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FLAVOUR TAGGING OF PARTON JETS AND SEPARATION OF PARTON SUBPROCESSES IN HARD PROTON-PROTON COLLISIONS AT THE ISR

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ABSTRACT

High energy proton-proton interactions yielding a single trigger particle with large transverse momentum give rise to a four-jet event structure with two transverse jets and two jets along the beam direction. The transverse jets are due to the fragmentation of point like scattered partons. It is shown that the quantum numbers of triggering charged pions and positive kaons are correlated with the flavour of the scattered parent parton; thus one can enhance data samples with a particular flavour of a scattered parton. The analysis, which is independent of detailed model calculations, exploits (a) the identification of the leading particles in the trigger jets (trigger particles), (b) the measurement of their relative production rates, (c) short range quantum number correlations within the trigger jets, and (d) long range correlations between leading particles from different jets. The data were obtained at $\sqrt{s}$ = 62 GeV with the Split Field Magnet detector at the CERN ISR.

1. INTRODUCTION

Rare hard proton-proton interactions yielding energetic transverse jets are generally interpreted as being due to hard scattering of quarks (q) and gluons (g) followed by their fragmentation into hadrons, as shown in fig. 1. A separation of these processes from the much more numerous soft hadronic interactions is achieved by triggering on a single particle with large transverse momentum p_T. It has already been demonstrated that events selected in this way show a four-jet structure [1], i.e. the scattered constituents fragment into the transverse "trigger" and "away" jets, whereas the non-interacting constituents hadronize into the longitudinal spectator jets (fig. 1).

Having established the four-jet structure, it is of interest to separate the various parton subprocesses, e.g. $qq \rightarrow qq$ from $qg \rightarrow qg$. In order to do so one has to identify at least one of the scattered partons. The aim of this paper is to show that this is possible, provided one has triggered on a single identified charged meson at large p_T, produced at a polar angle Θ(trig) away from 90° in the center-of-mass system (cms). The present paper is concerned with the easier cases of triggering π^+, π^- and K^+ mesons which share valence quarks with the incoming protons. In a subsequent paper [2] it will be argued that large p_T K^- triggers, which have no valence quark in common with protons, are mainly produced by fragmentation of neutral, rather soft partons.

In the following section the experiment is described and the method of analysis is briefly introduced. In sect. 3 through 7 applications to the data are shown, and the conclusions appear in sect. 8.

2. EXPERIMENT AND OUTLINE OF THE METHOD

Events with a triggering hadron of high transverse momentum p_T were taken with the Split Field Magnet detector at the CERN-ISR at a center-of-masss energy $\sqrt{s}$ = 62 GeV. The detector allows the reconstruction of charged particle trajectories over nearly the full solid angle. Experimental set-up and data taking are described in ref. [3]. The correlation measurements presented here are based upon 77,600 events, triggered by particles with $4 \leq p_T \leq 6$ GeV/c produced at $\theta(\text{trig}) \sim 50°$ (28,600 π^+, 31,000 π^-, and 18,000 K^+). Triggering pions were identified by threshold Cerenkov counters with an efficiency larger than 99.99% [3]. The sample of triggering K^+ mesons (which are below Cerenkov threshold) contains about 30% protons [4].

The following investigation of the origin of the trigger mesons is based upon the assumption that the observed jet structure is generally due to small angle scattering [5] and subsequent fragmentation of known proton constituents (quarks and gluons)(*). The flavour of a scattered parton is not directly accessible experimentally, hence it has to be derived from the observed fragments. Four independent sources of information have been exploited in the present analysis to prove, independently of detailed model calculations, that the flavour of the trigger particle, i.e. the leading particle in a parton jet, is strongly correlated with that of the scattered parton: (a) The fraction of the parton momentum carried by the trigger particles together with resonance contributions to the trigger; (b) production cross section ratios of the trigger particles as functions of transverse momentum p_T; (c) quantum number correlations between the trigger and associated particles in the trigger jet; and (d) long range correlations between the trigger particle and leading hadrons in spectator and away jets.

The latter correlations can only be observed, as explained below, with an asymmetric trigger configuration, e.g. for $\theta(\text{trig}) \sim 50°$ as in the present experiment. The kinematics of parton-parton scattering, as measured in the proton-proton rest system, are influenced by the structure functions of quarks and gluons in the proton. If the two interacting partons have approximately equal and opposite incident momenta, the parton-parton rest frame and the proton-proton cms nearly coincide and a collinear ("back-to-back") configuration of the scattered partons will dominate (fig. 2(a)). In contrast, if the momenta of the two partons are very different (in magnitude), the parton-parton rest frame moves relative to the proton-proton rest frame. Thus a Lorentz boost from the parton -parton system to the the proton-proton system will often result in a

(*) Experimental evidence for diquark scattering was found in ref. [4].

'back-to-antiback' configuration, where both scattered partons are produced in the same longitudinal cms hemisphere (fig. 2(b)). Since gluons have a softer structure function than quarks [6], one expects quark-quark scattering to dominate the back-to-back configuration and quark-gluon scattering to be present mostly in the back-to-antiback configuration.

Note also that the flavours of the parton yielding the trigger at $\theta(\mathrm{trig}) < 90°$ and of a spectator jet at $\theta \sim 0°$ should be strongly correlated [7], since they both originate from the same proton in most cases. Correlations of this type cannot be observed for $\theta(\mathrm{trig}) = 90°$.

In the following, the variable x denotes the fraction of the incident proton momentum carried by one of its constituents; similarly z is the momentum of a hadron along the jet axis scaled to the jet (i.e. parton) momentum. All kinematical quantities are given in the proton-proton cms throughout the paper.

3. LEADING PARTICLES IN THE TRIGGER JET

It has been shown previously that the trigger meson in the kinematic range of this experiment carries about 75% of the momentum of the scattered parton, independently of its flavour [8]. It follows from neutrino data [9] and from e^+e^- data [10] as well as from fragmentation models [11] that in this case the scattered quark is typically a valence quark of the leading hadron in the jet, i.e. of the trigger particle. The neutrino data [9] show for example, that 80% of all pions with $z \gtrsim 0.7$ contain the fragmenting quark.

