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Nuclear Transparency in 15 AGeV Si+Au Reactions?*

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Abstract

Recent data on central Si+Au collisions at 15 AGeV are shown to imply an unexpected high degree of nuclear transparency. The paucity of observed midrapidity protons and pions suggests that up to one half of the projectile nucleons may lose less than one unit of rapidity after traversing 5-10 fm of nuclear matter.

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The first detailed spectra of $p, \pi^{\pm}$, and $K^{\pm}$ from central $Si + Au$ reactions 14.6 AGeV/c have been reported recently by the E802 collaboration[1] at the AGS. These data are of interest in connection with estimating the nuclear stopping power and assessing whether high baryon density matter can be produced in nuclear collisions. Previous indirect data on transverse energy spectra and leading baryon spectra have been interpreted[2] as evidence for a large amount of nuclear stopping in such reactions. However, in Ref.[3] we noted that the paucity of pions and the shape of the proton rapidity distribution measured by E802[1] were more indicative of nuclear transparency at least for light ion induced reactions. Our aim in this letter is to analyze the new data in detail and to estimate the nuclear stopping power in this reaction using a multicomponent firestreak model.

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The data that we focus on are shown in Figs. 1-3. The p, π^-, $K^\pm$ rapidity densities in central Si+Au collisions are shown in the upper panels. The lower panels show the transverse momentum slope parameter, $T(y)$, obtained by fitting the invariant distributions at each rapidity with $\exp(-m_\perp/T(y))$. The curves and histograms show the results based on the models discussed below. Also shown are *extrapolations* of the E814 leading neutron data[2] from a 0.8 degree cone assuming the above $m_\perp$ distribution with T varied between 0.1 to 0.2 GeV for their $E_T > 13$ GeV trigger.

Based on $p + A \rightarrow p + X$ data at energies $E_{lab} \gtrsim 100$ GeV[4], it was expected that in central $Si + Au$ reactions the average rapidity of projectile baryons would be shifted downward by $\Delta y \sim 2.5$ while the rapidity of participant target baryons should be shifted upward by $\Delta y \gtrsim 1$. Therefore a substantial amount of equilibration between projectile and target baryons was expected to occur at 15 AGeV where the total rapidity gap is only 3.5. We therefore compare the data first with the firestreak model[5]. The short dashed curves in Figs. 1 and 3 show the results obtained with a cut on impact parameters $b \leq 2.9$ fm. The severe discrepancy between the data and the calculated results is obvious. No reasonable variation of the freeze-out density was found to improve this situation. Also shown by the long dashed curves in Fig.1, are the results using the Landau hydrodynamic fireball of Ref.[2]. While the proton distribution is in agreement with the extrapolated E814 data, it fails to account for the ramp form of E802 proton data, the difference between the pion and proton slope parameters, and the absolute pion yield. In Ref.[6] a hydrochemical version of the fireball model was able to reproduce the pion and kaon spectra, but that model also failed to account for the form and magnitude of the observed proton distribution. It follows that if the E802 data are correct all such equilibrium models assuming complete nuclear stopping are ruled out by the absence of a peak of dN_p/dy near $y \sim 1.2$, the small value of $dN_p/dy \approx 7$ at $y \sim 2$, and the small number of π^- observed at mid rapidity.

We therefore consider next non-equilibrium dynamical models such as the multi-string Lund Fritiof Model[7]. In that model multiple interactions are assumed to excite baryon strings which fragment independently and without final state interac-

tions. Such phenomenological string models have been successful in accounting for many of the features of multiparticle production in $p + A$ and $B + A$ collisions at higher energies $E_{lab} > 60$ AGeV[8]. The histograms in Fig. 1 show the results from the ATTILA version[9] of the Fritiof model for this reaction for the same range of impact parameters. While the ramp form of the proton distribution is much better reproduced, the proton slopes are much smaller than observed. In addition, the π^- rapidity density is overpredicted by 70%. We note that RQMD string model[10] also overpredicts the pion rapidity density by 70%.

