Title
Workshop on Heavy Ion Physics at the AGS: Outlook

Author
Gyulassy, M.

Publication Date
1990-05-01

LBL-29076

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Presented at the Workshop on AGS Heavy Ion Program,
Upton, NY, March 5–7, 1990, and
to be published in the Proceedings

Workshop on Heavy Ion Physics at the AGS: Outlook

M. Gyulassy

May 1990

NUCLEAR SCIENCE DIVISION

Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098.

LBL-29076

Workshop on Heavy Ion Physics at the AGS: Outlook

Miklos Gyulassy[1]

Nuclear Science Division
Lawrence Berkeley Laboratory
Berkeley, CA 94720 USA

May 25, 1990

Abstract

Abstract: This report presents the closing talk of the workshop on AGS heavy ion program held at BNL March 5-7, 1990. The emphasis is on new questions posed by the new data presented at this meeting with emphasis on the pion-proton puzzle.

1 Introduction

The purpose of this workshop was to review the status of the current AGS experimental program on *light* ion collisions with heavy target nuclei in the laboratory energy range 10-15 AGeV, to debate what the present data may be teaching us about the physics of such reactions, and to evaluate the prospects of producing and diagnosing extreme baryon dense matter when truly heavy ion beams become available around 1992-3. What distinguished this meeting was that all three major experiment groups, E802, E810, E814, as well as the emulsion collaborations reported new data for the first time. As evident from the contributions of those groups in these proceedings, there has been major progress at the AGS in the past year.

Until this meeting most interest in the AGS energy range has focused on the strangeness enhancement in Si+Au reactions reported by E802[1]. The debate revolved around the question of whether the observed enhanced K/π ratio is evidence of a quark-gluon phase transition at high baryon density or a manifestation of nuclear final state interactions such as $\pi + N \rightarrow K + \Lambda$. However, the new data presented at this meeting suggest that perhaps even more striking and interesting are the proton and pion distributions themselves. In fact, a rather complex picture is beginning to emerge from the comparison of pion, proton, kaon and antiproton rapidity and transverse momentum distributions and their dependence on A in $p + A$ and $Si + A$. As I will emphasize, those distributions taken together rule out most simple models

---

[1] Work supported by the U.S. Department of Energy under Contract DE-AC03-76SF00098

of nuclear reaction dynamics and call for the development of much more elaborate hadronic transport theories.

In this talk I present a personal outlook aimed at drawing attention to a number of interesting and controversial aspects of the new AGS data. The following topics are discussed:

1. The pion-proton puzzle.
2. Nuclear stopping in Si+Au reactions.
3. $\bar{p}$ suppression as a Baryometer.
4. Where have all the pions gone?
5. New kaon systematics from p+A to Si+Au.
6. Collective flow versus Staggering?

2 The pion-proton puzzle

The main surprize is illustrated in Fig.1. In Fig. 1a and 1b the proton and π^- rapidity distributions reported by E802[1, 2] for central (ZDC2 trigger) Si+Au collisions at $p_{lab} = 14.6$ AGeV/c are compared to three models[3]: (1) Lund string model[4] (histograms), (2) a fireball model[6] and (3) a firestreak model[6]. The ATTILA version[5] of the Lund/Fritiof model was used in the present comparison. The fireball and firestreak models for this application were developed by Scott Chapman[3]. The fireball model assumes sharp sphere geometry at impact parameter $b = 3.3$ fm with a baryon density fixed by the Goldhaber formula ($T \approx 228$ MeV, $\rho \approx 4.8\rho_0$) and assumes equilibrium between N, Δ, π, and ρ's. The firestreak model takes into account diffuse Wood-Saxon nuclear densities and assumes local equilibrium in tube-tube collisions. To test the sensitivity to the influence of heavy hadronic resonances, the lowest ten meson and baryon resonance states were allowed to equilibrate. At each transverse coordinate, the local temperature and density were determined by energy conservation and the Goldhaber compression formula. For the Lund and streak calculations an impact parameter average was performed for $0 < b < 4$ fm.

