Search for Squarks and Gluinos in Single-Photon Events with Jets and Large Missing Transverse Energy in $p\overline{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

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We search for new physics using events with one high transverse energy photon, two or more jets, and an apparent imbalance in transverse energy, in $p\overline{p}$ collisions at the Fermilab Tevatron at $\sqrt{s} = 1.8$ TeV. Such events are predicted for production of supersymmetric particles in some models. No excess is observed beyond expected background. For the parameter space of the minimal supersymmetric standard model with branching fraction $B(\tilde{\chi}_2^0 \rightarrow \gamma\tilde{\chi}_1^0) = 1$ and $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} > 20$ GeV, we obtain a 95% confidence level lower mass limit of 310 GeV for equal mass squarks and gluinos. The results are also interpreted in models with low energy gauge mediated supersymmetry breaking. [S0031-9007(98)08065-X]

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We search for physics beyond the standard model (SM) using events with one high transverse energy (E_T) photon, two or more jets, and large imbalance in transverse energy ($\not\!\!E_T$). We call these $\gamma \not\!\!E_T + \geq 2$ jets events. This search is motivated by recent suggestions [1,2] that supersymmetry may result in signatures involving one or more photons together with multiple jets and large $\not\!\!E_T$.

Supersymmetry introduces for every particle in the SM a supersymmetric partner differing in spin by one-half. R parity, defined as $+1$ for SM particles and -1 for their superpartners, is assumed to be conserved in this analysis, such that supersymmetric particles are produced in pairs and the lightest supersymmetric particle (LSP) is stable. In the minimal supersymmetric standard model (MSSM), the gaugino-Higgsino sector (excluding gluinos) is described by four parameters: M_1, M_2, μ, and $\tan\beta$, where M_1 and M_2 are the U(1) and SU(2) gaugino mass parameters, μ is the Higgsino mass parameter, and $\tan\beta$ is the ratio of the vacuum expectation values of the two Higgs doublets. Gaugino-Higgsino mixing gives four neutral mass eigenstates (neutralinos $\tilde{\chi}_i^0$, $i = 1, \ldots, 4$) and two charged eigenstates (charginos $\tilde{\chi}_i^{\pm}$, $i = 1, 2$). The radiative decay of $\tilde{\chi}_2^0 \rightarrow \gamma \tilde{\chi}_1^0$ dominates in some regions (not excluded by the CERN e^+e^- collider LEP Z data) of parameter space [3] assuming sfermions are heavy and has been proposed as an explanation [2] of a candidate event reported by the CDF Collaboration [4]. Assuming that $\tilde{\chi}_1^0$ is the LSP, then the production of $\tilde{\chi}_2^0$ will yield $\gamma \not\!\!E_T + X$ events. The $\gamma \not\!\!E_T + X$ events may also arise in low energy gauge mediated supersymmetry breaking (GMSB) models [1] in which the gravitino ($\tilde{G}$) is the LSP and the $\tilde{\chi}_1^0$ is the next-to-lightest supersymmetric particle (NLSP). In this case, $\tilde{\chi}_1^0$ is unstable and decays into a photon plus a gravitino ($\tilde{\chi}_1^0 \rightarrow \gamma \tilde{G}$).

In this Letter, we present the first search for physics beyond the SM in the channel $p\overline{p} \rightarrow \gamma \not\!\!E_T + \geq 2$ jets. Because of large backgrounds from QCD processes, we do not consider events with less than two jets. The data used in this analysis were collected with the D0 detector [5] during the 1992–1996 Tevatron run at a center of mass energy of $\sqrt{s} = 1.8$ TeV and represent an integrated luminosity of 99.4 ± 5.4 pb^{-1}. The trigger requires one electromagnetic (EM) cluster with $E_T > 15$ GeV, one jet with $E_T > 10$ GeV, and $\not\!\!E_T > 14$ GeV ($\not\!\!E_T > 10$ GeV for about 10% of the data). Photons are identified via a two-step process: the selection of isolated EM energy clusters and the rejection of such clusters with any associated charged tracks. The EM clusters are selected from calorimeter energy clusters by requiring (i) at least 95% of the energy to be deposited in the EM section of the calorimeter, (ii) the transverse and longitudinal shower profiles to be consistent with those expected for an EM shower, and (iii) the energy in an annular isolation cone with radius $[\mathcal{R} \equiv \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}]$ 0.2 to 0.4 around the cluster in $\eta - \phi$ space to be less than 10% of the EM energy in an $\mathcal{R} = 0.2$ cone, where η and ϕ are the pseudorapidity and azimuth, respectively. The EM clusters that have either a reconstructed track or a large number of hits in the tracking chamber along a road joining the cluster and the interaction vertex are vetoed. $\not\!\!E_T$ is determined from the energy deposition in the calorimeter within $|\eta| < 4.5$.