Having seen that the above simple equilibrium and nonequilibrium models for nuclear collision dynamics fail to reproduce the new data, we consider next a model independent fit in order to isolate possible causes for the discrepancies. In particular, this fit allows us to take into account all of the observed energy in longitudinal and transverse motion, pion production and kaon production. The measured transverse momentum distributions were fit with a form

$$dN_i/dyd^2p_\perp = \rho_i(y)\exp(-m_{i\perp}/T_i(y)) \quad . \tag{1}$$

where the slope parameters, $T_i(y)$, were parameterized by sums of Gaussians in rapidity. The data reported in [1] together with unpublished data from [11] were used to fix these slopes. The pion and kaon rapidity distributions were parameterized in terms of independent Gaussians. For the unobserved neutral mesons we assumed $\pi^0 = (\pi^+ + \pi^-)/2$, $K^0 = K^+$, and $\bar{K}^0 = K^-$. The nucleon rapidity distribution was taken to be parabolic in the region $0 < y < 3.0$ with a linearly dropping tail from $3.0 < y < 3.5$ and Gaussian tail $y < 0$. In the high rapidity region we allowed for an extra Gaussian distribution of baryons to test for nuclear transparency. For neutrons we assumed that $\rho_n(y) = 132/93\rho_p(y)$ to be on the safe side (i.e., allowing for larger unobserved neutral baryon energy than expected in the projectile fragmentation region). Total baryon conservation was enforced.

We found that without an extra, high rapidity, baryon contribution the total energy-momentum carried by nucleons and mesons integrated over all of phase space was (140 GeV, 165 GeV/c) less than the total initial energy-momentum ($E_0 = 594$

GeV, $P_0 = 409$ GeV/c). To take into account possible systematic errors introduced by extrapolations to unmeasured low $p_\perp$ regions and depletion of the proton yield due to composite fragment formation[1], we tried a fit to data enhanced by a factor 1.3 However, even with that enhancement the fit failed to account for (80 GeV, 93 GeV/c) of the incident energy-momentum!

Only by introducing an extra, high rapidity baryon contribution centered at $y = 2.75$ with an rms width $\Delta y = 0.25$ and containing approximately 11 of the 28 incident baryons were we finally able to account for all the incident momentum and energy to an accuracy of better than 1 GeV. This final fit is shown by the dot-dashed curves in Fig. 2 and 3. We have checked that neither the E_T nor the forward calorimeter data are sensitive to this unexpected baryon contribution in the region $2 < y < 3$. We emphasize that the energy contained in the observed transverse flow of baryons as well as in enhanced kaon production is taken into account by this fit. In addition our fit is conservative since we assumed that all the E802 rapidity densities must be multiplied by 1.3 due to systematic errors. From this analysis we conclude that the E802 spectrometer data are consistent with energy-momentum and baryon conservation only if a significant fraction of the projectile nucleons suffer less than one unit of rapidity shift after traversing $5 - 10$ fm of nuclear matter.

To estimate more quantitatively the nuclear stopping power implied by these data and to enable us to calculate the A and impact parameter dependences of the spectra, we developed a multicomponent firestreak model with enough flexibility to deal with many complex nonequilibrium features exhibited by the p, π, and K data. Instead of forming one fireball(streak) in each collision between rows of nucleons as in the conventional firestreak model, we allow each row-row collision to form up to four fireballs with different rapidities depending on the nuclear thicknesses involved. We found that four fireballs was the minimum necessary to reproduce all the features of the present data. While differing in detail, this model is similar to previous multi-component fireball and hydrodynamic models[12, 13]) which were introduced to take into account nuclear transparency.

In our model we assume that in a collision of two tubes of nuclear matter of

transverse area $\sigma_{in} = 30$ mb containing N_p and N_t nucleons, the total center of mass momentum P^* of both tubes is reduced by an amount proportional to the number of binary collisions, $N_p N_t$:

$$\Delta P^* = \delta p_z N_p N_t \ . \tag{2}$$

Here δp_z is the average longitudinal momentum loss per inelastic collision. Defining the effective nuclear thickness, z_i, via $N_i = \sigma_{in}\rho_0 z_i$, the momentum shift per baryon of the projectile (target) is thus assumed to increase linearly with the target (projectile) thickness. A measure of the nuclear stopping power is given by the stopping length

$$L_s = m_N \sinh((y_p - y_t)/2)/(\sigma_{in}\rho_0\delta p_z) \ , \tag{3}$$

where $y_p(y_t)$ is the rapidity of the projectile (target) tube. For symmetric collisions with $z_p = z_t = z$, the fractional momentum loss, $\Delta P^*/P^* = z/L_s$, increases linearly and reaches unity when $z = L_s$.

