Coulomb interaction, isospin symmetry and $\frac{\pi^-}{\pi^+}$ ratio in Au-Au collisions at $\sqrt{s_{NN}} = 200\ GeV$

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Introduction

The nuclear matter formed in relativistic heavy ion collisions evolves to freeze-out state through complex processes defined by the collision energy and the collision geometry. In ultrarelativistic heavy ion collisions a large number of particles are produced, mostly pions. The pion ratios reflect the equilibrium degree of isospin in the reaction and also the effects of the Coulomb repulsion, because the charged particles, especially the pions, are highly influenced by the Coulomb field produced by the net charge of the reaction protons. Information on the charge distribution in the participant region could be obtained from analysing the dependence of the negative to positive ratios of the produced pions on the transverse energy.

Since the Coulomb forces influence the matter essentially after freeze-out, the asymmetry in the number of charged particles can be directly related to the freeze-out parameters.

In this work we analyse the Coulomb interaction through $\frac{\pi_-}{\pi^+}$ ratio obtained in *Au-Au* collisions at $\sqrt{s_{NN}} = 200\ GeV$.

Experimental results

The Coulomb effect was studied in heavy ions collisions at much lower energies, at 1 A GeV (SIS - Darmstadt), 11.4 AGeV (AGS - Brookhaven National Laboratory) and 158 A GeV (SPS - CERN) [5-7]. From the analysis that was made, it have been observed that the Coulomb effect is much stronger at low transverse momentum, because the Coulomb interaction potential energy is smaller than the kinetic energy of particles and because of the low velocity of expansion for the net charge. At lower energies, the nuclei are fully stopped. Under these conditions, the total charge stays together sufficient time to significantly accelerate or decelerated the produced charged pions. Because of that, the pion spectra are modified, leading to nonuniform pion yield ratios.

At higher energies, the colliding nuclei are no longer completely stopped and in these collisions can be achieved a degree of transparency of the colliding nuclei. In these collisions one could expect a smaller Coulomb effect.

It has been proposed the introduction of the Coulomb momentum ("Coulomb kick") in order to study the π^+ - π^- asymmetry at AGS and SPS energies [1-4]. The authors consider that the interaction between charged pions and net charge of the participant protons changes transverse momentum with the quantity:

$$p_c \equiv \left|p_\perp - p_{\perp,0}\right| \cong 2e^2 \frac{dN^{ch}}{dy}\frac{1}{R_f} \qquad (1)$$

where $p_{\perp,0}$ is the transverse momentum at freeze-out and $p_\perp$ is the final momentum. The authors predicted the pion ratio can be described by the following relationship:

$$\frac{\pi^-}{\pi^+} = \left\langle \frac{\pi^-}{\pi^+} \right\rangle \frac{p_\perp + p_c}{p_\perp - p_c} \exp\left(\frac{m_\perp^- - m_\perp^+}{T} \right) \qquad (2)$$

where $m_\perp^\pm = \sqrt{m^2 + \left(p_\perp \pm p_c\right)^2}$.

The authors assume that the radius at freeze-out is:

$$R_f = R_{geom} + 0.5 \cdot \beta_\perp \cdot \tau_f \qquad (3)$$

Here, R_{geom} is the initial (geometrical) radius of the overlap zone at the collision time and β is the transverse flow velocity.

The experimental data from AGS (11.4 A GeV) and SPS (158 A GeV) are well reproduced with $p_c^{AGS} \cong 20\, MeV/c$, $p_c^{SPS} \cong 10\, MeV/c$, respectively. Using the measured proton rapidity distributions, $dN_p^{AGS}/dy \cong 70$, $dN_p^{SPS}/dy \cong 37$, respectively, it was calculated the size of the systems at freeze-out, namely: $R_f^{AGS} \cong 10\, fm$ and $R_f^{SPS} \cong 9\, fm$.

We analysed the $\frac{\pi^-}{\pi^+}$ ratio as a function of transverse mass ($m_\perp - mass$) for *Au+Au* collisions at $\sqrt{s_{NN}} = 200\, GeV$. The pions were detected with Mid-Rapidity Spectrometer at 90^0, at rapidity y=0 [8]. The ratios were obtained for different centrality cuts (0-10%, 10-20%, 20-40%, 40-60%). From central to peripheral data the π^- / π^+ ratios are fitted using the the expression (2), and assuming that the temperature is obtained as below.

The transverse mass distributions of the pions were fit to the expression:

$$\frac{1}{N_{ev}}\frac{1}{2\pi\, m_T}\frac{dN}{dm_T dy} = \frac{1}{2\pi}\frac{dN}{dy}\frac{1}{T(T+m_0)} e^{-\frac{m_T - m_0}{T}} \qquad (4)$$

with the slope parameter T and yield dN/dy set as free parameters, for different centrality cuts. The obtained results are listed in Table I.

centrality	***0-10%***	***10-20%***	***20-40%***	***40-60%***
T(π^+)[MeV]	243.4±0.9	245.5 ±1.1	241.2 ±1.2	230.3±1.9
T(π^-)[MeV]	242.6±0.9	241.6±1.1	240.7±1.2	231.5±2.0

Table I: Effective temperatures obtained from fits to pion spectra for four centrality cuts.

