Rapidity spectra from THERMINATOR*

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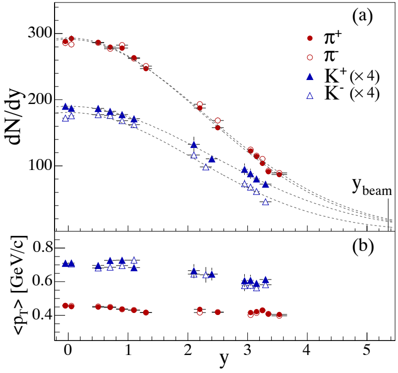
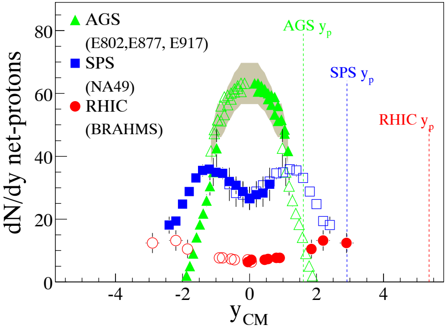
Outline

1. Experimental facts
2. The model
   - Geometry and kinematics
   - The single freeze-out model
3. Results
   - Fit
   - Rapidity spectra
   - p_T-spectra
   - Predictions

Typical data





This talk:

data from BRAHMS

4π vs. midrapidity

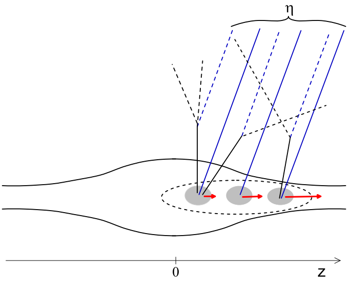
Up to now two basic categories of calculations:

- (1) 4π studies at low energies (SIS, AGS),
  $N_i = V \int d^3p\, f_i(\sqrt{m_i^2 + p^2}; T, \mu' s)$
- (2) Studies at mid-rapidity for approximately boost-invariant systems at highest energies (RHIC) at $|y| < 1$
- WB+Florkowski, PRL **87** (2001) 272302:

$$\frac{dN_i/dy}{dN_j/dy} = \frac{\int dy\, dN_i/dy}{\int dy\, dN_j/dy} = \frac{N_i}{N_j}.$$

- Inclusion of resonance decays simple in both approaches
- Cooper-Frye → spectra $dN/(2\pi p_T dp_T dy)$

Geometry and kinematics



- Boost non-invariant system
- Particles with the same pseudorapidity η originate from different regions
- Thermal conditions and flow in these regions are different

Boost-noninvariant calculation

- THERMINATOR [A. Kisiel, T. Tałuć, WB, WF, Comput.Phys.Commun. **174** (2006) 669-687] $\rightarrow$ Monte Carlo
- Choice of the shape of the freeze-out hypersurface Σ and collective expansion
- Dependence of thermal parameters on the position within Σ
- Parameters are fitted independently to various combinations of the data, reducing freedom

Result:

"topography" of the fireball, which forms the ground for other studies

Cracow model

1. At a certain stage thermal equilibrium between hadrons occurs (probably born that way)
2. The parameters: T, μ_B, μ_S, and μ_{I_3}. In a boost-non-invariant model these parameters depend on the position
3. The shape of the fireball is nontrivial in the longitudinal direction
4. Hubble flow $\to$ longitudinal and transverse flow. Again, in the boost-non-invariant model the form of the velocity field may depend on the longitudinal position
5. The evolution after freeze-out includes decays of (all) resonances which may proceed in cascades
6. Elastic rescattering after the chemical freeze-out is ignored (approximation)

