Charged particles produced in quark and gluon jets in proton-proton collisions

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Abstract. We investigate whether and how different fragmentation properties of quarks and gluons affect identified particle spectra. We present a systematic study of π, K and p production in minimum bias (inelastic, non-diffractive), two- and three-jet events at RHIC, Tevatron and LHC energies. Through the study of two- and three-jet events and various jet-production channels we can directly access the fragmentation properties of quark and gluon jets. We present MC estimate for the contribution of quark and gluon jets to individual particle species spectra, that can be compared to experimental results and test our current knowledge of the physics behind particle production inside jets.

Keywords: Quarks, gluons, jets, experimental study, fragmentation, particle spectra
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INTRODUCTION

Jets are produced in hard scatterings of partons of colliding particles. Emerging from the early stages of collisions they are ideal tools to study final states, hadronisation processes and hadron production. Such questions can be addressed through investigation of fragmentation properties of quark and gluon jets in different event shapes (2- or 3-jet) and jet-production channels.

Quarks and gluons carry different color factors. Gluon carries colour factor $C_A = 3$ and quark carries colour factor $C_F = 4/3$.

$$\frac{C_A}{C_F} = \frac{9}{4} \tag{1}$$

The colour factors are proportional to the probability that a parton radiates a soft gluon. Colour factor of a gluon is more than two times larger than the one of a quark in asymptotic limit of $Q^2 \rightarrow \infty$. This means, that gluons branch more easily and form higher multiplicity jets. Thus, gluon jets are expected to be broader with softer fragmentation function than quark jets [1], [2]. Apart from overall differences, the individual partons are expected to contribute differently to the yields of specific hadrons. Namely, gluons enhance baryons in an event, whereas quarks contribute mainly to meson production [3].

In the following, we show how gluon contribution to hadron spectra changes with collision energy, moreover, that this contribution is dominant for protons. In the case of 2- and 3-jet events, we show that additional hard gluon radiation has an effect of 20% - 40% to the relative proton production. The presented MC analysis is an extension of multiple jet studies [4]-[8], with the perspective of implication in the future experiments at LHC, which have good particle identification capabilities up to high momenta.

The data were simulated using PYTHIA event generator [9] with the settings of Perugia-0 tune [10]. Three types of data-sets, were created for each collision energy - 200 GeV, 1800 GeV and 7 TeV including pure gluon (GG), pure quark (QQ) and mixed (QG) jet event production. Every sample contains 300 000 events. Separating the production channels, we were able to see the parton-type effect on single hadron spectra. Additionally, as a reference, three respective minimum bias (MB) samples were generated, each containing 1M events.

In order to study particle production in different event shapes, we selected 2- and 3-jet-like events based on the so called thrust variable, T [9]. Events with T smaller than 0.9 were treated as 3-jet-like, events with higher values as 2-jet-like. This separation was earlier proposed for multi-jet analysis at LEP [11]. Additionally, we applied a jet finding algorithm in order to see how are the particle spectra in 2- and 3-jet events affected by an experimental jet definition. The effects of GG, QQ and QG production channels were studied via $p+\bar{p}/K^{+}+K^{-}$ (p/K) and $p+\bar{p}/\pi^{+}+\pi^{-}$ (p/π) ratios.

