RAPID COMMUNICATIONS

PHYSICAL REVIEW D VOLUME 44, NUMBER 3 1 AUGUST 1991

Multiplicity dependence of transverse-momentum spectra in hadron-hadron collisions and e^+e^- annihilations

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(Received 9 April 1991)

We argue that the observed, but still not fully comprehended, increase of the mean transverse momentum $\langle p_T \rangle$ with the number of charged particles n_{ch} in high-energy hadron-hadron collisions should be also observed in e^+e^- annihilations into hadrons. Since no such data are available, we study the correlation of $\langle p_T \rangle$ and n_{ch} using the Lund Monte Carlo model. The magnitude of the correlation increases much faster with energy for e^+e^- annihilations than in hadronic collisions showing that these last processes cannot be treated as simple superpositions of more elementary e^+e^- reactions.

The processes of e^+e^- annihilations into hadrons are regarded as the simplest and cleanest examples of multihadronic production processes. Usually they provide a first testing ground for new hadronization models and often serve outright as elementary building blocks of more complicated processes initiated by hadrons [1].

There are also repeated attempts to obtain a simple and universal description of both e^+e^- and hadronic interactions. They include the energy dependence of mean charged-particle multiplicities $\langle n_{ch}(s) \rangle$ [2,3] or multiplicity distributions $P(n_{ch};s)$ [4–6] as well as the combination of $\langle n_{ch}(s) \rangle$, the rapidity plateau height $(1/\sigma)d\sigma(s)/dy|_{y=0}$, and the mean transverse momenta $\langle p_T(s) \rangle$ together [7]. The necessary link between e^+e^- and hadronic interactions is then provided either by a geometrical picture of hadrons (at each impact parameter there is an e^+e^--like process) [5] or by the leading particles (which take away a fraction of energy in hadronic reactions; the remaining part is then used in an e^+e^--like process) [2–4,6]. In Ref. [7] this link is provided by the QCD-inspired conjecture that multiparticle production in low-momentum-transfer hadronic collisions is entirely due to gluon bremsstrahlung off highly virtual quarks of mass $Q^2 = A\sqrt{s}$. This leads to a new and universal scaling law unifying both types of processes.

In this Rapid Communication we would like to bring attention to the existence of yet another simple but very informative correlation, namely, $\langle p_T(s) \rangle$ vs n_{ch} (or charged-particle density $\Delta n_{ch}/\Delta y$ in the central rapidity interval). The observed increase of $\langle p_T \rangle$ with $\Delta n_{ch}/\Delta y$ and, especially, the distinct growth of this effect with the energy of the reaction observed in different hadronic experiments [8–13] is still not fully understood. The explanations put forth so far attribute it to one of the following mechanisms: (a) collective behavior of hadronic (gluonic) matter [14–16] (i.e., classify it as a manifestation of *nonperturbative* QCD phenomenon); or (b) gradual switching on of the hard component of the collision process [17–19] (subject to *perturbative* QCD description).

In thermodynamical models [14] of hot hadronic matter this measurement provides information on the relation between its temperature T (connected to $\langle p_T \rangle$) and entropy density S (given by $\Delta n/\Delta y$) and therefore it could, in principle, yield information on a possible deconfinement phase transition from a state of hadronic matter to a quark-gluon plasma state. But such behavior also can be obtained in a number of different approaches ranging from the statistical model with inelasticity [15], pure geometrical model with varying temperature [16], geometrical branching model with (mini)jets [17], explicit two-component model (soft plus hard) [18], up to the dual parton model with a semihard component [19]. This means then that the true source of this effect is still not clear.

We would like to point out that in certain models the observation of multiplicity dependence of $\langle p_T \rangle$ in hadronic collisions leads to very natural expectation of similar phenomenon in e^+e^- annihilations at high energies. A good understanding of hadronic production in e^+e^- annihilations in terms of QCD-inspired Monte Carlo models [20,21] should then throw some light on the origin of this phenomenon.

