Abstract. STAR has measured a variety of strange particle species in \( p + p \) collisions at \( \sqrt{s} = 200 \) GeV. These high statistics data are ideal for comparing to existing leading- and next-to-leading order perturbative QCD (pQCD) models. Leading-order (LO) models such as PYTHIA need to be tuned to describe identified strange particle data from STAR. We show that tuned PYTHIA can also describe the \( p_T \) spectra of strange resonances. More rigorous Next-to-Leading order \( p \)QCD calculations using parameterized fragmentation functions for quarks and gluons will also be compared to STAR data. The OPAL experiment has recently released \( e^+ + e^- \) data from light quark flavor tagged analyses allowing for the first time to make precise parameterizations of light flavor separated fragmentation function. We show that our \( \Lambda \) data put a more stringent constraint on the gluon fragmentation function than \( e^+ + e^- \) data. Furthermore we show that \( p \)QCD fails to describe the observed enhancement of baryon-to-meson ratio at intermediate \( p_T \) (2-6 GeV/c), which may be a first indication of other, non-perturbative mechanisms at play in \( p + p \) collisions at that momentum.

Keywords: \( p + p \) collisions, pQCD, PYTHIA, fragmentation functions

1. Introduction

Perturbative QCD has proven to be successful in describing inclusive hadron production in elementary collisions. Within the theory’s range of applicability, calculations at next-to-leading order (NLO) have produced accurate predictions for transverse momentum spectra of inclusive hadrons at different energy scales \([1,2]\). With the new high statistics proton-proton data at \( \sqrt{s} = 200 \) GeV collected by STAR, we can now extend the study to identified strange hadrons as well as strange resonances.

The perturbative QCD calculation applies the factorization ansatz to calculate
hadron production and relies on three ingredients. The non-perturbative parton distribution functions (PDF) are obtained by parameterizations of deep inelastic scattering data. They describe quantitatively how the partons share momentum within a nucleus. The second part, which is perturbatively calculable, consists of the parton cross-section amplitude evaluated to LO or NLO using Feynman diagrams. The third part consists of the non-perturbative Fragmentation functions (FF) obtained from $e^+ + e^-$ collider data using quark-tagging algorithms. These parameterized functions are sufficiently well known for fragmenting light quarks, but less well known for fragmenting gluons and heavy quarks. Recently, Kniehl, Kramer and Pötter (KKP) have shown that FF are universal between $e^+ + e^-$ and $p + p$ collisions \[3\].

In the following section we compare our $p + p$ data to PYTHIA, the most commonly used leading-order Monte Carlo event generator for elementary collision. We then move on to compare our data with more sophisticated NLO calculations. This will lead to a discussion of the difference between quark and gluon jets in $p + p$. In the final section we discuss the different contribution of these two jet types to the production of baryons and mesons.

2. Data Analysis

The present data were reconstructed using the STAR detector system which is described in more detail elsewhere \[4\]. The main detector used in this analysis is the Time Projection Chamber (TPC) covering the full acceptance in azimuth and a large pseudo-rapidity coverage ($|\eta| < 1.5$). A total of 14 million non-singly diffractive (NSD) events were triggered with the STAR beam-beam counters (BBC) requiring two coincident charged tracks at forward rapidity. Due to the particulary low track multiplicity environment in $p + p$ collisions only 76% of primary vertices are found correctly; from the remainder, 14% are lost and 10% are badly reconstructed as a MC-study showed. Of all triggered events, 7 million events passed the selection criteria requiring a valid primary vertex within 50cm along the beam-line from the center of the TPC detector. The strange particles were identified from their weak decay to charged daughter particles. The following decay channels and the corresponding anti-particles were analyzed: $K^0_{SL} \rightarrow \pi^+ + \pi^-$ (b.r. 68.6%), $\Lambda \rightarrow p + \pi^-$ (b.r. 63.9%), $\Xi^- \rightarrow \Lambda + \pi^-$ (b.r. 99.9%). Particle identification of the daughters was achieved by requiring the $dE/dx$ to fall within the $3\sigma$-bands of the theoretical Bethe-Bloch parameterizations. Further background in the invariant mass was removed by applying topological cuts to the decay geometry. Corrections for acceptance and particle reconstruction efficiency were obtained by a Monte-Carlo based method of embedding simulated particle decays into real events and comparing the number of simulated and reconstructed particles in each $p_T$-bin.
### 3. Comparison to PYTHIA

One of the most widely used models for simulating elementary collisions is PYTHIA \cite{5}. It is a parton-shower based event generator that includes leading order parton processes and parton fragmentation based on the Lund Model. The parton distributions of the initial state protons can be chosen from an array of PDFs (here we use CTEQ5M). The model is being actively used and the authors have recently released a version with completely overhauled multiple scattering and shower algorithms (version 6.3) \cite{6}. The PYTHIA version used in this paper is 6.317.