Such a clear correlation between a trigger meson and its parent parton would be diluted by strong neutral vector meson production, e.g. via the process: down quark $d \to \rho^0(\bar{K}^{*0}) \to \pi^+(K^+)$. However, the contribution of neutral vector mesons is determined in the present experiment and is found to be small. Figs 3(a)-(c) show uncorrected invariant mass spectra for $\pi^+\pi^-$ and $K^+\pi^-$ systems. The distributions were obtained by combining the trigger particle (π^+, π^-, K^+) with hadrons of opposite charge assuming they are pions; only secondaries produced at azimuthal angles < 90° relative to the trigger were used. In all cases one finds evidence for production of the lightest vector mesons (ρ^{o}, $\bar{K}^{*o}$). For π^{-} triggers fig. 3(d) shows, as an example, the acceptance corrected distribution after subtraction of a smooth background which was obtained by combining tracks from different events [12]. The distribution is consistent with the Breit-Wigner function for ρ mesons convoluted with the detector resolution. From the number of combinations above background and the number of triggers (see sect. 2) one finds that < 5% of all triggers come from decays of neutral vector mesons. These small fractions are consistent with the larger relative inclusive vector meson cross sections [13], since only rare asymmetric decays, where one meson carries most of the resonance's momentum, can yield triggering mesons of high transverse momentum [7a].

4. RELATIVE PRODUCTION OF MESONS AT HIGH TRANSVERSE MOMENTUM

A measurement of relative production rates of $\pi^{+}(= u\bar{d})$ and $\pi^{-}(= d\bar{u})$ mesons as function of $x_T = 2p_T/\sqrt{s}$ is shown in fig. 4(a) [14]. The ratio π^{+}/π^{-} is larger than 1 and increases with increasing p_T. A ratio different from 1 implies that π^{+} or π^{-} cannot both come exclusively from gluon fragmentation. From the facts (a) that $\pi^{+}/\pi^{-} > 1$ and (b) that the ratio of u-quark and d-quark structure functions u(x) and d(x) is also larger than 1 [15] and (c) that there exists a strong flavour correlation between a parent quark and its leading fragment, it follows that π^{+} mesons are to a large extent produced by u-quark scattering. Note that sea-quarks contribute less than 20% at $p_T \gtrsim 4$ GeV/c, i.e. $x \geq 0.13$ [15].

Since both π^{+} $(u\bar{d})$ and K^{+} $(u\bar{s})$ contain valence u-quarks and since there is little vector meson dilution, K^{+} triggers should also be leading fragments of u-quark jets. One expects therefore the ratio of the inclusive cross sections of K^{+} and π^{+} triggers to be independent of p_T. This is in good agreement with the data as shown in fig. 4(b) [16].

5. QUANTUM NUMBER CORRELATIONS WITHIN THE TRIGGER JET

In this section measurements are presented of quantum number correlations between the trigger particle and associated secondaries in the trigger jet. More details on the structure of the trigger jet are given in ref. [17]. The relevant densities of secondaries are determined as functions of the scaling variable z_f,

$$z_f = \frac{\vec{p}(\mathrm{sec})\cdot\vec{p}(\mathrm{trig})}{|\vec{p}(\mathrm{trig})|^2} \qquad (1)$$

where $\vec{p}(\mathrm{sec})$ and $\vec{p}(\mathrm{trig})$ are the cms momenta of the secondary and of the trigger particle. The densities $\rho_t^{\pm o}$ $(z_f;\, h)$ of positive, negative and neutral strange (K_s^o) secondaries in the trigger jet are given by:

$$\rho_T^{\pm o} \; (z_f;\, h) = \frac{1}{N_{ev}\Delta} \sum_{i=1}^{N_{ev}} n_i^{\pm o} \; , \qquad (2)$$

where N_{ev} is the number of events with triggering particles of type h and $n_i^{\pm o}$ is the number of secondaries in the i^{th} event with scaled momenta in the range $z_f \pm \Delta/2$. Background from spectator fragmentation, which turns out to be non-negligible for $0 \leq z_f \leq 0.4$, has been minimized in this range by accepting only secondaries with $\theta \geq \theta(\mathrm{tr.jet})$ [17], where $\theta(\mathrm{tr.jet})$ is the polar angle of the trigger jet secondaries averaged over all events. (To correct for the bias introduced by this asymmetric cut a weighting factor of 2 was applied). Only secondaries with transverse momentum $q_T < 1.5$ GeV/c relative to the axis defined by $\theta(\mathrm{tr.jet})$ are considered. After these cuts there is no significant background left for $z_f > 0.2$. Finally the particle densities were corrected for acceptance.

The data are displayed in fig. 5(a) for the π^+ trigger. One observes that $\rho_t^- > \rho_t^+$. In the framework of present fragmentation schemes this is qualitatively expected since charged particles created close in phase space tend to be of opposite charge more frequently than of same charge. Such a short range charge compensation was measured for quark jets from e^+e^- collisions [18]. In case of π^+ triggers one finds for the ratio

$$R_t(h) = \int_{0.4}^{1} \rho_t^{-Q_h}(z_f;\, h)dz_f / \int_{0.4}^{1} \rho_t^{Q_h}(z_f;\, h)dz_f \qquad (3)$$

of densities of particles with charges opposite or equal to the trigger charge Q_h: $R_t(\pi^+) = 1.77 \pm 0.12$.

The data in fig. 5(b) from K^+ triggers closely resemble those of fig. 5(a) with $R_t(K^+) = 2.41 \pm 0.22$. This indicates that both π^+ and K^+ come from the fragmentation of the same type of partons.

The data for π^- triggers are given in fig. 5(c); here one observes that $\rho_t^+ > \rho_t^-$ such that $R_t(\pi^-) = 3.94 \pm 0.27$, which is significantly different from $R_t(\pi^+)$ and $R_t(K^+)$. For local charge compensation within the jet the ratios R_t should become larger for increasing difference $\Delta Q = |Q_h - Q_p(h)|$ between the charge Q_h of the trigger h and the charge Q_p (h) of its parent parton. The data thus suggest that $|Q_p(\pi^+, K^+)| > |Q_p(\pi^-)|$ which precludes dominant production by sea-quarks, e.g. $\bar{d} \to \pi^+$. These data support the previous conclusion that u-quarks are the dominant sources of π^+ and K^+ production at high p_T and that π^- originate from d-quarks and/or gluons.