Since no data on the multiplicity dependence of $\langle p_T \rangle$ in e^+e^- annihilations are available up to now [22] we shall study this effect using events generated by the JETSET Lund Monte Carlo program [20]. It was shown experimentally that the shower version of this program is very successful in the description of hadronic production in e^+e^- annihilations at both the lower (SLAC PEP, DESY PETRA) [23] and the higher (CERN LEP) [24] energies. We shall study the effect both in the event plane, $\langle p_T \rangle_{in}$, and in the direction perpendicular to the event plane, $\langle p_T \rangle_{out}$. Both directions are defined in the standard way using the second-rank tensor constructed from the final charged hadrons momenta [23]. For the comparison with the hadronic reactions we shall also use $\langle p_T \rangle = (\langle p_T \rangle_{in}^2 + \langle p_T \rangle_{out}^2)^{1/2}$.

In Fig. 1 the dependence of $\langle p_T \rangle_{in}$ and $\langle p_T \rangle_{out}$ on charged-particle multiplicities is shown for five c.m. energies. The observed effect is qualitatively similar to that observed in hadron collisions: at low energies we observe the negative correlation of $\langle p_T \rangle_{in}$ and $\langle p_T \rangle_{out}$ with n_{ch} probably due to the limited phase space available. In the intermediate-energy region (PEP, PETRA) there is no correlation between $\langle p_T \rangle_{in}$ and n_{ch} and only a very weak positive correlation for $\langle p_T \rangle_{out}$. At the KEK TRISTAN

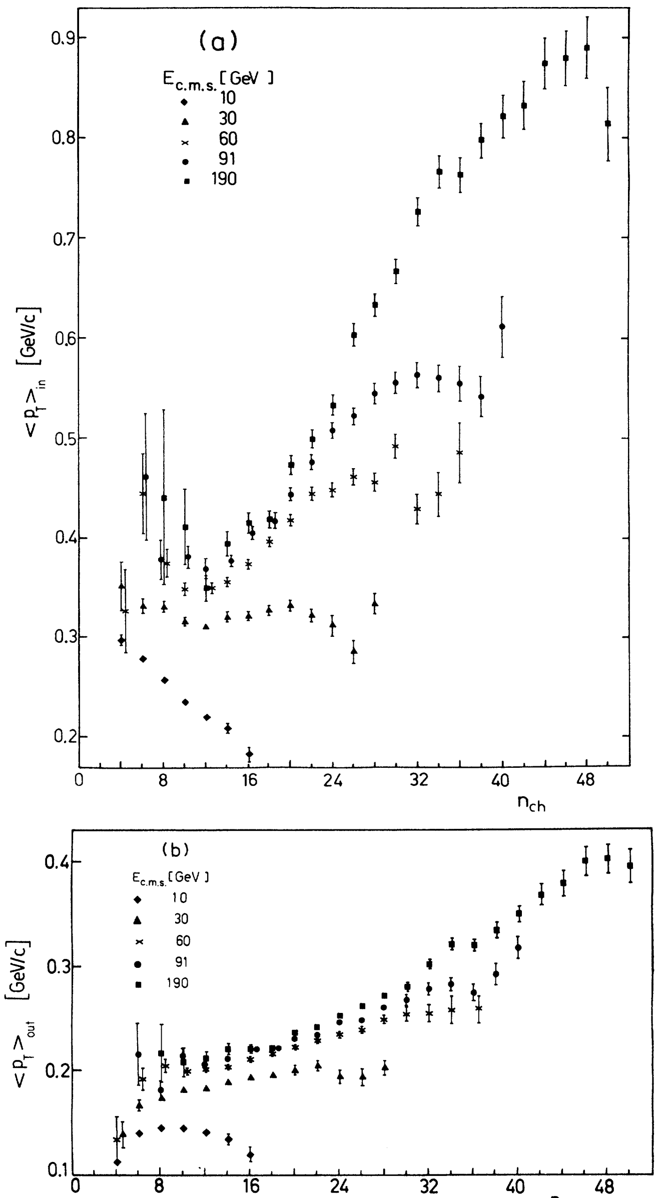

FIG. 1. Predictions of the Lund Monte Carlo parton shower model for the dependence of average transverse momenta (a) in the event plane, $\langle p_T \rangle_{in}$, and (b) in the direction perpendicular to the event plane, $\langle p_T \rangle_{out}$, on charged-particle multiplicities in e^+e^- annihilations into hadrons at five c.m.s. energies.