To be selected as $\gamma \not\!\!E_T + \geq 2$ jets candidates, events are first required to have at least one identified photon with $E_T^\gamma > 20$ GeV and pseudorapidity $|\eta^\gamma| < 1.1$ or $1.5 < |\eta^\gamma| < 2.0$ (the region with EM calorimeter coverage and good photon identification) and two or more jets reconstructed using the energy depositions in the calorimeter with cones of radius $\mathcal{R} = 0.5$, having $E_T^j > 20$ GeV and $|\eta^j| < 2.0$. We refer to the events passing these requirements as the $\gamma + \geq 2$ jets sample. The $\not\!\!E_T$ distribution of these events is shown in Fig. 1. We then require $\not\!\!E_T > 25$ GeV. A total of 318 events satisfies all requirements.

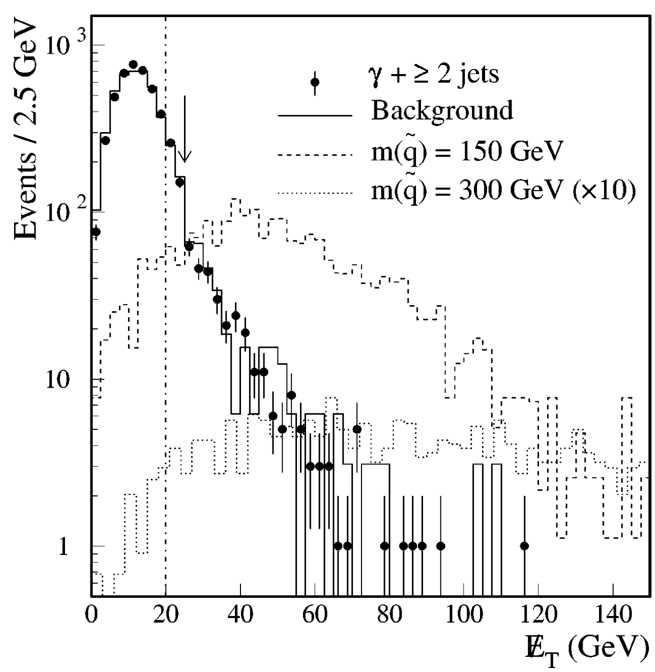

FIG. 1. The $\not\!\!E_T$ distributions of the $\gamma + \geq 2$ jets and background events. The number of events in the background is normalized to the $\gamma + \geq 2$ jets sample for $\not\!\!E_T < 20$ GeV, the region left of the dot-dashed line. The arrow indicates the $E_T > 25$ GeV cut. Also shown are the distributions expected from supersymmetry for $m_{\tilde{q}} = m_{\tilde{g}} = 150$ and 300 GeV.

TABLE I. Number of observed $\gamma \not\!\!E_T + n$ jets events (N_S) together with the corresponding number of background events (N_B) for $n \geq 2, 3, 4$, for three sets of cutoffs.