Finally, fig. 6 shows the number

$$N(K_s^o) = \int_{0.2}^{1} \rho_t^o \, dz_f$$

of reconstructed K_s^o [19] per event with $q_T < 1.5$ GeV/c and $z_f > 0.2$ for π^+, π^- and K^+ triggers. One finds more K_s^o associated with K^+ triggers. This also supports the idea that most K^+ triggers are leading fragments of scattered non-strange quarks such that strangeness is compensated within the trigger jet.

6. CORRELATIONS BETWEEN TRIGGER PARTICLE AND SPECTATOR JETS

The flavour of a scattered parton yielding a trigger particle at forward angles and the flavour of the spectator jet in the longitudinal hemisphere containing the trigger should be correlated (fig. 1), if both originate from the same incoming proton. Hence the parton composition of the spectator system should differ in a characteristic way for different types of trigger particles. Such a correlation can be studied in the present experiment since the leading spectator fragments with Feynman $x_F \geq 0.3$ are also detected. In fig. 7(a)-(b) the ratio $R_s^{\pm}$ of the densities $\rho_s^{\pm}$ of positive and negative secondaries associated with π^+ (K^+) and π^- triggers,

$$R_s^{\pm} = \frac{\rho_s^{\pm}(\pi^-)}{\rho_s^{\pm}(\pi^+,K^+)} \tag{4}$$

are shown as function of x_F. Here the densities $\rho_s^{\pm}$ are defined in analogy to eq. 2 for secondaries with $p_T(\text{sec}) > 0.3$ GeV/c. Acceptance effects tend to cancel in ratios defined in this way. The contribution from both transverse jets is negligible for $|x_F| \geq 0.2$. Notice that the trigger particle is produced at $x_F \simeq 0.1$.

For $x_F \leq 0$ the ratios are about equal to 1 (fig. 7(a), 7(b)); in the framework of parton scattering this indicates that for $x_F \leq 0$ the average parton composition of the spectator system for π^+, K^+ and π^- triggers is the same. Hence no strong charge exchange occurs in these hard processes, as expected e.g. from gluon exchange. Similar results were obtained in [7a].

On the trigger side, i.e. for $x_F \geq 0$, the densities $\rho_s^{\pm}(\pi^+)$ and $\rho_s^{\pm}(K^+)$ are the same and differ from $\rho_s^{\pm}(\pi^-)$. The observed effect is not the familiar short range charge compensation [20] at $|x_F - x_F(\text{trig})| \leq 0.2$, but rather a long range correlation between trigger and leading fragments of the spectator jet. It excludes that both π^+ (K^+) and π^- triggers come from valence quarks of the same charge or from gluons. Also production by sea quarks, e.g. $\bar{d} \rightarrow \pi^+$ and $\bar{u} \rightarrow \pi^-$, is unlikely if one assumes that the presence of a sea quark has no major influence on the leading fragments of a system of three relatively fast valence quarks. From the measured relation $R_s^+ > 1 > R_s^-$ it follows that the system of non-interacting spectator partons has a smaller positive charge for π^+ and K^+ triggers than for π^- triggers (fig. 1). This implies that $Q_p(\pi^+, K^+) > Q_p(\pi^-)$. As in sect. 5 one concludes that π^+ triggers are mainly produced by u-quark scattering, whereas π^- come from parent partons carrying no or negative charge. This interpretation (see also fig. 1) is supported by a measurement of relative production of Δ^{++} (= uuu) in spectator jets as shown in fig. 7(c). The data were obtained with pion triggers at $\sqrt{s}$ = 45 and 62 GeV having $0.13 \leq x_T \leq 0.2$. Experimental details can be found in ref. [12].

7. CORRELATIONS BETWEEN TRIGGER PARTICLE AND AWAY JETS

The data presented so far indicate that π^+ and K^+ triggers originate mainly from fragmentation of scattered u-quarks and hence only a small number of subprocesses contribute. The main aim of this section is to show that one can reduce the number of relevant subprocesses even further. As pointed out in sect. 2 the asymmetric trigger configuration makes it possible to enrich the contributions of the subprocesses $qq \rightarrow qq$ and $qg \rightarrow qg$ in selected regions of phase space (fig. 2). In order to check this hypothesis we have measured the ratios $R_a = \rho_a^+/\rho_a^-$ of densities of positive and negative secondaries in the away jet. Only away jet particles with azimuthal angles ϕ in the interval $\phi = 180° \pm 25°$ (ϕ(trig) = $0° \pm 10°$) are considered. No acceptance corrections were applied, since they are identical for all triggers and are symmetrical around $x_F = 0$ (see below). The densities are defined in analogy to eq. 2 and are measured as functions of x_E. The variable x_E for the away jet approximates the fragmentation variable z and is given by $x_E = p_T(\text{sec})/p_T$; here p_T(sec) is the transverse momentum of an away-jet particle. In fig. 8 one finds globally similar values of R_a for all trigger flavours. The fact that the average charge composition of the away jets is rather independent of the trigger charge supports the conclusion reached in the previous section (and in ref. [7a]) that no net flavour exchange occurs in these hard processes.

For all trigger flavours, however, a dependence of R_a on x_E and on the kinematical away jet configuration is measured as expected from the contributing parton-parton amplitudes (sect. 2).

For away jets in the back-to-back configuration, i.e. for away jet secondaries with $x_F < 0$, the charge ratio R_a in fig. 8(a) increases with x_E from 1.3 at $x_E = 0.2$ to about 2 at $x_E \simeq 0.8$ for all types of trigger particles considered. For $x_E \gtrsim 0.4$ the ratio should reflect the average charge of the scattered parton yielding the away jet. The measurement is consistent with a dominance of valence quark fragmentation with large contributions from u-quarks as expected from the proton composition. Keeping in mind that π^+ and K^+ are produced mainly by fragmentation of scattered u-quarks this means that the back-to-back configuration is dominated by "classical" valence quark - valence quark interactions with a large u-u scattering contribution.

For π^+ and K^+ triggers the results for secondaries in the back-to-antiback configuration ($x_F > 0$) in fig. 8(b) differ from those discussed above. The ratios are about constant with $R_a \sim 1.35$ for $x_E > 0.3$. This behaviour is consistent with away jet particles coming more often from partons which are neutral on the average. Because of the back-to-antiback configuration the parent partons of the away jets are also softer (sect. 2) than the valence quarks initiating the trigger jet. Soft (sea-)quarks and gluons are possible sources for these away jets.

