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MASS LIMITS ON PARTICLES FROM PULSED SOURCES: HOW RELIABLE ARE THEY?

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ABSTRACT

It is widely believed that the arrival at Earth of pulsed emission from a cosmic accelerator such as Cygnus X-3 puts mass limits on the particles carrying the radiation of order 1 GeV. We show that these simple kinematic estimates are unreliable and can often be avoided. The actual mass limit depends critically on the detailed structure of the pulse, i.e. on (i) the shape of the flux as a function of energy and (ii) the minimum and maximum energies. We illustrate this by showing that masses of 100 GeV or more for the "cygnets" responsible for the unexplained pulsed muon signal from Cygnus X-3 can be made consistent with present experiments. These masses are large enough to accomodate the 3° angular spread of the muon pulses and to exclude the production of cygnets in accelerator experiments.

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Episodic observation of muon emission by cosmic accelerators[1] has been received with great skepticism as the data cannot be understood in terms of standard particle physics[2]. The erratic behavior of the sources (Cygnus X-3, Hercules X-1 and Crab pulsar) makes a controlled study difficult. Nevertheless, further evidence for the muon signal has been accumulating[3]. Speculations on the source of the anomalous muons fall into two categories: (i) a new threshold[4] associated with very high energy γ-rays or neutrinos from the source resulting in an abundant production of muons or hadrons by γ-rays or neutrinos or (ii) new particles[5] (cygnets) accompanying the γ beam and acting as parents to the excess muons which cannot be accounted for by the muon poor γ showers. Not only the rate but also the 3° angular spread of the muon beam around the source direction constitute the Cygnus X-3 puzzle. In the threshold scenario, photons interact at Earth with momentum transfers large enough to produce several times the $\mu^+\mu^-$ mass. The angular spread from multiple Coulomb interactions, typically less than 1°, can easily be increased by an order of magnitude. In scenario (ii) large angles are produced by assuming that the stable cygnets C produce muons via the reaction $Cp \to X(C' \to \mu^+\mu^-)$. The intermediate C' carry only a fraction f of the cygnet energy. The angular spread of the muons $\delta\theta_\mu$ is then given by

$$\sin(\delta\theta_\mu) = M_{C'}/(fE_C) \tag{1}$$

and masses $M_{C'} \approx 10 - 40$ GeV can accomodate the underground data (the muon abundances at Kiel and Los Alamos are still unexplained). The production cross-section $\sigma_{Cp \to C'X}$ must be $O(10 - 40\mu\text{b})$ to explain the decay of the signal between SOUDAN and NUSEX. Problems arise as the mass M_C is constrained not only by the fact that the strongly interacting cygnets have not been observed in accelerator experiments but also by the pulsed nature of the muon signal. It is this problem which we reconsider here in detail.

The observation of muon pulses of width $\approx$ 30 minutes from the direction of Cygnus X-3 has lead to the conclusion that the signal carriers have a mass $O(1\text{GeV})$. Let us briefly review the argument: one assumes that the energy E of the muon parents is in the interval $E_{min}(\approx 10 \text{ TeV}) \leq E \leq E_{max}(\approx 10^5 \text{ TeV})$. A particle of energy E and mass m has a velocity $\beta(E) = \frac{\sqrt{E^2-m^2}}{E} \approx 1 - \frac{m^2}{2E^2}$. The time interval between the arrival of particles of energies E_{min} and E_{max} is thus:

$$\Delta t = \frac{L}{c}(\frac{1}{\beta(E_{min})} - \frac{1}{\beta(E_{max})}) \approx \frac{Lm^2}{2cE^2_{min}}(1 - \frac{E^2_{min}}{E^2_{max}}), \tag{2}$$

where L is the distance to the star. The usual mass limit is obtained when one imposes that all the particles arrive at Earth within a time small compared to the 4.8 hour period of the pulsed emission, i.e. $\tau \equiv \frac{Lm^2}{2cE^2_{min}} \approx \Delta t \leq 30$ min. For $L = 12$ kpc, one gets $m^2 \leq E^2_{min} \times \frac{\Delta t}{6.18\ 10^{11}} \approx (0.54 \text{ GeV})^2$. Replacing the 30 minutes by the period of the system (4.8 hours) leads to the limit $m \lesssim 1.7$ GeV. This limit thus assumes that the pulse is totally concentrated within one period.