No. of jets	$\not\!\!E_T > 25$ GeV No H_T cut N_S	N_B	$\not\!\!E_T > 25$ GeV $H_T > 200$ GeV N_S	N_B	$\not\!\!E_T > 50$ GeV No H_T cut N_S	N_B
$n \geq 2$	318	320 ± 30	30	20 ± 10	43	65 ± 15
$n \geq 3$	70	70 ± 15	17	8 ± 5	11	10 ± 5
$n \geq 4$	8	10 ± 5	6	4 ± 3	1	3 ± 3

The principal backgrounds are as follows: QCD direct photon and multijet events, where there is mismeasured $\not\!\!E_T$ and a real or fake photon; $W(\rightarrow e\nu)$ + jets events, where the electron is misidentified as a photon and the neutrino gives rise to the $\not\!\!E_T$; and $W(\rightarrow \ell\nu)$ + jets events (where $\ell = e, \mu, \tau$), in which one of the jets is misidentified as a photon. The background due to heavy quark production with a high E_T photon is found to be negligible. The background from mismeasurement of $\not\!\!E_T$ is estimated using events with one EM-like cluster that satisfies all photon criteria, except requirement (ii) on the shower profile. These events must also have two or more jets with $E_T^j > 20$ GeV and $|\eta^j| < 2.0$, making them similar to those of the $\gamma + \geq 2$ jets sample, and therefore of similar resolution in $\not\!\!E_T$. The events in this background sample are normalized to the $\gamma + \geq 2$ jets sample for $\not\!\!E_T < 20$ GeV, which provides an estimated background from $\not\!\!E_T$ mismeasurement of 315 ± 30 events beyond $\not\!\!E_T = 25$ GeV. $W + \geq 2$ jets events with $W \rightarrow e\nu$ can mimic $\gamma \not\!\!E_T + \geq 2$ jets events if the electron is misidentified as a photon. This contribution is estimated using a sample of $e \not\!\!E_T + \geq 2$ jets events that passes all our kinematic requirements, with the electron satisfying those defined for the photon. Electrons are selected from identified EM clusters that have matched tracks. Multiplying the probability (0.0045 ± 0.0008, determined from $Z \rightarrow ee$ data) that an electron is misidentified as a photon by the number of $e \not\!\!E_T + \geq 2$ jets events yields a background of 4 ± 1 events. The $W(\rightarrow \ell\nu)$ + jets background is estimated using a data sample of $W(e\nu) + \geq 3$ jets events passing all kinematic requirements, with at least one of the jets satisfying those imposed on photons. Using the probability (0.0007 ± 0.0002, determined using multijet data) that a jet is misidentified as a photon and the scale factor $N_{W(\rightarrow \ell\nu)+\geq 3\ \text{jets}}/N_{W(\rightarrow e\nu)+\geq 3\ \text{jets}}$ (determined from Monte Carlo), we estimate a background of 1.0 ± 0.3 events. The background from $Z(\rightarrow \nu\nu) + \geq 3$ jets is negligible.

The number of observed events and the expected backgrounds are summarized in Table I, together with the breakdown by jet multiplicity. The H_T distribution (defined as the scalar sum of the E_T of all jets with $E_T^j > 20$ GeV and $|\eta^j| < 2.0$) is shown in Fig. 2, for both $\gamma \not\!\!E_T + \geq 2$ jets and background samples. Also given in Table I is the number of observed events and the expected background if the cutoff $H_T > 200$ GeV is applied or if the $\not\!\!E_T$ cutoff is raised to 50 GeV. In all three comparisons, the estimated number of background events agrees with the number of events observed in the data.

We interpret our results in terms of squark ($\tilde{q}$) and gluino ($\tilde{g}$) production in the context of supersymmetric models with a dominant $\tilde{\chi}_2^0 \rightarrow \gamma \tilde{\chi}_1^0$ decay. We simulate $\tilde{q}$ and $\tilde{g}$ pair production and also production in association with $\tilde{\chi}_i^0$ and $\tilde{\chi}_j^{\pm}$ using the SPYTHIA program [6]. The MSSM parameters are set to $M_1 = M_2 = 60$ GeV, $\tan\beta = 2$, and $\mu = -40$ GeV. This set gives $m_{\tilde{\chi}_1^0} = 34$ GeV, $m_{\tilde{\chi}_2^0} = 60$ GeV, and $B(\tilde{\chi}_2^0 \rightarrow \gamma \tilde{\chi}_1^0) = 1$. Slepton ($\tilde{\ell}$) and stop ($\tilde{t}_1$) masses are set to 500 GeV while sneutrino masses are fixed by the sum rule $m_{\tilde{\nu}}^2 = m_{\tilde{\ell}}^2 - M_W^2 \cos 2\beta$. All other squarks are assumed to be degenerate in mass. Descriptions of superpartner decays can be found in Ref. [6]. However, we note that the mode $\tilde{q} \rightarrow q\tilde{\chi}_2^0$ dominates over the mode $\tilde{q} \rightarrow q\tilde{\chi}_1^0$ for the above values of supersymmetry parameters. Monte Carlo (MC) events are generated for three $\tilde{q}$ or $\tilde{g}$ mass possibilities: (i) equal mass $\tilde{q}$ and $\tilde{g}$ ($m_{\tilde{q}} = m_{\tilde{g}}$), (ii) heavy