We found, however, that the above two fireball model of stopping could not reproduce the apparent peaking of $T_p(y)$ near $y \sim 1.5$ as indicated by preliminary E802 data[11]. We therefore allowed a fraction, f_s, of the baryons from both the projectile and target nucleon in each tube to stop completely in the tube-tube cm frame. This fraction was also assumed to increase with nuclear thickness as

$$f_s = (z_p z_t)^{1/2}/L'_s \ . \tag{4}$$

Incomplete nuclear stopping is thus modelled by three separate baryonic fireballs (for each row-row collision) with rapidity and baryon number controlled by two stopping lengths, L_s and L'_s.

The baryon transverse momentum distribution is controlled by the excitation energy per baryon, M^*, in each of these fireballs. In order to fit the preliminary $T_p(y)$ data[11], we enforce the constraints $M^* \leq M_1^* = 1.4$ GeV for the noncentral fireballs and $M_c^* \leq M_2^* = 1.85$ GeV for the central ones. Any excess energy is assumed to be taken up by a fourth central fireball with zero baryon content (the "meson" fireball). The baryon fireball freeze-out densities are all chosen to be $\rho_f = \rho_0 = 0.15\ fm^{-3}$, while the meson fireball freeze-out temperature is chosen to be 160 MeV. In addition,

to account for incomplete chemical equilibration of strange hadrons seen from Fig.3, we reduced the thermal contributions of all strange hadrons by a factor 1/4. These hybrid aspects of the model essentially mimic effects in the hydrochemical model[6] without the constraint of full nuclear stopping.

The solid lines in Figs. 2,3 show the results of this multicomponent model for $L_s = L'_s = 26$ fm ($\delta p_z = 0.22$ GeV/c). With these parameters we recover essentially the results of the (dash-dot) fit discussed earlier. In particular, this model also leads to a high rapidity projectile contribution centered around $y \approx 2.5$ as required by energy-momentum and baryon conservation. The rather large values of these stopping lengths are surprizing in view previous expectations based on $p+A$ at higher energies [4, 15]. Also with $L_s = 26$ fm, the fraction of projectile baryons in the central fireball is only $f_s \sim 1/3$ for $Si + Au$. This value is much less than deduced in [2] based on transverse energy and leading neutron data and unpublished high multiplicity selected E802 $dN_{ch}/d\eta$ data.

We comment finally on the difference between collective longitudinal hydrodynamic flow and nuclear transparency. In Ref.[2] it was suggested that Landau hydrodynamics could account for the nonisotropic angular distributions in the cm frame. However, the comparison between that model and the data in Fig. 1 shows that no single expanding source can account for the different maxima and shapes of those distributions. On the other hand, detailed one fluid hydrodynamic calculations[14] predict a nonsymmetric baryon distribution with a shoulder between $2 \lesssim y \lesssim 3$. In fact so much longitudinal collective baryon flow was predicted that the calculated pion yield falls significantly below the E802 data. It would be interesting to check if variations of the equation of state and the freeze-out condition could improve the agreement with data for this reaction. In principle only the A dependence of the particle spectra can differentiate between such novel nuclear shock effects from transparency. For example, one fluid hydrodynamics predicts[16] a sharp peak at mid rapidity for the proton distribution in central $Si + Al$, whereas our model predicts a minimum in that case.

We conclude that none of the present models which assume complete nuclear stop-

ping and none of the nonequilibrium string models are consistent with the new E802 data. If the normalization error of the new E802 data does not exceed 30%, then energy-momentum and baryon conservation alone require there to be an unexpected shoulder in the baryon spectrum in the region $2 < y < 3$. Our fits to the data in terms of a multicomponent firestreak model suggest surprisingly long stopping lengths, $L_s \approx 26$ fm. Because these results deviate so much from previous expectations and analyses of more indirect data, systematic measurements of the A and multiplicity dependence of dN_p/dy over the full rapidity region should be undertaken to cross check these data and establish if indeed nuclei are as transparent as the present data seem to indicate.