Actually, the data only require that there is a pile-up of particles at a given arrival time. This can happen even if some of the (lower-energy) particles arrive at later times. Our argument can be intuitively understood as follows. Let us assume an incoming pulse of energy distribution $\frac{dN}{dE} = AE^n$ and let us divide the energy interval $[E_{min}, E_{max}]$ into four bins (i = 1, 2, 3, 4) of minimum energy $E_i = 10^i$ TeV and of maximum energy 10 E_i. The number of particles in the i$^{\text{th}}$ bin δN_i and the time interval δt_i within which they arrive are given by:

$$\begin{aligned} \delta N_i &\sim (10^i)^{n+1} \\ \delta t_i &\sim (10^i)^{-2}. \end{aligned} \tag{3}$$

Hence the energy dependence of the flux is given by:

$$\frac{\delta N_i}{\delta t_i}(E_i) \sim 10^{i(n+3)}. \tag{4}$$

So as long as $n > -3$, the in time signal of the highest energy particles will not be destroyed by the lower energy ones arriving later, i.e. the lower energy particles, although more numerous, are so spread out in time that they do not wash out the pulsed signal of the higher energy particles arriving first. For example, in the case of an E^{-2} spectrum, particles with one tenth of the maximum energy are 10 times more frequent but are spread out over a time interval 100 times larger, see Eq. 3. The high-energy part of the spectrum will be identified as the signal and the lower-energy part confused with the large background characteristic of present observations. The flux is still periodic in time. We have however to consider the pile-up of particles from different periods and see how this affects the signal.

We therefore consider an explicit model of the pulsed emission. We assume that the star emits a flux of energy dependence E^n and of constant intensity during a fraction $\delta\phi$ of the period T:

$$\frac{dN}{dt^* dE} = A \sum_{j=-\infty}^{\infty} \theta(t^* - jT)\theta(\delta\phi - t^* + jT)E^n, \tag{5}$$

with A a normalization constant. $\delta\phi$ can be thought of as the width of the signal in the phase plot at the source. The flux at Earth and the total beam energy are then given by:

$$\frac{dN}{dt} = \frac{A}{n+1} \sum_{j=(1/T)(t-\delta\phi-\tau)}^{(1/T)(t-\tau E_{min}^2/E_{max}^2)} (E_b^{n+1} - E_a^{n+1})$$
$$\frac{dE}{dt} = \frac{A}{n+2} \sum_{j=(1/T)(t-\delta\phi-\tau)}^{(1/T)(t-\tau E_{min}^2/E_{max}^2)} (E_b^{n+2} - E_a^{n+2}) \qquad (6)$$

with $E_b = E_{max}$ if $t - jT \leq \delta\phi$, $E_b = \inf(E_{max}, E_{min}\sqrt{\frac{\tau}{t-jT-\delta\phi}})$ otherwise, $E_a = \sup(E_{min}, E_{min}\sqrt{\frac{\tau}{t-jT}})$ and $t = t^* - L/c$.

The width $\delta\phi$ has to be adjusted so that the half-width of the high-energy peak at Earth reproduces the observed 30 minutes. We take a typical value $\delta\phi/T \approx 5\%$, with $T = 4.8$ hours. We consider values of n between -3 and -1 (which is the spectral index of γ rays from monoenergetic pp collisions before cascading).

Some illustrative calculations are shown in Figs. 1 and 2 where we calculated the particle distribution dN/dt and the average cygnet energy $\langle E_C(t)\rangle = \frac{dN/dt}{dE/dt}$. Fig. 1 shows the well-known results for the case $m = 1$ GeV. Fig. 2 gives the results for $m = 100$ GeV and 1 TeV. One sees that if one allows $n < -2$, these masses cannot be ruled out as we still obtain a pulsed signal. The peaks are no longer completely separated in time but experimental backgrounds prevent present experiments from observing this. We give our estimate of the signal over background ratio in Table I. We concentrate on the first tenth of the period and define the background as

$$B = \frac{1}{9} \int_{0.1T}^{T} dt \frac{dN}{dt} \qquad (7.a)$$

and the signal as

$$S = \int_0^{0.1T} dt \frac{dN}{dt} - B \qquad (7.b)$$

It is interesting to notice that the background particles arriving at later times will have lower energies and thus a higher angular spread: closing down the angle around the source should increase the signal to background ratio. If we limit our background calculation to the fraction of the muons arriving within a 3° cone, the mass limits are further weakened and masses $O(1\ \text{TeV})$ are allowed. One would also expect the experimental background to go up during periods of high activity such as radio bursts, as this background is determined by looking at the region of the sky around the source direction, which should contain a sizeable fraction of the muons from the low-energy part of the cygnet pulses.

The angular spread of the signal is given by equation (1), with $E_C = \langle E_C(t) \rangle$. We give in Fig. 3 the time-dependent angular spread we get for $f = 1\%$ and $M_{C'} \approx M_C = 0.1 - 1.0$ TeV. We see that a spread of 3° can be achieved for $n > -2$.

