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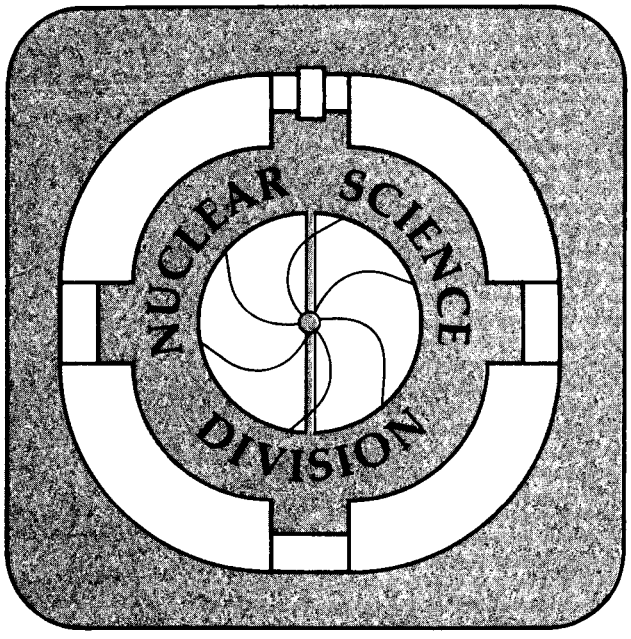
Transverse Flow due to Minijets in $p\bar{p}$ Collisions at $\sqrt{s}$ = 1.8 TeV

X.-N. Wang and M. Gyulassy

February 1992

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Transverse Flow due to Minijets in $p\bar{p}$ Collisions at $\sqrt{s}$=1.8 TeV

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Abstract

The multiplicity and flavor dependence of average transverse momentum of charged particles produced in high energy pp and $p\bar{p}$ collisions is studied in a PQCD inspired model. The experimentally observed transverse flow effect at $\sqrt{s} = 1.8$ TeV is naturally explained in the context of the fragmentation of multiple minijets which dominate the hadronic interaction mechanism at high collider energies.

PACS numbers: 13.87.Ce, 12.38.Mh, 13.85.Hd

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In hydrodynamic models transverse collective flow is usually generated from the expansion of the thermalized dense system[1]. Since all hadrons have the same flow velocity, heavy particles tend to have larger transverse momentum when they finally freeze out. If the average transverse momentum is plotted against the total multiplicity, it is anticipated that for heavy particles it will be larger and increase faster with the multiplicity than for light ones. Quite surprisingly, experiments on $p\bar{p}$ collisions at Tevatron Collider energy have recently reported observation of just this effect[2]. Lévai and Müller[3] have recently studied this reaction in a linearized transport theory. They found that there is no time for the baryons to equilibrate with the pions during the expansion of a hadronic fireball. They therefore suggested that a more novel explanation could be required to account for the apparent similarity of the flow velocities of the mesons and baryons. They noted that these observations could be understood if an equilibrated quark-gluon plasma (QGP) were formed in these collisions[4].

However, as also noted by Lévai and Müller, the common transverse flow of hadrons may also arise accidentally from the fragmentation of minijets. This is the possibility that we explore in detail here. We show that the observed transverse flow effect does in fact arise naturally from the fragmentation of multiple minijets. We show that not only the the correlation between the average transverse momentum and multiplicity but also the flavor dependence of detailed transverse momentum spectra can be quantitatively explained in terms of multiple minijet production at collider energies. Therefore, we conclude that the present data do not require the formation of a novel QGP state with subsequent hydrodynamic expansion as is popularly assumed[5]. As a prediction we also compute the energy dependence of the above phenomena between RHIC and Tevatron energies ($\sqrt{s} = 200 - 2000$ GeV).