P/π AND P/K RATIOS IN SELECTED PRODUCTION CHANNELS

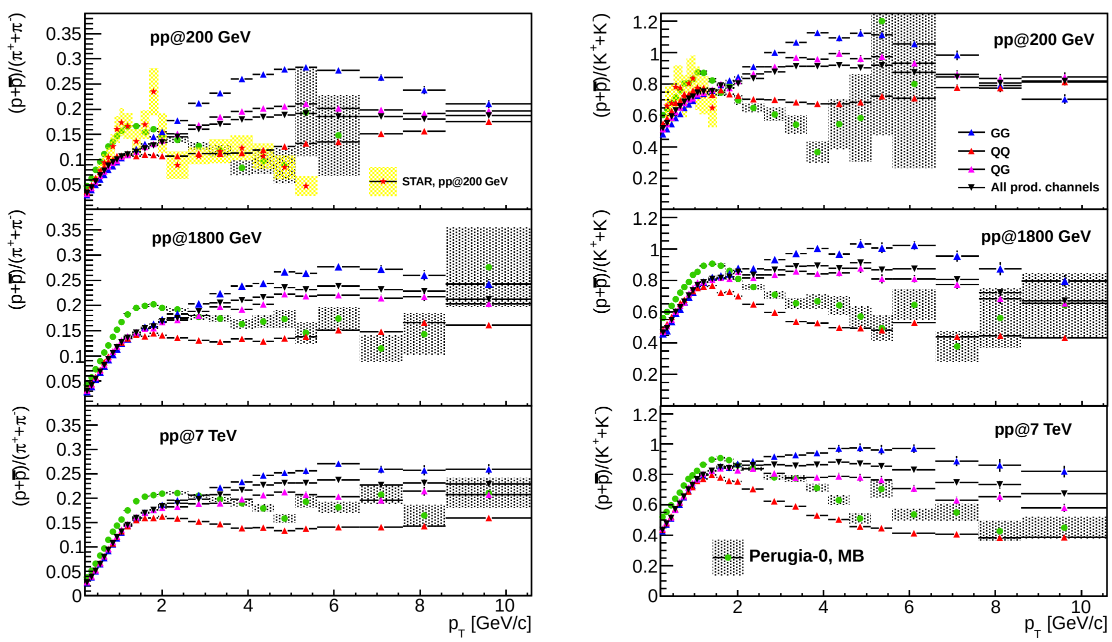

FIGURE 1. p/π (left panels) and p/K (right panels) for various production channels; GG (blue triangles), QG (magenta triangles), QQ (red triangles) compared to all production channels (black triangles) and MB (green circles). At $\sqrt{s}=200$ GeV ratio is compared to STAR data [12]

At first we examined the separate contributions of individual jet-production channels to the whole spectra (see Table 1) and to the p/π and p/K ratios (Fig. 1).

In the case of jet sample generation, we have taken into account, that the cross section for jet production varies strongly with jet energy. For this reason, the jet sample was

TABLE 1. Integrated fraction of jet events in MB production (second column) and fraction of various production channels contained in a jet production. In the last column; the fraction of 3- over 2-jet events.

$\sqrt{s}$ [TeV]	Jet/MB	GG/Jet	QQ/Jet	QG/Jet	3-Jet/2-Jet
0.2	0.1 %	17.7 %	27.3 %	55.0 %	4.0%
1.2	34.2 %	49.7 %	7.6 %	42.7 %	11.0%
7.0	95.0 %	60.0 %	5.3 %	34.7 %	18.0%

generated in three p_T^{hard} bins ($p_T^{hard} = \{15-50\ \text{GeV/c}, 50-100\ \text{GeV/c}, 100\ \text{GeV/c} \leq \}$), where p_T^{hard} is the transverse momentum of the partons in the rest frame of the interaction. After proper cross section scaling, the partial p_T^{hard} samples where merged into one.

From Tab 1 we see, that the fraction of jet events contributing to the MB spectra rises with energy, furthermore, jet sample becomes gluon dominated.

For both p/π and p/K, in the $2-6$ GeV/c region, the ratio is the highest for GG events. Specifically, p/π ratio reaches values between $\approx 0.25-0.3$ and p/K ratio rises up to ≈ 1. The combined ratio for all channels and the GG ratio get closer with collision energy (Fig. 1), demonstrating the gluon dominance in the sample. This behaviour can be connected to how protons are formed within the popcorn fragmentation model in PYTHIA [9], [13]. Observing the ratios experimentally can contribute to further understanding of particle production mechanisms.