These temperatures are greater than those obtained at SPS. At RHIC energies, the mass dependence of the slope parameters seems to be stronger than that at the SPS energies, indicating a larger colective flow in higher energy nuclear collisions. The obtained temperatures show a weak centrality dependence for the first three centrality class.

The results of the fit of the π^- / π^+ yields within each centrality cut are shown in Table II. No strong centrality dependence is observed in the centrality range measured. The χ^2 contour levels for the two parameters of the fit (Coulomb kick and the total ratio) are shown for each centrality cut (Fig.2., Fig.4., Fig.6., Fig.8.). The χ^2 /DOF is in the range ~ 1.1 – 1.5 for all centrality cuts.

centrality	***0-10%***	***10-20%***	***20-40%***	***40-60%***
p_c [MeV/c]	6.50±1.59	6.81±1.09	5.04±1.52	5.06±2.52

Table II: Coulomb kick obtained from fits to π^- / π^+ *yields for four centrality cuts*

Fig. 1. shows the fit to the π^- / π^+ ratios for the most central collisions 0-10%. The obtained Coulomb kick value is 6.5 MeV/c. This value of Coulomb momentum is smaller than values obtained at AGS and SPS. The result shows that at RHIC energies, the system expands collectively under strong internal pressure, the collective flow is faster and the pions experience a smaller Coulomb kick from the net charge of the protons. Therefore, the Coulomb repulsion is reduced than at AGS and SPS energies.

In these collisions, the two nuclei pass through each other forming a barion poor region in the middle, at these energies is obtained a smaller stopping than at SPS and AGS energies, and therefore the charge density is smaller at midrapidity.

Fig. 9. shows the transverse mass spectrum for the protons at y=0. The proton rapidity density was obtained by fitting the proton transverse mass spectrum with the (4) and the value obtained from the 0-10% most central events is dN/dy = 29.79 ± 0.38. Using the relation (1) the freeze-out radius obtained is R_f = 11.15 fm. This value which is greater than the geometrical radius indicate that significant expansion takes place before freeze-out (for 0-10%centrality).

In order to estimate the geometrical radius we use a phenomenological geometrical model [9,10], which consider that a very hot region is created from the overlapping region of the two colliding nuclei. The spectator regions slow down the flow and can absorb some particles created in the hot region. Different physical quantities can be calculated in the following working assumptions:

- the nucleons are spheres of radii r_0 and nuclei are spheres of radii $R=r_0A^{1/3}$;
- initially, in the target nucleus a geometrical spherical zone occurs, the volume of the geometrical spherical zone depends on the impact parameter b and on the beam energy;
- the ratio $(Z_P+Z_T)/(A_P+A_T)$ remains constant for the very hot region
- the geometrical spherical zone evolves in a very hot sphere and the volume of the sphere is equal to the volume of the geometrical spherical zone.

In these assumptions the radius of the very hot sphere is

$$R_{geom} = 2^{2/3} c(\gamma) h^{1/3} \left(3r_1^2 + 3r_2^2 + h^2\right)^{1/3} \quad (5)$$

where $r_{1,2}^2 = \left| R_T^2 - (b \pm R_P)^2 \right|$, $h = 2R_P$, $R_P = R_T = R$, $R = r_o A^{1/3}$. The factor $c(\gamma)$ is a quantity depending on the time evolution of the fireball. This evolution is related to the contraction Lorentz factor, γ. For the estimation of the impact parameter we use the simulated data with the HIJING code. For the most central collisions, 0-5%, average impact parameter is 1.42 fm. For $c(\gamma)=\gamma^{-2/3}$, we find the geometrical radius $R_{geom} = 6.87$ fm.

In *Au-Au* collisions at RHIC energies, the density of produced particles is high; following this, the number of secondary collisions among the produced particles or the number of rescatterings is high and thus collective transverse motion is very strong. At midrapidity (y=0), the observed particle density at $\sqrt{s_{NN}} = 200\ GeV$ is about 2.1 times greater than in Pb+Pb collisions at 17.2 GeV[11]. Assuming a transverse flow velocity of 0.6c, using the relation (3), and the value for $R_{geom} = 6.87$ fm, we obtained the freeze-out time: $\tau_f = 14 fm/c$. This freeze-out time is higher than the value obtained at SPS, indicating that in these collisions the source is more expanded longitudinal and that the freeze-out occurs much later (for 0-10%centrality).

At 10-20% centrality, the obtained value is very close to the value obtained for the most central events (Fig.3.). The pions multiplicities decrease slowly for the first two centrality cuts (0-10%, 10-20%); it follows that Coulomb kick is almost constant for these centrality cuts. For the 20-40% centrality, the Coulomb kick slowly decrease (Fig. 5.).

For the peripheral collisions (40-60% centrality), there are less produced particles and thus the collective flow is much reduced; in these collisins the rapidity density of the protons is much smaller. Because of that the obtained values could be affected (Coulomb kick could be obtained with much greater errors) (Fig.7.).

