The Effects of Varying the Correlation Volume on Strangeness Production in High Energy Collisions

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Preliminary results on strange particle production versus collision centrality are presented. STAR measurements from $\sqrt{s_{NN}}= 200$ GeV heavy-ion and $p$-$p$ collisions are compared to SPS measurements. A systematic study of strange particle production is presented with the aim of establishing how the correlation volume of the produced source affects the scale of strange particle creation, including that of the multi-strange baryons. A linear increase of strangeness production with volume has been suggested by thermal models as an indication that the collision region has reached sufficient size such that small volume effects can be neglected. Analysis of preliminary results from STAR show that, using the assumption that the number of participants is linearly correlated with the volume, no such regime was obtained. This suggests that the correlation volume "seen" by strange quarks is not merely that of the initial overlap.

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By studying the spectra and yields of the strange particles produced in heavy-ion collisions and comparing them to those resulting from elementary $p$-$p$ collisions, in which a QGP phase is not expected, we gain insight into the properties of the medium. While we cannot measure a state of free quarks and gluons directly, indirect methods can be used to provide evidence that such a phase did exist and whether the state was in chemical and/or thermal equilibrium. It is predicted that strangeness is suppressed in $p$-$p$ due to a lack of phase space \cite{1}. As the collision volume increases, this suppression reduces. The relevant volume is believed to be linearly proportional to the number of participants in the collision, $\langle N_{\text{part}} \rangle$. Calculations also show that the $p$-$p$ suppression increases with the strangeness content of the particle and decreases with increased collision energy. The scale of the suppression is very sensitive to the temperatures of the produced systems. For large systems this phase space suppression is removed and strangeness is produced freely, resulting in yields that are proportional to the volume. It is then appropriate to apply the Grand Canonical approach, where quantum numbers need only be conserved on average, to calculate the yields. Experimentally the scale of the suppression is measured via a so-called enhancement factor:

$$E(i) = \frac{Yield(i)_{AA}/N_{\text{part}}}{Yield(i)_{pp}/N_{\text{part}}}$$ \hspace{0.5cm} (1)

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Detailed predictions of the phase space suppression effects do not yet exist for 200 GeV collisions. However, for central events using $T=177$ MeV and $\mu_b=29$ MeV enhancements of $E(\Xi^-)=3.05$ and $E(\Lambda)=1.44$ are calculated. For $T=170$ MeV and $\mu_b=29$ MeV, $E(\Xi^-)=4.5$ and $E(\Lambda)=1.77$ [2].

We present here preliminary data taken with the STAR experiment from Au-Au and $p-p$ collisions at $\sqrt{s_{NN}}=200$ GeV. The $p_T$ spectra and yields have been analyzed as a function of centrality and a Glauber model is used to calculate $\langle N_{\text{part}} \rangle$ and $\langle N_{\text{bin}} \rangle$ for each centrality bin [3].

![Fig. 1. Preliminary measured enhancements for $\sqrt{s_{NN}}=200$ GeV Au-Au collisions. The uncertainties shown are a combination of statistical and systematic.](image1)

![Fig. 2. Preliminary measurements of the nuclear modification factor for baryons. The dotted curve represents the charge hadron measurement.](image2)

Fig. 1 shows the preliminary measured enhancement factors from STAR. The $\bar{p}$ show a linear scaling with $\langle N_{\text{part}} \rangle$ and almost no enhancement relative to $p-p$. Meanwhile, the $\Lambda$ and the $\Xi$ exhibit significant enhancements, even for the most peripheral data. The expected ordering with strangeness content is also observed, i.e. the $\Xi$ are more enhanced than the $\Lambda$. The particles and their anti-particles show similar enhancements - reflecting the near-zero net baryon number. However, neither the $\Lambda$ nor $\Xi$ show a linear scaling with $\langle N_{\text{part}} \rangle$, suggesting that the Grand Canonical regime is not reached even in central events. In contrast, calculations of $\gamma_s$, the strangeness saturation factor, using a thermal model show that it approaches unity for the more central bins from fits to STAR data [4]. These fits therefore support the use of the Grand Canonical approach and suggest that the strangeness yields should scale with the collision volume. As these results are contradictory, we conclude that the relevant volume for strangeness production is not linearly proportional to $\langle N_{\text{part}} \rangle$ and hence not purely related to that of the initial collision overlap. This idea allows for the Grand Canonical regime to have been reached, as suggested by thermal model fits together with a lack of proportionality of the yields with $\langle N_{\text{part}} \rangle$.

In order to explore how strangeness production in the central Au-Au data compares to $p-p$ as a function of $p_T$, we calculate the nuclear modification factor, $R_{AA}$, for baryons. The preliminary results are shown in Fig. 2. Previously reported measurements of $R_{CP}$ (the ratio of central/peripheral), show that all baryons follow the same curve and are suppressed at high $p_T$, the result of the modification of jets by the medium [5]. Our measured $R_{AA}$, however, reveals...
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Fig. 3. Preliminary Au-Au data scaled as defined by Eqn. 2 except the $\phi$ which is scaled by $\langle N_{\text{part}} \rangle$. All data are normalized to the most central bin.