We conclude with a few remarks. The total energy emitted by the pulsar is given by:

$$\left.\frac{dE}{dt}\right|_{tot} = \frac{F_\mu}{f_\mu} \langle E \rangle \; \frac{T}{\delta\phi} \qquad (8)$$

where $F_\mu \approx 10^{36}\text{s}^{-1}$ is the total muon flux, f_μ is the muon multiplicity in cygnet interactions and $\delta\phi/T$ is the duty factor of the binary system. $\langle E \rangle$ is given by:

$$\langle E \rangle = \frac{n+1}{n+2} \frac{(E_{max}^{n+2} - E_{min}^{n+2})}{(E_{max}^{n+1} - E_{min}^{n+1})} \qquad (9).$$

For $\delta\phi/T \approx 5\%$, $E_{min} = 10$ TeV, $E_{max} = 10^5$ TeV and $f_\mu \approx 1$, $n = -2.2$ gives a total energy output of 10^{39} ergs s^{-1}, which is the total proton flux in the Hillas model. For $n = 0$ we obtain 10^{42} ergs s^{-1}, which is the highest flux consistent with a Cygnus half-life (due to neutrino heating) of 10 years, assuming that 1% of the flux heats the companion[6]. These bounds are of course very loose as they depend strongly on the muon multiplicity and on the fraction of the flux going into neutrino heating of the companion. We also did not include the fact that Cygnus X-3 seems to be on only a fraction of the time, so that the effective heating should be multiplied by 5% or less[7]. Notice that the flux of cygnets will not have an E^{-2} energy dependence if it is produced by a monochromatic beam and is not affected by cascading (this would indeed be the case of a strongly interacting neutral particle). Also, the energy dependence of the cygnet flux should not be confused with the effective energy dependence of the muon flux experimentally observed, which results from the combined energy dependence of the cygnet flux at the source and of the cygnet interaction (or decay) length at Earth that determines the acceptance of the experiment. For instance, an E^{-2} muon spectrum could result from an E^{-1} cygnet flux folded in with a flat $pC \to XC'$ cross-section and an E^{+1} C' decay length[8].

The width $\delta\phi$ over which the cygnets are emitted could also be much smaller than the phase width of the accompanying γ rays if the particles are produced only in the last interaction length of the proton beam. One has indeed to assume that the width is smaller than the one observed in the γ spectrum, as it will be smeared on Earth by time retardation. We show in Fig. 4.a the effect of decreasing the width on the signal. One must have $0.05\ T \lesssim \delta\phi \lesssim 0.1\ T$ to reproduce the observed half-width of the pulses. Notice also that changing the width does not appreciably affect the signal over background ratio. The lowest cygnet energy

E_{min} has also a big effect on the sharpness of the peak, as illustrated in Fig. 4.b for $n = -2$. The limits on the highest n permitted by companion stability are essentially unaffected when one raises E_{min}.

We finally point out that the above argument still holds true for the observation of pulsed muons from sources with much smaller periods such as pulsars. The allowed masses would then have to be scaled down. The resulting upper bounds on the masses might then become inconsistent with the present accelerator experiments, and the only present explanation of the underground muon signal would then be the threshold mechanism briefly mentioned in the introduction[4].

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8. We thank S. Pakvasa for pointing this out to us.

Table I. The signal over background ratio (see eq. 7) for $E_1 = 10$ TeV, $E_2 = 10^5$ TeV, $T = 4.8$ hours, $\delta\phi = 0.05\ T$, $M_{C'} \approx M_C$ and $f = 1\%$.

M_C (TeV)	n	S/B	S/B in 3° cone
0.1	-1.0	6.7	6.8
0.1	-1.5	0.6	1.2
0.1	-2.0	0.05	2.1
1.0	-1.0	1.8	2.2
1.0	-1.5	0.1	3.2
1.0	-2.0	0.01	2.2

FIGURE CAPTIONS

Fig. 1. Time differential flux of cygnets and average cygnet energy at Earth for a cygnet mass $m = 1$ GeV, a period $T = 4.8$ hours, a pulse width at the star $\delta\phi = 5\ 10^{-2}T$, a flux normalized to 1 particle per second, an energy spread $[E_{min} = 10\ \text{TeV}, E_{max} = 10^5\ \text{TeV}]$ and an energy exponent $n = -1, -2, -3$. $t = 0$ is taken to be the arrival time of the first highest-energy particles.