Our focus in this letter is on the effects of the production and fragmentation of minijets which are simply the *non-equilibrium* moderate $p_T \gtrsim 2$ GeV/c partons

produced copiously at high energies in perturbative QCD (PQCD). The effects of multiple minijets in hadronic interactions have been studied extensively by many authors[6, 7, 8]. They provide an explanation for the increase of the total pp and $p\bar{p}$ cross sections with energy[6] and the violation of Koba-Nielsen-Olesen (KNO) scaling of charged multiplicity distributions[7, 8]. The general tendency for an increase of average transverse momentum with the total charged multiplicity has also been shown to arise naturally from minijets[9]. However, to study the detailed flavor and multiplicity dependence of $\langle p_T \rangle$ requires a more detailed investigation. In this paper, we address this problem using a newly developed (HIJING) Monte Carlo model[10] which combines low p_T string phenomenology with PQCD for high p_T processes. We have shown that multiple minijet production explains quantitatively the observed transverse "flow" behavior of produced hadrons in addition to many other observables over a wide energy range in high energy $p + \bar{p}(p)$ collisions[11]. In this letter, we extend those studies by comparing in detail the low and high multiplicity transverse momentum spectra and testing against data including recent Λ spectra. In addition we make predictions relevant to RHIC energies for these phenomena.

A detailed discussion of the HIJING Monte Carlo model and comparison with a wide variety of data in pp, pA and AA collisions was reported in Ref. [10, 11]. We recall here that it includes multiple minijet production with initial and final state radiation along the lines of the PYTHIA model[12] and with cross sections calculated within the eikonal formalism. In addition, soft beam jets are modeled by quark-diquark strings with gluon kinks along the lines of the DPM and FRITIOF models[13, 14]. HIJING also has a number of features such as the use of exact diffuse nuclear geometry, a model of the A dependence of nuclear structure functions, and a model of jet quenching due to final state interactions for applications to reactions involving nuclei.

Assuming independent multiple minijet production, the cross sections for no and

$j \geq 1$ number of jet productions with $p_T \geq p_0$ are,

$$\sigma_0 = \int d^2b[1 - e^{-\sigma_{soft}T_N(b,s)}]e^{-\sigma_{jet}T_N(b,s)} , \quad (1)$$

$$\sigma_j = \int d^2b\frac{[\sigma_{jet}T_N(b,s)]^j}{j!}e^{-\sigma_{jet}T_N(b,s)} . \quad (2)$$

Their sum gives rise to the total inelastic cross section σ_{in}. In the above equations, $\sigma_{jet}(p_0)$ is the total inclusive jet cross section with $p_T \geq p_0$ calculated via PQCD, σ_{soft} is the phenomenological inclusive cross section for soft interactions and $T_N(b,s)$ is the partonic overlap function between two nucleons at impact parameter b which we approximate by using the Fourier transform of a dipole form factor as the partonic density for each nucleon[8].

Once the interaction cross section and the number of jets produced at given impact parameters are determined as the above, we use the PYTHIA Monte Carlo program to determine their kinetic variables, including the initial and final state radiations associated with each hard scattering. The soft interactions are modeled by two-string excitation. A gluon jet is represented by a kink in one of the beam diquark-quark strings. The final hadronization stage is treated by the Lund JETSET7.2 model[15]. We emphasize here two important parameters of the model (see [10] for a detailed discussion). As in many other models which attempt to merge low and high p_T dynamics, we introduce a p_T cutoff scale p_0, which we regard as a model dependent phenomenological parameter separating PQCD at high p_T from the nonperturbative low p_T regime. Our guideline for choosing a value for p_0 is that it should be much larger than $\Lambda_{QCD} \sim 200$ MeV/c in order to apply PQCD but low enough to permit the simplest possible model to parameterize the nonperturbative dynamics. Choosing $p_0 = 2$ GeV/c allows us to use a *constant* $\sigma_{soft} = 57$ mb in an eikonal formalism consistent with the observed energy dependence of the total, elastic, and inelastic cross sections in pp or $p\bar{p}$ collisions[8, 11]. With these parameters, we also find that the simplest possible two-string model for soft interactions suffices to parameterize

the nonperturbative dynamics at low p_T.