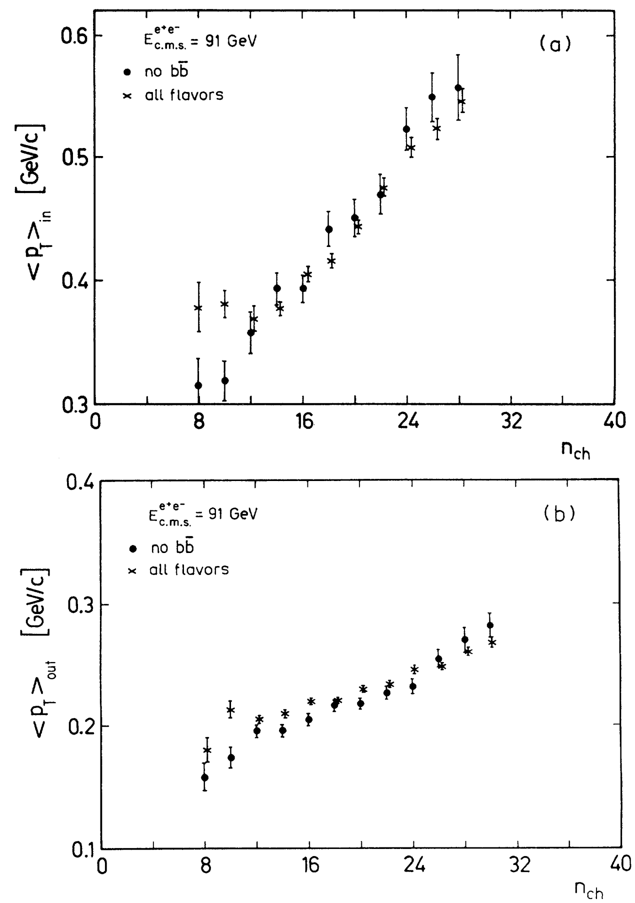

FIG. 2. Predictions of the Lund Monte Carlo parton shower model for the dependence of average transverse momenta (a) in the event plane, $\langle p_T \rangle_{in}$, and (b) in the direction perpendicular to the event plane, $\langle p_T \rangle_{out}$, on charged-particle multiplicities in e^+e^- annihilations into hadrons at $\sqrt{s}=91$ GeV. The sample of events generated for all five flavors is compared with the sample with beauty quarks and antiquarks removed.

energy range we observe the positive correlation both for $\langle p_T \rangle_{in}$ and $\langle p_T \rangle_{out}$ and the magnitude of the correlation increases quickly with energy.

Two mechanisms in high-energy e^+e^- annihilations could lead naturally to the positive $\langle p_T \rangle$ and n_{ch} correlations: heavy-quark production and gluon radiation. In Fig. 2 we compare, therefore, the magnitude of the effect for events with beauty-quark production $b\bar{b}$ removed from the Monte Carlo sample at $\sqrt{s}=91$ GeV with those from the full Monte Carlo sample. Since no differences of the $\langle p_T \rangle_{in}$ and $\langle p_T \rangle_{out}$ behavior in both samples are observed, we conclude that the heavy-quark production does not contribute substantially to the observed increase of $\langle p_T \rangle_{in}$ and $\langle p_T \rangle_{out}$. To study the influence of gluon radiation we introduce the matrix element version of the Lund Monte Carlo program [25]. Although the description of e^+e^- data by this version of the Lund program is less successful it allows gradual switching on of hard-gluon radiation. In Figs. 3(a) and 3(b) only a very slight difference is observed for the two versions of the Lund Monte Carlo at the PEP/PETRA energies. This difference is enhanced for LEP energies, as shown in Figs. 3(c) and 3(d). The Lund matrix element version shows stronger dependence of $\langle p_T \rangle_{in}$ on n_{ch} than the Lund parton shower model and the main contribution to the observed correlation comes from single-hard-gluon radiation as shown by the dramatic difference between $\langle p_T \rangle_{in}$ behavior for two-jet $q\bar{q}$ events and three-jet $q\bar{q}g$ events. The second-order corrections (radiation of the second gluon or $q\bar{q}$ pair) do not change the magnitude of the effect. A different picture can be observed for $\langle p_T \rangle_{out}$. Here the main contribution to the ob-