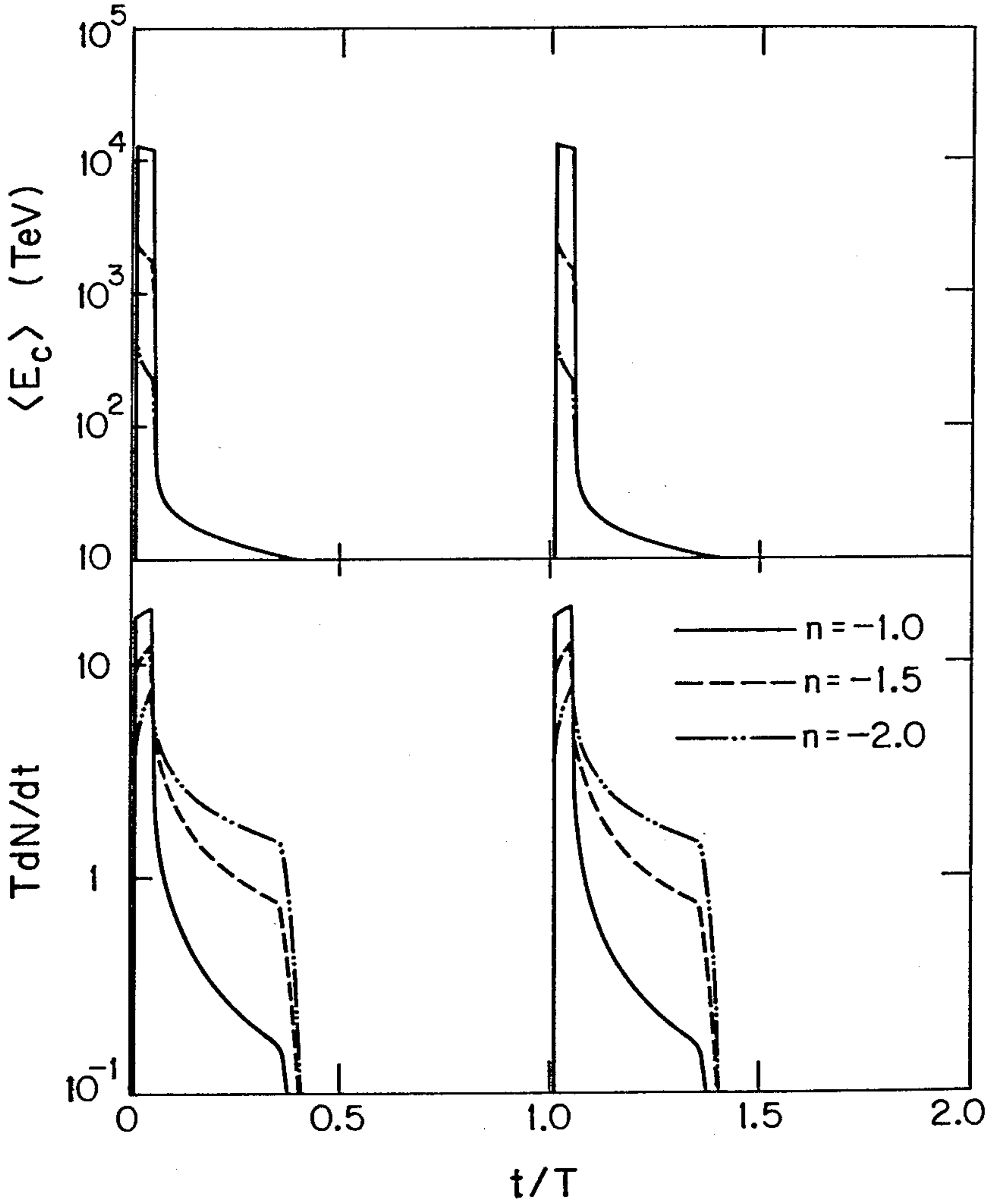
Fig. 2.a Same as Fig. 1 for $m = 100$ GeV and $n = -1, -1.5, -2$.

Fig. 2.b Same as Fig. 1 for $m = 1$ TeV and $n = -1, -1.5, -2$.

Fig. 3. Time-dependent angular spread of the muon signal assuming $M_{C'} \approx M_C$ and $f = 10^{-2}$. The results are given for $M_C = 100$ GeV and 1 TeV, the other parameters being the same as in Fig. 1.

Fig. 4.a $\delta\phi$ dependence of the signal and of the average cygnet energy for $m = 100$ GeV, $n = -2$,$E_{min} = 100$ TeV and $\delta\phi/T =$ 10%, 5% and 1% (the other parameters are as in Fig. 1).

Fig. 4.b E_{min} dependence of the signal and of the average cygnet energy . Same parameters as in Fig. 4.a with $\delta\phi/T =$ 5% and $E_{min} = 10$, 10^2 and 10^3 TeV.



10^5
10^4
10^3
10^2
10
⟨E_c⟩ (TeV)
10
1
10^{-1}
TdN/dt
n = −1.0
n = −1.5
n = −2.0
0
0.5
1.0
1.5
2.0
t/T

