Production of Mesons and Baryons at High Rapidity and High P_T in Proton-Proton Collisions at $\sqrt{s} = 200\,\mathrm{GeV}$

I. Arsene[12], I. G. Bearden[7], D. Beavis[1], S. Bekele[11], C. Besliu[10], B. Budick[6], H. Bøggild[7], C. Chasman[1], C. H. Christensen[7], R. Debbe[1], J. J. Gaardhøje[7], K. Hagel[8], H. Ito[1], A. Jipa[10], E. B. Johnson[11], C. E. Jørgensen[7], R. Karabowicz[4], E. J. Kim[1,11], T. M. Larsen[12], J. H. Lee[1], S. Lindal[12], R. Lystad[9], G. Løvhøiden[12], Z. Majka[4], M. Murray[11], J. Natowitz[8], B. S. Nielsen[7], R. Płaneta[4], F. Rami[2], F. Renault[7], C. Ristea[7], O. Ristea[10], D. Röhrich[9], B. H. Samset[12], S. J. Sanders[11], R. A. Scheetz[1], P. Staszel[4], T. S. Tveter[12], F. Videbæk[1], R. Wada[8], Z. Yin[9], H. Yang[9], and I. S. Zgura[13]

The BRAHMS Collaboration

[1] Brookhaven National Laboratory, Upton, New York 11973

[2] Institut Pluridisciplinaire Hubert Curien and Université Louis Pasteur, Strasbourg, France

[4] Smoluchkowski Inst. of Physics, Jagiellonian University, Krakow, Poland

[6] New York University, New York 10003

[7] Niels Bohr Institute, Blegdamsvej 17, University of Copenhagen, Copenhagen 2100, Denmark

[8] Texas A&M University, College Station, Texas, 17843

[9] University of Bergen, Department of Physics, Bergen, Norway

[10] University of Bucharest, Romania

[11] University of Kansas, Lawerence, Kansas 66049

[12] University of Oslo, Department of Physics, Oslo, Norway

[13] Institute for Space Science, Bucharest, Romania

(Dated: December 12, 2006)

Abstract

We present particle spectra at forward rapidities (2.95 and 3.3) from pp collisions at $\sqrt(s) = 200$ GeV. Large proton to pion ratios are observed at values of transverse momentum that extend up to 3-4 GeV/c. Such protons have momenta of order 30-35GeV. Next-to-leading order perturbative QCD calculations describe well the production of pions and kaons but fail to account for the large proton yields. The description of baryon transport in the most current QCD calculations appears to be inadequate. This may reflect our ignorance of the $low - x$ part of the proton wave function.

PACS numbers: 13.85.Ni, 13.87.Fh, 25.75.Dw, 13.85.Hd, 25.75.-q

Even though proton-proton collisions are often used as a simple hadronic reference system to disentangle nuclear effects in p-A or A-A systems, much of that interaction remains unknown. Quantum Chromo Dynamics (QCD), the accepted theory of hadronic systems, has had impressive success in describing many aspects of these collisions, specially when the underlying partonic processes are hard and a perturbative approach is possible. Such an approach starts to be applicable at the CERN ISR energies ($\sqrt{s} = 30 - 60$GeV), but only near mid-rapidity [1, 2]. Measurements of jet production and neutral pion production from anti-proton+proton collisions at higher energies at the SppS [3] and the TEVATRON [4] show that those systems can be well described perturbatively in a wide range of rapidities. The RHIC program at BNL has brought the focus back to proton-proton collisions at $\sqrt{s} = 200\,\mathrm{GeV}$ as part of its Heavy Ion and polarized proton studies with an impressive array of probes that range from fully identified hadrons in a wide rapidity range, direct photons, heavy quark production and jets. Calculations based on perturbative QCD where the partonic cross sections are calculated up to Next-To-Leading-Order level of accuracy (NLO pQCD) [5, 6] reproduce the measured yields of neutral pions and direct photons at mid-rapidity [7, 8] and are also successful in describing neutral pion production at high rapidity [9] measured at RHIC.