Final remarks

The Coulomb effects in pion spectra are sensitive to the degree of stopping and the distribution of positive charge, as well as at the flow velocity of the participant region. Using the experimental results obtained by BRAHMS experimental set-up, a modification in the transverse momentum due to the Coulomb interaction smaller than obtained in other experiments at lower energies is observed. This value can reflect a reduced Coulomb effect at higher flow velocities of the nuclear matter from participant region.

References

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Figure caption:

1 Transverse mass dependence of the π^- / π^+ yields. The data are at y=0 and for 0-10% centrality. The full curve is for the fit, as described in text.
2 The χ^2 contour levels of the parameters of the fit: Coulomb kick (vertical) and the total pion ratio (the total production)(horizontal) for 0-10% centrality
3 Transverse mass dependence of the π^- / π^+ yields. The data are at y=0 and for 10-20% centrality. The full curve is for the fit to the data.
4 The χ^2 contour levels of the parameters of the fit: Coulomb kick (vertical) and the total pion ratio (horizontal) for 10-20% centrality
5 Transverse mass dependence of the π^- / π^+ yields. The data are at y=0 and for 20-40% centrality. The full curve is for the fit to the data.
6 The χ^2 contour levels of the parameters of the fit: Coulomb kick (vertical) and the total pion ratio (horizontal) for 20-40% centrality
7 Transverse mass dependence of the π^- / π^+ yields. The data are at y=0 and for 40-60% centrality. The full curve is for the fit to the data.
8 The χ^2 contour levels of the parameters of the fit: Coulomb kick (vertical) and the total pion ratio (horizontal) for 40-60% centrality
9 Transverse mass spectra of protons from Au-Au collisions at 200 AGeV for central events (0-10%) at y=0

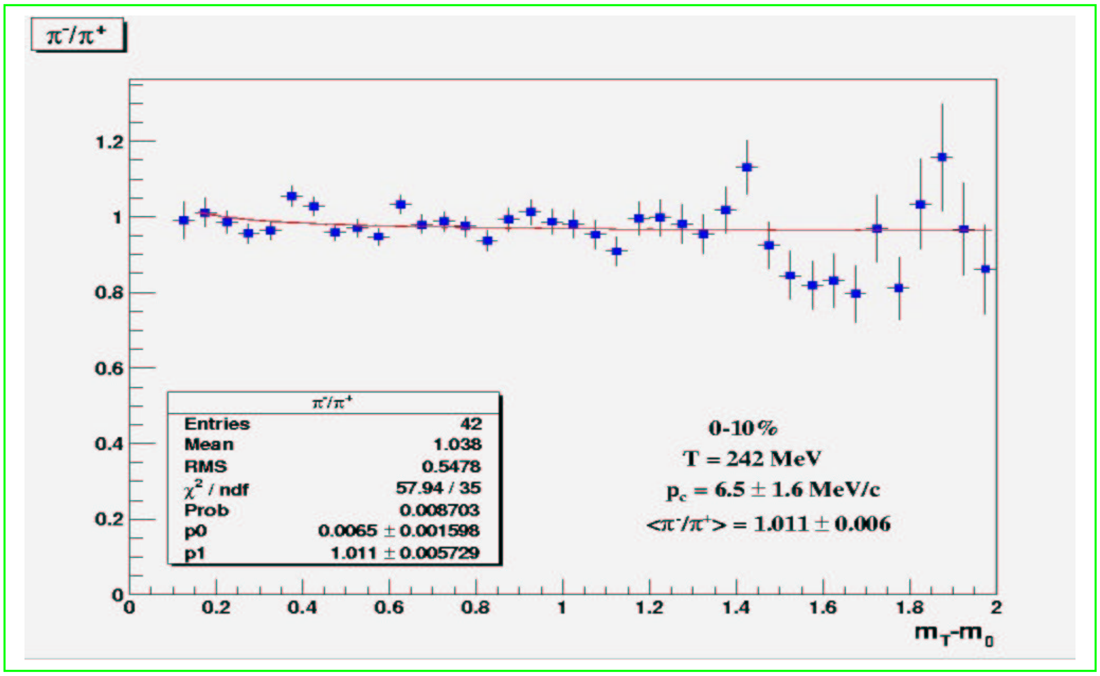

π^-/π^+
Entries 42
Mean 1.038
RMS 0.5478
χ^2 / ndf 57.94 / 35
Prob 0.008703
p0 0.0065 ± 0.001598
p1 1.011 ± 0.005729
0-10 %
T = 242 MeV
$p_c = 6.5 \pm 1.6$ MeV/c
$<\pi^-/\pi^+> = 1.011 \pm 0.006$
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
m_T-m_0

Fig.1.

