Strange particle production in $p+p$ collisions at $\sqrt{s} = 200$ GeV

Mark Heinz † for the STAR Collaboration‡
Laboratory of High Energy Physics, University of Bern, CH-3012 Switzerland

Abstract. We present measurements of the transverse momentum spectra, yield and $\langle p_T \rangle$ systematics for $K^0_S$, $\Lambda$ and $\bar{\Lambda}$ in $p+p$ collisions at $\sqrt{s} = 200$ GeV. We show a dependence of the $\langle p_T \rangle$ with event multiplicity and infer that this is consistent with a mini-jet dominated particle production mechanism. These observations are compared to available data from $p+\bar{p}$ experiments as well as to pQCD theoretical predictions.

1. Introduction

Particles which contain strange quarks are valuable probes of the dynamics of $p+p$ collisions as constituent strange quarks are not present in the initial colliding nuclei. The enhancement of the strange particle yield from $p+p$ collisions to heavy ion collisions has been suggested as a possible Quark Gluon Plasma signature [1]. We report preliminary results from the 2001/2002 $p+p$ run by the STAR experiment. The main focus of this paper is on presenting a high statistics measurement of $K^0_S$, $\Lambda$ and $\bar{\Lambda}$ at $\sqrt{s} = 200$ GeV and obtaining the yield and $\langle p_T \rangle$ for each species. A discussion of appropriate parameterizations to the particle spectra will ensue. We will show that the widely used power-law extrapolation in $p+\bar{p}$ collisions is not sufficient to obtain the best $\chi^2$ results for fits to the strange particle spectra and we will consider alternatives [2]. Furthermore, we will study the dependency of $\langle p_T \rangle$ and spectral shape as a function of charged particle event multiplicity ($N_{ch}$), an effect that has been observed previously in high energy $p+\bar{p}$ collisions. Several authors ascribe this phenomenon to pQCD mini-jets fragmenting into hadronic final states [3, 4]. However, we show that present string models incorporating 'semi-hard' pQCD processes, such as PYTHIA, do not describe the STAR data well without significant parameter tuning [5].

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2. Analysis

2.1. Event selection and Pile-up

The data were reconstructed using the STAR detector system which is described in more detail elsewhere [6, 7]. The main tracking detector used in this analysis is the TimeProjection 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 ($3.5 < |\eta| < 5.0$). Due to the particularly low track multiplicity environment in $p+p$ collisions a special vertex finder was developed. A Monte-Carlo study showed that only 76% of primary vertices are found correctly; from the remainder, 14% are lost and 10% are badly reconstructed. A total of 11 million events passed the event level selection criteria requiring a valid primary vertex within 100cm along the beam-line from the center of the TPC detector. An additional multiplicity dependant vertex efficiency factor $\epsilon_{vtx}(N_{ch})$ must therefore be applied to the particle spectra.

The high luminosity of the RHIC proton beams has the unfortunate effect of producing several collisions during the read-out time of the TPC, a condition known as “pile-up”. These pile-up events cannot be identified separately, however the triggered vertex can be identified by allowing only tracks that match to a very fast scintillating Central Trigger Barrel (CTB) detector to be used in the vertex reconstruction.

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The strange particles were identified from their weak decay to charged daughter particles via topological identification algorithm. The following decay channels were analyzed: $\Lambda \rightarrow p + \pi^-$ (b.r. 63.9%), $\bar{\Lambda} \rightarrow \bar{p} + \pi^+$ (b.r. 63.9%), $K^0_S \rightarrow \pi^+ + \pi^-$ (b.r. 68.6%).

Particle identification of 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, i.e. requiring the parent to originate from within 2cm of the primary vertex and have a minimum decay length of 2cm. These cuts also ensure that the particle decay is matched to the correct vertex with a high probability.

 Corrections for particle reconstruction efficiency were obtained through 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. The $\Lambda$ and $\bar{\Lambda}$ spectra were corrected for feed-down from $\Xi$ ($\Xi^- \rightarrow \Lambda + \pi^-$). Finally, the corrected transverse momentum spectra have to be multiplied by the multiplicity dependant primary vertex efficiency $\epsilon_{vtx}(N_{ch})$ to account for yield losses.
Strange particles in \( p + p \) at \( \sqrt{s} = 200 \text{ GeV} \)