These models illustrate the expected distributions of protons and pions from extreme different points of view. The Lund model extrapolates *pp* string phenomenology to nuclear collisions ignoring both initial and final state interactions. Multiple string interactions are treated via the Fritiof algorithm[4], and all strings are assumed to fragment independently into hadrons that suffer no final state interactions. This model therefore corresponds to an extreme *nonequilibrium* model. The fireball and streak models corresponds, on the other hand, to the opposite extreme in which local thermal and chemical equilibrium are assumed to be reached reached and that the final spectra are controlled mainly by nuclear geometry, kinematics, and the freeze-out density. More realistic hadron transport models are expected to yield results intermediate between the curves shown.

Fig 1a clearly shows that the fireball and firestreak assumptions of *complete* stopping of participant baryons is ruled out by the ramp form of the proton rapidity equilibrate. The nonequilibrium Lund model seems to provide a much better description of both the magnitude and the shape of that distribution. However, examining the transverse momentum distribution in Fig 1c, we see that the string model completely fails to account for the large transverse momentum of the observed protons. Hence, the Lund model agreement in Fig. 1a may be only accidental. Comparing the proton transverse momentum data to the simple fireball model, on the other hand, with the high freezeout density $5\rho_0$ agrees much better with those data. Chapman found[3] that a lowering freezeout density to $0.5\rho_0$ leads to a lower temperature 150 MeV in disagreement with the observed proton slope ($T_p \approx 215$ for a $\exp(-m_\perp/T_p)$ fit[1]). However, both thermal models fail to reproduce the observed ramp shape of the proton rapidity distribution.

In Fig. 1b we see that not only is the proton double differential distribution, $d\sigma/dydp_\perp^2$, inconsistent with the above expectations but the observed pion distribution is inconsistent as well. In this case both the string model and the thermal models overpredict the π^- rapidity data by a factor $\gtrsim 2$. The final surprize is shown in Fig 1d. In contrast to the proton transverse momentum distribution in Fig 1c, the shape of the pion distribution happens to resemble in this case the string model prediction and disagrees with the fireball model for the high density freezeout needed to reproduce the proton slope.

In my opinion, this pion-proton puzzle is the most important new result to emerge from the recent AGS experiments. Clearly, any model claiming to explain the enhancement of less abundant kaons or the suppression of even rarer antiprotons must account first for the combined rapidity and transverse momentum distributions of the abundant pions and protons.

3 Stopping or not?

The proton puzzle discussed above is of course central to the problem of nuclear stopping power[7, 8]. Recall that the main motivation for studying heavy ion collisions at the AGS is the expectation that the stopping power of nuclei to high energy baryons is sufficiently high at AGS energies to produce the highest baryon density matter ($\rho \sim 10\rho_0$) possible to study in terrestrial experiments. Does the ramp rapidity distribution in Fig 1a then disprove this expectation? No, because full stopping is expected only for the collisions of the heaviest nuclei. With Au+Au both projectile and target baryons are expected to be shifted toward mid rapidity by ~ 2 units, in accord with p+Pb data[7, 8]. The problem is that Si is small and surface dominated. Au baryons in the target just don't see enough projectile nuclear matter to accelerate them to mid rapidity. In fact the Lund model, which is consistent with the $p + A \rightarrow p$ stopping data, leads precisely to the ramp form of the data for this reaction. The same model predicts that the baryons in $Au + Au$ should be strongly peaked at mid rapidity in accord with the earlier expectation. We therefore conclude that the rapidity data are consistent with the *lack* of full nuclear stopping expected in *light* ion collisions.