Fig. 4. Preliminary RHIC and SPS strange baryon yields relative to the measured $p$-$p$ data as a function of $dN_{ch}/d\eta$. Open symbols are for the SPS data and closed symbols from STAR.

a striking dependency on the strangeness content. This can be explained by considering that $R_{CP}$ uses peripheral events to determine the baseline spectra and $R_{AA}$ uses $p$-$p$ data. Fig. 1 has already shown that the peripheral Au-Au yields are enhanced compared to scaled $p$-$p$. Thus, $R_{AA}$ reveals a combined effect of suppressed $p$-$p$ production, due to phase space effects, and suppressed Au-Au production, due to "jet quenching". The $R_{CP}$ measure only reveals the jet quenching. What is unexpected is that the soft physics phase space suppression in $p$-$p$ appears to dominate the $R_{AA}$ ratio out to $p_T > 3$ GeV/c.

Since the Au-Au strangeness data appear to show that $\langle N_{\text{part}} \rangle$, or the initial nuclear overlap, is not the appropriate scaling volume for strangeness production we take a closer look at the centrality dependence. Our goal is to try to determine if there is a measurable quantity that is proportional to the strangeness production volume in which case the yields as a function of centrality will scale linearly. Fig. 1 shows that the anti-proton alone scales with $\langle N_{\text{part}} \rangle$. A closer look at the strange baryons reveals that as strange quarks are added to the particle, the scaled yield deviates more strongly from a linear dependence on $\langle N_{\text{part}} \rangle$ and in fact comes closer to $\langle N_{\text{bin}} \rangle$ scaling. This suggests that the strange quarks have a large $\langle N_{\text{bin}} \rangle$ contribution whereas the light u/d quarks scale with $\langle N_{\text{part}} \rangle$. This idea is supported by $R_{AA}$ (Fig. 2) which shows that the strange baryons scale significantly above that of simple $\langle N_{\text{bin}} \rangle$ scaling at intermediate $p_T$. We therefore consider a normalization that is dependent on the quark content of the particle:

$$C_{\text{scaling}} = N_{\text{light}} * N_{\text{part}}/N_q + N_s * N_{\text{bin}}/N_q$$

(2)

where $N_q$ is the number of quarks in the particle, $N_{\text{light}}$ is the number of light (u and d) quarks, and $N_s$ is the number of strange quarks. While this scaling is mostly successful, the $\phi$, which according to Eqn. 2 should scale with $\langle N_{\text{bin}} \rangle$, appears to scale with $\langle N_{\text{part}} \rangle$. This $\langle N_{\text{part}} \rangle$ scaling
is used in Fig. 3 while all other particles are scaled by Eqn. 2. It can be seen that the scaling is good to \( \sim 20\% \) level.

The PHOBOS collaboration has reported a strong correlation between \( \text{d}N_{ch}/\text{d}\eta \) and \( \langle N_{\text{part}} \rangle \) [8]. A two component fit

\[
N_{ch}/\text{d}\eta = n_{pp}((1 - x)\langle N_{\text{part}} \rangle/2 + x\langle N_{\text{bin}} \rangle/2)
\]

was used to fit the data. Where \( n_{pp} = 2.29 (1.27) \) at \( \sqrt{s_{NN}} = 200 (19.7) \text{ GeV} \) and is the mid-rapidity charged particle yield in \( p(p)-p \) collisions. \( x \) represents the contribution to the yield from hard processes. Independent fits to the data using Eqn. 3 leaving \( x \) as a free parameter, determined that the 200 GeV and 19.6 GeV Au-Au data resulted in the same value of \( x \). A simultaneous fit gave \( x = 0.13 \pm 0.01 \pm 0.05 \). This suggests that the contributions from hard processes are independent of collision energy, a result not predicted by pQCD calculations.

Building on the idea from PHOBOS, M. Lisa et al. [9] have recently reported that when the measured HBT radii are plotted versus \( \text{d}N_{ch}/\text{d}\eta^{1/3} \), a linear scaling is observed. Their reasoning is that HBT correlation measurements are related to the source size and therefore they must have some dependence on the initial geometrical overlap, i.e. \( \langle N_{\text{part}} \rangle^{1/3} \). This, however, does not give a perfect scaling, which could be due to the fact that \( \langle N_{\text{part}} \rangle^{1/3} \) relates to the original overlap volume and HBT measurements resolve the sources final state. Since \( \text{d}N_{ch}/\text{d}\eta \) is closely related to final state density, this variable, or rather \( \text{d}N_{ch}/\text{d}\eta^{1/3} \) which gives an approximate length scale, should result in a stronger correlation, and indeed it does. Fig. 4 shows the strangeness yields scaled by the \( p-p \) (Be) data from STAR and NA57 at the SPS [7] as a function of \( \text{d}N_{ch}/\text{d}\eta^{1/3} \), estimated using Eqn. 3 and the calculated values of \( \langle N_{\text{part}} \rangle \) and \( \langle N_{\text{bin}} \rangle \). This results in an apparent energy independent scaling for the strange anti-baryons which are linear in \( \text{d}N_{ch}/\text{d}\eta^{1/3} \). Eqn. 3 shows that \( \text{d}N_{ch}/\text{d}\eta \) combines contributions from \( \langle N_{\text{part}} \rangle \) and \( \langle N_{\text{bin}} \rangle \) which seems to be necessary to describe strangeness production in A-A collisions.

In summary, strange baryon production is not trivially related to the number of participants in the collision and the number of binary collisions seems to have a significant impact on the \( p_T \) integrated yields. The measured \( R_{AA} \) of these baryons suggests that the strong effect of the phase space suppression extends out to high \( p_T \). Meanwhile, three independent observations appear to provide evidence that \( \text{d}N_{ch}/\text{d}\eta \), which is closely related to the entropy of the system, is the underlying drive for many of the global observables measured in heavy-ion collisions.

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