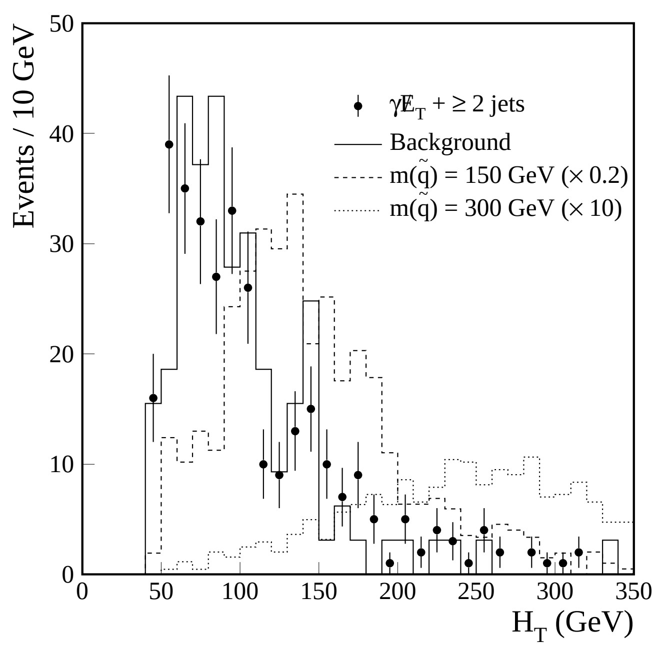

FIG. 2. The H_T distributions of the $\gamma \not\!\!E_T + \geq 2$ jets and background events. The expected distributions from supersymmetry are also shown for comparison.

TABLE II. The percentages of events (ϵ_0) generated containing $\tilde{\chi}_2^0$ in the final state, and the efficiencies (ϵ_S) for their detection. The decrease in efficiency from $m_{\tilde{q}/\tilde{g}} = 150$ to 200 GeV is due to the change in the cuts as discussed in the text. The uncertainties are purely statistical.

$m_{\tilde{q}/\tilde{g}}$	$m_{\tilde{q}}(= m_{\tilde{g}})$		$m_{\tilde{g}}(\ll m_{\tilde{q}})$		$m_{\tilde{q}}(\ll m_{\tilde{g}})$	
(GeV)	ϵ_0(%)	ϵ_S(%)	ϵ_0(%)	ϵ_S(%)	ϵ_0(%)	ϵ_S(%)
150	66.2	15.1 ± 0.8	69.1	11.6 ± 0.9	60.0	16.8 ± 1.1
200	62.3	7.9 ± 0.6	59.6	5.3 ± 0.6	53.8	9.5 ± 0.9
250	59.6	14.8 ± 0.8	49.7	13.6 ± 1.1	55.4	14.8 ± 1.1
300	56.1	21.5 ± 1.0	43.1	19.0 ± 1.3	55.4	22.1 ± 1.2
350	51.8	22.8 ± 1.1	39.3	23.5 ± 1.5	52.7	26.6 ± 1.4
400	46.7	23.5 ± 1.1	33.3	22.7 ± 1.6	54.3	25.8 ± 1.3