A non-negligible contribution to high p_T π^- production by (backscattered) gluons in the process $qg \rightarrow qg$ would raise R_a in the back-to-antiback configuration above the values found for π^+ and K^+ triggers due to a larger valence quark contribution to the away jets. Such a trend is suggested by the data shown in fig. 8(b).

8. CONCLUSIONS

The results presented here come from an ISR experiment at the Split Field Magnet detector which uses an identified charged particle trigger with $0.1 < x_T < 0.2$ at a cms polar angle of about 50°. Correlations between the trigger meson and associated secondaries in the trigger jet, in the spectator jets and in the away jets were measured. Their interpretation is based on simple arguments and gives therefore only qualitative results. The virtue of this approach, however, is its complete independence of detailed numerical calculations. The analysis shows that with this type of experiment various subprocesses contributing to hard proton-proton interactions can be separated. One finds that different charged trigger mesons are leading fragments of scattered partons with different flavours.

In particular, π^+ and K^+ triggers enhance u-quark jets while π^- triggers are probably due to d-quark jets with a non-negligible gluon component (see table 1). In this sense the identification of the leading particle in a jet allows tagging the flavour of the scattered parton. Thus enriched samples of the various parton subprocesses are obtained. Furthermore, selecting events with away jets in the back-to-back configuration yields a sample dominated by quark-quark scattering.

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Summary of flavour tagging

Experimental tools: / Hypotheses trigger: parton	jet-leader $z(trig) > .7$	inclusive ratios	charge ratio, trigger jet	correl. with spect. jet	charge ratio, away jet
π^+/K^+: $\bar{d}$ π^-: $\bar{u}$	yes	no	no	no	?
π^+/K^+: g π^-: g	yes	no	no	no	no
π^+/K^+: g π^-: d	yes	no	no	yes	no
π^+/K^+: u π^-: g	yes	?	yes	yes	?
π^+/K^+: u π^-: d	yes	yes	yes	yes	yes

Definition: no: data qualitatively inconsistent with hypothesis

yes: data qualitatively consistent with hypothesis

?: numerical calculations are needed for reasonable conclusions.

FIGURE CAPTIONS

Fig. 1 Pictorial representation of a hard proton-proton interaction.

Fig. 2 Parton kinematics for (a) back-to-back and (b) back-to-antiback configurations.

Fig. 3 Distribution of effective masses obtained from combining the trigger particle ((a) π^+; (b) K^+; (c) π^-) with secondaries of opposite charge assuming they are pions. The distribution in (d) shows the data from (c) after subtracting a smooth background (see text). The masses of the expected vector mesons are indicated by an arrow.

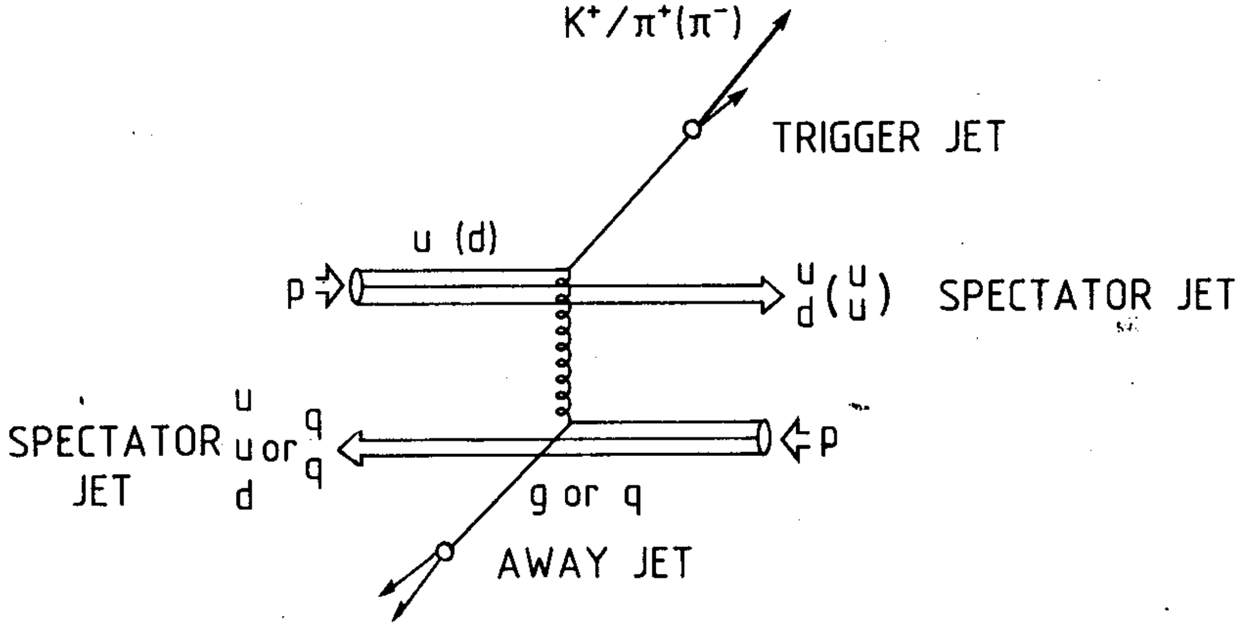
Fig. 4 Ratio of the inclusive cross sections versus x_T at $\sqrt{s} = 45$ and 62 GeV: ((a) π^+/π^-; (b) K^+/π^+).

Fig. 5 Particle density in the trigger jet versus z_f for particles with charges equal (crosses) or opposite (dots) to the charge of the trigger ((a) π^+; (b) K^+; (c) π^-).

Fig. 6 Average number of reconstructed K_s^o with $z_f > 0.2$ per event for different triggers.

Fig. 7 Density of positive (dots) and negative (crosses) particles versus x_F in events with π^- triggers relative to that for π^+ triggers (a) and K^+ triggers (b) (c) Relative Δ^{++} production in events with π^- and π^+ triggers at $\sqrt{s} = 45$ and 62 GeV.

Fig. 8 Ratio of particle densities for positive and negative away jet secondaries versus x_E for (a) back-to-back and (b) back-to-antiback configurations.