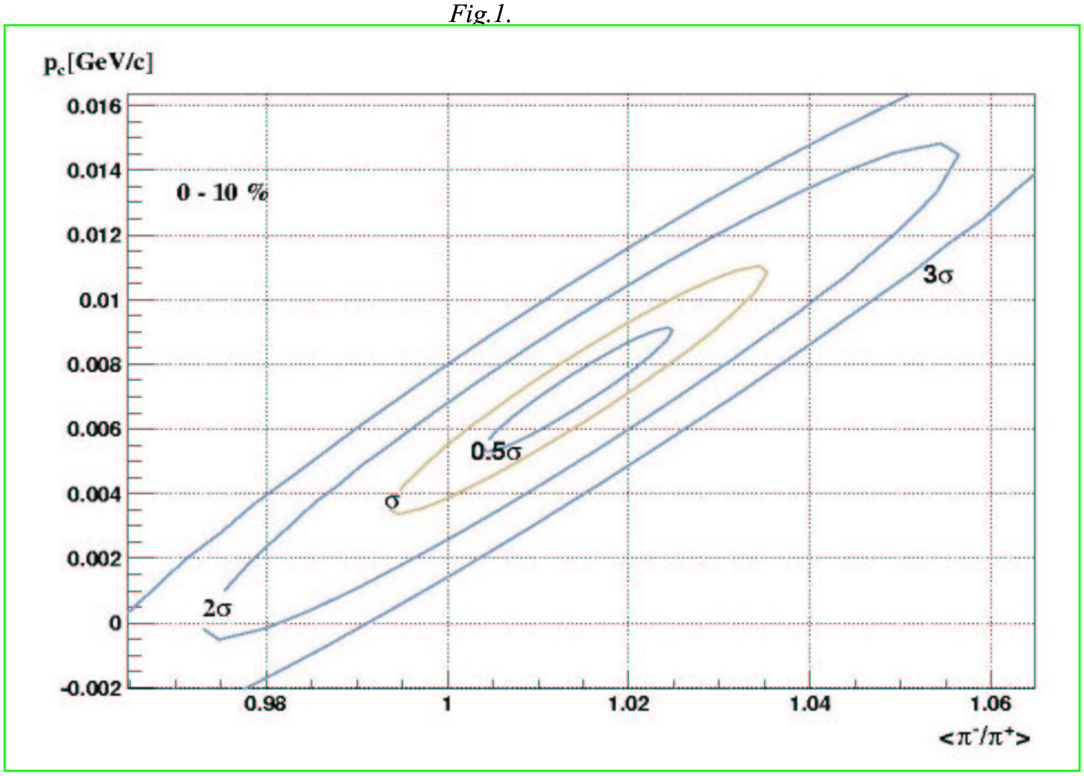

p_c[GeV/c]
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
-0.002
0 - 10 %
3σ
0.5σ
σ
2σ
0.98
1
1.02
1.04
1.06
$<\pi^-/\pi^+>$

Fig.2.

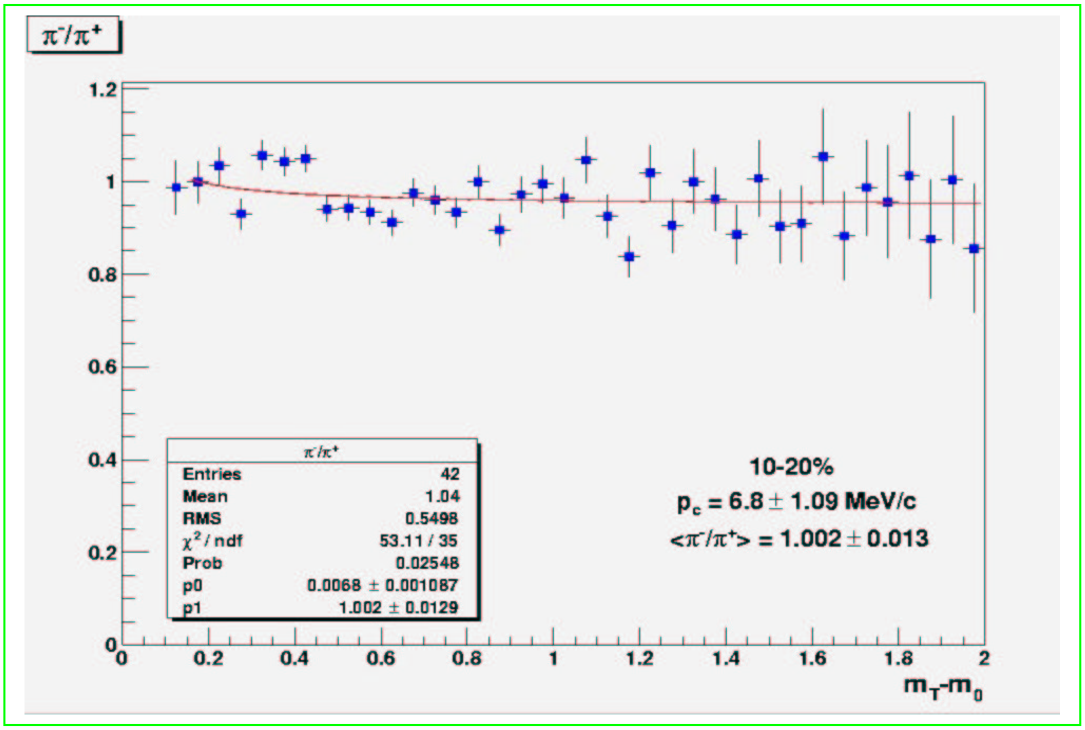

π^-/π^+
1.2
1
0.8
0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
m_T-m_0
π^-/π^+
Entries 42
Mean 1.04
RMS 0.5498
χ^2 / ndf 53.11 / 35
Prob 0.02548
p0 0.0068 ± 0.001087
p1 1.002 ± 0.0129
10-20%
p_c = 6.8 ± 1.09 MeV/c
$<\pi^-/\pi^+>$ = 1.002 ± 0.013

Fig.3.