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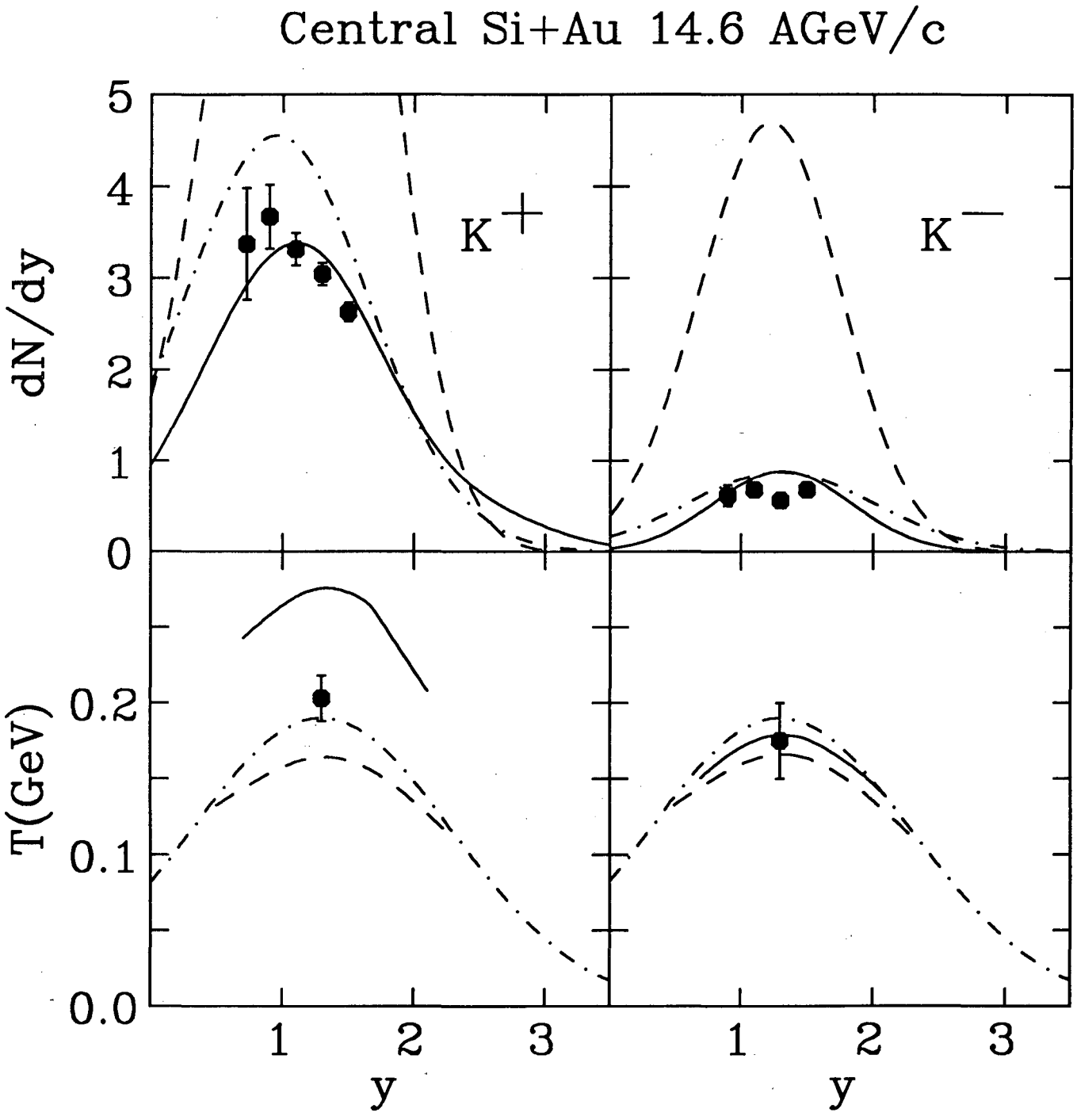
Figure Captions