Hypersurface and flow

$$x^\mu = \begin{pmatrix} t \\ x \\ y \\ z \end{pmatrix} = \begin{pmatrix} \tau \cosh\alpha_\perp \cosh\alpha_\parallel \\ \tau \sinh\alpha_\perp \cos\phi \\ \tau \sinh\alpha_\perp \sin\phi \\ \tau \cosh\alpha_\perp \sinh\alpha_\parallel \end{pmatrix}.$$

$\alpha_\parallel$ - *spatial rapidity*, $\alpha_\perp$ - transverse rapidity

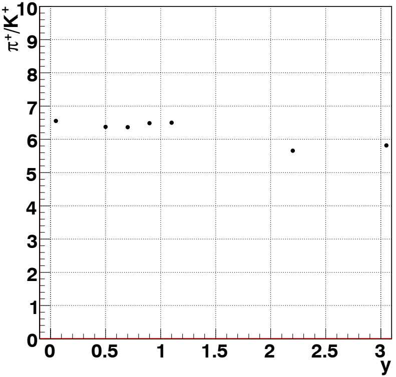
$$\rho = \sqrt{x^2 + y^2} = \tau \sinh\alpha_\perp$$

The four-velocity follows the Hubble law

$$u^\mu = x^\mu / \tau.$$

The longitudinal flow $v_z = \tanh\alpha_\parallel = z/t$ as in the Bjorken model, the transverse flow (at $z = 0$) has the form $v_\rho = \tanh\alpha_\perp$.

Cooler or thinner?



Yields drop with $y \rightarrow$ (1) decrease the transverse size with $|y|$, or (2) decrease T, or both. BRAHMS: $(dN_\pi/dy)/(dN_K/dy)$ is, within a few %, independent of $y \rightarrow T \sim$ const., and we must take (1)!

Approximate constancy of T

- The *universal freeze-out curve* gives from $\mu_B = 0$ to $\mu_B = 250$ MeV a practically constant value of T. Thus, in the present analysis we may fix

$$T = 165 \text{ MeV}.$$

- At larger rapidity and/or lower collision energies, T does depend on $\alpha_\parallel$.
- Eventually, when the fragmentation region is reached, $T \sim 0$ and $\mu_B \sim 1$ GeV

The farther, the thinner!

A new element in this work:

$$0 \leq \alpha_\perp \leq \alpha_\perp^{\max}(\alpha_\parallel) \equiv \alpha_\perp^{\max}(0) \exp\left(-\frac{\alpha_\parallel^2}{2\Delta^2}\right).$$

- As we depart from the center by increasing $|\alpha_\parallel|$, we reduce $\alpha_\perp$, or $\rho_{\max}$. The rate of this reduction is controlled by a new model parameter, Δ. The farther, the thinner!
- We admit the dependence of chemical potentials on the spatial rapidity, necessary to describe the increasing density of net protons towards the fragmentation region

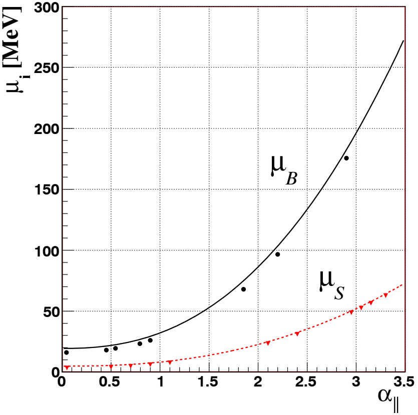
Fitting strategy

- For a given set of parameters we generate THERMINATOR events
- First optimize $\mu_B(0)$ and A_B with the experimental $p/\bar{p}$ rapidity dependence
- Then fix $\mu_S(0)$ and A_S using K^+/K^-
- Iterate two above items until a fixed point is reached
- $\mu_{I_3}(0)$ and A_{I_3} are consistent with zero and thus irrelevant
- The Δ parameter is fixed with the pion rapidity spectra $dN_{\pi^\pm}/dy$, with the optimum value $\Delta = 3.33$

Result:

$$\mu_B(0) = 19 \text{ MeV}, \ \mu_S(0) = 4.8 \text{ MeV}, \ A_B = 0.65, \ A_S = 0.70$$

The farther, the denser!