The MB points seem to prefer the region between QG and QQ values, especially in the region above 3 GeV/c, where hard scattering becomes important. The MB ratio rises with collision energy towards QG value.

There is another point to Fig. 1 that is important to mention. Going from 200 *GeV* to 7 *TeV* we are leaving the quark dominated region and entering a gluon dominated one (see Tab. 1). Thus, one would expect the ratio to rise with collison energy, however, this is not the case. Instead, the combined p/π ratio stays rather same, whereas the GG value decreases. Such a behaviour may be the result of the MC tune, that is based on past experimental tests, in which the quark and gluon production channels were not treated separately. This point stressses the importance of studying quark and gluon jets for MC tuning purposes.

In Fig. 2 we see the GG channel contribution to the jet spectra for individual hadrons as it changes with hadron momentum and collision energy. The contribution weakens with momentum and rises with collision energy (also see Table 1). The highest contribution from the GG channel belongs to protons, which complements Fig. 1.

PARTICLE RATIOS IN 2- AND 3-JET LIKE EVENTS

In the second part of our investigation, we focused on how the ratios change in the presence of additional hard gluon radiation, i.e. in 3-jet events. This was done in two ways. First we distinguished between different event shape using the thrust variable and then we applied jet-finding algorithm.

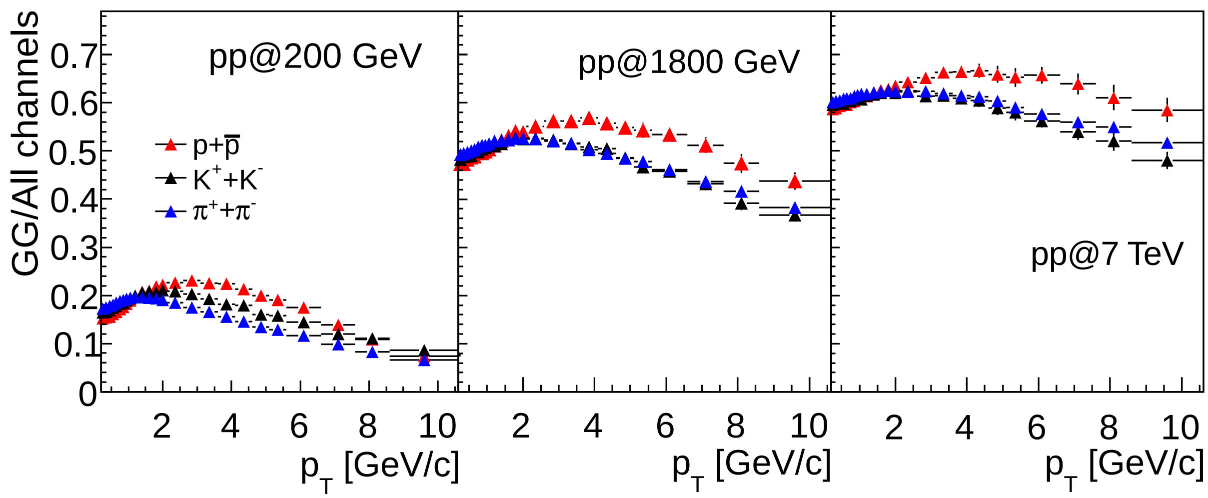

FIGURE 2. GG production channel contribution to all production channels for individual particle spectra.

Thrust variable application. In Fig. 3 we plot the p/K and p/π ratios for 2- and 3-jet like events. The hard gluon radiation, present in 3-jet like events, causes an excess in proton spectrum w.r.t pion or kaon. The effect being stronger for p/π. This is true for regions below 6 GeV/c, where increase is up to $\approx$ 40% for p/π and up to $\approx$ 20% for p/K. The enhancement, caused by hard gluon radiation, in the individual spectra originates, as mentioned in section , in the fragmentation model used within PYTHIA.

