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# Parton transverse momentum distribution at the moment of hadronization at RHIC

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**Abstract** : We extract the transverse momentum distribution of effective partons using the spectra of $\Omega$, $\Xi$, $\Lambda$ and $\phi$ hadrons measured by the STAR Collaboration from Au + Au collisions at $\sqrt{s_{NN}}$ = 200 GeV at RHIC. The extracted momentum distribution of strange quarks is flatter than that of up/down quarks consistent with hydrodynamics expansion in partonic phase prior to hadronization. Consistency in quark ratios derived from various hadron spectra gives clear evidence for hadron production as suggested by quark coalescence or recombination model.

**Keywords :** Quark coalescence/recombination, multi-strange hadron, spectra

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## I. Introduction

Measurements of elliptic flow $v_2$ and nuclear modification factor $R_{CP}$ at RHIC have displayed a number of constituent quark (NCQ) scaling [1–5]. Such scaling can be explained by quark coalescence or recombination model, which provided an intriguing mechanism for hadronization of bulk partonic matter created at RHIC [6–8]. The essential degrees of freedom at the hadronization seem to be effective constituent quarks which have develop a collective elliptic flow during the partonic evolution. The elliptic flow $v_2$ of the constituent quarks at hadronization can be characterized by the hadron $v_2$ scaled by the NCQ. While the transverse momentum distributions of the effective quarks haven't been explored systematically yet. In this paper, we will use high statistics multi-strange hadron data to examine the constitute quark number scaling in transverse momentum.

Multi-strange hadrons, $\Omega$s, $\Xi$s and $\phi$s, are predicted to have a relatively small hadronic interaction cross section [9,10]. This way, these hadrons won't be affected by

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the later hadronic rescattering stage and can retain partons information directly from the hadronization stage. In addition, there is no decay feed-down contributions to $\Omega$ and $\phi$ spectra. Multi-strange hadrons offer unique advantages to probe properties of the partonic degrees of freedom at hadronization.

## 2. Spectra extraction

Quark coalescence or recombination models have been used extensively in explaining RHIC data recently [6–8]. There are some common features in the intermediate $p_T$ region below 5 GeV/c in these models : (i) baryons with transverse momentum $p_T$ are formed mainly from quarks with transverse momentum ~$p_T/3$, whereas mensons mainly from quarks with transverse momentum ~$p_T/2$. (ii) The production probability for a baryon or meson is proportional to the local constituent quarks densities. This way, as $\Omega$ baryon consists of three valence strange quarks and $\phi$ meson carries the hidden strangeness, $\Xi$ baryon is composed of one light valence quark plus two strange quarks, we argued that the $\Omega(p_T/3)/\phi(p_T/2)$ ratio can reflect the strange quark transverse momentum distribution prior to hadronization and $\Xi(p_T/3)/\phi(p_T/2)$ ratio will reflect the light quark information. We have assumed that the strange and anti-strange quark distributions are the same and the particle formation dynamics are dominated by coalescence or recombination in the intermediate $p_T$ region.

Figure 1 presents the ratios of $\dfrac{\frac{\Omega+\bar{\Omega}}{2}(p_T/3)}{\phi(p_T/2)}$ and $\dfrac{\Xi^-(p_T/3)}{\phi(p_T/2)}$ as a function of

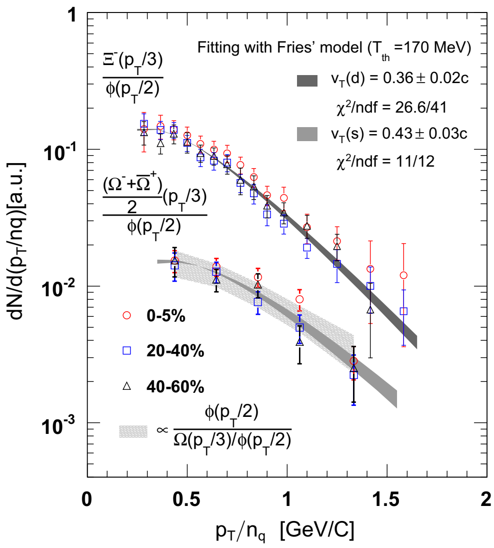


**Figure 1.** The derived light and strange quark transverse momentum distributions in Au + Au collisions at $\sqrt{s_{NN}}$ = 200 GeV at RHIC. Gray bands are fittings with hydrodynamics inspired model. Hatched area is the scaled range for $\phi$ meson $dN/d(p_T/2)$ divided by the extracted strange quark $dN/dp_T$ distribution.

$p_T/n_q$, where $n_q$ is the number of constituent quarks. We find that there is no significant variation in the quarks $p_T$ distributions at hadronization for centralities from 0–5% to 40–60%. The collision geometry factor is cancelled out in these ratios.

According to our assumption on quark coalescence or recombination mechanism, the ratio of $\frac{\phi(p_T/2)}{\Omega(p_T/3)/\phi(p_T/2)}$ will represent the anti-strange quark transverse momentum distribution. Hatched area in Figure 1 is the ratio as a function of $pT/n_q$. We find that it is consistent with the ratio of $\frac{\frac{\Omega+\bar{\Omega}}{2}(p_T/3)}{\phi(p_T/2)}$. This result provides a positive evidence supporting the quark distributions derived from our method.