Fig. 1

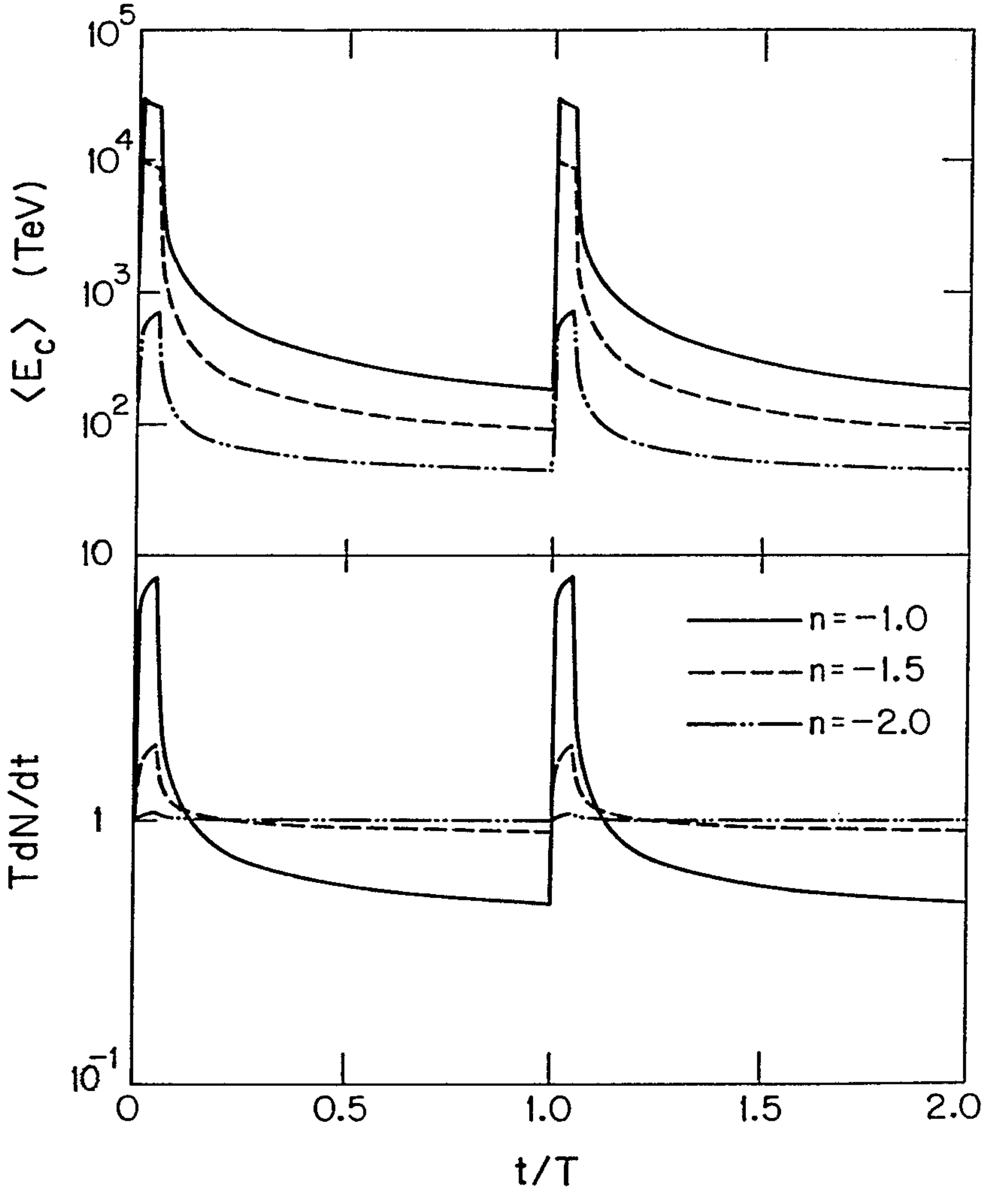