Hard gluons causing the effect observed in Fig. 3, carry the smallest momentum in the jet-system. Thus, they contribute to particle spectra at lower p_T. This can explain the vanishing of differences between 2- and 3-jet-like events above 6 GeV/c.

Jet-finding algorithm application. In order to see the effect of jet-finding algorithm we ran so called anti-kT algorithm on the events. Details about the algorithm and the problematic of experimental jet-finding can be found in [14] and references therein. The jet size in $\eta - \phi$ space was set to 0.4 and only jets in $|\eta| < 0.5$, with at least three charged particles were accepted.

Figure 4 shows p/π and p/K ratios for two- and three-jet events at 1800 GeV and 7 TeV. We see that after jet reconstruction, the ratio values have risen compared to Fig. 3. However, the differences between two- and three-jet events are not as pronounced.

A jet is defined by the parameters that make up the input of a jet-finding algorithm. This procedure thus creates merely an approximation of the true jet. True jet may extend beyond our experimental jet definition through interaction with the underlying event. A fact that must not be omitted when studying the particle spectra inside jets.

DISCUSSION

We presented a MC study of hadrons produced in hard scatterings in proton-proton collisions. Through the investigation of p/K and p/π ratios in different jet-production

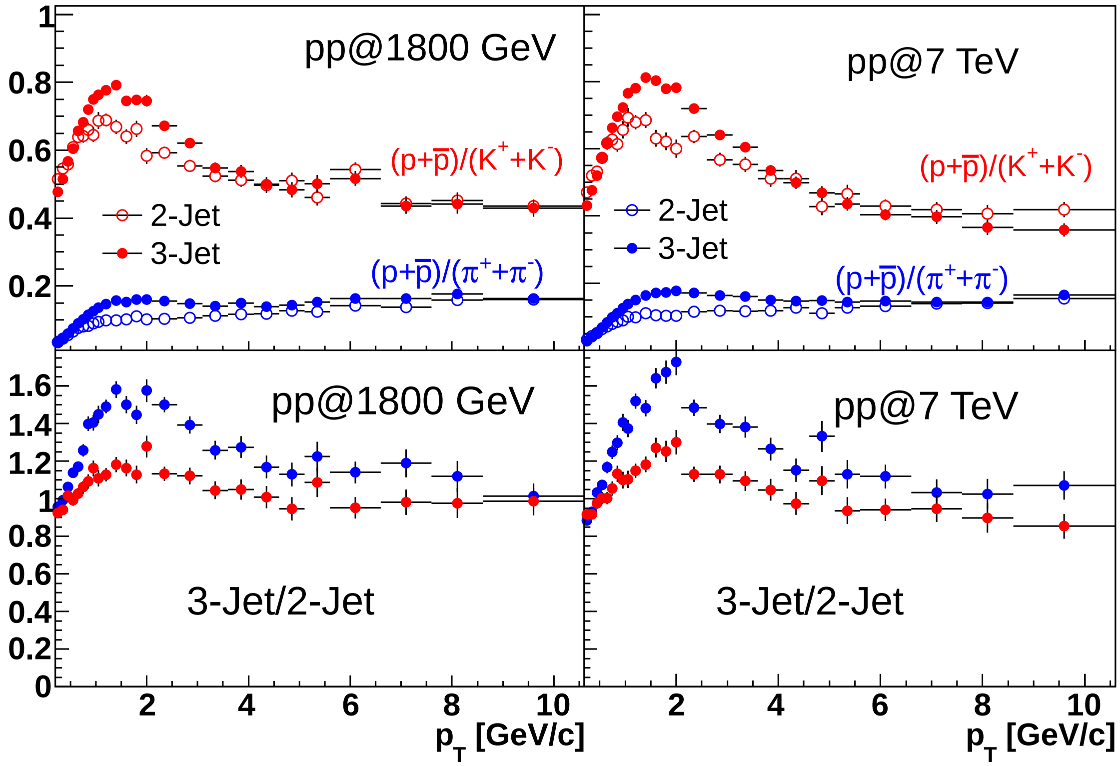

FIGURE 3. Top panels: p/π (blue) and p/K (red) ratios for all production channels spectrum. Bottom panels: (3-jet ratio)/(2-jet ratio).

channels we were able to see if and how the differences in the ratio values reflect the different fragmentation properties of quarks and gluons. Generally, we observed that gluon contribution to jet spectra rises with energy (see Table 1), and it is highest for protons (Fig. 1, Fig. 2).