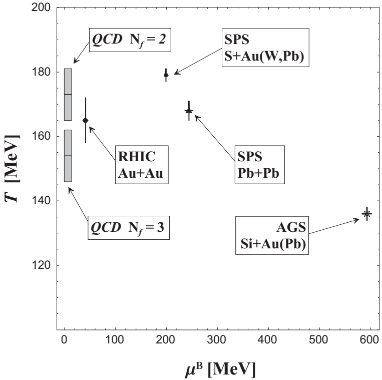


Lines - parameterization: $\mu_i(\alpha_\parallel) = \mu_i(0)\left[1 + A_i \alpha_\parallel^{2.4}\right]$

Points - approximate result: $\frac{p}{\bar{p}} \simeq \exp(2\beta\mu_B)$, $\frac{K^+}{K^-} \simeq \exp(2\beta\mu_S)$

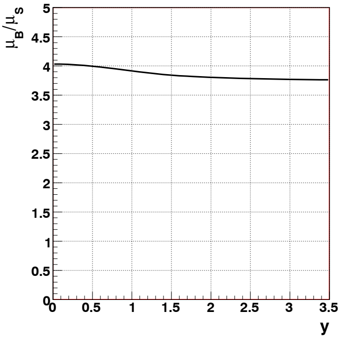
μ_B at large rapidities

- Near $\alpha_\parallel = 3$ μ_B is around 200 MeV, more than 10 times larger than at the origin – comparable to the highest-energy SPS fit, where $\mu_B \simeq 230\ \mathrm{MeV}$ (Michalec, Ph.D., 2001)



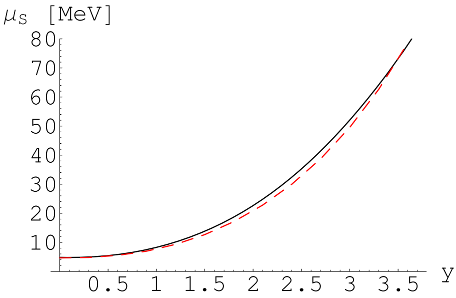
μ_B/μ_S

- $\mu_B(\alpha_\parallel)/\mu_S(\alpha_\parallel)$ is very close to a constant, $\simeq 4 - 3.5$



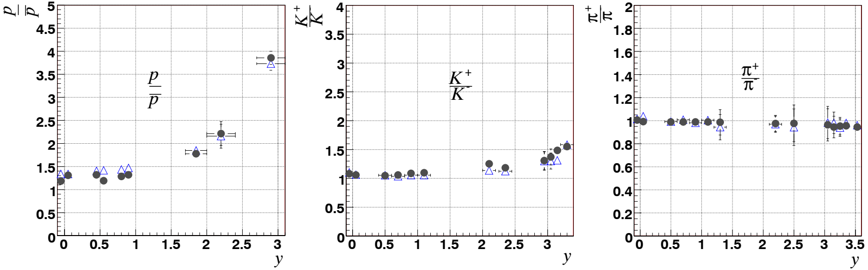
Zero strangeness density

- Results consistent with zero strangeness density



solid – μ_S from the fit to the data
dashed – from the condition of zero local strangeness density