Some debate was generated at this meeting also on the interpretation of new high rapidity neutron data from E814. Those data complement the E802 data by extending the measurement of baryon rapidity distributions up to beam rapidity. Unfortunately, as emphasized by Bellwieds, the E802 and E814 data are not yet directly comparable because of the different E_T triggers used to select "central" collisions and because E814 measurements are limited to the small $p_\perp < 200$ MeV/c range below the acceptance range of E802. The controversy surrounded the definition of nuclear stopping. The E814 data show that the probability of finding a projectile neutron within 0.34 units of the beam rapidity is very small. However, as emphasized in ref.[8], the rapidity distribution near the beam rapidity is very insensitive to the dynamics and fixed by the geometrical Glauber probability ($P_1(A) \approx (R/\lambda)\exp(-(R/\lambda))$) for a projectile nucleon to suffer only one inelastic interaction in a central Si+Au collision!. This measurement confirms then that the inelastic mean free path $\lambda \approx 2$ fm is indeed significantly smaller than the diameter $2R \sim 10$ fm of heavy nuclei. The rapidity range $2 < y < 3$, where E814 can eventually provide decisive data on the question of nuclear stopping power, is still under analysis.

4 Baryometer

The first preliminary data on antiproton production in Si+Au reactions was reported by Costales of the E802 experiment. While the present data are limited to the narrow rapidity range $1.2 < y < 1.6$, several interesting features emerged. First, the transverse momentum distribution of $\bar{p}$ appears to be significantly narrower than that of protons (Fig 1c). Thus these produced particles do not exhibit the apparent transverse flow of the valence baryons. This casts doubt on the collective flow interpretation of the enhanced transverse momentum observed for the protons.

The second main observation was that the absolute $\bar{p}$ yield seems to be about an order of magnitude smaller than predicted by string models. If this data is confirmed, it may be the first direct evidence that the $\bar{p}$'s tend to be produced in a high baryon density environment. In ref.[9] we proposed that the suppression of the $\bar{p}$ yield can be regarded as a baryon chemical potential meter and probes the baryon density evolution in nuclear collisions. The idea is very similar to that applied to explain CERN J/ψ suppression data due to final state interactions. Given a nucleon density $\rho(\tau)$, the survival probability of an antinucleon is given simply by

$$P = \exp\{-\int_{\tau_0}^{\tau_f} d\tau \langle \sigma_a v_r \rangle \rho(\tau)\} \ , \tag{1}$$

where $\tau_0 \sim 1$ fm/c is the proper formation time, $\tau_f \sim R$ is the escape time from the dense system, and σ_a is the annihilation cross section. For scaling dynamics with $\rho(\tau) \approx (\tau\pi R^2)^{-1} 2dN_p/dy$, $P = (\tau_0/\tau_f)^\beta$, where $\beta \approx \sigma_a \tau \rho(\tau) \approx 4-5$ for AGS conditions. However, at AGS energies one cannot neglect the finite nuclear interpenetration time even in the mid rapidity frame. This implies that we must average over production time comparable to the escape time. Averaging P over τ_0 in the range $0 < \tau_0 < \tau_f$ leads to the pocket estimate $P \sim 1/(1+\beta) \sim 0.2$ for the suppression factor of antinucleons due to annihilation for AGS conditions. While this estimate is very rough and must be refined by detailed transport model calculations, it shows that large suppression observed is consistent with annihilation in a dense baryon rich system with $\rho_{max} \sim 30/(5\pi 3^2) \sim 4\rho_0$. Based on familiar coalescence ideas, antinuclei production should be suppressed by further powers of P.

