COLLECTIVE SEA-GULL EFFECT IN
π^+p INTERACTIONS AT 250 GeV/c

EHS/NA22 Collaboration

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ABSTRACT: A collective "sea-gull" effect is observed for a system of fast hadrons produced in the fragmentation regions of non-diffractive π^+p-interactions at 250 GeV/c. The effect is not reproduced by the FRITIOF fragmentation model in its details. It is demonstrated that hard-like processes, both in the collision phase and in the fragmentation phase, are not properly treated in the model.

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As observed recently [1], scaling violation in the dependence of the average transverse momentum $\langle p_T \rangle$ on Feynman x_F (lifting of the so-called "sea-gull" wings with increasing energy $\sqrt{s}$) does not only occur in hard collisions such as $e^+ e^-$ annihilation [2] or lepton-nucleon scattering [3-5], but also in "soft" hadron-hadron collisions. In hard collisions, the non-scaling effects are attributed to hard gluon emission by one or two leading quarks, but the underlying mechanism is not yet established in soft hadron-hadron collisions.

In meson-proton collisions, strong non-scaling effects are observed for hadrons produced in the meson fragmentation ($x_F > 0.2$) and proton fragmentation ($x_F < -0.4$) regions [1], i.e. for the fast products of valence quark (or diquark) hadronization. In the fragmentation regions, the s-dependence of $\langle p_T \rangle$ is not reproduced by currently used models of soft hadronic interactions [6-8]. This and the comparison to $e^+ e^-$ and lh collisions indicates the presence of hard-like effects causing larger values of $\langle p_T \rangle$ than predicted so far.

In the search for an explanation, it is important to establish in what phase of the interaction these hard-like effects might occur: in the collision phase or in the fragmentation (hadronization) phase. Depending on the type of hard-like process, a large p_T of a fast hadron (e.g. with $|x_F| \gtrsim 0.2$) produced in the beam (target) fragmentation region should be balanced by the transverse momentum of hadrons produced either (a) in the central region, (b) in the target (beam) fragmentation region, or (c) by other hadrons produced in the same fragmentation region.

Hard-like processes are schematically shown in Fig. 1. Fig. 1a represents the type (a) processes: gluon bremsstrahlung by the interacting constituent of the projectile [9] or quark-gluon scattering, both leading to gluon emission with relatively large p_T and small $|x_F|$, followed by gluon hadronization into the central rapidity region. Fig. 1b represents the type (b) process: quark-quark (diquark) scattering [10] leading to large-p_T hadron production in the two fragmentation regions. Finally, Fig. 1c represents the type (c) processes: a gluon with a comparatively large p_T and large $|x_F|$ being radiated by the spectator quark of the incident hadron [9] or by the excited state of the collided hadron behaving as a colour antenna [11].

Note, that the type (c) processes also include the "high-twist" processes of the direct pion coupling [12] leading to the production of a pair of large-p_T jets in the pion fragmentation region (via sub-processes $\pi q_N \rightarrow gq$ and $\pi g_N \rightarrow q\bar{q}$, where the label N refers to the target nucleon constituent). However, as predicted theoretically [12] and observed experimentally [13], the rate of these processes is small (few percent) in a minimum-bias sample.

The hard-like processes of type (a) and (b) (Figs. 1a and 1b) take place in the collision phase, processes of type (c) (Fig. 1c) in the fragmentation phase of the hadronic interaction.

In case (c), hard-like effects observed in the single particle spectra [1] should, at least partially, be cancelled in the dependence of the collective transverse variable $P_T = |\Sigma \vec{p}_T|$ on the collective longitudinal variable $X_F = \Sigma x_F$, where the sums include the charged particles in the beam fragmentation or the target fragmentation region, respectively. On the other hand, for cases (a) and (b) no cancellation takes

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place within the fragmentation region and a hard-like effect will be observed in the X_F-dependence of P_T.

The study of the collective sea-gull effect for a system of hadrons produced in the fragmentation regions is, therefore, expected to give new information on the relative importance of these processes.

This paper is devoted to the experimental study of the "collective sea-gull" effect in π^+p-interactions at 250 GeV/c. A related analysis of the same data in terms of $\vec{p}_T$-compensation is reported in [14].