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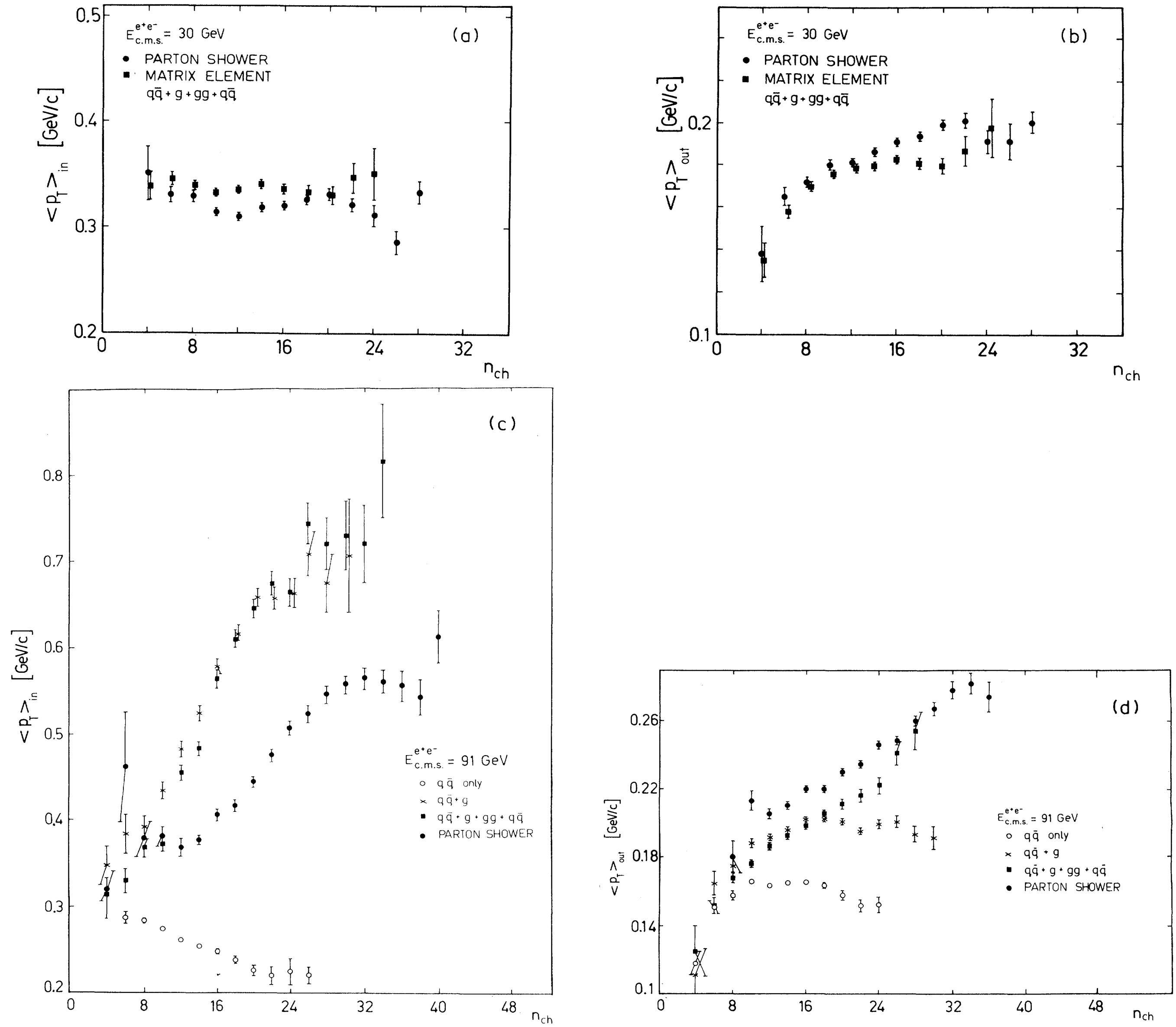