A sytematic comparison[11] with data on pp and $p\bar{p}$ in a wide energy range, $\sqrt{s}$ =50–1800 GeV revealed that minijet production and fragmentation as implemented in the HIJING model provides a *simultaneous and consistent* explanation of the energy dependence of the central rapidity density, moderate p_T inclusive spectra, two particle correlation functions, and violation of Koba-Nielsen-Olesen (KNO) scaling. These global systematics provide in our opinion the strongest phenomenological evidence to date for the existence and importance of minijet dynamics at collider energies.

We turn now to the expected correlations in this model between the average transverse momenta and multiplicity for different hadronic species. Shown in Fig. 1 are our calculation (solid lines) and the experimental data on the p_T spectra of pions, kaons, antiprotons, and lambdas in the central region of $p\bar{p}$ collisions at $\sqrt{s}$ =1800 GeV. The data are from Ref. [2, 19] and are normalized to the number of particles in the specified rapidity region. We see that for heavy particles like lambdas and antiprotons, the distributions are flatter at large p_T and tend to saturate faster at small p_T. This leads to larger $\langle p_T \rangle$ for heavy particles as well as to the increase of K/π and $\bar{p}/\pi$ ratio with p_T[11]. We also show as dashed lines (with one overall normalization factor to facilitate comparison) the p_T spectra in those events with $n_{ch}(|\eta| < 3.25) > 50$. It is apparent that the spectra have higher large p_T tails for large n_{ch} events leading to the increased $\langle p_T \rangle$. From the same events generated by HIJING we can also study the correlation between $\langle p_T \rangle$ and the total charged multiplicity n_{ch} for different hadrons. The result is shown for pions, kaons, and antiprotons (from bottom to top) in Fig. 2 as solid lines. The average multiplicity density $\langle dn_{ch}/d\eta \rangle$ is calculated as $n_{ch}(|\eta| < \Delta\eta)$ divided by $2\Delta\eta$. The average p_T is obtained by applying the same procedure as used in the experiment[2] in which the p_T distributions are first fitted with parametrizations (power law $a(p_T + b)^{-n}$ for pions and exponential

$\beta \exp(-\alpha p_T)$ for kaons and antiprotons) and then the fitted parameters are used to calculate $\langle p_T \rangle$ in the restricted range $0 < p_T < 1.5$ GeV/c. For all hadrons, $\langle p_T \rangle$ increases with n_{ch}. However, as we noted in Ref. [11], the extrapolated values of $\langle p_T \rangle$ depend very strongly on the fitting procedure used in the experimental analysis. The calculated distributions in Fig. 1 all saturate at small p_T. This is inconsistent with the small p_T behavior of the parameterizations used in Ref.[2] though quite consistent with measured distributions. The only exception is the K distribution that does not appear to turn over for $p_T < 0.5$ GeV/c as expected in our calculation. This discrepancy may also be related to the kaon enhancement in large multiplicity events reported in [2] which is not accounted for by our calculation. Obviously, it would be important to check the predicted form of the low p_T distributions for all flavors experimentally. Such detailed comparisons could shed light on possible limitations of the present low p_T phenomenology or of the hadronization scheme of minijets employed in HIJING. Nevertheless, the data in Fig. 1 and its reduction to Fig. 2 is on the whole quite consistent with the flavor and multiplicity dependence expected due to multiple minijets.

We also show as dashed lines in Fig. 2 our calculated results for pp collisions at RHIC energy, $\sqrt{s} = 200$ GeV. They are similar to the results at $\sqrt{s} = 1.8$ TeV, except that pions have lower saturated value of $\langle p_T \rangle$ at RHIC energy. Since pions are the dominant produced particles, the high multiplicity $\langle p_T \rangle$ for all charged hadrons at $\sqrt{s} = 200$ GeV is smaller than at $\sqrt{s} = 1.8$ TeV.