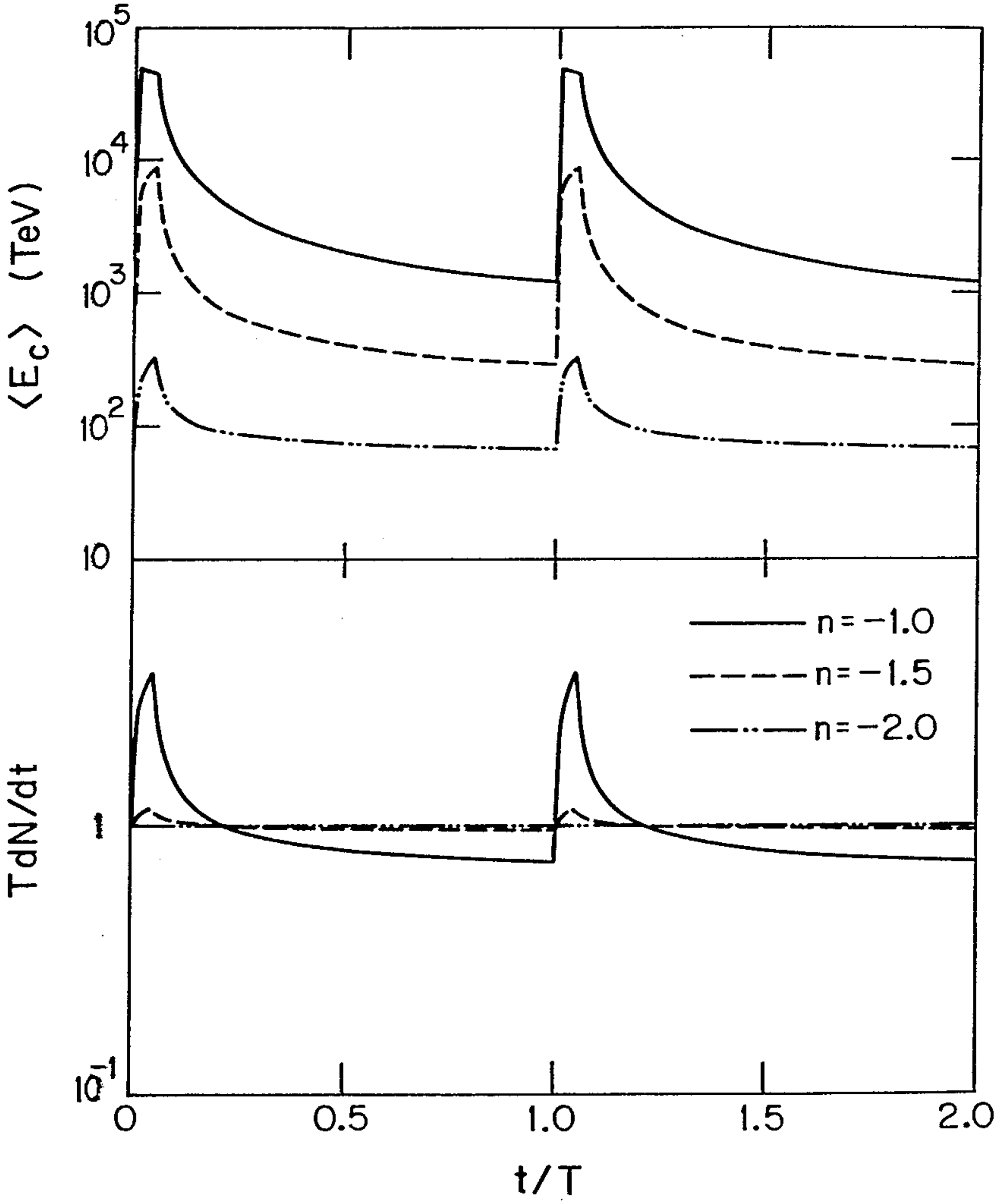
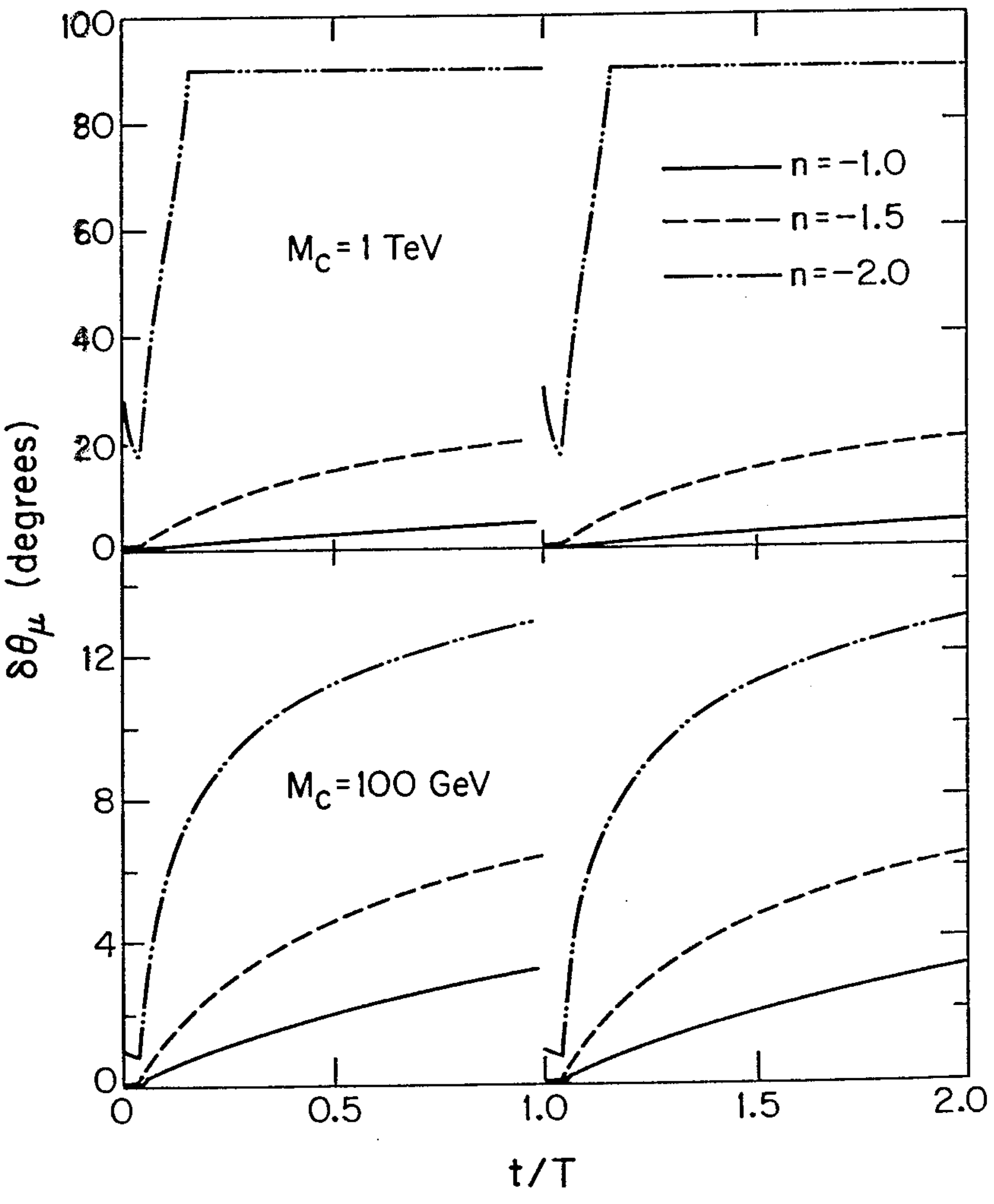


