Collective sea-gull effect in $\pi^+ p$ interactions at 250 GeV/c

EHS/NA22 Collaboration

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Received 26 November 1993
Editor: L. Montanet

A collective “sea-gull” effect is observed for a system of fast hadrons produced in the fragmentation regions of non-diffractive $\pi^+ p$-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.

As observed recently [1], scaling violation in the dependence of the average transverse momentum $(p_T)$ on Feynman $x_F$ (lifting of the so-called “sea-gull” wings with increasing energy $\sqrt{\mathcal{S}}$) 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 $(p_T)$ is not reproduced by currently used models of soft hadronic interactions [6–8]. This and the comparison to $e^+e^-$ and $\bar{p}p$ collisions indicates the presence of hard-like effects causing larger values of $(p_T)$ 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 $|x_F| \geq 0.2$) produced in the beam.
Hard-like processes in hadron-hadron interactions. (a), (b) hard-like processes occurring in the collision stage: gluon emission or $qg$-scattering (a), $qg$-scattering (b); (c) hard-like processes occurring in the fragmentation stage. (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 subprocesses 
$\pi q_N \rightarrow gq$ and $\pi g_N \rightarrow qg$, 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 (a 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 sin-
particle spectra [1] should, at least partially, be 
cancelled in the dependence of the collective trans-
verse variable $X_F = |\sum x_F|$, 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 
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 sys-
tem 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 $\pi^+p$-interactions at 
250 GeV/c. A related analysis of the same data in 
terms of $p_T$-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 po-
itive 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 recon-
structed charge multiplicity $n$ are consistent, charge 
balance is satisfied, no electron (positron) is de-
lected 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 $\pi^+p$ 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 $Q_{\perp}$ is given to the string ends. 
This is assumed to have a Gaussian distribution with 
an average $\langle Q_{\perp}^2 \rangle = 0.42$ (GeV/c)$^2$ 
for the primordial transverse moment.

This value is similar to the one adopted in deep-
inelastic $\mu$ and $\nu (\bar{\nu}p)$ interactions [4,18]. In ver-

tion 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 
moment. The RPS involves mainly veV partons 
(gluons) and is usually associated by gluon brems-
strahlung. 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, 1b) and can, therefore, 
give rise to relatively large transverse momentum of 
the leading hadrons. In version 7.0 the inclination 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 ex-
tended string behaves as a colour dipole (antenna) 
radiating semi-hard gluons [11,17]. In the string 
c.m., the transverse momentum of radiated gluons 
is restricted by energy–momentum conservation, 
$k_{\perp} < (M/2)\ e^{-\nu^*}$ (where $M$ is the dipole mass and 
$\nu^*$ is the gluon rapidity in the string c.m.), and by 
the requirement that the gluon wavelength should 
allow the transverse size $L$ of the string, 
k_{\perp} < \sqrt{\pi M/L}\ e^{-\nu^*^2/2}$, where $L$ is estimated to be about
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 strongly disturbs the colour field of the string, which now acts as two dipoles with smaller mass, radiating gluons with smaller $k_T$ 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 $p_T$ 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 $p_T < 1.2$ 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 FRITIOF7.0 has problems and is even considerably worse in the $n^+$ 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 $n^+$ fragmentation region. Both models fail for $|x_F| \approx 0.8$.

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 $\langle P_T \rangle_{\text{max}}$ from $\sim 0.63$ GeV/c to $\sim 0.45$ GeV/c when $y_{cut}$ increases from 1.5 to 2.5 is due to the cut $|y| > y_{cut}$, which restricts $p_T \left( < \sqrt{3|x_F|} \ e^{-y_{cut}} \right)$ as $y_{cut}$ increases.

Note also, that the value $|X_F|_{\text{max}}$ of $|X_F|$ at maximum $\langle P_T \rangle$ is shifting towards larger values with increasing $y_{cut}$: in the beam (target) fragmentation region $|X_F|_{\text{max}}$ 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 $\theta^* < 9^\circ$ or $\theta^* > 171^\circ$ (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

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$\approx 0.6-0.9$ fm [17]. The analysis [1] was based on negative particles in part (40%) of the final statistics.
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.

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 (cf. 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 $y_{cut} = 1.5$ ($0 < \theta^* < 21^\circ$ or $159 < \theta^* < 180^\circ$) 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 $|x_F| \geq 0.5$, 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 acquired 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

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.
the fragmentation regions of non-diffractive $\pi^+p$-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 $0^\circ < 9^\circ$ or $0^\circ > 171^\circ$ (or at restricted $p_T < \sqrt{3} |X_F| e^{-\text{cen}}$), 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 ($0^\circ < 21^\circ$), the collective sea-gull 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.

It is a pleasure to thank the EHS coordinator L. Montanet and the operating crews and staffs of EHS, SPS en H2 beam, as well as the scanning and processing teams of our laboratories for their invaluable help with this experiment. We are grateful to III. Physikalisches Institut B, RWTH Aachen, Germany, DESY-Institut für Hochenergiephysik, Zeuthen, Germany, Department of High Energy Physics, Helsinki University, Finland, University of Warsaw and Institute of Nuclear Problems, Warsaw, Poland for early contributions to this experiment. We thank the Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO) for support of this project within the program for subsistence to the former Soviet Union (07-13-038).

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