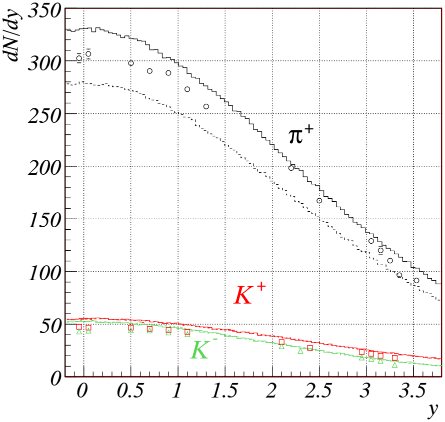
Ratios



triangles – BRAHMS data

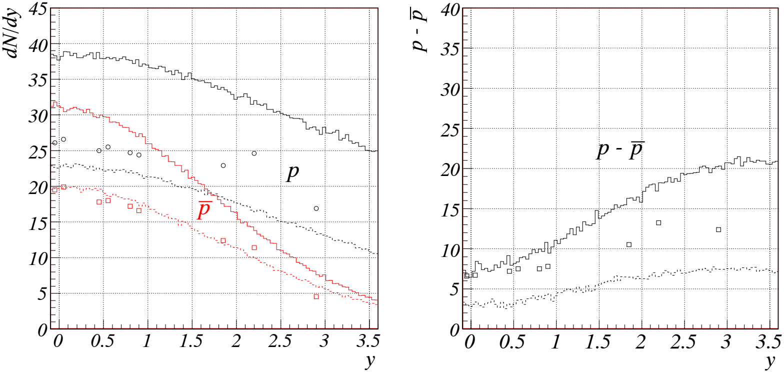
dots – model with fitted dependence of $\mu' s$ on $\alpha_\perp$

π and K



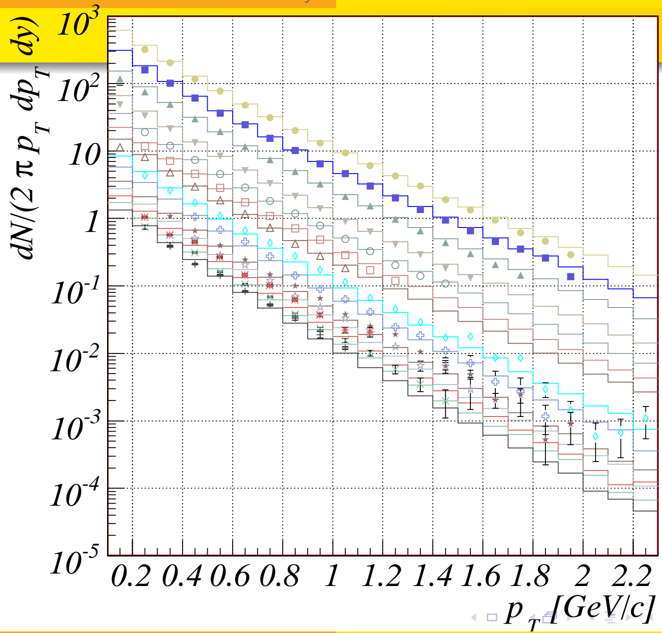
π^+ with (upper) and without (lower) feeding from the weak decays

p and $\bar{p}$

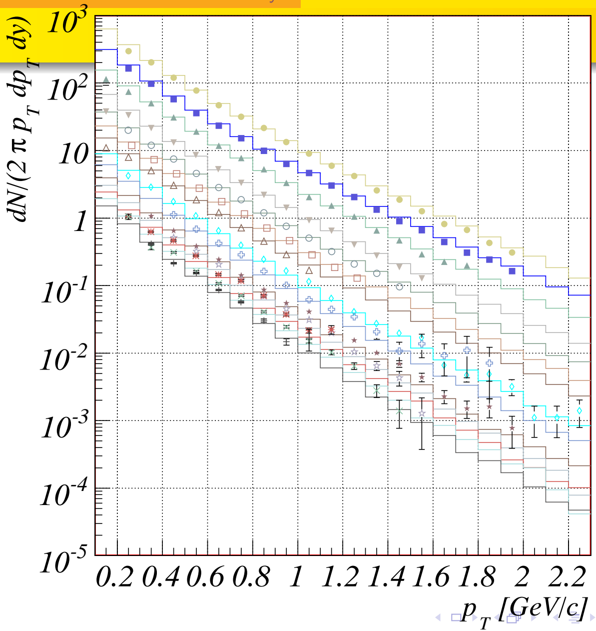


Left: with (black) and without (red) feeding from the weak decays (experiment is without the feeding)