$\tilde{q}$ and light $\tilde{g}$ ($m_{\tilde{q}} \gg m_{\tilde{g}}$), and (iii) light $\tilde{q}$ and heavy $\tilde{g}$ ($m_{\tilde{q}} \ll m_{\tilde{g}}$). The $\not{E}_T$ and H_T distributions for $m_{\tilde{q}} = m_{\tilde{g}} = 150\,300$ GeV events are shown, respectively, in Figs. 1 and 2, where the MC distributions are scaled by the factors shown in parentheses. The distributions expected from supersymmetry differ considerably from those of the background. To increase the sensitivity to supersymmetry, we introduce an H_T cutoff and maximize the $\epsilon_S/\delta N_B$ ratio by varying the $\not{E}_T$ and H_T cutoffs. Here ϵ_S is the efficiency for signal, and δN_B is the uncertainty on the estimated number of background events. To ensure high efficiencies for both low and high $\tilde{q}$ and $\tilde{g}$ masses, the optimization is done for two MC points $m_{\tilde{q}} = m_{\tilde{g}} = 150$ and 300 GeV. The optimum values are $\not{E}_T > 35$ GeV and $H_T > 100$ GeV for 150 GeV, and $\not{E}_T > 45$ GeV and $H_T > 220$ GeV for 300 GeV. The $\epsilon_S/\delta N_B$ results (a function of $\tilde{q}/\tilde{g}$ mass) for the two sets are equal near 200 GeV. We apply the cutoffs optimized for the 150 GeV mass point to MC events with $\tilde{q}$ and $\tilde{g}$ masses below 200 GeV and apply those optimized for the 300 GeV mass point to masses of 200 GeV or above. The number of events observed for these two sets of cutoffs are 60 and 5, with 75 ± 17 and 8 ± 6 events expected from background processes. We observe no excess beyond the standard model.

The ϵ_S for predictions from the supersymmetric models are given in Table II. MC studies show that the overall efficiency varies by 4% for different choices of M_1, M_2, $\tan\beta$, and μ that are consistent with $B(\tilde{\chi}_2^0 \to \gamma\tilde{\chi}_1^0) = 1$ and $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} > 20$ GeV [2]. The total systematic error on the efficiency is 9%, including uncertainties in photon identification efficiency (7%), the choice of values of the supersymmetry parameters (4%), and the jet energy scale (3%). We set a 95% confidence level (C.L.) upper limit on $\sigma \times B \equiv \sigma(p\overline{p} \to \tilde{q}/\tilde{g} \to \tilde{\chi}_2^0 + X) \times B(\tilde{\chi}_2^0 \to \gamma\tilde{\chi}_1^0)$ using a Bayesian approach with a flat prior distribution for the signal cross section. The resulting upper limit is tabulated in Table III.

Figure 3 shows the limit for $m_{\tilde{q}} = m_{\tilde{g}}$, together with the theoretical cross section, calculated using SPYTHIA with the CTEQ3L parton distribution functions [7]. The renormalization scale is set to the average transverse energy of the outgoing partons in the calculation. The band represents the range of predictions obtained by varying the supersymmetry parameters with the constraints that $B(\tilde{\chi}_2^0 \to \gamma\tilde{\chi}_1^0) = 1$ and $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} > 20$ GeV. The intersection of the limit with the lower edge of the band is at $\sigma \times B = 0.38$ pb, leading to a lower limit for equal mass $\tilde{q}$ and $\tilde{g}$ of 310 GeV at the 95% C.L.

We vary the slepton mass from 500 GeV to the lower experimental limit of about 80 GeV [8] in the MC. For $m_{\tilde{q}} = m_{\tilde{g}} = 300$ GeV MC events, the percentage ϵ_0 increases by 25% which leads to an increase in the mass limit by $\sim$10 GeV. A light stop $\tilde{t}_1$ would modify $\tilde{q}$ and $\tilde{g}$ decays and would affect $\tilde{\chi}_2^0$ production. If $m_{\tilde{t}_1}$ is lowered from 500 to 80 GeV (approximate lower experimental limit [9]), a 15% reduction in $\tilde{\chi}_2^0$ production is predicted which lowers the limit for equal mass $\tilde{q}$ and $\tilde{g}$ by about 6 GeV.

TABLE III. The theoretical cross sections $\sigma \times B$ and our measured 95% C.L. upper limits on $\sigma \times B$. The predictions are calculated for $M_1 = M_2 = 60$ GeV, $\tan\beta = 2$, and $\mu = -40$ GeV.