K⁺/π⁺(π⁻)
TRIGGER JET
u (d)
p
u d (u u)
SPECTATOR JET
SPECTATOR JET
u u or d
q q
p
g or q
AWAY JET

Fig. 1

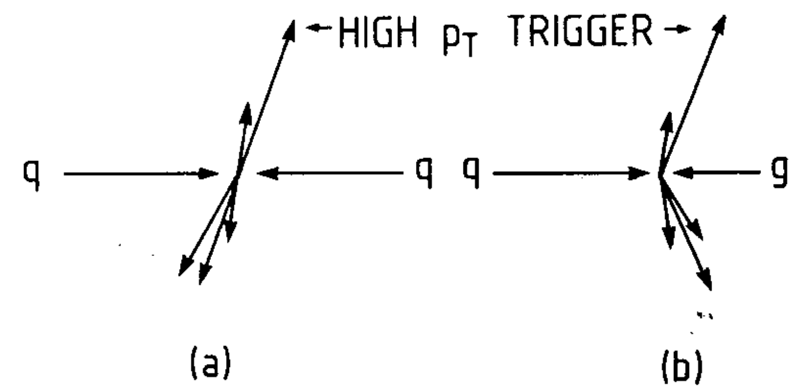


Fig. 2

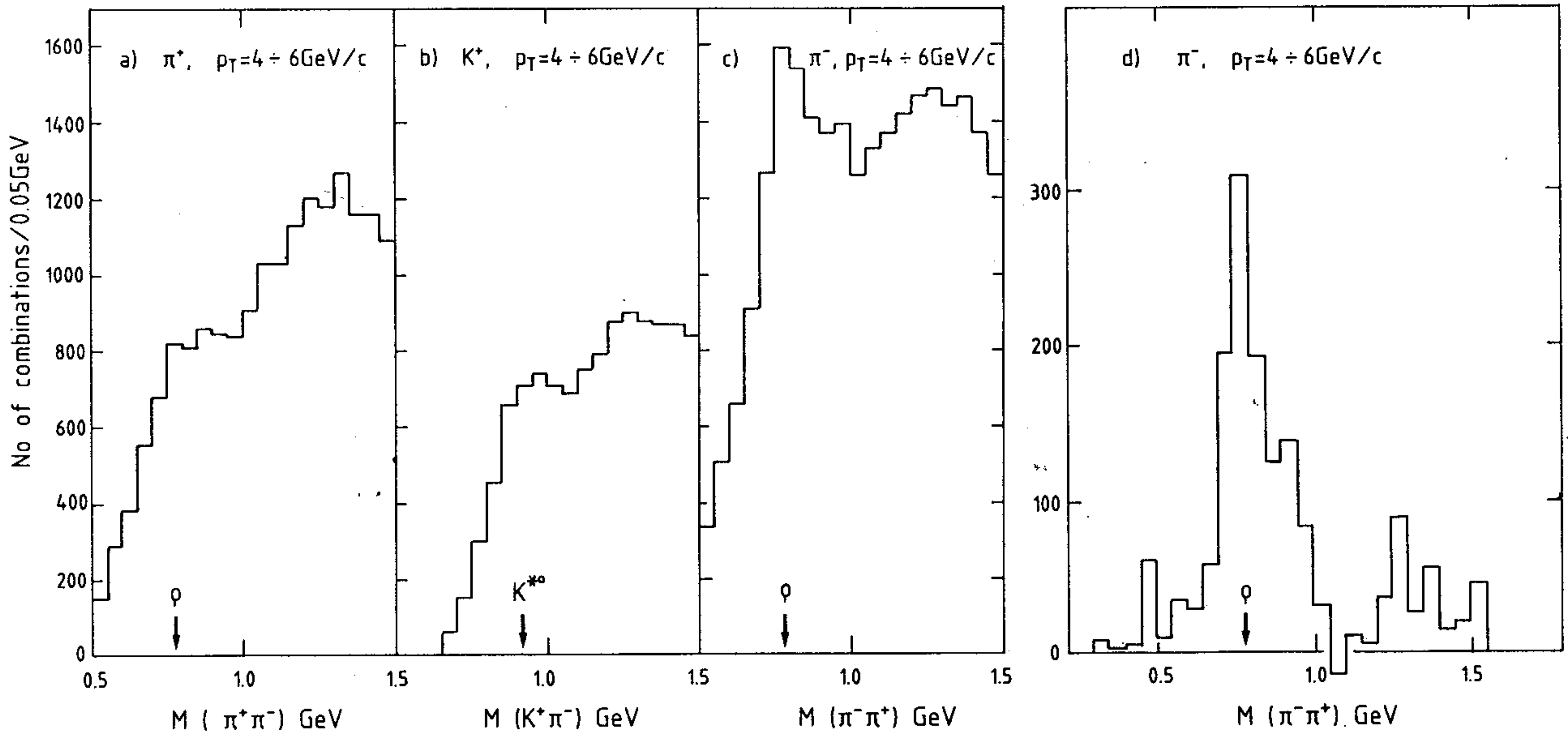

No of combinations/0.05GeV
a) π⁺, p_T=4 ÷ 6GeV/c
b) K⁺, p_T=4 ÷ 6GeV/c
c) π⁻, p_T=4 ÷ 6GeV/c
d) π⁻, p_T=4 ÷ 6GeV/c
ρ
K*°
M (π⁺π⁻) GeV
M (K⁺π⁻) GeV
M (π⁻π⁺) GeV
M (π⁻π⁺) GeV