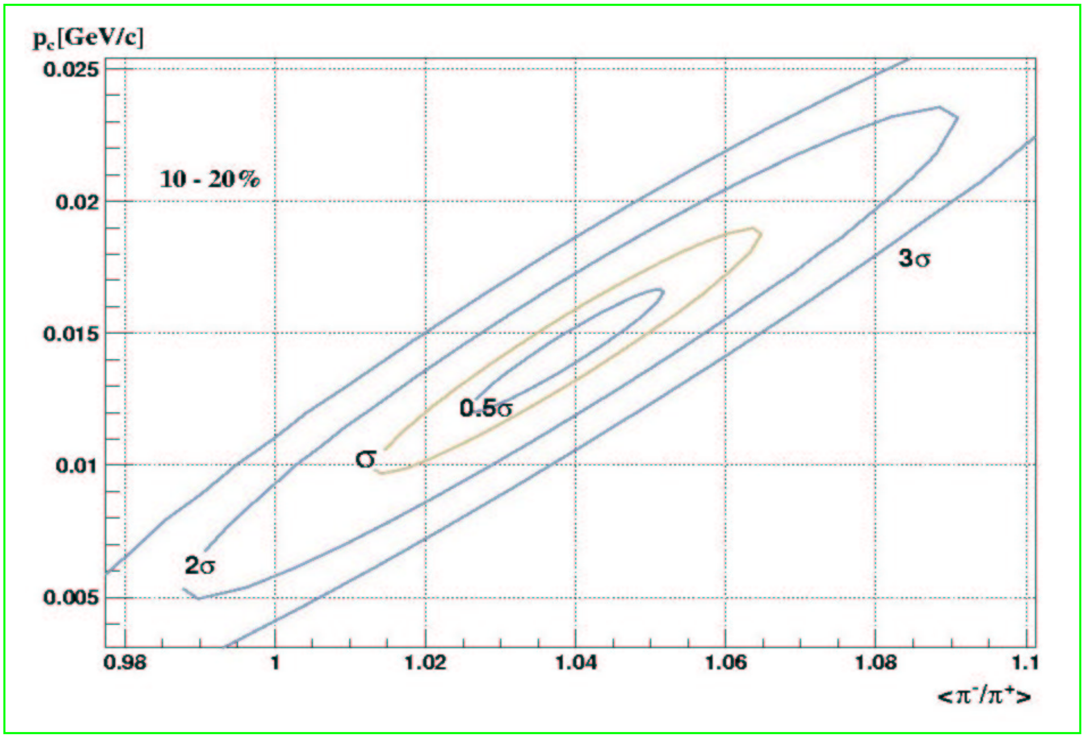

p_c[GeV/c]
0.025
0.02
0.015
0.01
0.005
10 - 20%
3σ
0.5σ
σ
2σ
0.98
1
1.02
1.04
1.06
1.08
1.1
$<\pi^-/\pi^+>$

Fig.4.