The experiment (NA22) has been performed at CERN in the European Hybrid Spectrometer (EHS), equipped with the Rapid Cycling Bubble Chamber (RCBC) and exposed to a 250 GeV/c tagged positive meson enriched beam. The experimental set-up and the trigger conditions are described in [15] and references given therein.

Events are accepted when measured and reconstructed charge multiplicity n are consistent, charge balance is satisfied, no electron (positron) is detected and the number of tracks with bad quality is restricted to 0,1,1,2 and 3 for charge multiplicity 2,4,6,8 and >8, respectively.

Charged-particle momenta are measured over the full solid angle with a resolution $\Delta p/p$ varying from a maximum of 2.5% at 30 GeV/c to around 1.5% above 100 GeV/c. Ionization information is used to identify protons up to 1.2 GeV/c and electrons (positrons) up to 200 MeV/c. All unidentified tracks are given the pion mass. For the present analysis, we exclude elastic and single-diffraction dissociation events with $n \leq 6$ [16]. After these cuts, the sample consists of about 86 000 π^+p events. These events are given weights according to the corrected inelastic non-single-diffractive multiplicity distribution [15].

We compare the data with two versions of the FRITIOF model: FRITIOF2.0 [7] and the recently proposed FRITIOF7.0 [17].

In the *collision phase*, the colliding hadrons emerge as two excited (colour singlet) strings. A primordial transverse momentum Q_{2T} is given to the string ends. This is assumed to have a Gaussian distribution with an average $\langle Q_{2T}^2 \rangle$. In both models, we use $\langle Q_{2T}^2 \rangle$=0.42 (GeV/c)^2 for the primordial transverse momentum. This value is similar to the one adopted in deep-inelastic μp and $\nu(\bar{\nu})$p interactions [4,18]. In version 7.0, also soft transverse momentum transfer Q_T takes place between the colliding hadrons according to a Gaussian with $\langle Q_T^2 \rangle$=0.01 (GeV/c)^2.

In addition, a hard parton-parton elastic scattering (Rutherford parton scattering, RPS) can take place in both versions with a comparatively large transverse momentum. The RPS involves mainly vee partons (gluons) and is usually associated by gluon bremsstrahlung. This leads to an increase of the multiplicity of particles produced in the central rapidity region. With a much smaller rate, the RPS also involves the valence quarks (cf Figs.1a-b) and can, therefore, give rise to relatively large transverse momentum of the leading hadrons. In version 7.0 the inclusion of RPS allows [17] to reproduce the high multiplicity tail of the charged particle distribution

measured recently in the NA22 experiment [15].

In the *fragmentation phase* both versions are based on the physical picture, according to which the extended string behaves as a colour dipole (antenna) radiating semihard gluons [11,17]. In the string c.m., the transverse momentum of radiated gluons is restricted by energy-momentum conservation, $k_\perp < (M/2)e^{-|y^*|}$ (where M is the dipole mass and y^* is the gluon rapidity in the string c.m.), and by the requirement that the gluon wavelength should exceed the transverse size L of the string, $k_\perp < \sqrt{\frac{\pi M}{L}}e^{-|y^*|/2}$, where L is estimated to be about $L \approx 0.6\text{-}0.9$fm [17]. At our energy ($\sqrt{s}=21.7$ GeV) the mass M is, according to [19], on average less than $0.1^*\sqrt{s}$. Evidently, these restrictions limit also the transverse momentum of hadrons produced in string fragmentation, including hadrons with valence quark content, which can acquire a recoil p_T as a consequence of the gluon radiation.

One should stress that the character of the string radiation can be influenced by the RPS included in the FRITIOF7.0 version. The RPS disturbs strongly the colour field of the string, which now acts as two dipoles with smaller mass, radiating gluons with smaller $k_\perp$ as compared with the case of one undisturbed string.

In both versions, the width of the Gaussian p_x and p_y transverse momentum distributions for direct (primary) hadrons is $\sigma_x = \sigma_y = 0.37$ GeV/c as in the OPAL setting [20]. With these parameters we describe in particular the p_T^2 distribution of our data up to the experimentally measured values of 4.5 (GeV/c)^2 (not shown).