Fig. 3

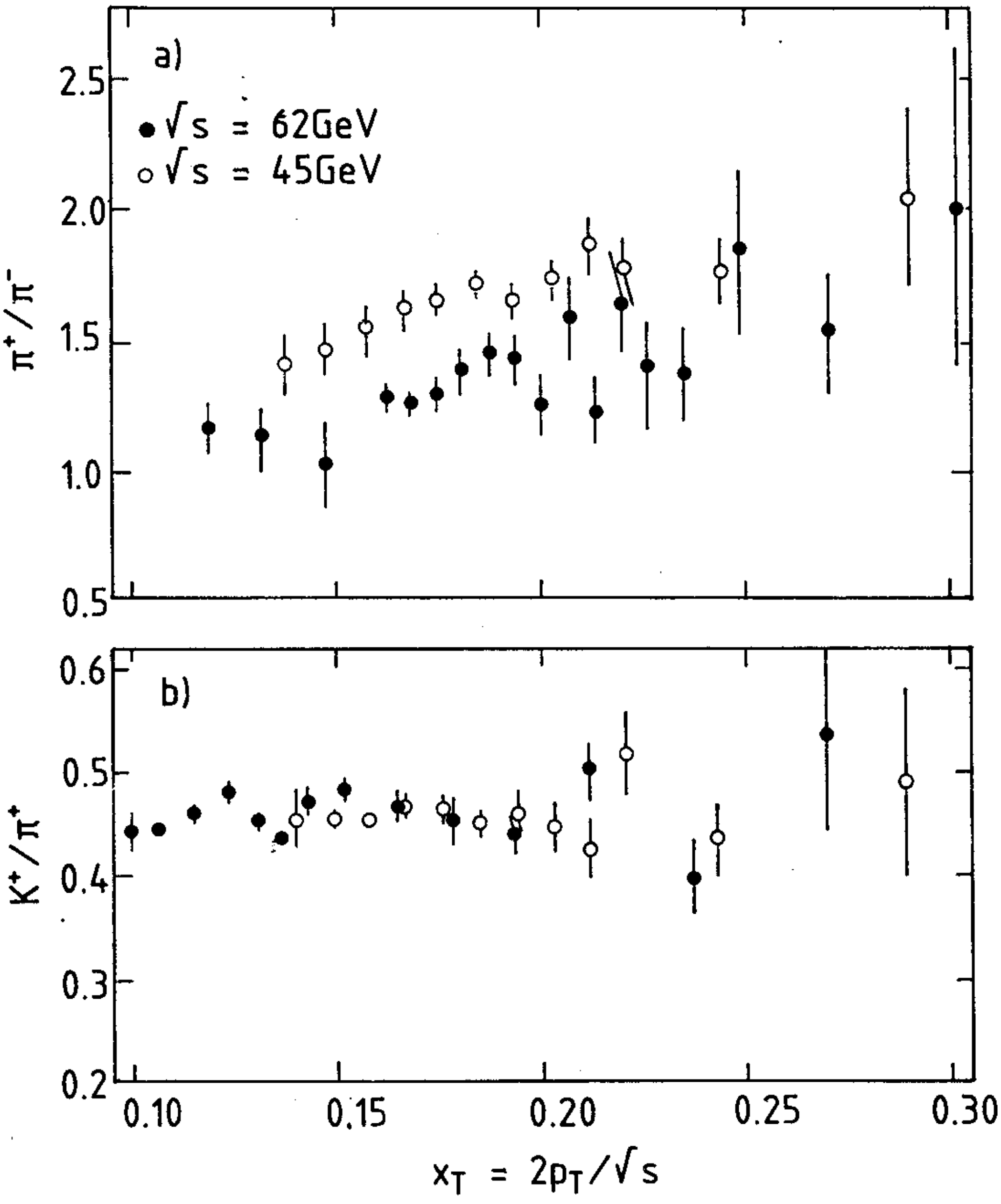
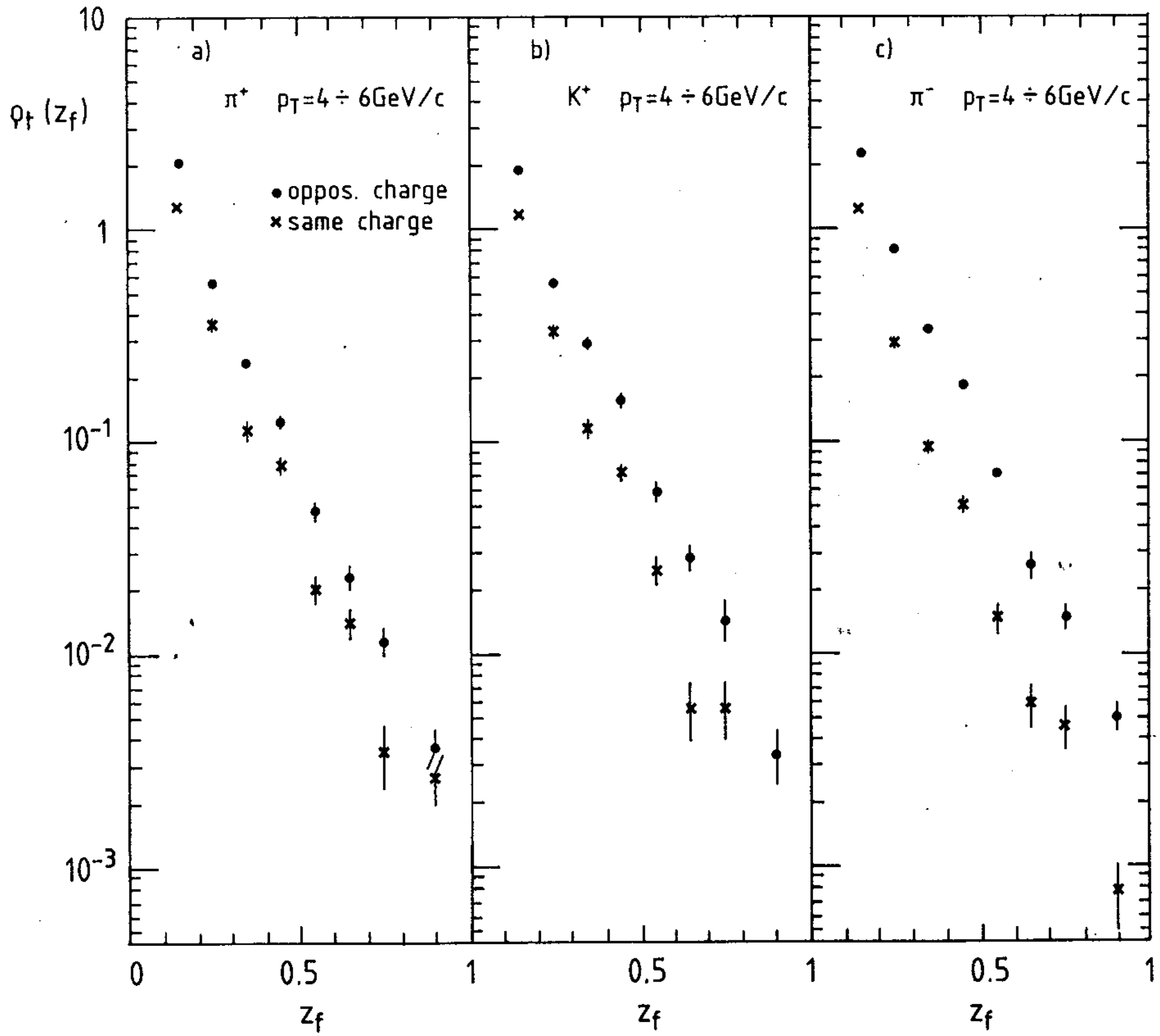