This letter reports recent measurements of minimum bias differential cross sections at high rapidity for identified charged hadrons produced in polarized p+p collisions at $\sqrt{s} = 200\,\mathrm{GeV}$ at RHIC in a data sample corresponding to an integrated luminosity of 2.4 pb^{-1}. Yields of charged pions, kaons, protons and their anti-particles at high rapidity have not been measured before at this energy, and a comparison of these data to a QCD framework contributes to the further understanding of the hadron-hadron interaction. The detailed studies of protons and anti-protons at high rapidity presented here bring new insights into the mechanism driving baryon transport in hadronic interactions.

Collider measurements at high rapidities ($y_{beam} = 5.4$ at RHIC) offer a window to an interesting region of the proton wave function; the kinematics of the collision at the partonic level is skewed such that one of the protons is probed at small values of fractional longitudinal momentum x by valence quarks from the other proton that have higher values of x. The nucleon internal structure has been well measured for a wide range of x values, but the *small-x* components are not fully explored and high rapidity measurements are an appropriate tool to expand the applicability of QCD. These data will serve as a reference to understand the evolution of the gold wave function with rapidity observed in d+Au collisions, and the formation of a dense and opaque colored medium in Au+Au collisions [**?**].

The data were taken with the BRAHMS forward spectrometer set at 4 and 2.3^o with respect to the beam [14]. These settings correspond to y=2.95 and 3.30 respectively. At these two rapidities the acceptance and particle identification allow us to reach large values of p_T, which is essential for testing the ability of NLO pQCD to reproduce the measured yields.

The minimum bias trigger used in these measurements was defined with a set Cherenkov radiators (CC) placed symmetrically with respect to the nominal interaction point and covering pseudo-rapidities that range from 3.26 to 5.25. This trigger required that at least one hit is detected in both sides of the array, and it is estimated that it is sensitive to $70 \pm 5\%$ of the total inelastic proton-proton cross section of 41 mb. The data used for this analysis was collected with an spectrometer trigger defined by three scintillator hodoscopes, one just after the first dipole magnet, a second one at 8.80 m, and a third one after the last tracking station, 18.9 m away from the nominal interaction point. GEANT simulations of the experiment with input events generated by PYTHIA [15] have been used to estimate the bias introduced by the CC detectors in the trigger. The deduced correction was applied to all spectra and is equal to 14.7$\pm$1.%, approximately independent of p_T and rapidity. The CC detectors have good timing resolution and were used to define the position of the interaction along the beam line with a resolution of approximately 2 cm. The present analyzes was done with charged particles that originated from an interaction vertex in the range of $\pm$40 cm. The transverse polarization of each beam bunch (arranged to point up or down in an alternating way) is estimated to have a negligible contribution to the inclusive cross-sections presented here: even though the bunch intensities for opposite polarizations can differ by as much as 10%, the asymmetries in produced particles were measured and have small values (2-8%) resulting in a net effect smaller than 1%.

Invariant cross sections were extracted in narrow ($\Delta y = 0.1$) rapidity bins centered at y=2.95 and y = 3.3, respectively. Each distribution is obtained from the merging of up to five magnetic field settings. The data are corrected for the spectrometer geometrical acceptance, multiple scattering, weak decays and absorption in the material along the path of the detected particles. Track reconstruction efficiencies in the order of 80-90% were obtained from careful study of the data and their effect was included in the extraction of the

$p_T[GeV/c]$	vertex location	normalization	PID (π)	decay and absopt.	p resol.
0 - 1	5.6	1.5	5.	2	1
1 - 3	11.	1.5	8	2	1
3 - 6	11	1.5	13	2	3

TABLE I: Estimated systematic errors shown as a per-cent of the measured cross-sections presented in this letter.

cross sections. Particle identification is done with the BRAHMS Ring Imaging Cherenkov detector (RICH) [16]. The efficiency of this detector has been studied with pions identified with a scintillator time-of-flight counter in an overlapping momentum range and reaches an upper value of 97%. The low momentum part of the proton spectra is done using the RICH in veto mode.