To be consistent with the experimental cuts, all particles except protons with $p_{lab} < 1.2$ GeV/c are assumed to be pions and Monte Carlo events satisfying the "diffractive" criteria [16] are excluded.

In Fig. 2a we show the "sea-gull" ($\langle p_T \rangle$ as a function of x_F) for charged particles. As already observed in [1] for negative particles*, FRITIOF2.0 stays below the data over most of the x_F range, except in the central region. Also the new version FRIFIOF7.0 has problems and is even considerably worse in the π^+ fragmentation region. The structure near $-0.5 < x_F < -0.4$ is due to misidentification of protons in data and models.

In Fig. 2b, we show the sea-gull for charged particles with rapidity $|y| > y_{cut}$, where $y_{cut} = 2.5$. For $|x_F| < 0.5$, FRITIOF2.0 shows reasonable agreement; FRITIOF7.0 is too low in the π^+ fragmentation region. Both models fail for $|x_F| \gtrsim 0.8$.

The collective $\langle P_T \rangle$ is displayed in Figs. 3a-3c as a function of the collective X_F for clusters containing more than one charged particle with $|y| > y_{cut}$ in the same hemisphere. The maximum value of $\langle P_T \rangle$ is the same in beam and target fragmentation. The decrease of $\langle P_T \rangle_{max}$ from ~ 0.63 GeV/c to ~ 0.45 GeV/c when y_{cut} increases from 1.5 to 2.5 is due to the cut $|y| > y_{cut}$, which restricts p_T ($< \sqrt{s}|x_F|e^{-y_{cut}}$) as y_{cut} increases. Note also, that the value $|X_F|_{max}$ of $|X_F|$ at maximum $\langle P_T \rangle$ is shifting towards larger values with increasing y_{cut}: in the beam (target) fragmentation

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* The analysis [1] was based on negative particles in part (40%) of the final statistics.

region $|X_F|_{max}$ changes from 0.65 (0.55) to 0.75 (0.65).

Again, the experimental data are compared with predictions of FRITIOF2.0 and FRITIOF7.0. For y_{cut}=2.5, i.e. for a system of hadrons all emerging at cms production angles $\theta^* < 9^0$ or $\theta^* > 171^0$ (Fig. 3c), the models describe the data reasonably well. This is in contrast to the observation for single hadrons in Fig. 2b. A possible explanation is that the large transverse momentum of the fastest product of fragmentation is partially balanced by that of other fragmentation products within the same hemisphere. To verify this point, we plot in Fig. 4 the single particle $\langle p_T \rangle$ as a function of x_F for single charged particles from the clusters used in Fig. 3 (note the difference with Fig. 2, where *all* charged particles accepted by the corresponding rapidity cut have been used). Indeed, $\langle p_T \rangle$ is *larger* in the single particle "sea-gull" of Fig. 4c than $\langle P_T \rangle$ of the parent clusters in Fig. 3c.

As pointed out in the introduction, the X_F-dependence of the collective $\langle P_T \rangle$ originates from the collision phase of the interaction. As the models reproduce this dependence (Fig. 3c), one can conclude, that they properly include the hard-like effects in the collision phase (Figs. 1a and 1b), yielding fast hadrons at small angles. So, the hard-like effects observed in the single-particle "sea-gull" not reproduced by the models (cfr. Fig. 2b) seem to originate from the fragmentation phase of the interaction (Fig. 1c). The semi-hard mechanism of colour antenna radiation in the fragmentation phase underestimates the data at $x_F > 0.85$ in the FRITIOF2.0 model. This underestimation is much more significant and involves a larger interval of x_F (Fig. 2b) in the FRITIOF7.0 model, in which the transverse momentum of the radiated gluon is more restricted due to RPS of gluons.