5 Where have all the pions gone?

We now return to the pion part of the puzzle in Fig 1b. The arose at the meeting whether the normalization of the data is underestimated due to the extrapolation of the measured $p_\perp > 200$ MeV range to low $p_\perp$. Comparing the Lund curve in Fig 1d with the data, we see that the calculation has a low $p_\perp$ component in significant excess of that obtained by simple extrapolation from the high $p_\perp$ domain. The transverse momentum distribution from Lund can be fit as a sum of two components of the form $\exp(-m_\perp/T)$ with $T = 100$ and 160 MeV respectively for the two components. New data reported by Love from E810 showed clear evidence for such a two component structure for negatives with slopes very close to the ones predicted by Lund. However, as emphasized by Miake, this low momentum component can account for only $\sim 20\%$ of the missing pion yield. The problem with the Lund curve is that it is systematically too high even in the higher $p_\perp$ range. Therefore, there appears to be a real problem in accounting for the small number of observed pions.

One possibility is that the multistring phenomenology developed for energies above 100 GeV may need substantial modification for AGS energies. At 200 AGeV, relevant for the CERN SPS, string masses up to 12 GeV are excited and the Lund fragmentation scheme adapted to fit e^+e^- multiparticle distributions above 10 GeV cm energies may be expected to work well. Indeed the pseudorapidity distribution systematics measured in emulsions for $E > 60$ AGeV are well accounted for by the Lund model as emphasized by Stenlund at this meeting. However, at AGS energies the very restricted kinematic range limits the masses of excited projectile baryons to less than 3 GeV. In fact most of the target nucleons are excited to below 2 GeV masses. Since each string must fragment into at least one baryon, pion production could be rather sensitive to small changes in kinematic conditions.

In my opinion the problem is due a breakdown of the independent fragmentation scheme because we have checked[11] that the fragmentation of strings in the low mass range 4-5 GeV with the Lund scheme provides a very good description of $\nu + p$ deep inelastic data. In addition, we showed in ref.[12] that QCD sum rules together with heavy quark spectroscopy indicate that QCD strings could be unusually thin ($r < 0.5$ fm) and weakly interacting. Thus independent fragmentation is not unreasonable even for the high string densities ($\sim 2/fm^2$) expected in nuclear collisions.

However, the simple Fritiof ansatz for multiple string excitation probability ($dP \propto dM/M$) may breakdown for the small mass range accessible at AGS. Clearly detailed pion production data from pp and pA in this energy range are needed to test for such a possible breakdown of string phenomenology. Fortunately, such data have been taken and should be available soon (see contribution of Miake).

Another possible mechanism that could be responsible for depleting the pion yield is of course pion absorption. It could be that the *initial* pion number and distribution are predicted well by the Lund model, but that pions (like $\bar{p}$'s) are depleted through absorption in the (moderately) dense baryon rich system. Recall that even in the BEVALAC energy range ($\sim$ 1 AGeV), cascade calculations systematically overpredicted the pion yields[10]. John Schiffer and Gerry Brown have speculated about the possible importance of multi-baryon resonance channels for pion absorption. Pion absorption could perhaps also explain partly the observed enhanced transverse momentum of the protons (Fig. 1c). The non-enhancement of $\bar{p}$ transverse momentum may be due to the fact that only those $\bar{p}$'s survive that were produced in the low baryon density corona of the interaction zone where pion absorption is also less probable.

Clearly, much more experimental and theoretical work remains to answer where have all the pions (and their energy) gone.

6 Kaon/pion systematics from p+A to Si+Au

The high of the meeting was the masterful presentation by Miake of new E802 data on $p, \pi^{\pm}, K^{\pm}$ production in $p + Be$, $p + Au$, central $p + Au$ and $Si + Au$. The data presented are so comprehensive that they virtually tell their own story without need for model calculations.

The first remarkable observation reported was that there is a large enhancement of dN_{K^+}/dy around $y_K \approx 1$ in going from $p + Be$ to $p + Au$. The enhancement factor decreases toward unity as $y \rightarrow 2$. The strong enhancement of K^+ near the target nucleus fragmentation region hints strongly that this enhancement is due to the $\pi + N \rightarrow K + \Lambda$ channel. E810 will eventually be able to confirm this through their Λ measurements. Next in comparing to central $p + Au$, the K^+ yield goes up by another large factor in the target region consistent with the above mechanism. Most impressive was the a comparison between between the K^+ yield in central $p + Au$ and central $(Si + Au)/28$ normalized by the incident beam atomic number. The striking observation was that those two distributions not only had the same shape but the same normalization within 20%!! QED. I believe that this series of measurement rule out convincingly all thermal model explanations of the K/π enhancement.