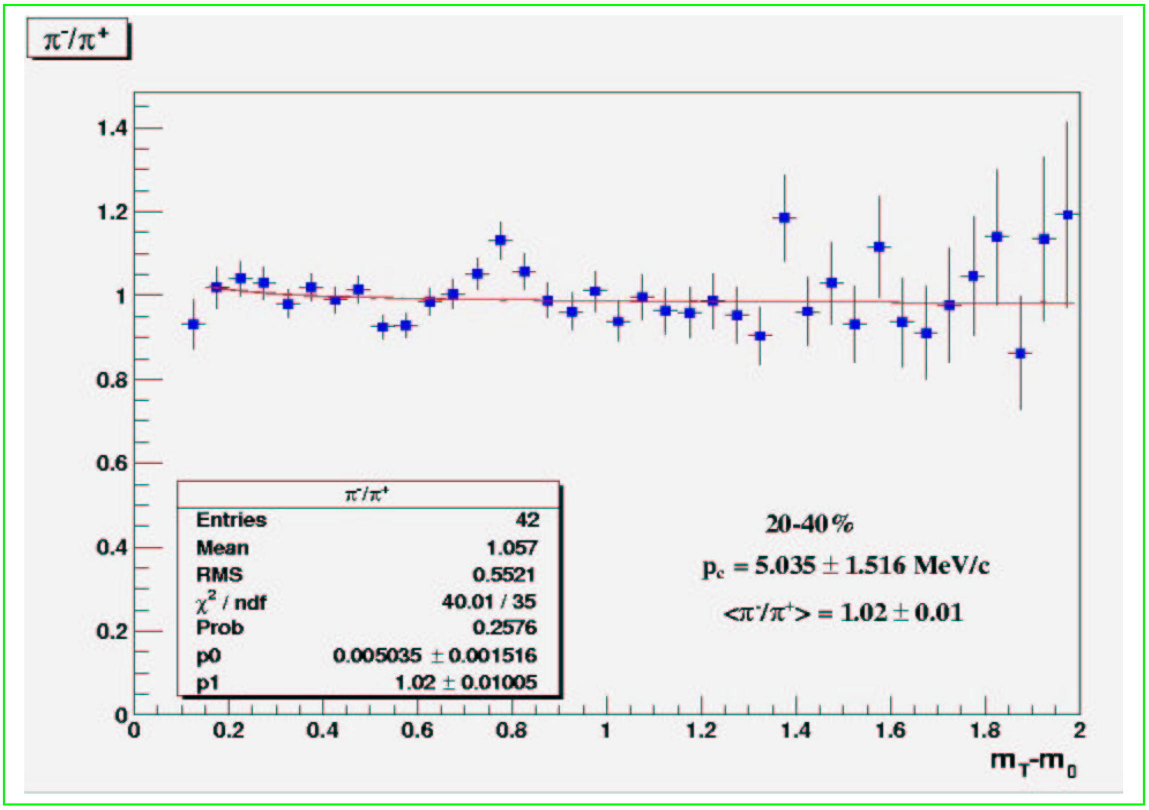

π^-/π^+
Entries 42
Mean 1.057
RMS 0.5521
χ^2 / ndf 40.01 / 35
Prob 0.2576
p0 0.005035 ± 0.001516
p1 1.02 ± 0.01005
20-40%
p_c = 5.035 ± 1.516 MeV/c
$<\pi^-/\pi^+>$ = 1.02 ± 0.01
m_T-m_0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2

Fig.5.

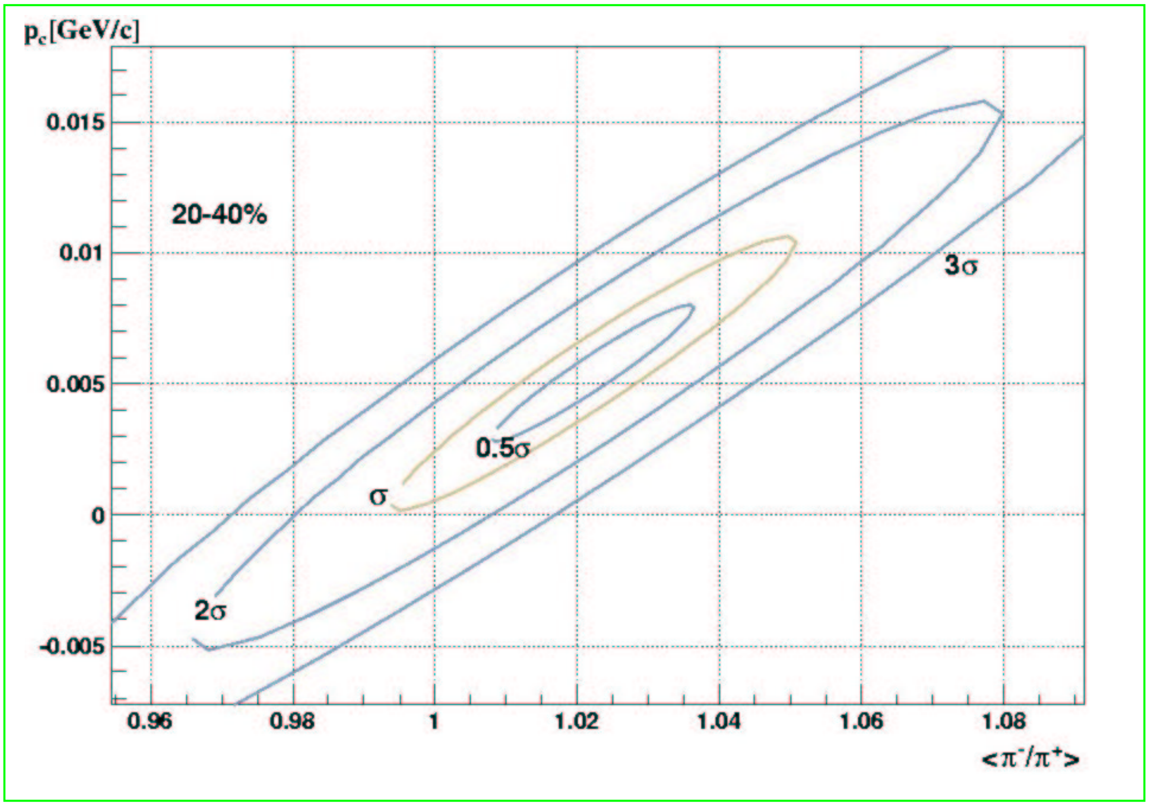

p_c[GeV/c]
20-40%
0.015
0.01
0.005
0
-0.005
0.5σ
σ
2σ
3σ
0.96
0.98
1
1.02
1.04
1.06
1.08
$<\pi^-/\pi^+>$

Fig.6.