The collective sea-gull for charged particles produced up to larger angles are presented in Fig. 3a with $y_{cut} = 1.5$ ($0 < \theta^* < 21^0$ or $159 < \theta^* < 180^0$) and Fig. 3b with $y_{cut} = 2$. The description by the models becomes less satisfactory than in Fig. 3c. Furthermore, comparing data for $y_{cut} = 1.5$ in Figs. 3a and 4a at $|x_F| \gtrsim 0.5$, the trend is opposite to that for $y_{cut} = 2.5$ in subfigures c. For $y_{cut} = 1.5$ the collective $\langle P_T \rangle$ now is indeed *larger* than the single particle $\langle p_T \rangle$. So, no compensation takes place in this case within the same hemisphere. The situation is consistent with the picture that a relatively large transverse momentum P_T is aquired by the fast hadron cluster in a hard scattering process as those sketched in Figs. 1a and/or 1b. The two models underestimate this effect. One can conclude, that hard-like effects in the inclusive production of fast hadrons at relatively large angles originate from the collision phase of the interaction, but are not properly included in the models.

Correlations between the collective transverse momentum P_T and the collective Feynman X_F are studied for a system of hadrons produced in one of the fragmentation regions of non-diffractive π^+p-interactions. The X_F-dependence of $\langle P_T \rangle$ has a characteristic sea-gull shape. Two cases seem to be distinguished by our data:

1. For a system of hadrons produced at small cms angle $\theta^* < 9^0$ or $\theta^* > 171^0$ (or at restricted $p_T < \sqrt{s}|x_F|e^{-y_{cut}}$), the collective sea-gull can be described by the FRITIOF models. For this sample, hard-like effects (manifesting themselves in the spectra of the individual particles) mainly originate from the fragmentation

phase. This phase is treated as colour-antenna radiation in the FRITIOF model, which, however, fails (especially in the FRITIOF7.0 version) in reproducing the single particle spectra.

2. However, when including larger emission angles ($\theta^* < 21^0$), the collective seagull effect is *underestimated* by these models. This suggests that hard-like processes yielding particles with comparatively large c.m. emission angle or large transverse momentum take place in the collision phase, but are not properly included in the models.

ACKNOWLEDGEMENT

REFERENCES

1. I.V. Ajinenko et al., NA22 Coll.: Phys. Lett. B197 (1987) 457
2. M. Althoff et al.: Z. Phys. C22 (1984) 307
3. M. Derrick et al.: Phys. Rev. D17 (1978) 1;
   P. Allen et al.: Nucl. Phys. B188 (1981) 1;
   D. Allasia et al.: Z. Phys. C27 (1985) 239
4. M. Arneodo et al.: Phys. Lett. B149 (1984) 415
5. B. Andersson, G. Gustafson, G. Ingelman, T. Sjöstrand: Phys. Rep. 97 (1983) 31
6. T. Ahmed et al., H1 Coll.: Phys. Lett. B298 (1993) 469
7. B. Andersson, G. Gustafson, B. Nilsson-Almqvist: Nucl. Phys. B281 (1987) 289; *A high energy string dynamics model for hadronic interactions*, Lund preprint LUT 87-6, unpubl.
8. A. Capella, U. Sukhatme, C.I. Tan, J. Tran Thanh Van: Phys. Lett. B81 (1974) 68; Z. Phys. C3 (1980) 329
9. J.F. Gunion, G. Bertsch: Phys. Rev. D25 (1982) 746
10. W. Ochs, T. Shimada: Phys. Lett. B215 (1988) 757 and Z. Phys. C49 (1991) 325
11. G. Gustafson: Nucl. Phys. B (Proc. Suppl.) 16 (1990) 441
12. E.L. Berger, S.J. Brodsky: Phys. Rev. D24 (1981) 2428
13. C. Naudet et al.: Phys. Rev. Lett. 56 (1986) 808
14. N.M. Agababyan et al., NA22 Coll.: *Transverse momentum compensation in $\pi^+ p$ interactions at 250 GeV/c*, Nijmegen preprint 363 (1993)
15. M. Adamus et al., NA22 Coll.: Z. Phys. C32 (1986) 475
16. M. Adamus et al., NA22 Coll.: Z. Phys. C39 (1988) 301
17. Hong Pi: *An event generator for interactions between hadrons and nuclei-FRITIOF version 7.0*, Lund preprint LU TP 91-28;
    B. Anderson, G. Gustafson, Hong Pi: Z. Phys. C57 (1993) 485
18. M. Arneodo et al.: Z. Phys. C36 (1987) 527
19. I.V. Ajinenko et al., NA22 Coll.: Z. Phys. C49 (1991) 367
20. M.Z. Akrawy et al.: Z. Phys. C47 (1990) 505

FIGURE CAPTIONS

Fig. 1 Hard-like processes in hadron-hadron interactions. **a-b** hard-like processes occuring in the collision stage: gluon emission or qg-scattering **a**, qq-scattering **b**; **c**: hard-like processes occuring in the fragmentation stage.