When comparing 2- and 3-jet like events, we saw that additional hard gluon radiation, which is present in the 3-jet case, causes an enhancement in proton spectrum w.r.t pion (up to $\approx$ 40%) as well as kaon (up to $\approx$ 20%) (Fig. 3). However, the differences are not as pronounced after jet-algorithm application.

To conclude, the differences in particle production in the individual production channels (GG, QG and QQ) as well as 2- and 3-jet events are present in the mid-p_T region ($2-6$ GeV/c) and are directly connected to the fragmentation model used in PYTHIA. In this sense, the presented study suggests methods to investigate fragmentation in an experimentally interesting momentum region for this kind of analysis.

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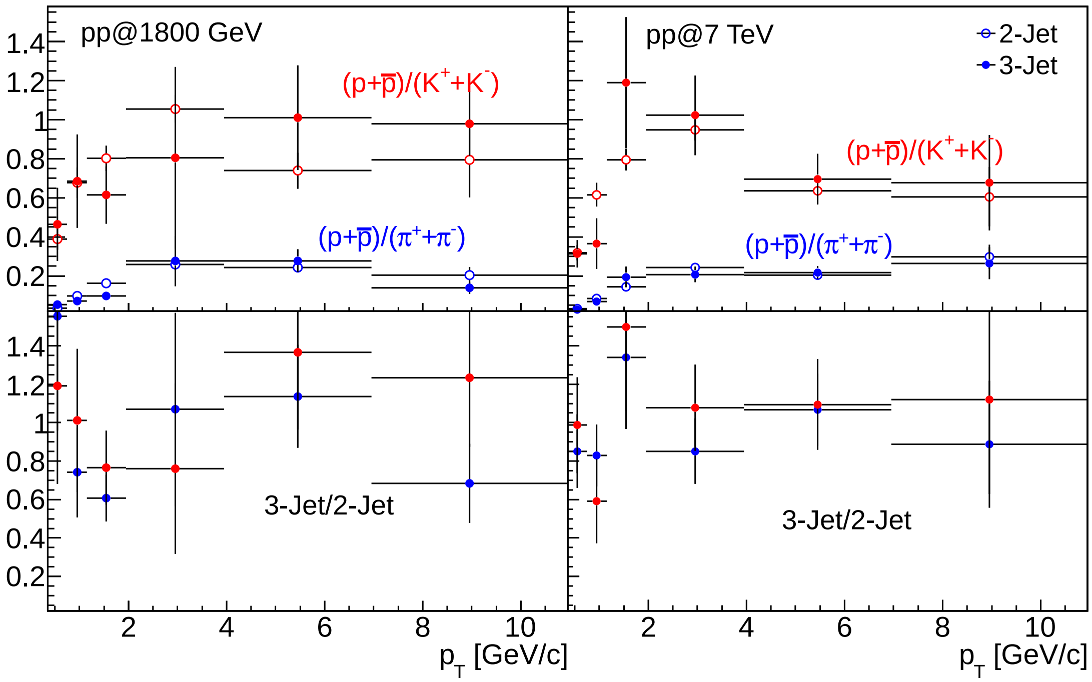

FIGURE 4. Top panels: p/π (blue) and p/K (red) ratios for jets reconstructed using anti-kT jet-finding algorithm. Bottom panels: (3-jet ratio)/(2-jet ratio).

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