3. Transverse Momentum Spectra

Non-feeddown corrected spectra for \( K_S^0 \), \( \Lambda \) and \( \bar{\Lambda} \) are shown in Figure 1. The particle acceptance at mid-rapidity (\(|y| \leq 0.5\)) in the TPC starts at transverse momentum 0.2 GeV/c for \( K_S^0 \) and 0.3 GeV/c for \( \Lambda \) and \( \bar{\Lambda} \). The spectra are parameterized to allow extrapolation to low \( p_T \) and to extract \( \langle p_T \rangle \) and yield \((dN/dy)\). In contrast to previous \( p + \bar{p} \) experiments [2], which used either a single exponential function in transverse mass or power-law functions, we found that a combination of these functions is more effective in fitting the STAR data. The \( \chi^2 \) results from different fit-functions are presented in Table 1. Composite fits, represented in equation 1 (for \( K_S^0 \)) and equation 2 (for \( \Lambda \) and \( \bar{\Lambda} \)) yield the lowest \( \chi^2 \) and were used to extract the final values for \( \langle p_T \rangle \) and yield as shown in Table 2.

\[
\frac{1}{2\pi p_T} \frac{d^2N}{dy dp_T} = Ce^{-m_T} + D(1 + \frac{p_T}{p_0})^{-n}
\]

\( \text{(1)} \)

**Table 1.** A summary of \( \chi^2 \) values for different fit-functions to the particle spectra

| Particle | \( m_T \)-exponential | power-law | composite equation |
|----------|------------------------|-----------|---------------------|
| \( \Lambda \) | \( \chi^2/\text{ndf} \) = 3.2 | \( \chi^2/\text{ndf} \) = 6.0 | \( \chi^2/\text{ndf} \) = 1.0 |
| \( \bar{\Lambda} \) | \( \chi^2/\text{ndf} \) = 4.7 | \( \chi^2/\text{ndf} \) = 4.1 | \( \chi^2/\text{ndf} \) = 1.4 |
| \( K_S^0 \) | \( \chi^2/\text{ndf} \) = 15.9 | \( \chi^2/\text{ndf} \) = 1.6 | \( \chi^2/\text{ndf} \) = 0.7 |

**Figure 1.** Minimum-bias, non-feeddown corrected spectra for \( K_S^0 \) (left) and \( \Lambda \) (right) with \(|y| \leq 0.5\) from \( p + p \) at \( \sqrt{s} = 200 \text{ GeV} \). The errors in the plot are statistical only. The fit is composite and is described in the text.
Strange particles in $p + p$ at $\sqrt{s} = 200$ GeV

$$\frac{1}{2\pi p_T} \frac{d^2N}{dy dp_T} = Ae^{-\frac{m_T}{T}} + Be^{-\frac{p_T}{T}}$$

(2)

The systematic errors are dominated by the different possible fit parameterizations and amount to 10% for $\langle p_T \rangle$ and 15% on the yield. The remaining systematical uncertainties are from the background and efficiency corrections. Table 2 compares the STAR results to the measurements by UA5 \[8\]. The UA5 measurements were made over a larger rapidity interval ($|y| < 2$) and have been scaled to match the STAR acceptance by the use of a PYTHIA simulation. The $\Lambda/\bar{\Lambda}$ ratio is 0.88$\pm$0.09 and is flat as a function of $p_T$, consistent with a nearly net-baryon free environment at mid-rapidity.

| Particle | extrapolated yield (dN/dy) | feed-down corr. yield (dN/dy) | $\langle p_T \rangle$ (GeV/c) |
|----------|-----------------------------|--------------------------------|-------------------------------|
| $\Lambda$ | 0.044 $\pm$0.003            | 0.034 $\pm$0.004               | 0.76 $\pm$ 0.01               |
| $\bar{\Lambda}$ | 0.042 $\pm$0.003           | 0.032 $\pm$0.004               | 0.75 $\pm$ 0.01               |
| $K^0_S$   | 0.123 $\pm$0.006            |                                | 0.60 $\pm$ 0.01               |

Table 2. A summary of yield and $\langle p_T \rangle$ for measured strange particles. The errors quoted are statistical only.

| Particle | STAR dN/dy $|y| < 0.5$ | UA5 dN/dy $|y| < 2.0$ | UA5 dN/dy $|y| < 0.5$ | UA5 $\langle p_T \rangle$ $|y| < 2.0$ |
|----------|----------------|----------------|----------------|---------------------|
| $\Lambda + \bar{\Lambda}$ | 0.066 $\pm$0.006 | 0.27 $\pm$0.07 | 0.076 $\pm$0.02 | 0.8$+0.2,-0.14$ |
| $\frac{\Lambda - \bar{\Lambda}}{2K^0_S}$ | 0.27 $\pm$0.05 | 0.31 $\pm$0.09 | 0.31 $\pm$0.09 | 0.53$+0.08,-0.06$ |

Table 3. A summary of yield and $\langle p_T \rangle$ for and $\Lambda$, $\bar{\Lambda}$ (feed down corrected) and $K^0_S$ measured by the UA5 \[8\]. UA5 yields have been scaled to the STAR measured rapidity interval using a Pythia simulation.