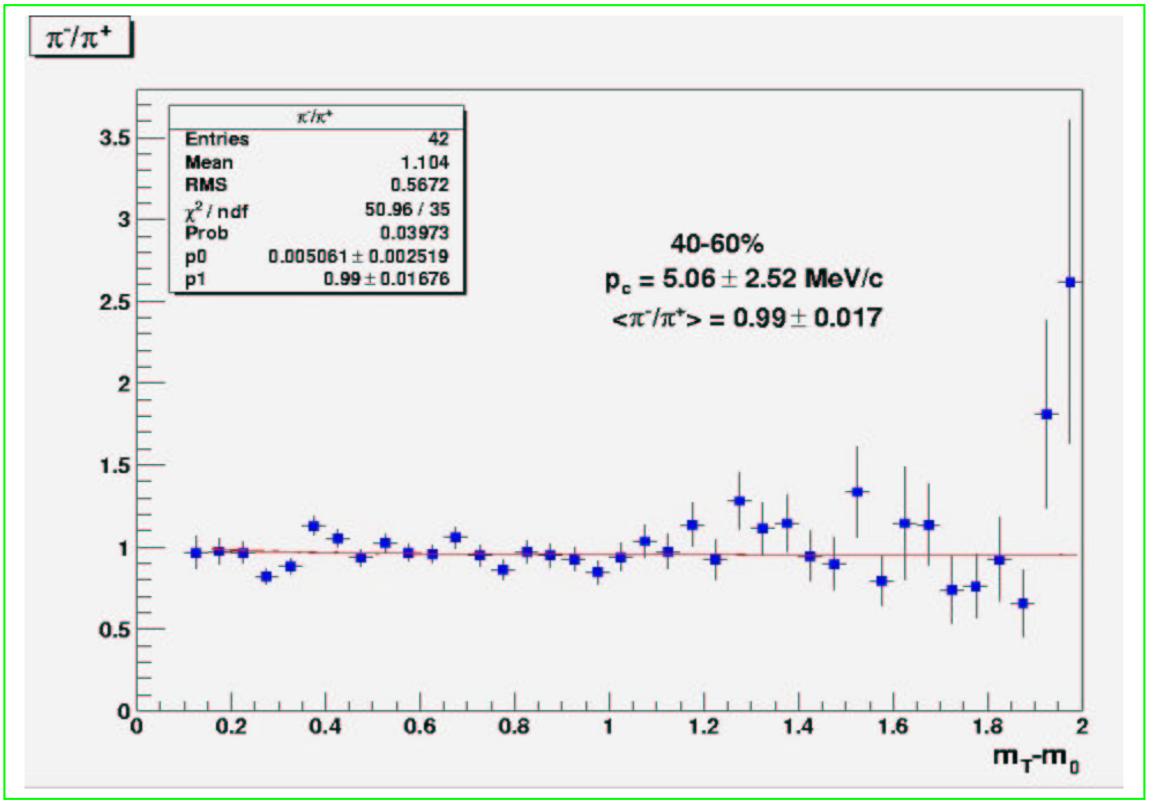

π^-/π^+
π^-/π^+
Entries 42
Mean 1.104
RMS 0.5672
χ^2 / ndf 50.96 / 35
Prob 0.03973
p0 0.005061 ± 0.002519
p1 0.99 ± 0.01676
40-60%
p_c = 5.06 ± 2.52 MeV/c
$<\pi^-/\pi^+>$ = 0.99 ± 0.017
0
0.5
1
1.5
2
2.5
3
3.5
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
m_T-m_0

Fig.7.