a)
● √s = 62GeV
○ √s = 45GeV
2.5
2.0
1.5
1.0
0.5
π⁺/π⁻
b)
0.6
0.5
0.4
0.3
0.2
K⁺/π⁺
0.10
0.15
0.20
0.25
0.30
x_T = 2p_T/√s

Fig. 4



$\rho_f\ (z_f)$
a)
π^+ $p_T=4\div6$GeV/c
• oppos. charge
× same charge
b)
K^+ $p_T=4\div6$GeV/c
c)
π^- $p_T=4\div6$GeV/c
10
1
10^{-1}
10^{-2}
10^{-3}
0
0.5
1
z_f

Fig. 5

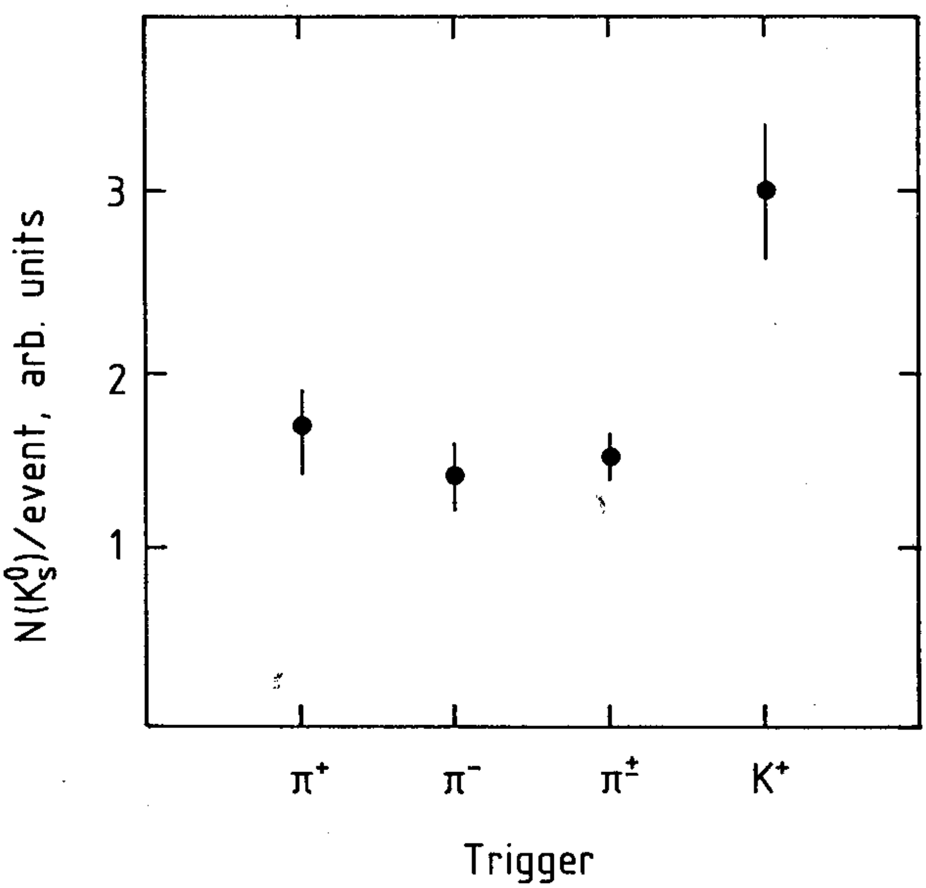