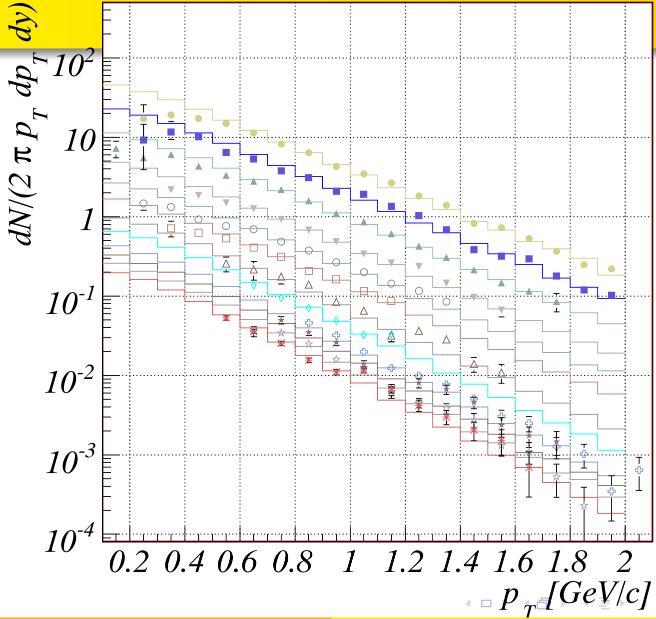
π^+


dN/(2 π p_T dp_T dy)
10^3
10^2
10
1
10^-1
10^-2
10^-3
10^-4
10^-5
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
p_T [GeV/c]

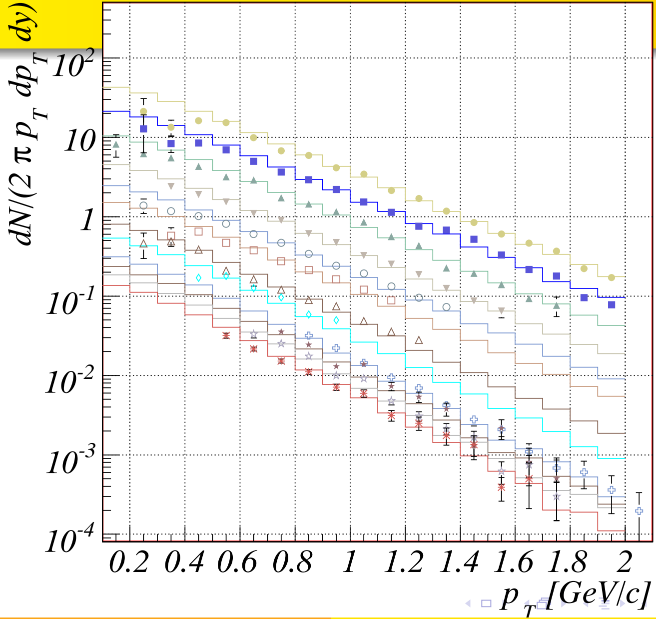
π^-


$dN/(2\pi p_T\, dp_T\, dy)$
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2 2.2
p_T [GeV/c]