Another clear story was told by the K^- systematics. The new twist in this case was that the K^- rapidity distributions shown for $p + Be$ and $p + Au$ and central $p + Au$ were flat and identical! On the other hand, the normalized central $(Si + Au \rightarrow K^-)/28$ was also flat but enhanced by a factor of two. Thus the K^- enhancement is the first light ion effect that does not extrapolate smoothly from central $p + A$ systematics. Since K^- can only be produced in pairs with K^+ and phase space at the AGS is very limited, $K^-/K^+ \sim 0.2$. The K^- channel is therefore very sensitive to any new final state interaction channels such as $\pi\pi \rightarrow KK$ or $MM' \rightarrow KK$. These meson annihilation channels can of course only open up if the pion multiplicities become large. This is just what happens in $Si + Au$ as clear from the observation that the pion multiplicity between $1 < y < 2$ in central $Si + Au$ is close to 28 times that in central $p + Au$. Thus it is very likely that the K^- enhancement is due to meson-meson final state interactions This result has great potential interest because it could be the first clear signature that high density mesonic matter is formed in even in light ion collisions.

These beautiful E802 systematics will provide very stringent tests on developing transport models. A simultaneous fit to the absolute pion,proton, kaon, and antiproton distributions as a function of A in $p + A$ and $Si + A$ will require a thorough understanding of all the competing dynamical mechanism. This in turn will provide the solid foundation for the interpretation of future data on truly heavy ion reactions. These data underscore again the great importance of comparing possible new phenomena in heavy ion collisions with possible precursors in $p + A$.

7 Collective flow or Staggering?

The final topic I will discuss is whether the enhanced transverse momentum slope of the protons in Fig. 1c is a manifestation of collective transverse hydrodynamic flow or something else. In section 5 the possibility that it may be due to the eating of pions by baryons was mentioned. Here I consider another possible mechanism: initial state interactions. This is motivated again by similar considerations that explain the enhancement of J/ψ transverse momenta measured by NA38 at CERN. In addition it is motivated by the analysis in Matt Bloomer's thesis[2] showing that the proton slopes increase monotonically with the centrality of the interaction.

Initial state scattering can increase the mean transverse momentum of the valence nucleons according to a random walk formula

$$\langle p_\perp^2 \rangle = p_0^2 + (\nu - 1)\delta p_\perp^2 \ , \tag{2}$$

where p_0^2 is the rms transverse momentum after one collision including the fragmentation dynamics and $\delta p_\perp^2$ is the rms transverse kick resulting from $\nu - 1$ initial state interactions. These two parameters may be fit from $p + A \rightarrow p$ data. From the Eichten et al data at 24 GeV analyzed in [2], I found that

$$p_0^2 \approx (0.54\,GeV)^2 \ , \ \delta p_\perp^2 \approx (0.2\,GeV)^2 \ , \tag{3}$$

could fit the observed rise of $\langle p_\perp \rangle$ from 0.55 to 0.63 GeV in going from Be to Pb ($\nu_{Be} = 1.4, \nu_{Pb} = 3.7$). For A+B collisions, the only difference is that $(\nu - 1)$ must be replaced by a weighted average value

$$\langle \nu - 1 \rangle_{BA}(y) = ((\nu_B - 1)dN_B/dy + (\nu_A - 1)dN_A/dy)/(dN_B/dy + dN_A/dy) \ , \tag{4}$$

reflecting the fraction of protons at a given rapidity coming from the target or the projectile and their respective number of inelastic collisions.