Fig. 2.a



10^5
10^4
10^3
10^2
10
$\langle E_c \rangle$ (TeV)
n = −1.0
n = −1.5
n = −2.0
TdN/dt
1
10^{-1}
0
0.5
1.0
1.5
2.0
t/T

Fig. 2.b



100
80
60
40
20
0
12
8
4
0
0
0.5
1.0
1.5
2.0
n = −1.0
n = −1.5
n = −2.0
M_c = 1 TeV
M_c = 100 GeV
δθ_μ (degrees)
t/T

Fig. 3

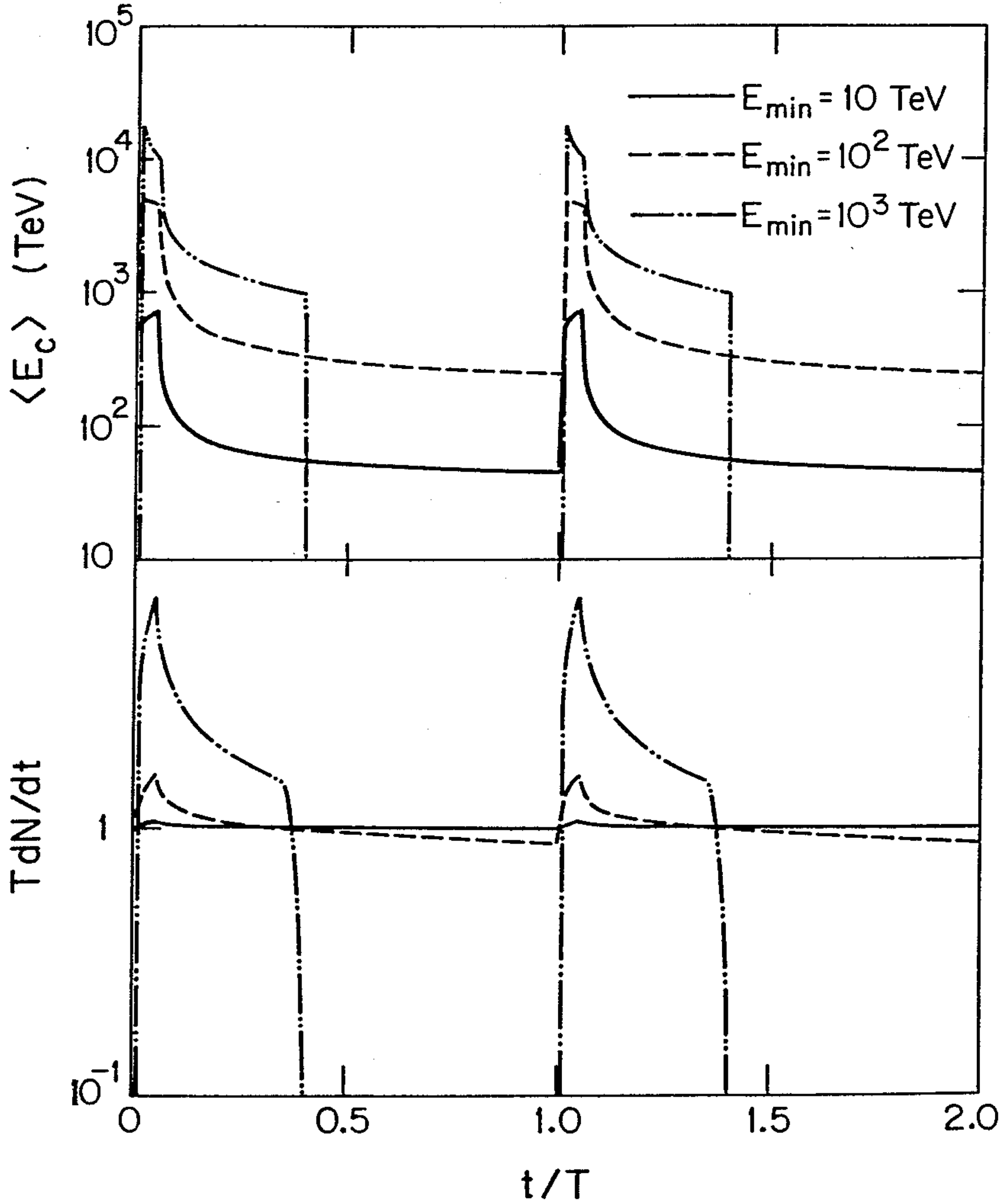