The momentum resolution of the spectrometers, δp, is calculated from the angular resolution of the tracking detectors. If p is in GeV/c $\delta p/p = 0.0008p$ at the highest field setting. From a comparison of the 3 independent spectrometer measurements and the momentum extracted from the ring radius in the RICH we estimate that our systematic error on the absolute momentum scale is less than 1%. We have identified several sources of possible systematic error and they are listed in Table I for three momentum ranges.

Figure 1 shows the invariant cross sections for $\pi^{\pm}, K^{\pm}, p$ and $\bar{p}$ versus p_T at y=2.95 and 3.3. For each bin the data were placed at p_T values such that the cross-section at those points equals the average cross section calculated in the bin. The yields of produced particles at high p_T drop quickly as rapidity changes from 2.95 to 3.3, in contrast with those for protons which vary little with rapidity. The upper panels of Fig. 2 show the π^-/π^+ ratio with a $p_T$dependence consistent with pion production dominated by valence quark fragmentation as it tends toward a value of 1/2. The small value of the $\bar{p}/p$ ratios shown in the middle panels are a clear indication that proton and anti-protons at these high rapidities are not produced by a common mechanism like $g \to p$ fragmentation. The bottom panels of Fig. 2 show the p/π^+ ratio as solid triangles and the $\bar{p}/\pi^-$ ratio with open circles at y=2.95 and y=3.3. The dashed line is maximum value for the measured $(p+\bar{p})/(\pi^+ + \pi^-)$ ratio in $e^+ + e^-$ annihilation at 91.2 GeV [18]. The abundance of baryons compared to that of mesons at these high rapidities shows a marked deviation from a factorized description of cross sections that makes use of conventional fragmentation functions extracted from inclusive hadron production in e^+e^- annihilation. The difference between p/π^+ and $\bar{p}/\pi^-$ at y=3.3 is remarkable and must be mainly related to the way baryon number is transported by the collisions from its initial location at both beam rapidities. What remains an open question is the mechanism that gives these protons such high transverse momentum.

We have compared our differential cross-sections with NLO pQCD calculations evaluated at equal factorization and renormalization scales, $\mu \equiv \mu_F = \mu_R = p_T$, using the CTEQ6 parton distribution functions and a modified version of the "Kniehl-Kramer-Potter" (KKP) set of fragmentation functions [21] referred here as mKKP, as well as the "Kretzer" K set [22]. The KKP set includes functions that fragment into the sums $\pi^+ + \pi^-$, $K^+ + K^-$ and $p+\bar{p}$. Modifications were necessary to obtain functions producing separate charges for π and K. These modifications involve the following operations[17]: to obtain the fragmentation functions producing π^+, the functions fragmenting favored light quarks $u, \bar{d}$ into π^0 were multiplied by $(1 + z)$ (e.g. $D_u^{\pi^+} = (1 + z) D_u^{\pi^0}$ with $D_u^{\pi^0} = \frac{1}{2} D_u^{\pi^+ + \pi^-}$) where z is the fraction of the parton momentum carried by the hadron, and the functions fragmenting unfavored quarks $\bar{u}, d$ into π^0 by $1 - z$. The same operation is done for π^-, but this time the favored quarks are $\bar{u}$ and d. The fragmentation functions of strange quarks and gluons are left unmodified. Similar modifications were applied to obtain fragmentation functions into K^+ and K^-, but this time, the starting functions were the ones fragmenting $u, \bar{u}, s, \bar{s}$ into the sum $K^+ + K^-$. The agreement between the NLO calculations that include the mKKP fragmentation functions and the measured pion cross sections is remarkable (within 20% above 1.5 GeV/c) even though the modifications applied can be considered as "crude". Similar good agreement was obtained for neutral pions at y=0 [7] and at y=3.8 [9] at RHIC. The agreement between the calculated and the measured kaon cross-sections is equally good. The difference between the mKKP and Kretzer parametrizations is driven by higher contributions from gluons fragmenting into pions, such difference has been identified as an indication that the gg and gq processes dominate the interactions at mid-rapidity [7], these results indicate that such continues to be the case at high rapidity.