In a model with multiple minijet production, it is easy to understand why $\langle p_T \rangle$ increases with n_{ch}. If we decompose the multiplicity distribution into different contributions from events with different number of minijets, we find[8, 11] that large multiplicity events are dominated by multiple minijet production while low multiplicity events are dominated by those of no jet production. At $\sqrt{s} = 1.8$ TeV, the average number of individual minijets in $p\bar{p}$ is only about two, but on rare occasions

up to ten partons with $p_T > 2$ GeV/c are produced over the whole rapidity interval. In this sense, the produced nonequilibrium partonic system is quite tenuous in $p\bar{p}$ collisions. Nevertheless, those few partons are enough to explain the increase of the average transverse momentum with n_{ch}. In order to understand the different behavior of the correlation between $\langle p_T \rangle$ and n_{ch} for different particles, we recall that the jet fragmentation functions for heavy hadrons tend to be harder as measured in e^+e^- annihilation experiments[20]. Therefore, heavy hadrons from jet fragmentation carry larger transverse momentum than the light hadrons in pp or $p\bar{p}$ collisions as well. This leads naturally to the larger slopes of $\langle p_T \rangle$ vs n_{ch} correlation for heavier particles. Since the mass difference between Λ and $\bar{p}$ is very small, we find that n_{ch} dependence of $\langle p_T \rangle$ for the two are almost the same in agreement with the recent data[19].

In conclusion, we emphasized here that multiple minijet production and fragmentation provide a natural explanation for the apparent transverse flow phenomena observed in $p\bar{p}$ reactions without having to resort novel quark-gluon plasma (QGP) mechanisms. In addition, we made predictions for RHIC energies to demonstrate that this effect is likely to be an important source of background for this proposed signatures of QGP in heavy ion collisions. We note that the minijet explanation can and should be further tested[21] experimentally via two-particle correlations vs the azimuthal angle ϕ. Since minijets tend to be produced as back-to-back pairs, large p_T particles can be expected to have enhanced correlations not only in the backward region ($\Delta\phi = \pi$) but also in the forward region ($\Delta\phi = 0$). Such tests are needed because at least one of the features of the present data remains unexplained by our model, namely, the apparent low p_T excess of kaons as seen in Fig.1. This may point to a limitation of the present low p_T phenomenology or the hadronization model of minijets. This interface between soft and hard QCD dynamics remains one of the challenging frontiers for future investigation.