Figure 1. The proton and π^- rapidity distributions and transverse mass slope parameters in central $Si + Au$ reactions[1] (solid dots). Short dashed curves and histograms show results from the firestreak[5] and Lund models[9], resp.. The long dashed curves show results form the Landau hydrodynamic model[2]. The extrapolated leading neutron data[2] are indicated by the crosses together with estimated extrapolation uncertainties.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dN/dy
T(GeV)
K+
K−
y
y
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2
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4
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0.1
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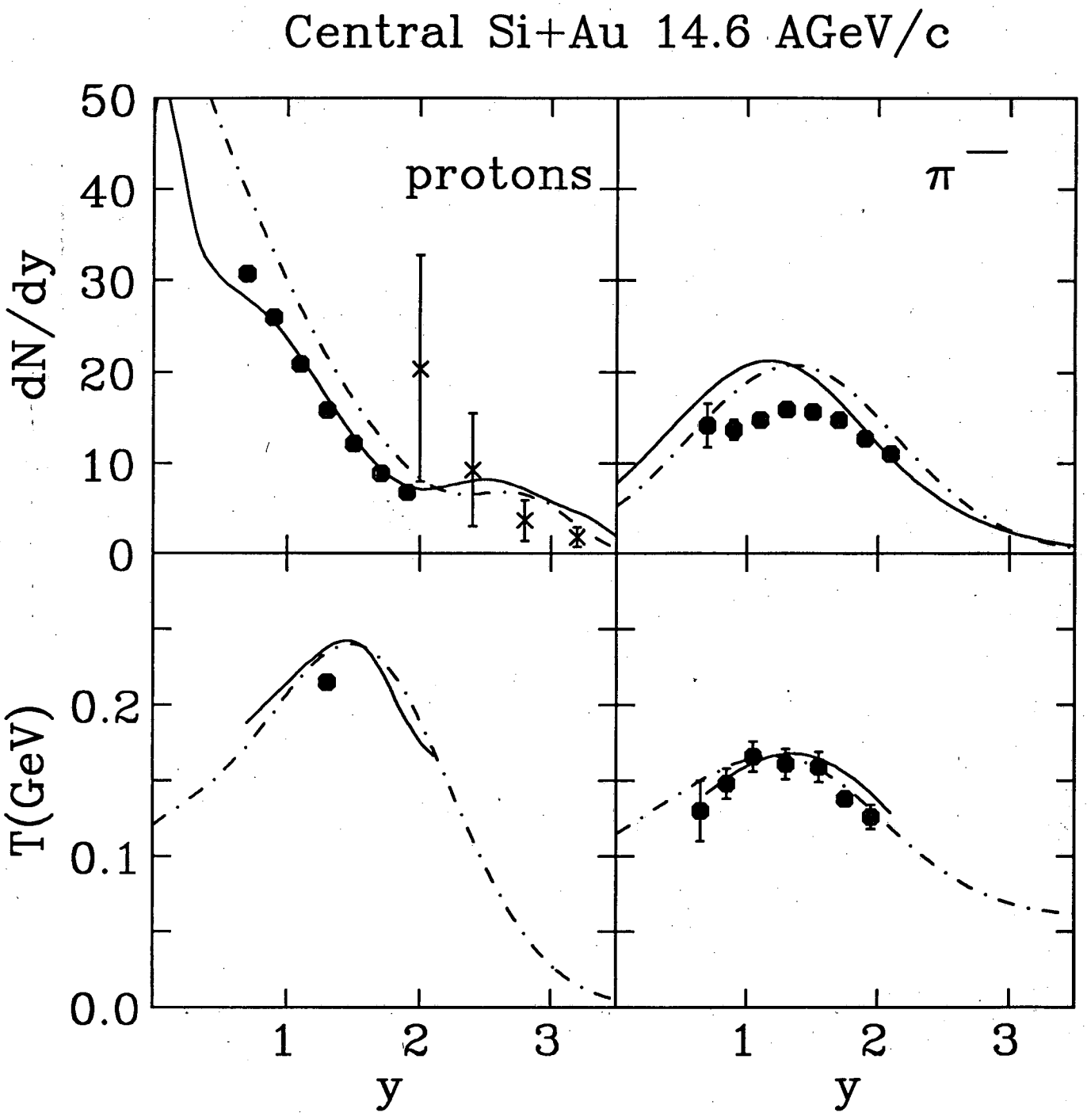
1
2
3
1
2
3