An updated version of fragmentation functions that we will refer to as the "Albino, Kniehl and Kramer" (AKK) set [19] has been extracted from more data made available recently. It reproduces well the $p+\bar{p}$ distributions at mid-rapidity measured by the STAR collaboration

[20]. But the small $\bar{p}/p$ ratio measured at high rapidity would contradict the high rate of $g \rightarrow p$ fragmentation that the AKK functions entails.

The comparison between $(p + \bar{p})$ and the NLO calculation with the standard KKP set is off by a factor of ~ 8. In contrast, the AKK set does a better job but its use at these high rapidities is in conflict with the small and rapidly decreasing $\bar{p}/p$ ratio shown in the middle panels of Fig. 2 whereas the AKK with more gluons fragmenting into roughly equal numbers of p and $\bar{p}$, would produce ratios with values closer to 1.

In summary, unbiased invariant cross sections of identified charged particles as function of $p_T$were measured at high rapidity, we find the abundance of protons with $p_T$high values at these high rapidities puzzling as it deviates from the expected "soft" nature of baryon transport. NLO pQCD calculations reproduce reasonably well the produced particle (pions and kaons) distributions but the sum of protons and anti-protons cannot be described well unless one introduces additional gluon fragmentation into proton in contradiction with the measured $\bar{p}/p$ ratio. These results show a limitation of the factorized description of p+p cross sections because it does not include the effects of baryon transport that, as the data show, extend to intermediate values of p_T. It may also be stated that NLO calculations may not applicable at p_T values comparable to the scale of the system, in this case the mass of protons.

We thank Werner Vogelsang for providing us with the NLO pQCD calculations shown in this letter as well as many fruitful discussions during the preparation of this manuscript. This work was supported by the Office of Nuclear Physics of the U.S. Department of Energy, the Danish Natural Science Research Council, the Research Council of Norway, the Polish State Committee for Scientific Research (KBN) and the Romanian Ministry of Research.

[1] A. Breakstone *et al.*, Z. Phys. **C69** 55, (1995).

[2] C. Bourrely and J. Soffer Eur.Phys.J. **C36** 371 (2004).

[3] J. Alitti *et al.*, Phys. Lett. **B257** 232, (1991).

[4] B. Abbott *et al.*, Phys. Rev. Lett. **86** 1707 (2001).

[5] B. Jager, A. Schafer, M. Stratmann and W. Vogelsang, Phys. Rev. D **67**, 054005 (2003).

[6] D. de Florian, Phys. Rev. D **67**, 054004 (2003).

[7] S.S. Adler *et al.*, Phys. Rev. Lett. **91**, 241803 (2003).

[8] S.S. Adler *et al.*, Phys. Rev. **D71**, 071102(R) (2005).

[9] J. Adams *et al.*, Phys. Rev. Lett. **92** 171801 (2004).

[10] I. Arsene *et al.*, Phys. Rev. Lett. **93** 242303, (2004).

[11] D. Kharzeev, Y. V. Kovchegov and K. Tuchin Phys. Rev. **D68**, 094013, (2003).

[12] B.B. Back *et al.*, Phys. Rev. Lett. **91** (2003) 72302; S.S. Adler *et al.*, Phys. Rev. Lett. **91** (2003) 72303; J. Adams *et al.*, Phys. Rev. Lett. **91** (2003) 72304.

[13] I. Arsene *et al.*, Phys. Rev. Lett. **91**, 072305 (2003).

[14] M. Adamczyk *et al.*, Nuclear Instruments and Methods, **A499** 437 (2003).

[15] T. Sjöstrand, *et al.*, Comp. Phys. Commun. **135**, 238, (2001). Version 6.303 was used.

[16] R. Debbe *et al.*, Nuclear Instruments and Methods, A (in print)

[17] W. Vogelsang, private communication..

[18] P. Abreu *et al.*, Eur. Phys. J. **C17**, 207, (2000); R. Barate *et al.*, Phys. Rept **294**, 1-165, (1998).