The string fragmentation based on the Lund Model requires only two parameters to define the shape of the fragmentation function and is universal for all light quark flavors. Baryons are produced from di-quarks and their probability is suppressed with respect to $\bar{q}q$ pair production. Next-to-leading order processes can be "simulated" in PYTHIA by tuning the K-factor (MSTP(33)) or by increasing the parton shower activity. This will enhance the relative probability of hard processes of type quark-gluon and thus mock-up the contributions from higher order processes. In figure 1 we first compare the measured STAR spectra for identified pions and protons to a simulation from PYTHIA. The pions agree very well with the default parameters whereas the protons seem to lie in between the default and the tuned K-factor calculation. In figure 2 (upper row) we compare PYTHIA calculations for strange mesons and baryons to the measured STAR data. Whereas the default parameters agree quite well for the $K_0^0$, they clearly underestimate the yields at intermediate $p_T$ for the $\Lambda$ and $\Xi^-$. By increasing the K-factor to 3 we achieve a reasonable agreement with the data. In figure 2 (lower row) we compare PYTHIA to the strange resonances $K^*$, $\phi$ and $\Sigma^*$. Again, only when applying a

![Fig. 1. Identified $\pi^+$ and protons in minimum-bias $p + p$ collisions at $\sqrt{s} = 200$ GeV compared to predictions from PYTHIA v6.3 with and without K-factor. Data from \cite{7}](image)
higher K-factor does the calculation agree with our data.

In summary, PYTHIA is capable of describing $p_T$ spectra for a variety of particles from $p+p$ collisions at RHIC energies. However, we have presented evidence that a tune of the LO K-factor is necessary in particular for strange baryons and resonances. Of course, we have not explored all possibilities of parameter “tunes” and there may be other, equivalent ways of reproducing the data.

What are the possible reasons for this discrepancy? The “naive” reason, supported by the K-factor tune, is that higher order contribution may be significant. However it is troubling that the pions in figure 1 do not seem to require this tune, thus introducing a rather “unnatural” particle species dependence. Nevertheless, a similar study of K-factors for non-identified hadrons found that at $\sqrt{s} = 200\text{GeV}$ a value of 3 was needed [11]. Another, maybe more plausible explanation may be related to fragmentation functions in PYTHIA. It could be that some flavor dependant refinements to the Lund symmetric string fragmentation are necessary. This will be discussed in the next section with the use of NLO calculation and a set of parameterized FF.
4. Comparison to next-to-leading order pQCD

A next-to-leading order calculation can help solve both these problems by including higher order parton processes and rigorously parameterized fragmentation functions. Fragmentation functions for separated quark flavors have been notoriously difficult to obtain due to the lack of sufficiently precise collider data. However, recently OPAL has published flavor tagged data which allowed theorists to compute better fragmentation functions \[12\].

**Fig. 3.** $p_T$ spectra for $K_0^S$ (left), $\Lambda$ (right) at midrapidity ($|y|<0.5$) from $p+p$ at $\sqrt{s}=200\text{GeV}$ compared to two different NLO calculations. Dashed lines indicate the scale uncertainty of the NLO calculation, i.e. $\mu = 0.5p_T$ (lower), $\mu = 2p_T$ (upper).

In figure 3 we compare two different NLO calculations to our $K_0^S$ and $\Lambda$ data. The first one (black lines) uses older FF by Kniehl \emph{et al.} (KKP) and Vogelsang \emph{et al} (WV) \[13\]. The second one (red lines) was done by Albino \emph{et al.} (AKK) using more recent FF based on light flavor tagged OPAL data \[15\]. Clearly, these newer parameterizations improve the description of our $\Lambda$ data greatly. However, in order to achieve this agreement they fix the initial gluon to $\Lambda$ fragmentation function ($D^\Lambda_g$) to that of the proton, then estimate that an additional scaling factor of 3 is necessary to achieve agreement with STAR data. This modified FF for $D^\Lambda_g$ however also works well in describing the $p+\bar{p}$ SPS data at $\sqrt{s}=630\text{GeV}$. So it appears that the STAR data is a better constraint for the high $z$ part of the gluon fragmentation function than the OPAL $e^+ +e^-$ data. Similar conclusions with respect to the important role of $p+p$ collisions have been drawn elsewhere \[16\].
5. Hadrons from quark vs gluon-jets

In order to investigate the fragmentation of gluons further, we looked at other observables that may be sensitive to this. For this study we used the PYTHIA Monte Carlo generator to differentiate events with gluon jets vs. quark jets in the final state. We define a “Gluon-jet” event as one where the final partons are g-g or g-q and a “Quark-jet” event one where the final partons are q-q. The overall weighting of these events in the total $p+p$ cross-section is dominated in favor of gluon-jets in PYTHIA. We then compared PYTHIA to the arbitrarily scaled $m_T$ spectra from data. The scaling was adjusted such that all spectra would overlap in the 0-1.5 GeV region.

