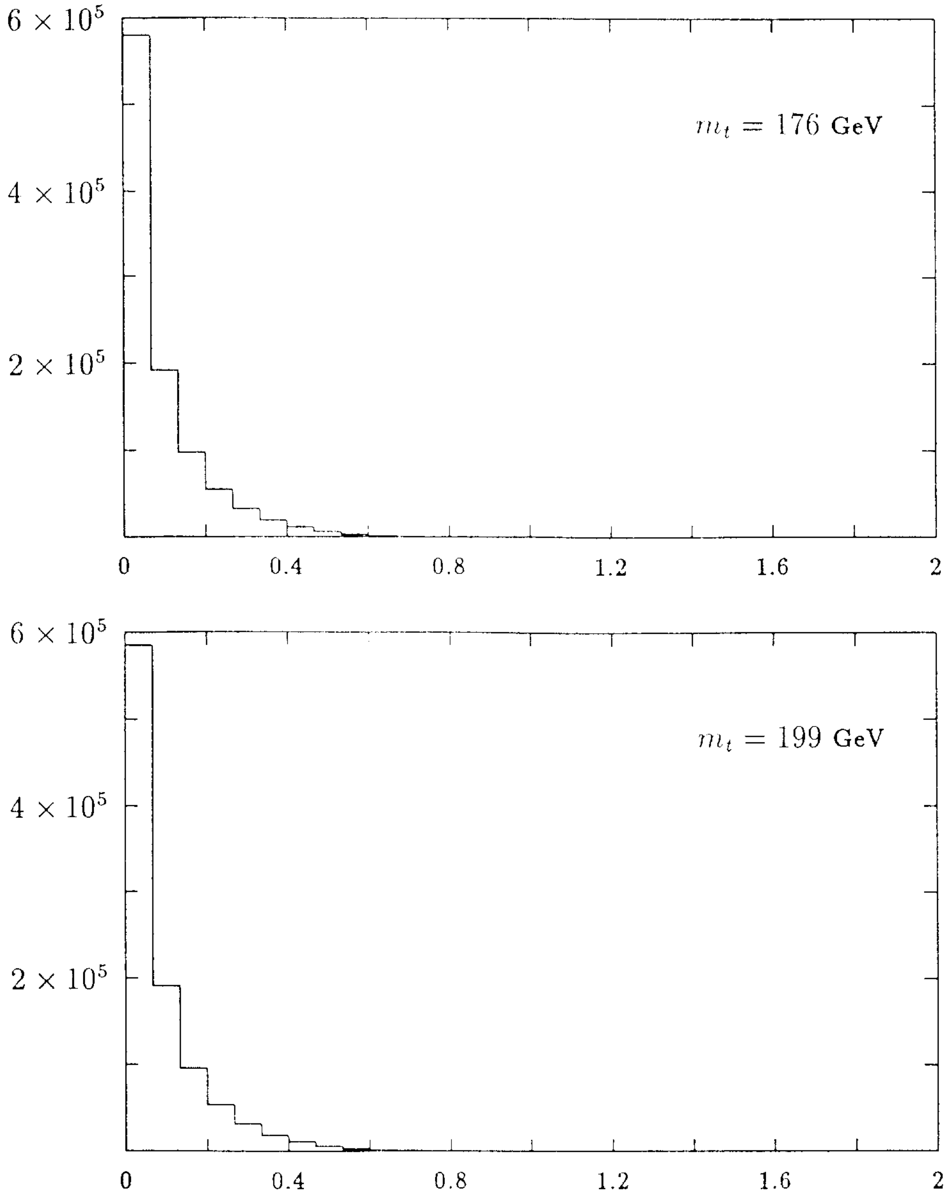


Fig. 4