Central Si+Au 14.6 AGeV/c
protons
π^-
dN/dy
T(GeV)
y
y
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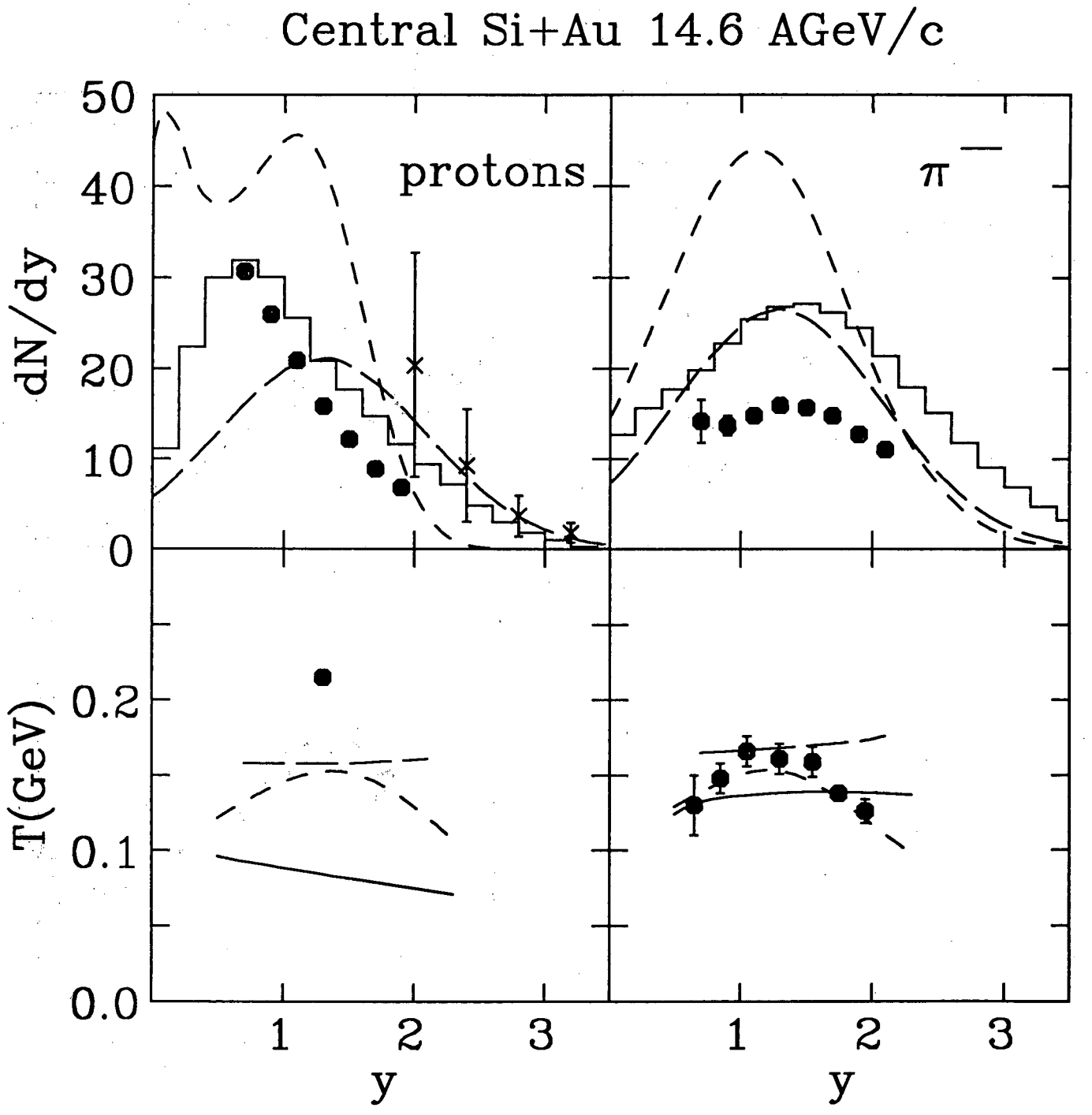
30
20
10
0
0.2
0.1
0.0
1
2
3
1
2
3

p. 11 Fig. 2


Central Si+Au 14.6 AGeV/c
protons
π^-
dN/dy
T(GeV)
y
y
50
40
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0
0.2
0.1
0.0
1
2
3
1
2
3

p. 10 Fig. 1

Figure 2. As in Fig. 1 but compared to a constrained fit (dot-dashed) to data enhanced by a factor 1.3. The solid curves show results of our multicomponent model with $L_s = L'_s = 26$ fm.

Figure 3. $K^{\pm}$ data[1] compared to firestreak (dashed), constrained fit (dot-dashed), and multicomponent model (solid) calculations.

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