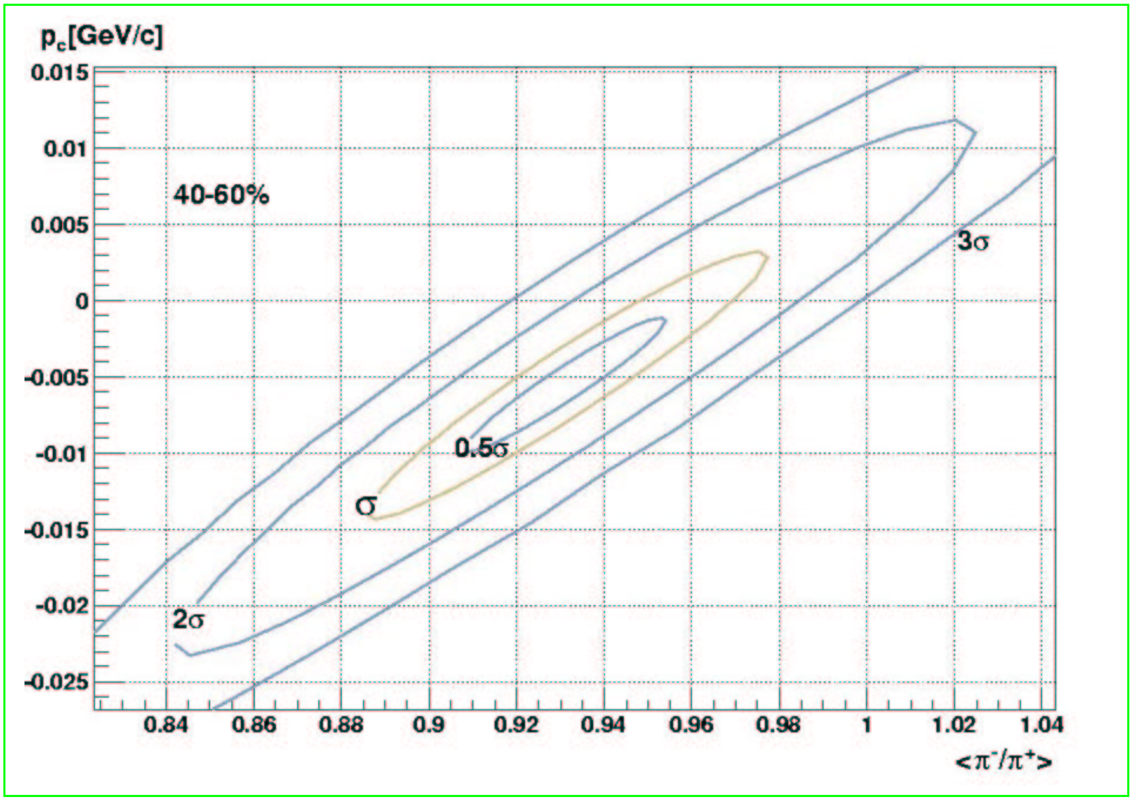
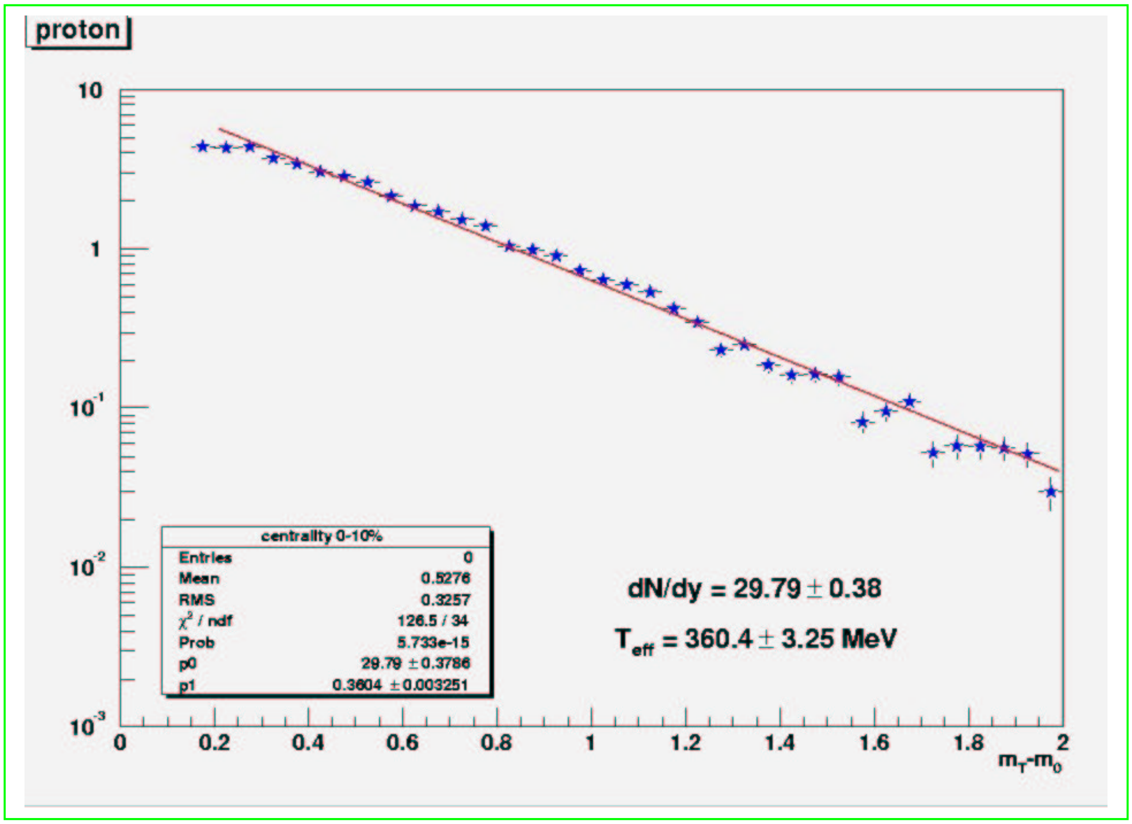

p_c[GeV/c]
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
-0.02
-0.025
40-60%
3σ
0.5σ
σ
2σ
0.84
0.86
0.88
0.9
0.92
0.94
0.96
0.98
1
1.02
1.04
$<\pi^-/\pi^+>$

Fig.8.

Fig.9.


proton
10
1
10^{-1}
10^{-2}
10^{-3}
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
m_T-m_0
centrality 0-10%
Entries 0
Mean 0.5276
RMS 0.3257
χ^2 / ndf 126.5 / 34
Prob 5.733e-15
p0 29.79 ± 0.3786
p1 0.3604 ± 0.003251
dN/dy = 29.79 ± 0.38
T_{eff} = 360.4 ± 3.25 MeV