Fig. 2 The x_F-dependence of $\langle p_T \rangle$, **a** for hadrons, **b** for hadrons with $|y| > 2.5$. Dash-dotted curves are the FRITIOF2.0, solid curves are the FRITIOF7.0 predictions. The behaviour around $x_F = -0.5$ is due to the cut-off in proton identification.

Fig. 3 The X_F-dependence of $\langle P_T \rangle$ for a system of hadrons with $|y| > y_{cut}$. Dash-dotted curves are the FRITIOF2.0, solid curves FRITIOF7.0 predictions.

Fig. 4 The x_F-dependence of $\langle p_T \rangle$ for hadrons inside clusters of at least two hadrons, with $|y| > y_{cut}$. Dash-dotted curves are the FRITIOF2.0, solid curves FRITIOF7.0 predictions.
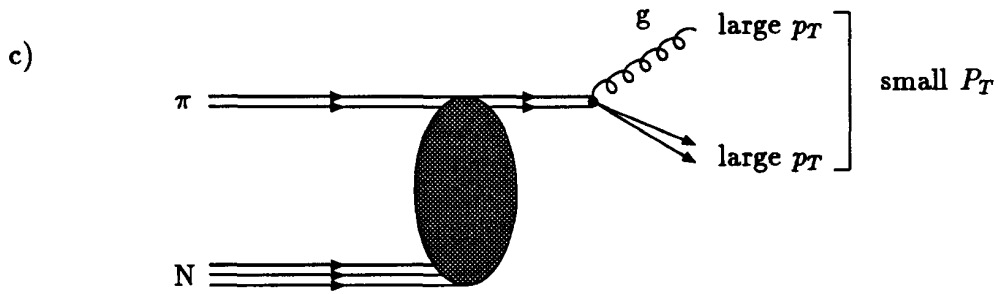
a)
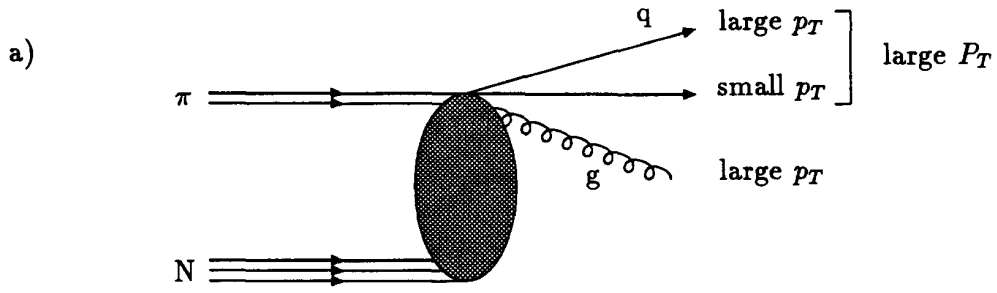
i) gluon bremsstrahlung by the interacting constituents of projectile
ii) $q_\pi g_N$ - scattering

b)
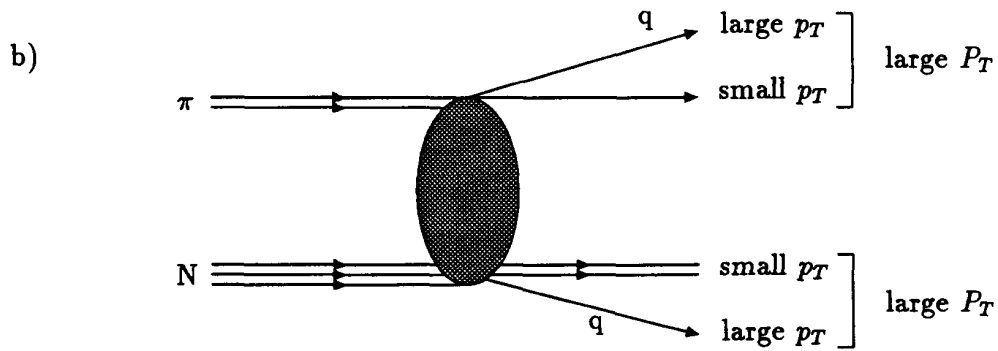
i) quark-quark(diquark) scattering

c)