FIG. 3. The comparison of the Lund Monte Carlo parton shower model results with the results of the different versions of the Lund matrix element model for the dependence of the average transverse momenta in the event plane, $\langle p_T \rangle_{in}$, and in the direction perpendicular to the event plane, $\langle p_T \rangle_{out}$, on charged-particle multiplicities in e^+e^- annihilations into hadrons at $\sqrt{s}=30$ GeV and $\sqrt{s}=91$ GeV. The three versions of the Lund matrix element model at $\sqrt{s}=91$ GeV correspond to zero ($q\bar{q}$ only), first (one gluon radiation), and second (two gluons and/or additional $q\bar{q}$ pairs) order QCD corrections.

served increase of $\langle p_T \rangle_{out}$ is slightly higher for the parton shower version probably due to the production of additional soft gluons. We conclude, then, that the study of the correlations of $\langle p_T \rangle_{in}$ and $\langle p_T \rangle_{out}$ with n_{ch} provides a very sensitive test of the models for hadron production in e^+e^- annihilations at LEP energies.

With the results presented above we would like to look back into hh collisions from the perspective of more elementary e^+e^- processes in the way mentioned before. The natural picture for this purpose is the one inspired by the QCD idea of radiation off highly virtual quarks presented in Ref. [7]. In a nutshell, it is conjectured there that in the low-momentum-transfer hh collisions at c.m. energy $\sqrt{s}$ (valence) quarks go off mass shell in a similar fashion as in e^+e^- annihilation processes attaining large virtual masses $Q^2=A\sqrt{s}$ with $A=5$–10 GeV—an energy-independent constant. The same mechanism of perturbative evolution of partons followed by universal hadronization should then be responsible for hadron production both in e^+e^- (with Q^2) and in pp (with $A\sqrt{s}$) processes. The fits to $\langle n_{ch} \rangle$, $(1/\sigma)d\sigma/dy|_{y=0}$, and $\langle p_T^2 \rangle$ are roughly consistent with this conjecture of a new scaling law in multihadronic production processes [7]. Unfortunately, as it is obvious from the comparison of the e^+e^- results and $\bar{p}p$ data in Fig. 4, this simple conjecture breaks down for the $\langle p_T \rangle$ and n_{ch} correlations. Two characteristic features are apparent there instead.

(i) The qualitative similarity of the effect in both types of processes, namely the *increase* of $\langle p_T \rangle$ with n_{ch} and with the energy. Because of the much smaller multiplicities in e^+e^- annihilations than in hadronic collisions the comparison can be made only for the limited range in n_{ch}.

(ii) The much faster growth with energy of the effect for e^+e^- annihilation (together with its possible saturation for hh reactions at Fermilab Tevatron energies).

If confirmed experimentally in e^+e^- annihilations and at Tevatron and higher energies for hh collisions, these features will cause the following dilemma. We know that in e^+e^- processes the effect is due to the gluonic bremsstrahlung off highly virtual quarks. From what we said above we expect that sooner or later (either already in soft collisions [7] or at least in hard or semihard ones) such highly virtual quarks should occur also in hh reactions. We would expect then that $\langle p_T \rangle$ vs n_{ch} correlations should increase there as well. Any hint of saturation of this effect would be then of utmost interest as it could suggest some highly collective (i.e., nonperturbative) mechanism at work.