	$\sigma \times B$ (pb)					
$m_{\tilde{q}/\tilde{g}}$	$m_{\tilde{q}}(= m_{\tilde{g}})$		$m_{\tilde{g}}(\ll m_{\tilde{q}})$		$m_{\tilde{q}}(\ll m_{\tilde{g}})$	
(GeV)	Theory	Limit	Theory	Limit	Theory	Limit
150	83.4	2.0	24.1	2.6	8.51	1.8
200	12.1	1.1	3.48	1.6	1.59	0.9
250	2.37	0.57	0.51	0.63	0.43	0.58
300	0.53	0.39	0.12	0.44	0.12	0.38
350	0.13	0.37	0.02	0.37	0.03	0.32
400	0.04	0.36	0.01	0.37	0.01	0.32

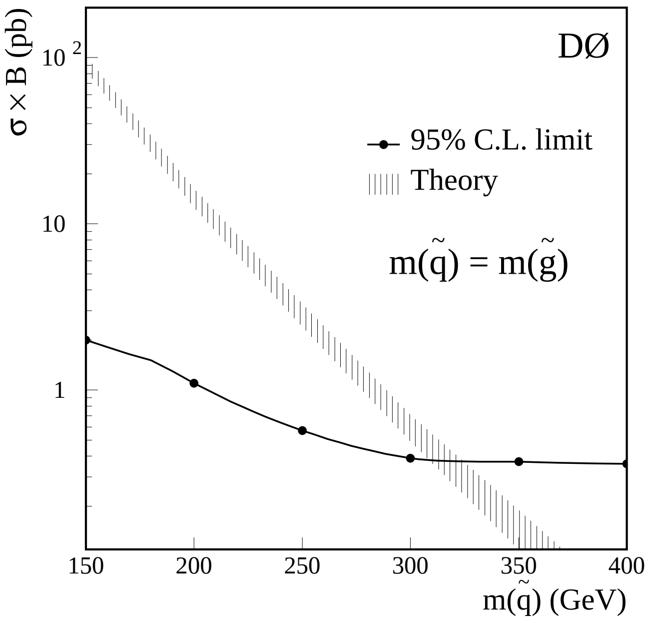

FIG. 3. The 95% C.L. upper limit on $\sigma \times B$ as a function of $m_{\tilde{q}/\tilde{g}}$, assuming equal $\tilde{q}$ and $\tilde{g}$ masses. The hatched band represents the range of expected cross sections for different sets of MSSM parameters; see text. The inflection below 200 GeV in the limit curve is the intersection of the two curves using the two sets of optimized cutoffs discussed in the text.

Following the above procedure, we obtain a lower limit for $\tilde{g}$ ($\tilde{q}$) mass of 240 GeV when squarks (gluinos) are heavy. Again, these limits vary by approximately 10 GeV if $\tilde{t}_1$ and/or sleptons are light.

The results of this analysis can also be interpreted in the GMSB models. In this case, every event from supersymmetry will have two photons in the final state for the prompt decay of the NLSP. This results in $\epsilon_0 =$ 100% and leads to about a 50% increase in ϵ_S. Using the above values of supersymmetry parameters, we set lower mass limits of 360, 320, 320 GeV for the cases of $m_{\tilde{q}} = m_{\tilde{g}}$, $m_{\tilde{g}} \ll m_{\tilde{q}}$, and $m_{\tilde{q}} \ll m_{\tilde{g}}$, respectively. These results are insensitive to the choice of slepton and stop masses. Finally we note that the analysis is also sensitive to the delayed decay of the NLSP.

In summary, we have searched for an excess of $\gamma \not{E}_T$ events with two or more jets in $p\overline{p}$ collisions at $\sqrt{s} = 1.8$ TeV. We find that the number of observed $\gamma \not{E}_T + \geq 2$ jets events agrees well with that expected from background processes. Within the MSSM, with choices of parameters consistent with $B(\tilde{\chi}_2^0 \rightarrow \gamma \tilde{\chi}_1^0) = 1$ and $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} > 20$ GeV, we obtain a 95% C.L. lower mass limit of 310 GeV for equal mass squarks and gluinos and of 240 GeV for squarks (gluinos) when gluinos (squarks) are heavy. These limits constrain the models discussed in Ref. [2] but do not exclude all of them. These results are complementary to those [10] recently published by the LEP experiments.

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