[19] S. Albino, B.A. Kniehl and G. Kramer, Nucl. Phys. **B725**, 181, (2005).

[20] J. Adams *et al.*, nucl-ex/0601033, (2006).

[21] B.A. Kniehl *et al.*, Nucl. Phys. **B597**, 337 (2001).

[22] S. Kretzer *et al*, Eur. Phys. J. **C22**, 269 (2001).

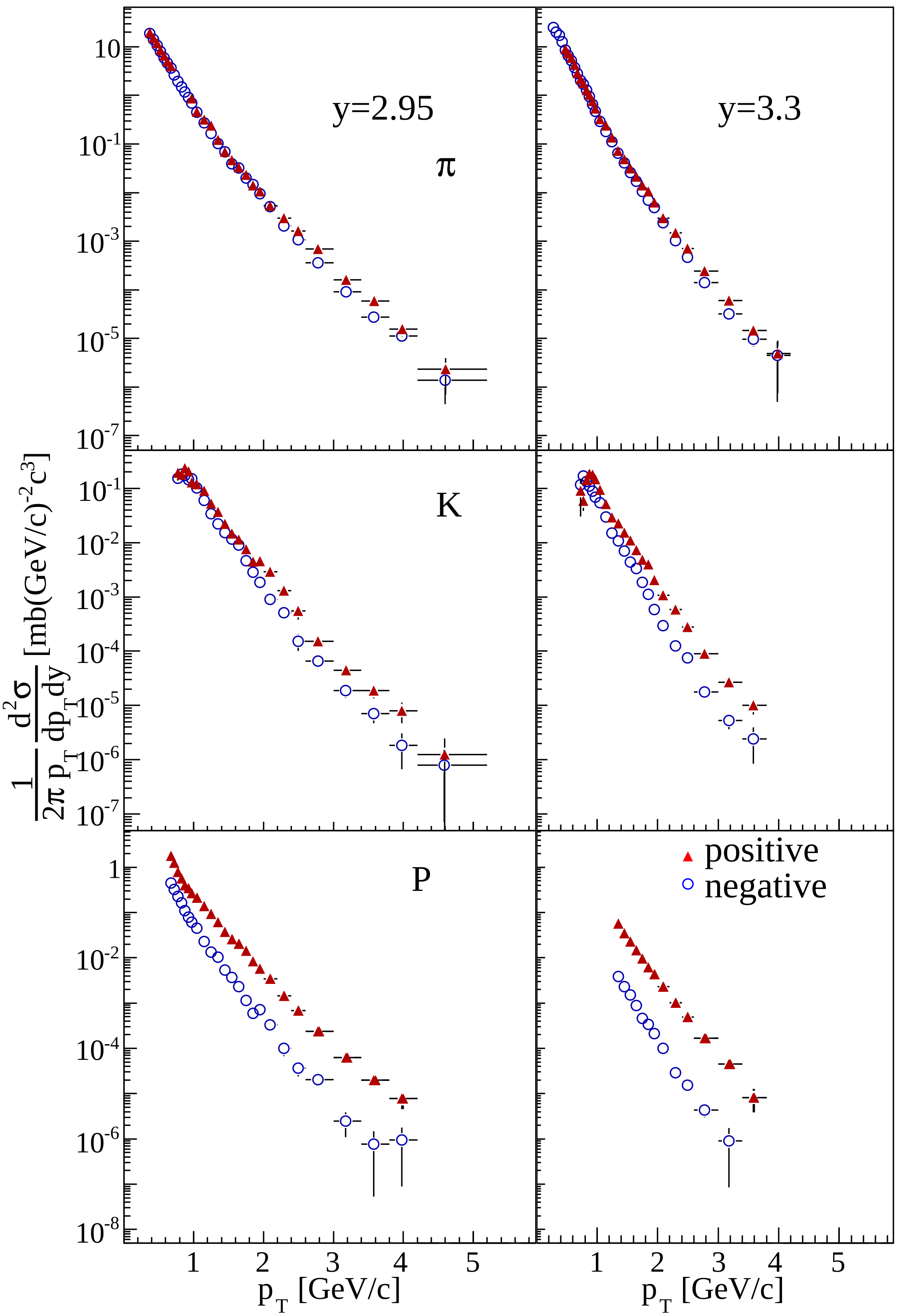

FIG. 1: Invariant cross section distributions for pion, kaons protons and anti-protons produced in p+p collisions at $\sqrt{s} = 200\,\text{GeV}$ at rapidities y=2.95 (left panels) and y = 3.3 (right panels). In all panels, positive charged particles are shown with filled triangles (red in online version) and