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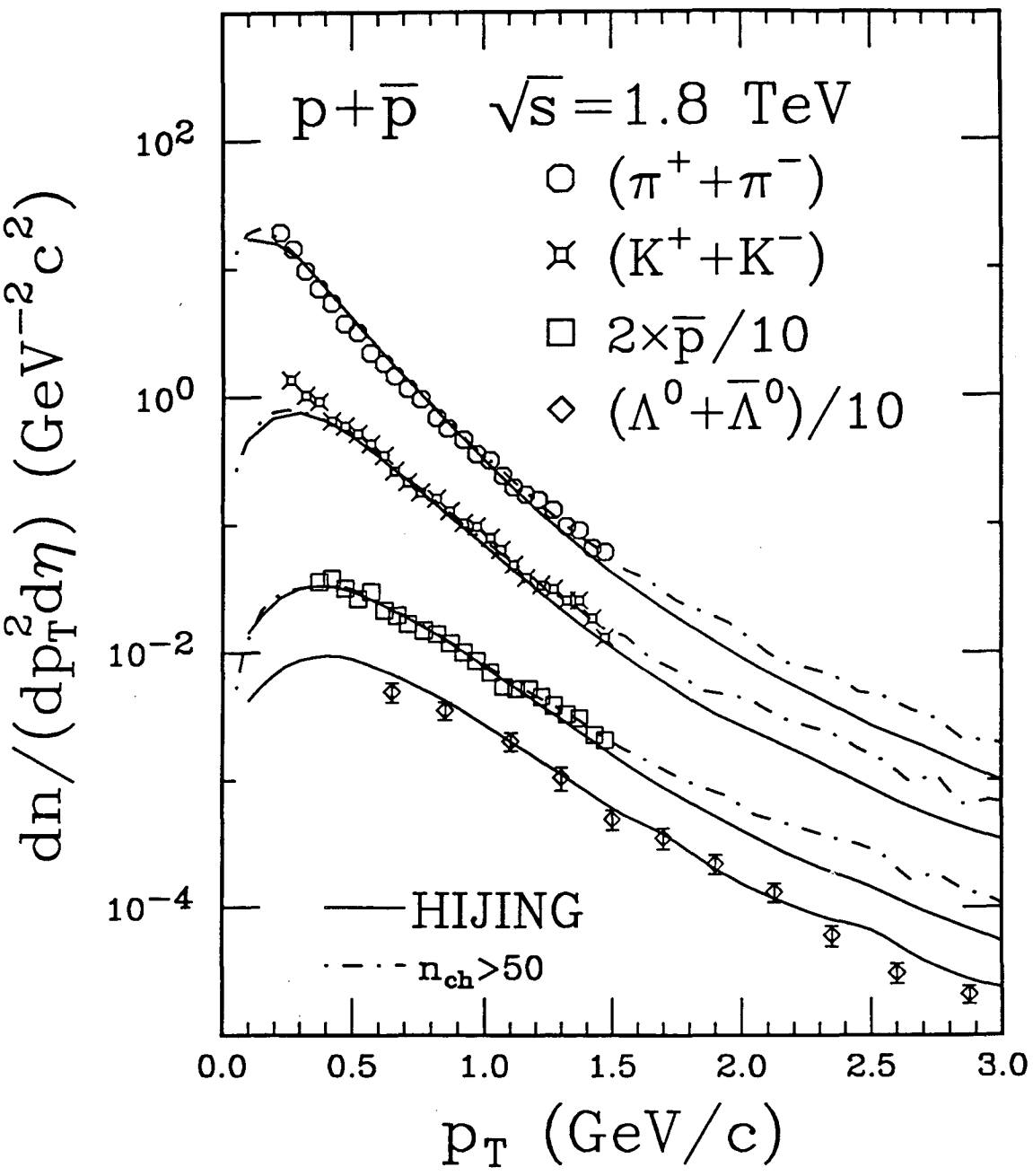
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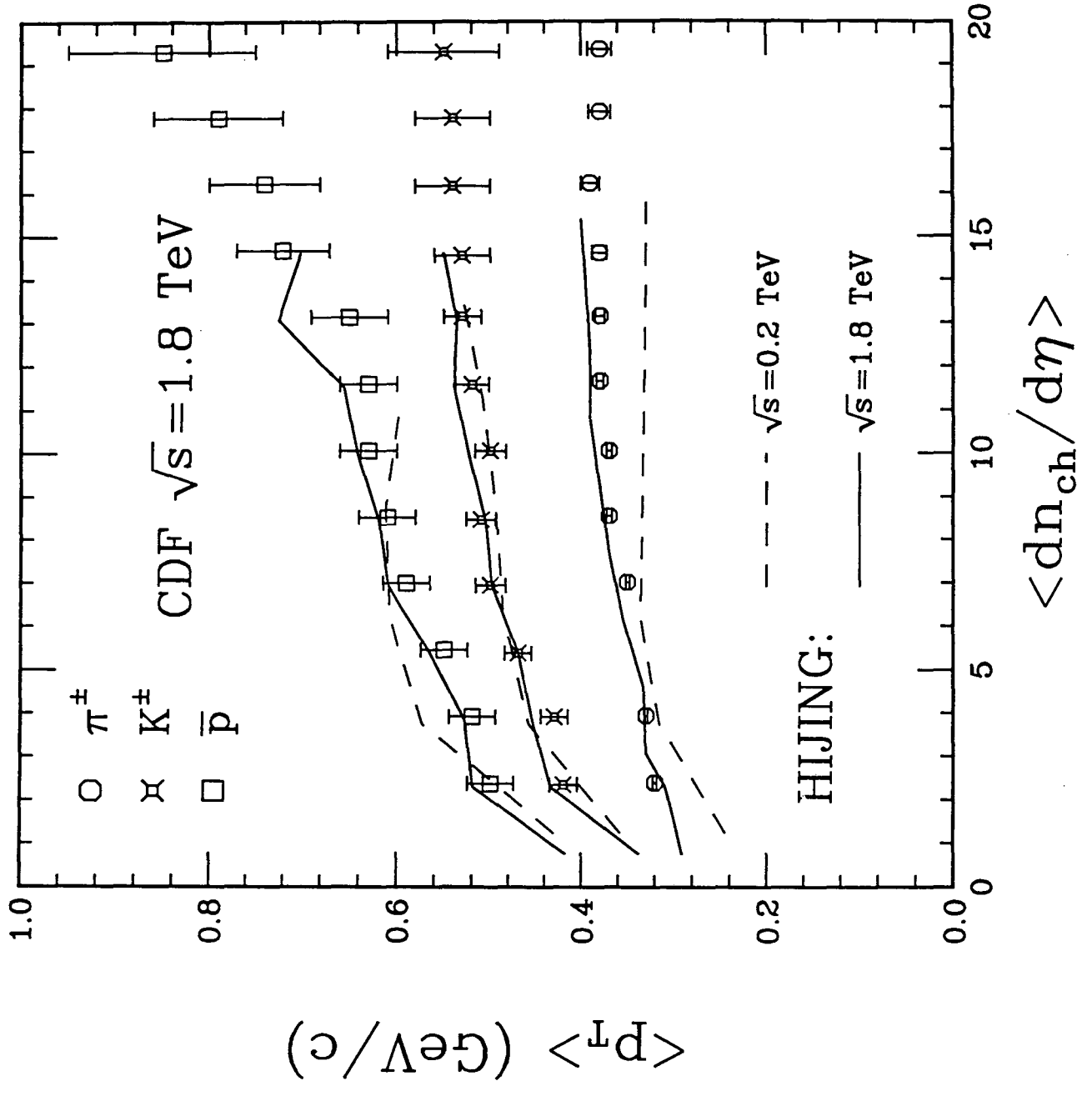
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Figure Captions