In order to characterize the quark $p_T$ distribution, hydrodynamics inspired functions have been used to fit the derived quark distributions, permitting extraction of model parameters characterizing the bulk freeze-out temperature ($T_{\rm th}$) and collective radial flow velocities ($\upsilon_T$). We follow Fries's model [7], assuming $\upsilon_T$ to be independent of source radii and azimuth angle with the radial expansion velocity profile. Fixed the parameter $T_{\rm th}$ = 170 MeV and fitting the ratio derived from various hadrons in different centrality simultaneously, we obtained $\upsilon_T = 0.43 \pm 0.03c$ with $\chi^2/ndf = 11/12$ for strange quarks and $\upsilon_T = 0.36 \pm 0.02c$ with $\chi^2/ndf = 26.6/41$ for light quarks. The results are consistent with the picture that strange quarks may undergo a stronger hydrodynamical expansion in partonic phase than light up/down quarks possibly due to larger effective quark mass.

## 3. Quark ratio

In order to investigate the physical picture related to the ratio of strange quark to light quark, we investigated the ratios $\frac{\Omega(p_T/3)}{\Xi(p_T/3)}$ and $\frac{\Xi(p_T/3)}{\Lambda(p_T/3)}$ as a function of $p_T/3$. Figure 2 shows the $s/d$ ratios extracted from the $\Omega$, $\Xi^-$ and $\Lambda$ spectra from central Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV at RHIC. The raw $\frac{\Omega(p_T/3)}{\Xi(p_T/3)}$ and $\frac{\Xi(p_T/3)}{\Lambda(p_T/3)}$ have a similar $p_T/3$ shape indicating the validity of our approach. Recombination model calculation by Fries *et al*, [7] predicted a consistent shape between $s/d$ quark ratio and the $\frac{\Omega(p_T/3)}{\Xi(p_T/3)}$ or $\frac{\Xi(p_T/3)}{\Lambda(p_T/3)}$ after removing the different spin degeneracy factor. The calculated $s/d$ ratio *vs.* quark $p_T$ deviated somewhat in shape from our parameterized curve based on experiment data. The overall agreement is reasonably well because of large experimental uncertainty involved. There is a normalization offset, presumably due to the fact that the model calculation does not include all resonance decay contributions.

We present the feed-down correction on $\Xi^-$ and $\Lambda$ spectra in Figure 2. Ignoring

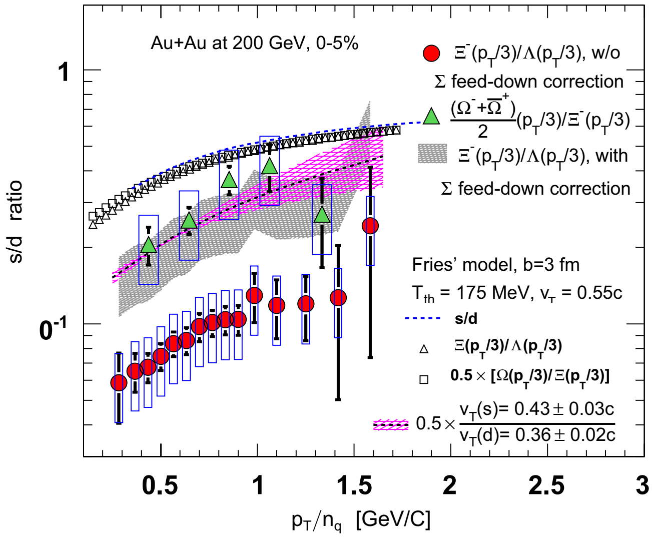


**Figure 2.** The s/d ratio derived from $\Omega$, $\Xi^-$ and $\Lambda$ spectra in central Au + Au collisions at $\sqrt{s_{NN}}$ = 200 GeV at RHIC. Red circles represent the $s/d$ ratio without $\Sigma$ decays correction while gray hatched region is the corresponding ratio range after taking into $\Sigma$ decays correction. The blue boxes represent the uncertainty in $\Xi$(1530) feed-down estimation. Theoretical predictions (see text for details) have also been plotted for comparison.

the contribution to $\Xi^-$ from $\Omega$ decays, we corrected these shapes including three aspects : the contribution to $\Xi^-$ from $\Xi°$(1530) decays (46% ± 14%) [11], the contribution to $\Lambda$ from $\Xi$ and $\Omega$ decays. This is shown as red circles in Figure 2. We find the $\dfrac{\Xi(p_T/3)}{\Lambda(p_T/3)}$ ratio is about a factor of 3 smaller than the $\dfrac{\Omega(p_T/3)}{\Xi(p_T/3)}$. The contribution to the $\Lambda$ spectrum from $\Sigma$ decays is significant. We take into account the $\Sigma$ decays contribution including two aspects : the contribution from $\Sigma$(1380) (26% ± 5.9%) [12] and the contribution from $\Sigma^0$ (THERMUS thermal model and string fragmentation model prediction : 25%–36%) [13–15]. After taking into account $\Sigma$ feed-down correction, we find the distributions between $\dfrac{\Omega(p_T/3)}{\Xi(p_T/3)}$ and $\dfrac{\Xi(p_T/3)}{\Lambda(p_T/3)}$ are consistent with each other shown as gray hatched region in Figure 2.

The $s/d$ tatio deriveid from multi-strange hadron data both increase with $p_T < 1.0$ (GeV/c) and approach saturation at $p_T > 1.0$ (GeV/c). This $p_T$ dependence may indicate the strange quark have developed a stronger collective radial flow than that of light quarks at the moment of hadronization.

## 4. Summary

In summary, we have presented constrains on transverse momentum distributions for the effective quarks at hadronization of the bulk partonic matter produced at RHIC. Our results suggest that strange quarks may have developed a collective radial flow stronger than that of light quarks during evolution of the initial parton. The validity of our approach to extract quark transverse momentum distribution at hadronization has been tested with independent particle ratios. The extracted parton $p_T$ distribution will provide unique constraints on partonic evolution history up to the hadronization epoch, detail elaborate can be found in Ref. [16].

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