To see how big this effect could be I used the tabulated number of projectile and target participants and average ν values from table 5.6a of Bloomer's thesis. These were obtained from a Fritiof analysis of the trigger conditions of the E802 experiment. Then I assumed that the target proton rapidity distribution for light projectiles such as Si is given simply by

$$dN_{targ}/dy = (79/197)N_{targ}e^{-}y \ . \tag{5}$$

Trigger	N_{proj}	N_{targ}	ν_{proj}	ν_{targ}	$\langle p_\perp^2 \rangle_{stagger}$	$\langle p_\perp^2 \rangle_{E802}$
ZDHI	4	5	1.9	1.5	0.37	0.36
ZDM1	14	20	2.7	2.0	0.45	0.49
ZDM2	21	34	3.4	2.2	0.51	0.56
ZDC1	25	46	4.1	2.3	0.56	0.55

Table 1: Average transverse momentum squared (in GeV*GeV) of protons at y=1.05 from Si+Au at 14.5 GeV as a function of centrality trigger.

Using the measured dN/dy to fix the projectile proton distribution, all quantities in (4) are then determined for each trigger configuration. In table 1 the results of this exercise are shown to resemble closely the trend of the data.

This shows that we have to be careful about interpreting enhanced $p_\perp$ in this energy range in terms of collective flow. The staggering mechanism applies only to the valence protons and therefore provides a natural explanation of why the transverse momentum of antiprotons is not enhanced.

8 Summary

The new data presented at this meeting open the first serious chapter on heavy ion physics at AGS energies. While the CERN/SPS heavy ion program enjoyed an early head start, the AGS program has now matured and caught up. Unique world wide are detailed spectra of identified hadron species presented for the first time here. Also the especially beautiful systematics from $p+Be$ to central $p+Au$ to central $Si+Au$ make it possible for the first time to start sorting out the new physics from extrapolations of the old.

I have outlined a number of new puzzles posed by the new data and indicated a variety of possible interpretations. The main message, illustrated in Fig. 1, was that the physics of these reactions is very rich and defy simple model interpretations. The transverse momentum and rapidity distributions of the pions,kaons, protons and antiprotons all differ and have different A dependences. It is clear that we have a great deal to learn already from the light ion AGS program.

References

[1] T. Abbott et al (E802 collab) Phys. Rev. Lett., 64 (1990) 847.

[2] M. A. Bloomer, MIT Ph.D thesis 1990.

[3] S. Chapman, M. Gyulassy, LBL-preprint in preparation

[4] B. Andersson, et. al., Nucl. Phys. B281 (1987) 289.

[5] M. Gyulassy, CERN-TH.4794 (1987), Proc. Balatonfured Conf. on Nuclear Physics (1987).

[6] J. Gosset, J. Kapusta, G. D. Westfall, Phys. Rev. C18 (1978) 844; W. D. Myers, Nucl. Phys. A296 (1978) 177.

[7] W. Busza, R. Ledoux, Ann. Rev. Nucl. Part. Sci. (1988) 119.

[8] S. Date, M. Gyulassy, H. Sumiyoshi, Phys. Rev. D32 (1985) 619.

[9] S. Gavin, M. Gyulassy, M. Plumer, R. Venugopalan, Phys. Lett. 234B (1990) 175.

[10] Proc. 8th High En. Heavy Ion Study, LBL-24580 (1988), CONF-8711116.

[11] M. Gyulassy, M. Plümer, LBL-27234 (1989).

[12] M. Grabiak, M. Gyulassy, J. Casado, LBL- 28857 (1990).