Fig. 1 The p_T spectra of pions, kaons, anti-protons and lambdas ($-0.36 < \eta < 1.0$) in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV as calculated by HIJING model (solid lines). The data are from Ref. [2, 19]. Dashed lines are for events with $n_{ch}(|\eta| < 3.25) > 50$.

Fig. 2 $\langle p_T \rangle$ of pions, kaons, and anti-protons (from bottom to top) in $-0.36 < \eta < 1.0$ versus the average charged multiplicity density $dn_{ch}/d\eta$ in $|\eta| < 3.25$. The HIJING results are obtained by fitting the calculated p_T distributions in Fig.1 with the same simplified parametric functions in the restricted p_T intervals as done experimentally in Ref.[2] to obtain the data points. The dashed lines are for pp collisions at $\sqrt{s} = 200$ GeV.


p+p̄ √s=1.8 TeV
(π⁺+π⁻)
(K⁺+K⁻)
2×p̄/10
(Λ⁰+Λ̄⁰)/10
HIJING
n_ch>50
dn/(dp_T²dη) (GeV⁻²c²)
p_T (GeV/c)
10²
10⁰
10⁻²
10⁻⁴
0.0
0.5
1.0
1.5
2.0
2.5
3.0


CDF $\sqrt{s}$=1.8 TeV
$\pi^{\pm}$
$K^{\pm}$
$\bar{p}$
HIJING:
$\sqrt{s}$=0.2 TeV
$\sqrt{s}$=1.8 TeV
$\langle p_T \rangle$ (GeV/c)
$\langle dn_{ch}/d\eta \rangle$
0.0
0.2
0.4
0.6
0.8
1.0
0
5
10
15
20

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