Coming back to the conjecture of Ref. [7], it seems that one could reconcile e^+e^- and pp results only with much smaller and decreasing with energy parameter A in [7]. In fact the energy excitations of elementary strings in both FRITIOF [26] and dual topological unitarization [27] models of soft hadronic processes (widely regarded as the most successful ones) both follow the $1/M$ rule [28] (where M = mass or mean mass of a string which itself is assumed to follow e^+e^- hadronization pattern); i.e., they are much milder than considered here (very roughly, A is consistent with $A \simeq \text{const}/\ln s$ in such a case) [29]. It means also that the two other methods of unifying e^+e^- and hh processes (with the notion of leading particles [2–4,6] and geometrical picture [5]) would fail as well in tempering the rapid growth of $\langle p_T \rangle$ vs $\Delta n_{ch}/\Delta y$ with energy in e^+e^- to much milder in $\bar{p}p$. The new LEP data for these correlations could thus provide a decisive test for the idea of e^+e^--hh universality.

If one accepts that our results show that such an universality, in fact, does not exist (and was only accidental if tested only on the simplest observables and in a limited energy span) the question arises, why is it so? In our opinion the reason is that whereas in e^+e^- reactions we have initially only off-mass-shell quarks from which later on develops a mainly gluonic shower, the hh processes involve from the very beginning a large fraction of a preexisting gluonic component. Its momentum distribution is of the $1/P$ type (i.e., energy is traded off more easily for the number of partons than for their energy) resulting in much milder interactions. Another factor resulting in a similar conjecture is the obvious space-time difference of both processes: e^+e^- annihilation is highly localized initially to the $1/Q^2$ region, whereas in hadronic reactions such a localization is secured, if at all, only for the transverse dimensions of the order of $1/m_\pi$ (m_π = pion mass). The different properties of these two kinds of jets were, in our opinion, already observed in deep-inelastic μN scattering [30]. It turns out that $\langle p_T \rangle$ increases there with the hadronic energy W in the current (quark) jet (forward hemisphere), whereas in the target jet (i.e., spectator diquark plus all glue going into the backward hemisphere) $\langle p_T \rangle$ is almost W independent. It would be extremely interesting to see the corresponding $\langle p_T \rangle$ vs n_{ch} correlations for these two kinds of jets.

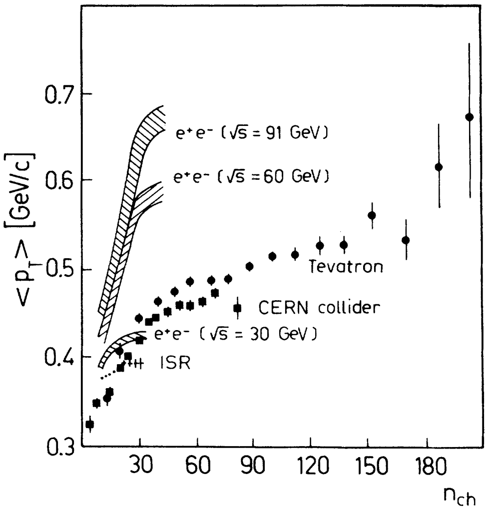

FIG. 4. The comparison of the dependence of the average transverse momenta on charged-particle multiplicities at the CERN ISR ($\sqrt{s}$ = 63 GeV [9]), the CERN collider ($\sqrt{s}$ = 540 GeV [10]), and the Fermilab Tevatron ($\sqrt{s}$ = 1800 GeV [12]) with the predictions of the Lund Monte Carlo parton shower model for e^+e^- annihilations into hadrons at three c.m.s. energies $\sqrt{s}$ = 30, 60, and 91 GeV, where $\langle p_T \rangle = (\langle p_T \rangle_{in}^2 + \langle p_T \rangle_{out}^2)^{1/2}$.

To summarize, we would like to stress once more that the correlations of $\langle p_T \rangle$ and n_{ch} provide a very important test for the multiparticle production models both in e^+e^- and hh collisions. They should therefore be measured not only in hadronic but also in e^+e^- annihilation processes and deep-inelastic scattering at all available energies.

We would like to thank Professor S. Pokorski for very useful and illuminating discussions.

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