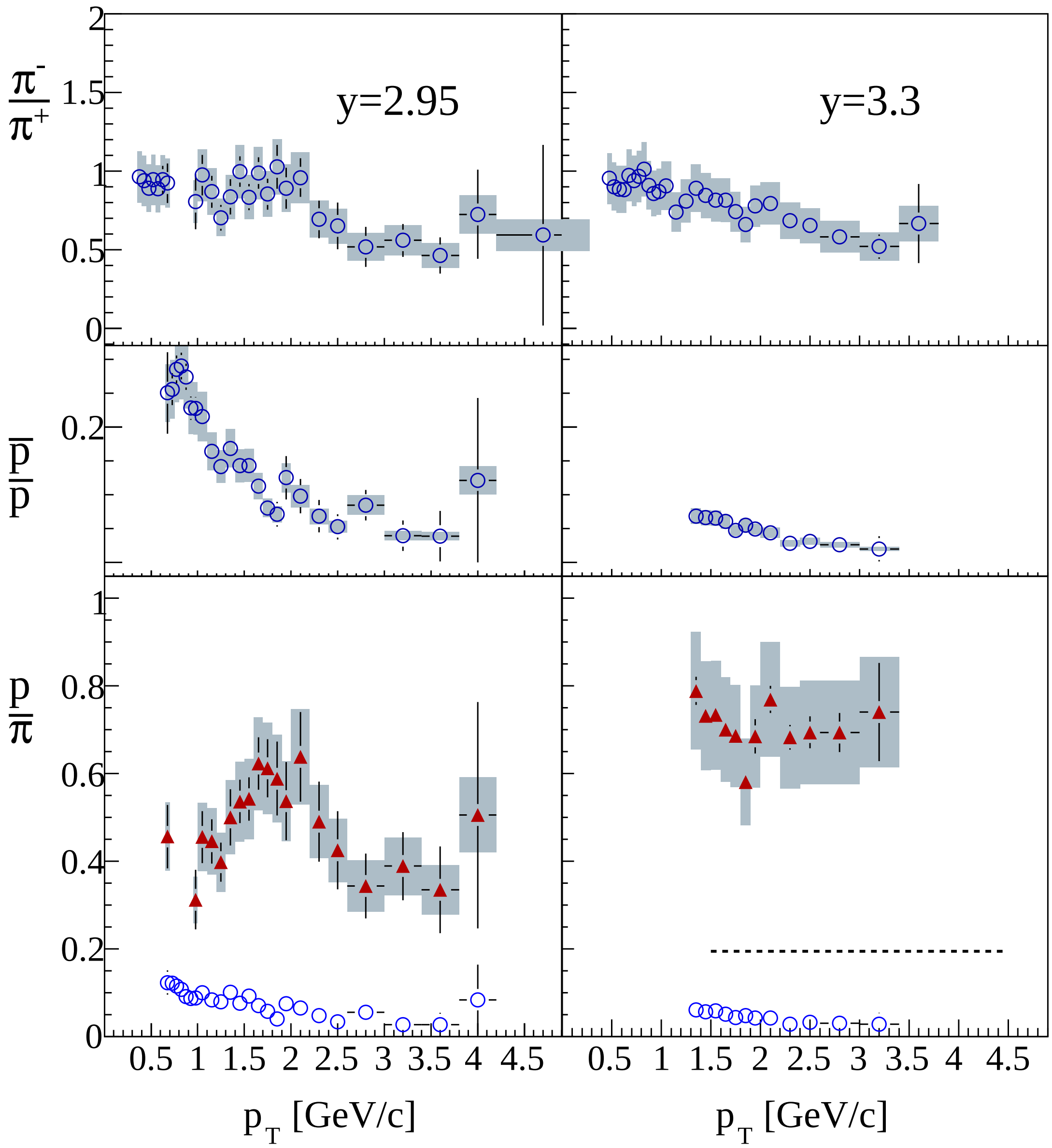

FIG. 2: Particle ratios versus p_T at y=2.95 and 3.3. Top) π^-/π^+, Middle) $\bar{p}/p$ and Bottom) p/pi^+ (red circles) and $\bar{p}/\pi^-$ (blue squares). The dashed line shows an upper limit for the p/π^+ ratio from e^+e^- collisions.

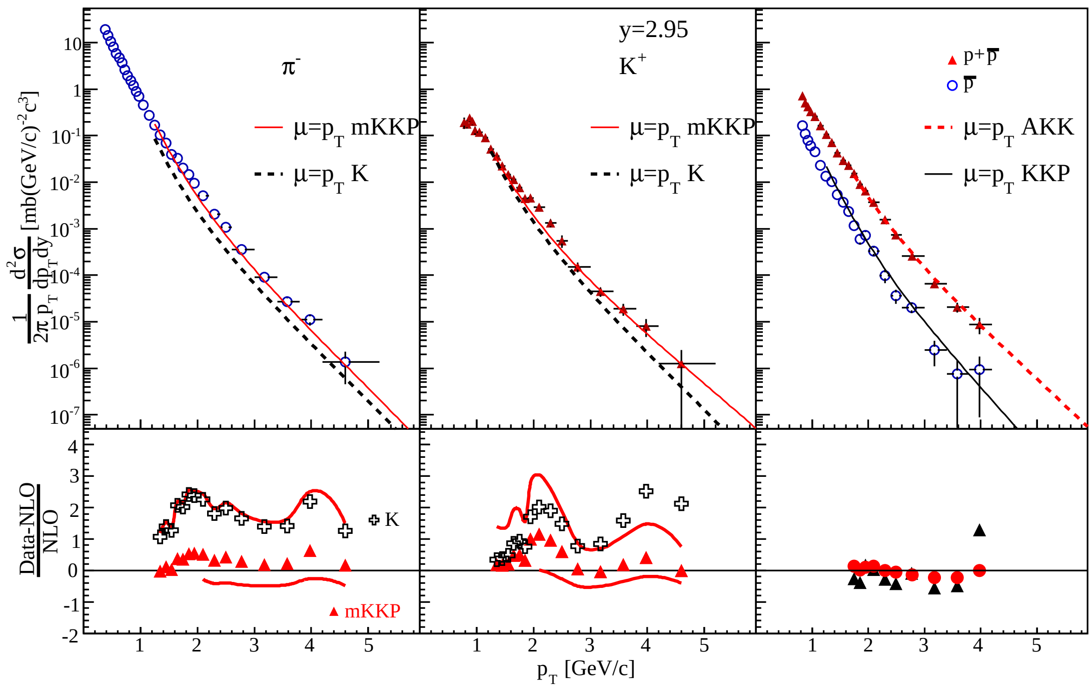

FIG. 3: Top) Comparison of invariant cross sections for π^-, K^+, $\bar{p}$ and the sum $\bar{p}+p$ at y=2.95 and NLO calculations. The calculations were performed with factorization and renormalization scales both set to p_T. The mKKP set of fragmentation functions (full red line online) produce the best agreement with the π^- and K^+ data. The sum $\bar{p}+p$ is well described by calculations that use the AKK set (dashed red line in online version) while the KKP describes the $\bar{p}$s (see text for details). Bottom) Relative differences between data and calculations. For the mesons the top smooth curve shows the effect of setting $\mu = 2p_T$and the bottom curve $\mu = 1/2p_T$. For the baryons the (red) filled circles are $\bar{p}+p$ data vs the AKK set while the filled triangles are for $\bar{p}$s versus the KKP set.