4. Comparison to PYTHIA

Figure 2 shows the comparison of the STAR spectra to the spectra from the default setting of PYTHIA event generator (version 6.22, MSEL1) which includes hard processes and a modelling of soft processes, through a pQCD model.

Even at $p_T \geq 1.5$, a regime were pQCD should give a better description, the differences between the model and the data are considerably large. Further studies are planned in order to optimally tune the model to match the STAR strangeness data.

5. $\langle p_T \rangle$ vs event multiplicity

The minimum bias event sample was split into 6 event classes according to mean charged particle multiplicity per unit $\eta$ ($\langle dN_{ch}/d\eta \rangle$). A similar analysis has been performed in previous $p + \bar{p}$ experiments at different collision energies \[2,9\]. High multiplicity events
Strange particles in $p + p$ at $\sqrt{s} = 200$ GeV

$\langle p_T \rangle$ vs. $N_{ch}$ for $K^0_S$ (left) and $\Lambda$ (right) compared to PYTHIA (triangles) (ver 6.22, MSEL1). The errors on data are both statistical and systematic.

Figure 3 presents a comparison of the $\langle p_T \rangle$ vs $\langle dN_{ch}/d\eta \rangle$ for $\Lambda$ and $K^0_S$ with the corresponding PYTHIA calculations. A rise in $\langle p_T \rangle$ with increasing $N_{ch}$ is observed and is stronger for the heavier particle ($\Lambda$). Several authors have attributed these phenomena to the increased number of fragmenting mini-jets in the high-multiplicity events [11, 12]. In fact, the HIJING model even makes a prediction for the expected number of mini-jets contributing to each multiplicity [10].
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It is also interesting that PYTHIA under-predicts the magnitude and correlation strength of $\langle p_T \rangle$ with multiplicity. Similar comparisons for inclusive charged particles $\langle p_T \rangle$ have been recently published by the CDF Collaboration and demonstrate similar discrepancies [13].

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In Figure 4 the $\langle p_T \rangle$ is shown for all particle species measured in $p + p$ collisions in STAR as a function of particle mass. The black line is an empirical parameterization to ISR data for $\pi, K, p$ only, at $\sqrt{s} = 25$ GeV. There is very little energy dependance for the lower mass particles between the ISR and RHIC energies, whereas the higher mass particles show a clear breaking from the parameterization. The dependance of $\langle p_T \rangle$ on particle mass has been explained by mini-jet production in $p + p$ and $p + \bar{p}$ collisions and a stronger contribution for higher mass particles is expected [4].

![Figure 4](image)

Figure 4. $\langle p_T \rangle$ vs particle mass, where the black curve represents the ISR parametrization from $\pi, K, p$ at $\sqrt{s} = 25$ GeV.

7. Summary

The STAR experiment has made the first high statistics measurement of mid-rapidity $K^0_S, \Lambda$ and $\bar{\Lambda}$ in $p + p$ collisions at $\sqrt{s} = 200$ GeV. The results agree with those made by the UA5 collaboration for $p + \bar{p}$ at $\sqrt{s} = 200$ GeV. The ratio of $\bar{\Lambda}/\Lambda$ suggests a small net baryon number at mid-rapidity. We have show that the shape of the particle spectra is best described with a two-component fit function accounting for both the soft and hard parts of the spectra. Furthermore, we have undertaken studies to understand the change in shape and $\langle p_T \rangle$ of the spectra with increased event multiplicity. We compared our results to pQCD inspired models which infer mini-jets and string fragmentation. We
Strange particles in $p + p$ at $\sqrt{s} = 200$ GeV have shown that the current default version of PYTHIA is not well tuned for strange particles at this collision energy.

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![Figure 1. Minimum-bias, non-feeddown corrected spectra for $K^0_S$ (left) and $\Lambda$ (right) with ($|y| \leq 0.5$) from $p+p$ at $\sqrt{s} = 200$GeV. The errors in the plot are statistical only. The fit is composite and is described in the text.](image)

| Particle | $m_T$-exponential | power-law | composite equation |
|----------|------------------|-----------|--------------------|
| $\Lambda$ | 3.2              | 6.0       | 1.0                |
| $\bar{\Lambda}$ | 4.7              | 4.1       | 1.4                |
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Strange particles in $p + p$ at $\sqrt{s} = 200$ GeV

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![Graphs showing particle spectra](image)

**Figure 2.** \( \Lambda^0 \) (left) and \( \Lambda \) (right) particle spectra (circles) compared to PYTHIA (line) (ver 6.22, MSEL1)

are particularly interesting as they are likely dominated by contributions from large momentum transfer parton-parton collisions.

![Graphs showing mean transverse momentum vs. mean charged particle density](image)

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