i) gluon radiation by the spectator quark
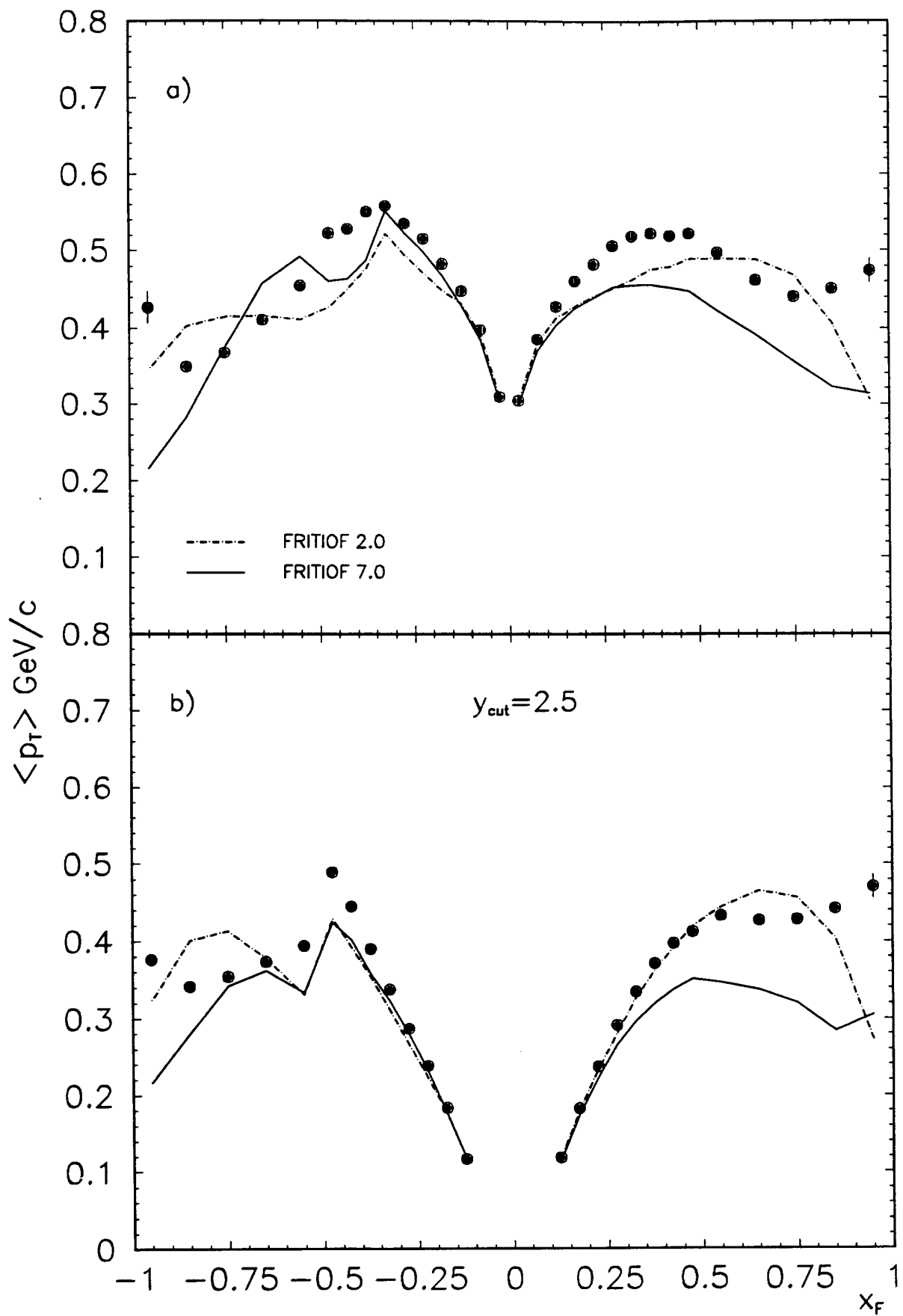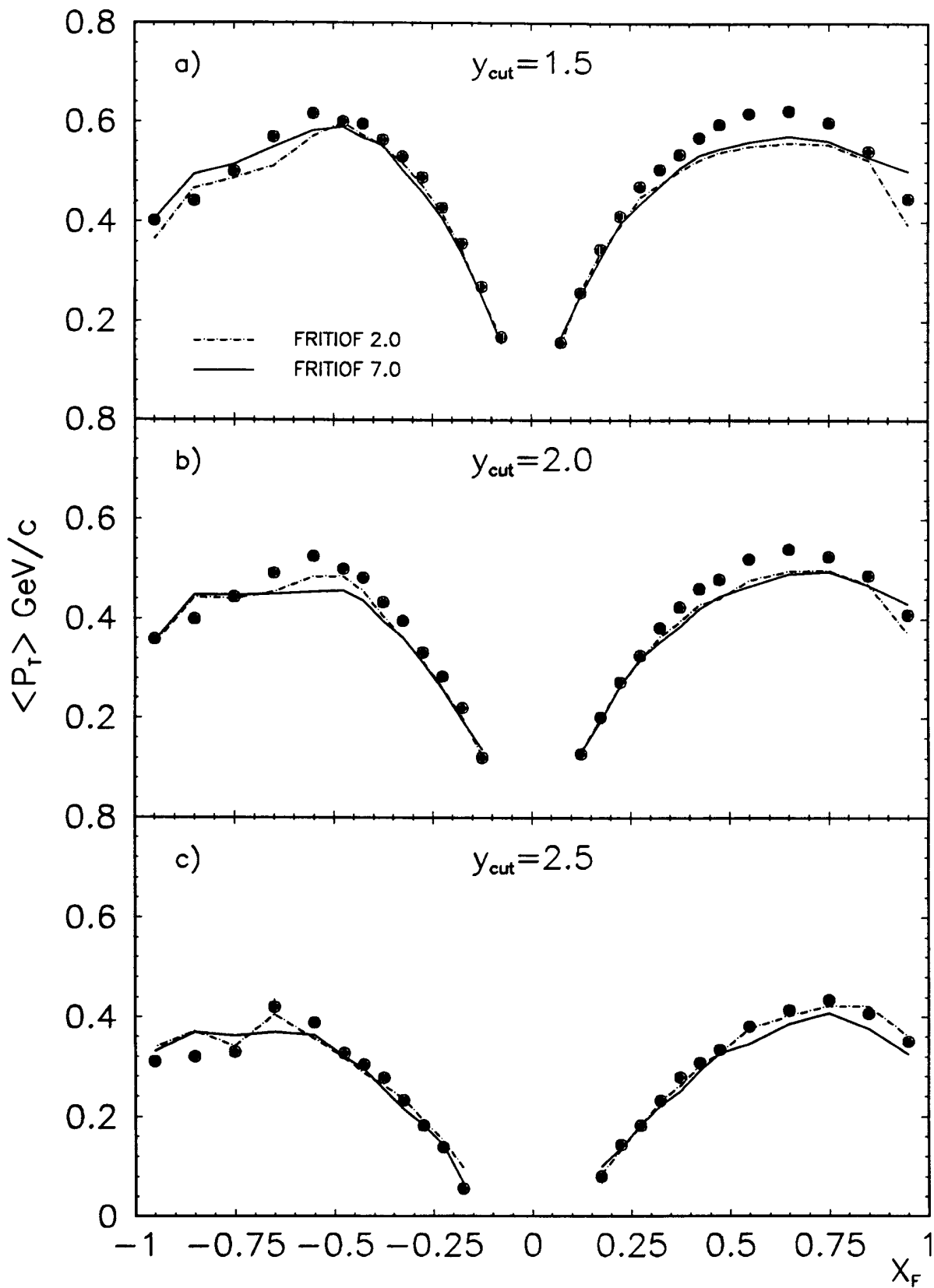