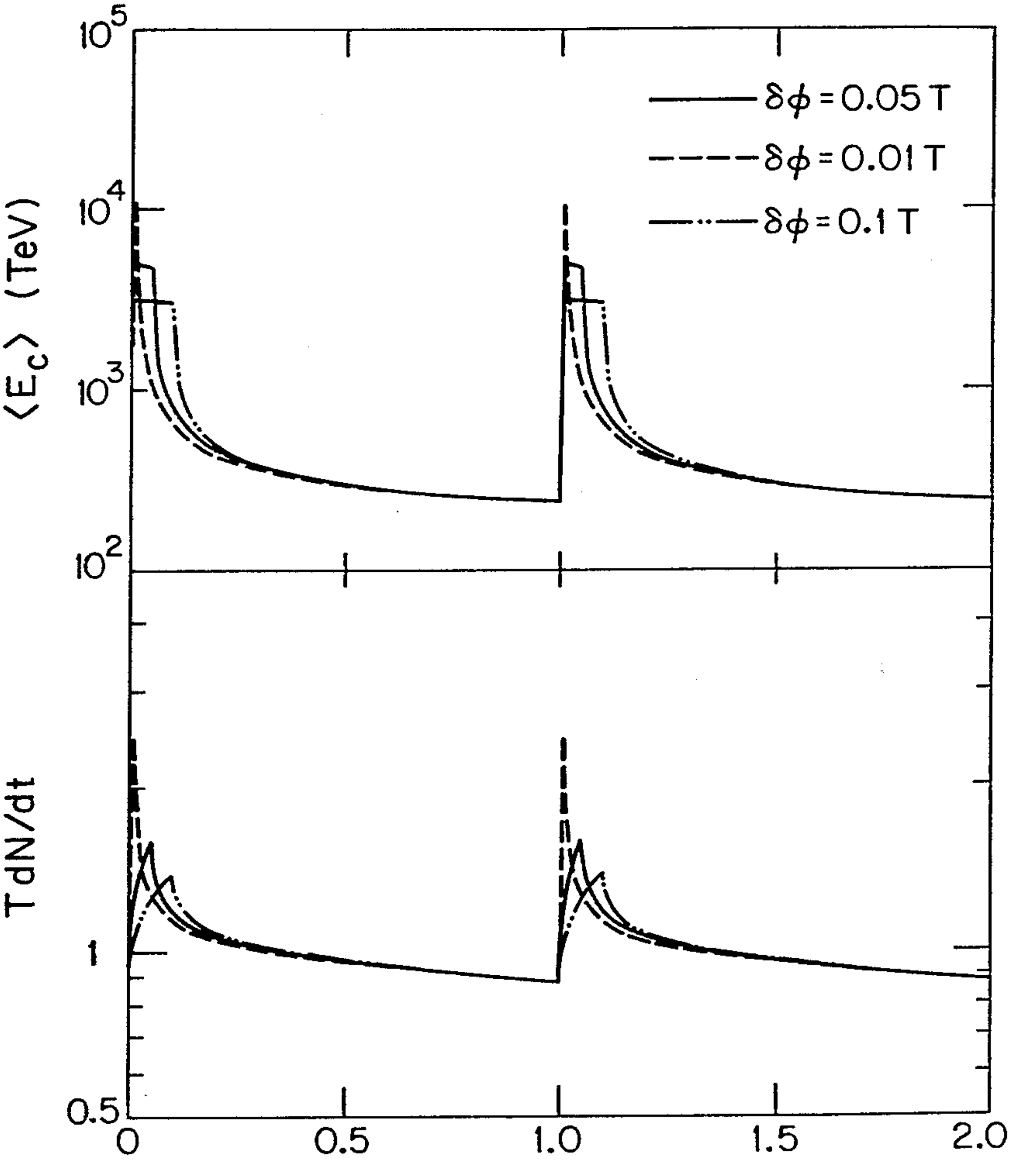

E_{min} = 10 TeV
E_{min} = 10^2 TeV
E_{min} = 10^3 TeV
$\langle E_c \rangle$ (TeV)
10^5
10^4
10^3
10^2
10
TdN/dt
1
10^{-1}
0
0.5
1.0
1.5
2.0
t/T

Fig. 4.a



10^5
10^4
10^3
10^2
δφ = 0.05 T
δφ = 0.01 T
δφ = 0.1 T
⟨E$_c$⟩ (TeV)
T dN/dt
1
0.5
0
0.5
1.0
1.5
2.0
t/T

Fig. 4.b