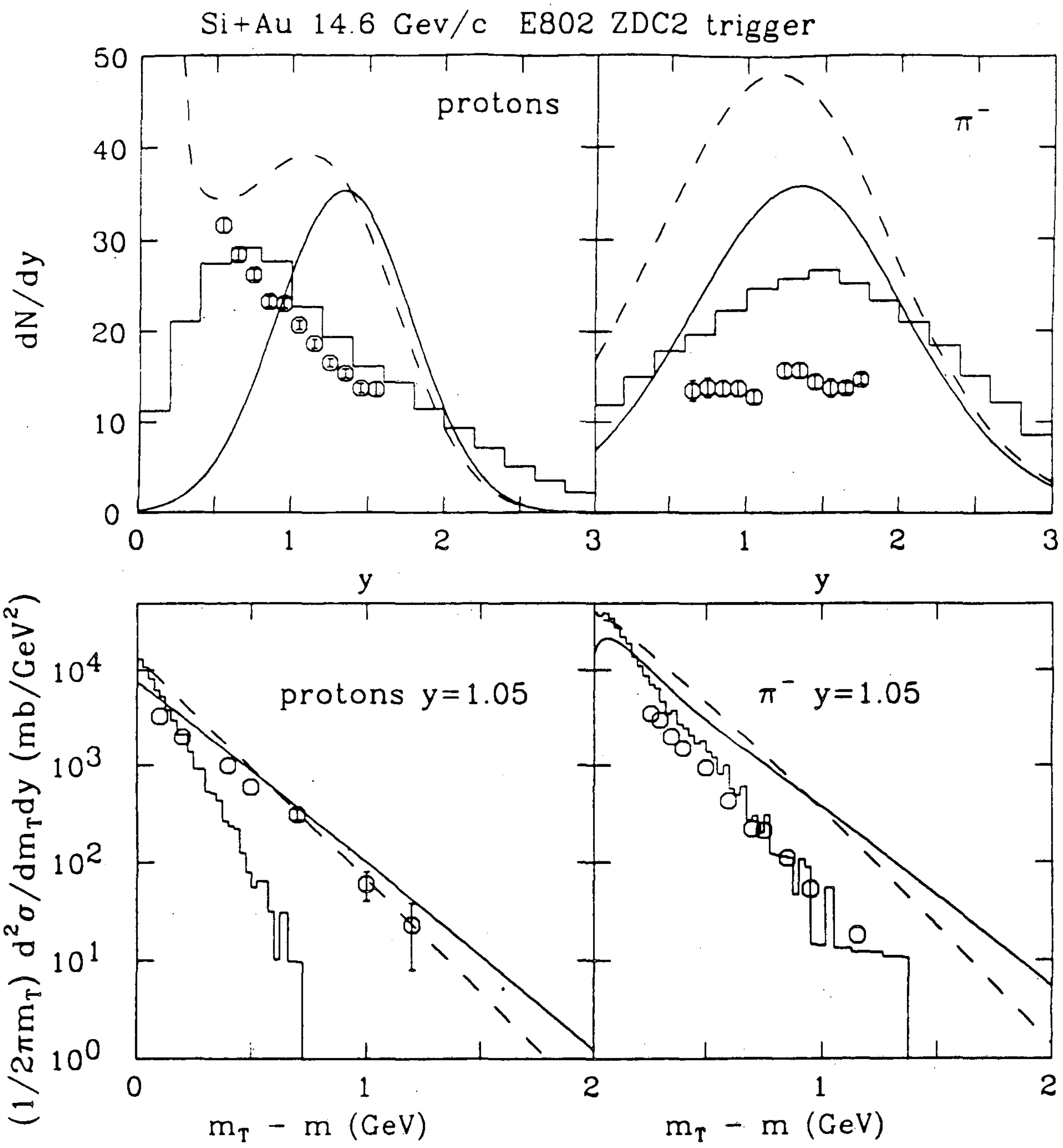

Figure 1: The pion-proton puzzle. Data are taken from M. Bloomer's thesis. Histograms correspond to the ATTILA version of the Lund/Fritiof model, solid and dashed curves correspond to S. Chapman's sharp sphere fireball model and diffuse firestreak models.