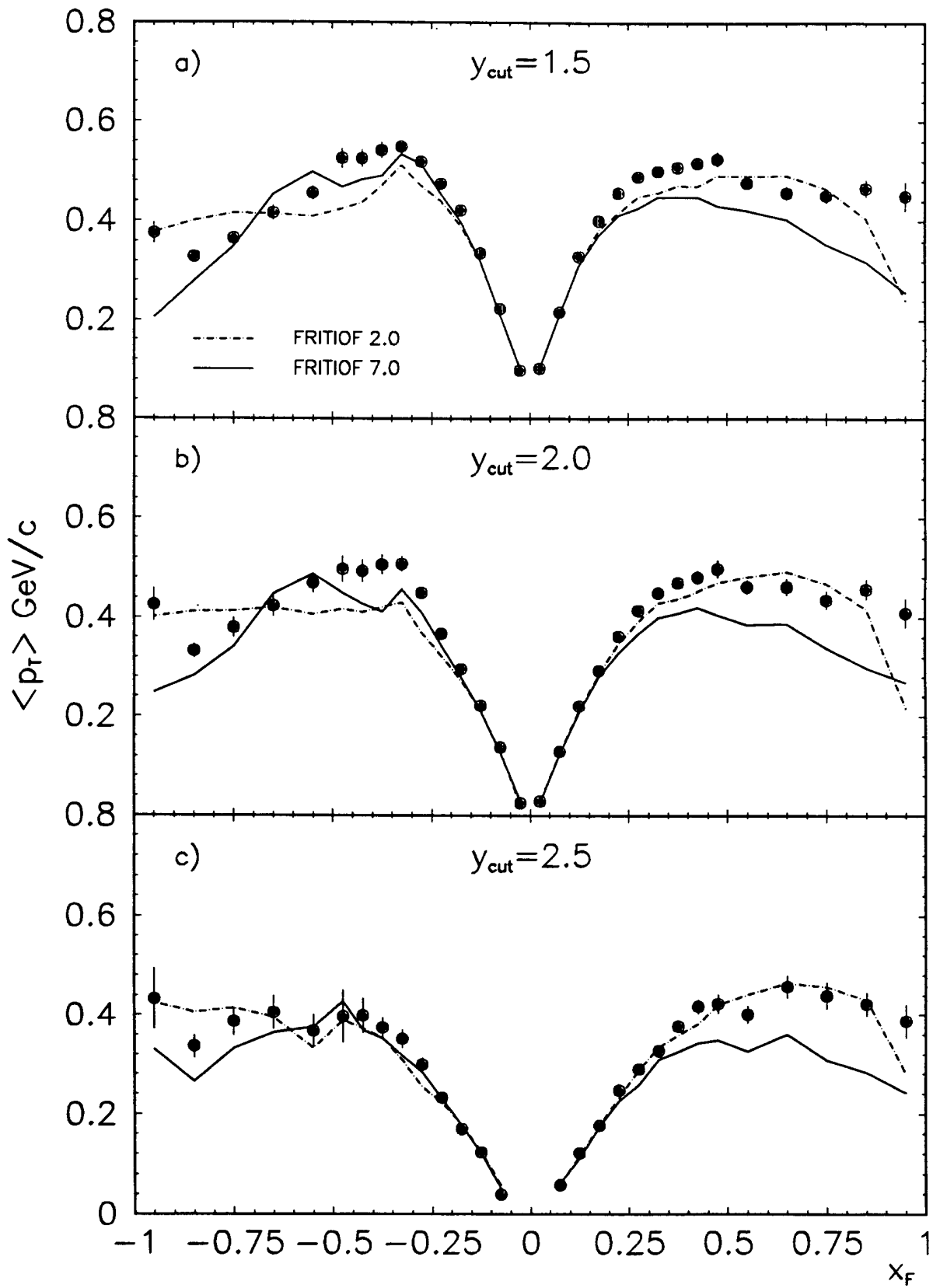ii) gluon radiation by the colour antena

Fig.1

Fig.2

a) $y_{cut} = 1.5$

FRITIOF 2.0
FRITIOF 7.0

b) $y_{cut} = 2.0$

c) $y_{cut} = 2.5$

$\langle P_T \rangle$ GeV/c

X_F

Fig.3

Fig.4