Fig. 6

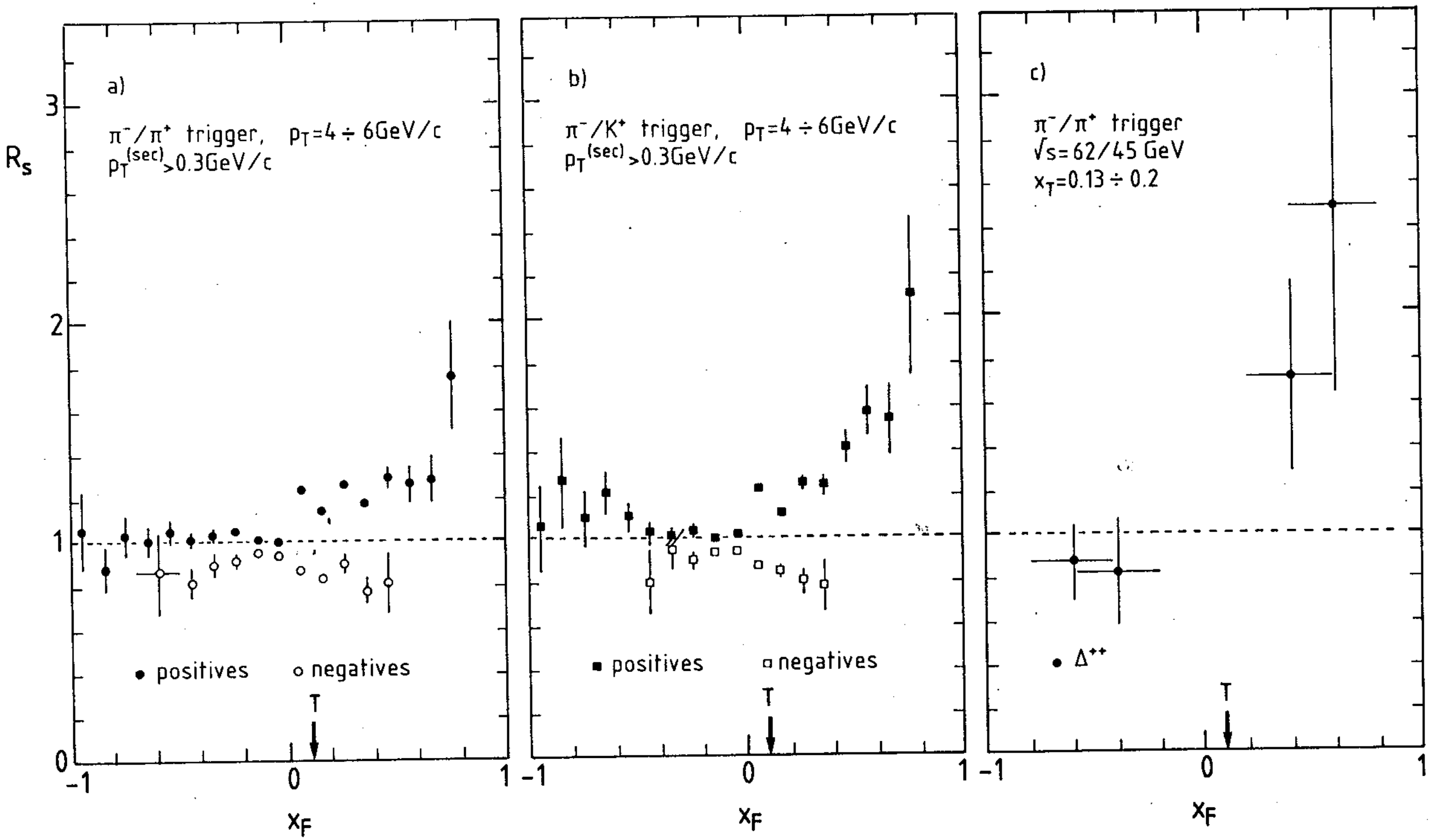

a)
π⁻/π⁺ trigger, p_T=4 ÷ 6GeV/c
p_T^(sec)>0.3GeV/c
R_s
3
2
1
0
-1
0
1
x_F
T
• positives
○ negatives
b)
π⁻/K⁺ trigger, p_T=4 ÷ 6GeV/c
p_T^(sec)>0.3GeV/c
■ positives
□ negatives
c)
π⁻/π⁺ trigger
√s=62/45 GeV
x_T=0.13 ÷ 0.2
• Δ⁺⁺

Fig. 7

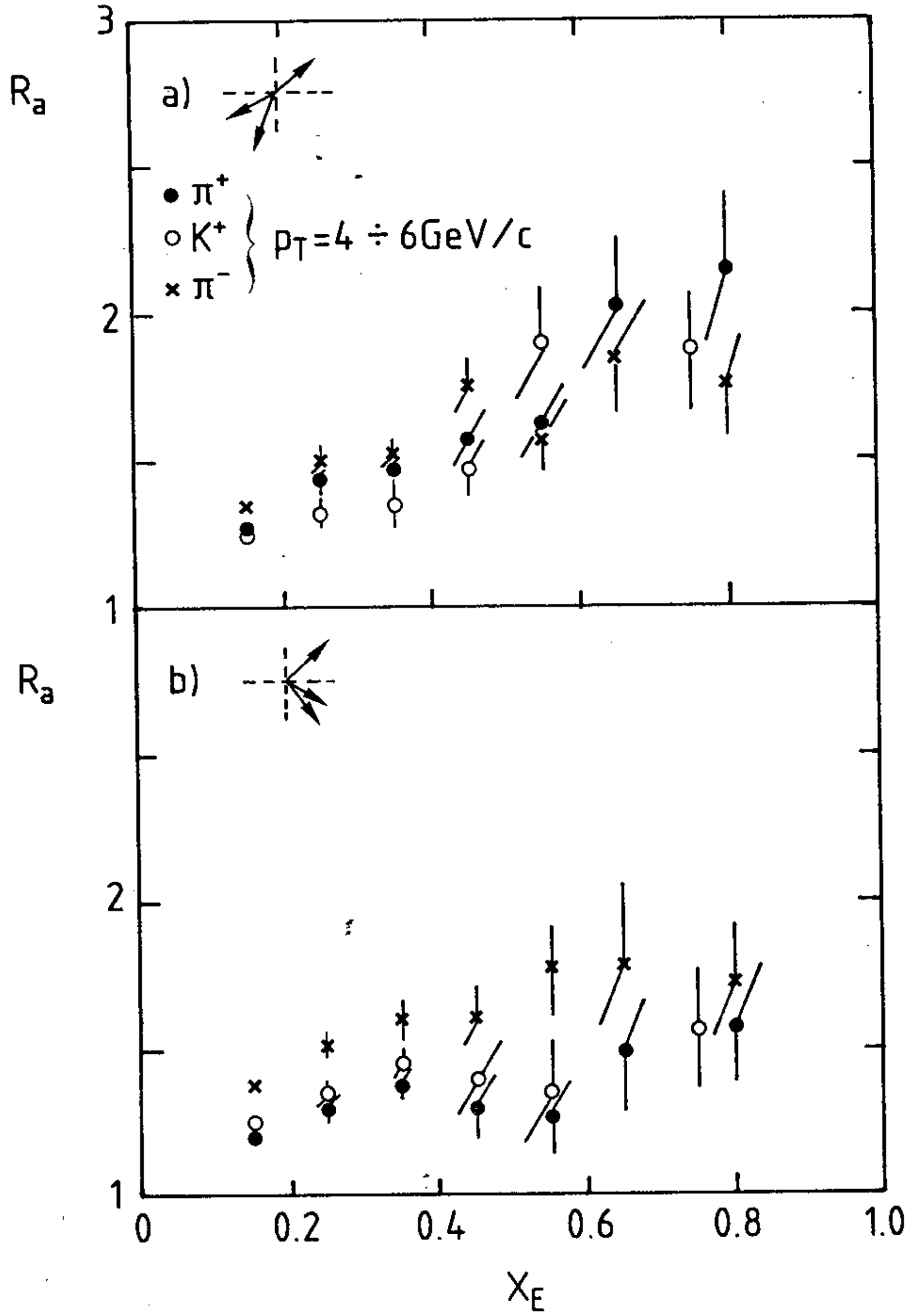


Fig. 8