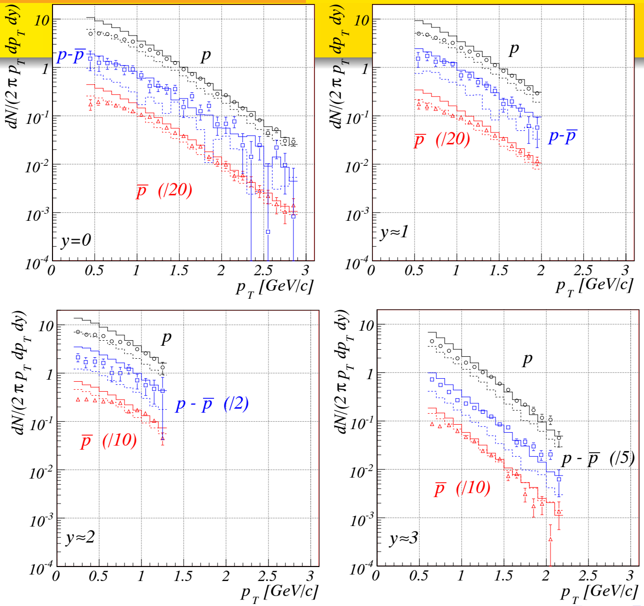
K^+


dN/(2 π p_T dp_T dy)
10^2
10
1
10^-1
10^-2
10^-3
10^-4
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
p_T [GeV/c]

K^-

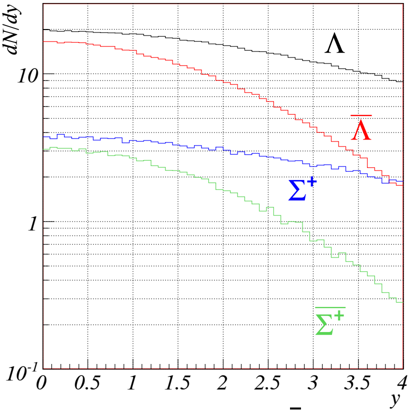

dN/(2 π p_T dp_T dy)
10^2
10
1
10^-1
10^-2
10^-3
10^-4
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
p_T [GeV/c]

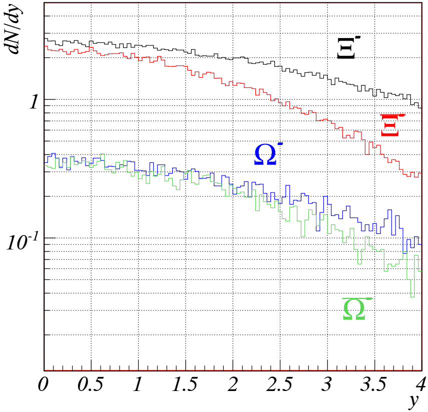
p and $\bar{p}$


$dN/(2\pi p_T\, dp_T\, dy)$
p
$p-\bar{p}$
$\bar{p}$ (/20)
y=0
p_T [GeV/c]
y≈1
$p-\bar{p}$ (/2)
$\bar{p}$ (/10)
y≈2
$p-\bar{p}$ (/5)
y≈3

Hyperons

We have accomplished the goal of fixing the "fireball topography"!





Small splitting of Ω and $\bar{\Omega}$, resulting from $\mu_B \simeq 3\mu_S$

Summary

- Naive extraction of the $\mu_B$and μ_S from $p/\bar{p}$ and K^+/K^- works surprisingly well!
- $\mu_B$and μ_S grow with $\alpha_\perp$, reaching at $y \sim 3$ values close to those of the highest SPS energies (cf. Roehrich)
- At mid-rapidity the values of $\mu' s$ are lower than derived from the previous thermal fits to the data for $|y| \leq 1$, with our values taking $\mu_B(0) = 19$ MeV and $\mu_S(0) = 5$ MeV
- The local strangeness density of the fireball is compatible with zero at all values of $\alpha_\parallel$.
- μ_B/μ_S varies very weakly with rapidity, ranging from ~ 4 at midrapidity to ~ 3.5 at larger rapidities.
- The $d^2N/(2\pi p_\perp dp_\perp dy)$ spectra of pions and kaons are well reproduced

Summary 2

- The rapidity shape of the spectra of p and $\bar{p}$ is described properly, while the model overpredicts the yields by about 50%. This suggests a lower value of T at increased rapidity, or presence of the γ factors
- Increasing yield of the net protons with rapidity is obtained naturally, explaining the shape of the rapidity dependence on purely statistical grounds