It is interesting to observe that gluon jets will fragment very differently into baryons and mesons than quark jets. For gluon jets, there is a clear shape difference between baryons and mesons at $m_T \sim 1.5$GeV, consistent with the di-quark suppression in the string fragmentation picture. For quark jets, the shape difference is modified by an additional dependency on mass of the produced particle. When comparing the result from PYTHIA with our data, this picture indicates the dominance of gluon jets in $p+p$ at RHIC energies.

6. Baryon production in pQCD

In string models (i.e. PYTHIA) baryon production is understood via the production of di-quarks pairs from string-breaking and their recombination with other quarks. This process is suppressed with respect to $\bar{q} - q$ pairs from string-breaking resulting in systematically lower baryon yields than mesons.
Recent heavy ion data from STAR show a large enhancement of the baryon to meson ratios at intermediate $p_T$, which is associated with parton coalescence and recombination models [18]. Figure 5 (a) shows the predictions from PYTHIA for the $\Lambda/\bar{K}_0$ ratio vs $p_T$. We have separated the results for gluon and quark jet events to show how these contribute to the ratio differently. The overall PYTHIA result lies in between, closer to the red line. We observe that the prediction underestimates our data by at least a factor of 2 in the $p_T$ range from 0.8-3 GeV/c.

In figure 5 (b) we show that the disagreement is not specific to our energy scale but also exists at Tevatron energies. At $\sqrt{s} = 630$ GeV, the difference between PYTHIA and data is about a factor of 3 and the enhancement of $\Lambda/\bar{K}_0$ is twice as large as in STAR. This may be an indication that the effects observed in this ratio in heavy-ion data are present in some form in $p + p$ data and therefore this should be noted before attributing heavy-ion phenomena to explain this effect.

7. Summary

We have shown that the theoretical description of identified strange particles in $p + p$ and $p + \bar{p}$ collisions is still not fully understood. This is especially important since these models are now extensively used to predict observables for the LHC-era, and therefore one should be aware of their limitations. Phenomenological LO models can be tuned to describe the data but are unable to describe the baryon enhancement at intermediate $p_T$. NLO calculations have greatly improved with light flavor tagged fragmentation functions. However the high-$z$ range of the gluon FF
previously extracted from $e^+ + e^-$ data seems inconsistent with $p + p$ and $p + \bar{p}$ data, indicating that RHIC data could be valuable in constraining the gluon FF. Arbitrarily scaled $m_T$ spectra for strange particles exhibit $m_T$ scaling and confirm the dominance of gluon jets in $p + p$ and therefore the importance of understanding gluon fragmentation. Finally, the baryon to meson ratio at intermediate $p_T$ is about a factor 2 larger than predicted by pQCD. This difference is even larger at $\sqrt{s} = 630$ GeV in $p + \bar{p}$ collisions. This is an indication that the baryon/meson effects previously observed in heavy ion collisions are present in some form in $p + p$ data, and that the associated physics phenomena therefore need to be explained without requiring the presence of a quark-gluon plasma.

Acknowledgments

The author would like to acknowledge theoretical calculations and enlightening discussions with Simon Albino, Peter Skands and Werner Vogelsang.

References

1. F. M. Borzumati and G. Kramer, Z. Phys. C 67, 137 (1995)
2. M. van Leeuwen for the STAR Collaboration, J. Phys. G: Nucl. Part. Phys. 31 (2005) S881
3. B. A. Kniehl, G. Kramer and B. Potter, Nucl. Phys. B 597, 337 (2001)
4. K.H. Ackermann et al (STAR Collaboration), Nucl. Instrum. Meth. A 499, 624 (2003)
5. H. U. Bengtsson and T. Sjostrand, Comput. Phys. Commun. 46, 43 (1987)
6. T. Sjostrand and P. Z. Skands, Eur. Phys. J. C 39, 129 (2005)
7. J. Adams et al. (STAR collaboration), Phys. Lett. B 637, 161 (2006)
8. J. Adams et al. (STAR collaboration), Phys. Rev. C 71, 064902 (2005)
9. J. Adams et al. (STAR collaboration), Phys. Lett. B 612, 181 (2005)
10. J. Adams et al. (STAR collaboration), submitted to Phys. Rev. Lett., [nucl-ex/0604019]
11. K. J. Eskola and H. Honkanen, Nucl. Phys. A 713, 167 (2003)
12. G. Abbiendi et al. [OPAL Collaboration], Eur. Phys. J. C 16, 407 (2000)
13. B.A. Kniehl et al Nucl. Phys. B582 514(2000)
14. D. de Florian, M. Stratmann and W. Vogelsang, Phys. Rev. D 57, 5811 (1998)
15. S. Albino et al., Nucl. Phys. B734, 50 (2006)
16. X. F. Zhang, G. I. Fai and P. Levai, Phys. Rev. Lett. 89, 272301 (2002)
17. G. Bocquet et al. [UA1 Collaboration], Phys. Lett. B 366,441 (1996)
18. J. Adams et al. (STAR collaboration), submitted to Phys. Rev. C, [nucl-ex/0601042]