PROCEEDINGS OF SCIENCE

Shannon entropy for pp collisions at RHIC and LHC energies

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We present an analysis of the transverse momentum spectra using thermal and hypergeometric confluent U functions, derived from the Schwinger mechanism convoluted with Gaussian and q-Gaussian string tension fluctuations, respectively. We investigate the statistical information of charged particles' invariant yield by analyzing experimental data from minimum-bias pp collisions reported by the RHIC and LHC experiments. Our computations of the Shannon entropy reveal that the heavy tail of the spectrum contributes significantly to the monotonically increasing behavior in entropy as a function of center-of-mass energy.

International Conference on High Energy Physics
18-24 July 2024
Prague, Czech Republic

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PoS(ICHEP2024)577

The study of ultrarelativistic particle collisions offers valuable insights into the behavior of strongly interacting matter under extreme conditions. One key experimental observable is the transverse momentum distribution, which is a histogram constructed using the transverse momentum (p_T) of charged particles produced in the events [1]. In the framework of color string models, the p_T distribution can be described through color string fragmentation, a mechanism related to the Schwinger effect, which governs particle pair production in strong gauge fields [2].

Building on this theoretical framework, this work aims to analyze the invariant yield of charged particle production in minimum-bias pp collisions, using the data reported by the STAR-RHIC and ALICE-LHC experiments. To achieve this, we derive a thermal and a nonthermal p_T distribution, by considering the Schwinger mechanism with Gaussian and non-Gaussian distributions for string tension fluctuations, respectively. We fit each function to the experimental data and compute the Shannon entropy for both approaches. Finally, we discuss the subtle differences between the two models, emphasizing the significance of the information encoded in the heavy tail of the p_T distribution.

In color string models, particle production can be described by the creation of neutral color pairs through the breaking of color strings stretched between colliding partons [2]. The Schwinger mechanism can model the transverse momentum distribution of such particles as: $dN/dp_T^2 \propto \exp(-\pi p_T^2/x^2)$.

If the string tension x^2 fluctuates, the p_T distribution must be computed as a marginal distribution. Specifically, when the string tension fluctuates according to a Gaussian distribution, the resulting p_T distribution resembles the Boltzmann distribution [1]:

$$\frac{dN}{dp_T^2} \propto \int_0^\infty \left[\frac{1}{\pi T_{\text{th}}}\exp\left(-\frac{x^2}{4\pi T_{\text{th}}^2}\right)\right]\exp\left(-\frac{\pi p_T^2}{x^2}\right)dx = \exp\left(-\frac{p_T}{T_{\text{th}}}\right), \tag{1}$$

where the inverse of the exponential decay, T_{th}, is associated with an effective temperature of the collision system [1].

Moreover, if the string tensions fluctuate according to a q-Gaussian distribution, the p_T spectrum becomes a confluent hypergeometric function (also named Tricomi's function)

$$\frac{dN}{dp_T^2} \propto \int_0^\infty \left[\mathcal{N}_q\left(1+\frac{(q-1)x^2}{2\sigma^2}\right)^{\frac{1}{1-q}}\right]\exp\left(-\frac{\pi p_T^2}{x^2}\right)dx = \frac{\Gamma(a+1/2)}{\sqrt{\pi}}U(a,1/2,z_0 p_T^2), \tag{2}$$

with $a = \frac{1}{q-1} - \frac{1}{2}$ and $z_0 = \frac{\pi(q-1)}{2\sigma^2}$ [1].

Equation (2) successfully reproduces the asymptotic behaviors observed in the experimental p_T distribution: at low p_T values, it behaves as a thermal distribution, while at high p_T values, it transitions to a power-law regime. This makes it capable of fitting the entire experimental p_T distribution [1].

We fit the experimental p_T distribution data reported by the STAR and ALICE experiments following the procedure in Ref. [1]. Notably, the Tricomi's function in Eq. (2) performs exceptionally well in reproducing the experimental data (as shown in Fig. 1(a)). In particular, we accurately reproduce the mean p_T values by computing them over the same range used by the experiments [1]. Interestingly, all the fitting parameters follow a power-law trend of the form $X(\sqrt{s}) = a_X \sqrt{s}^{\alpha_X}$,

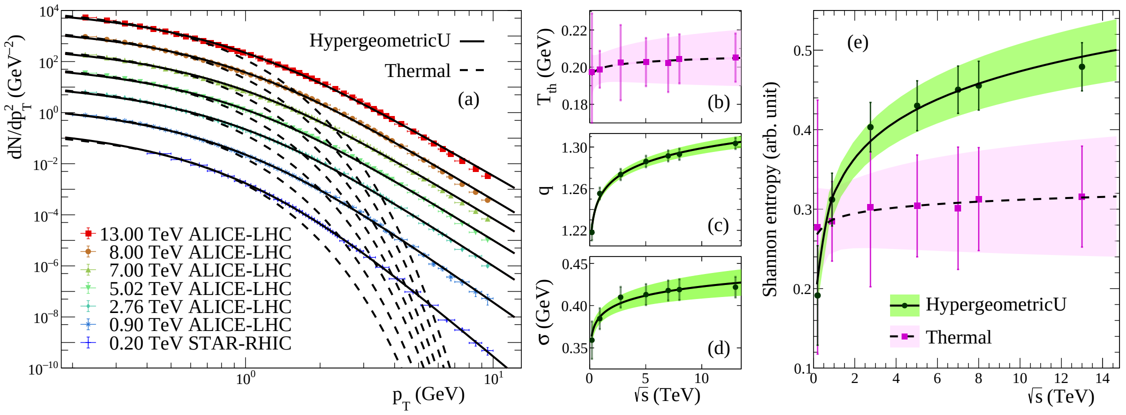

Figure 1: (a) Fits to the experimental data (markers) using the thermal model (dashed line) and the U function (solid line). (b) T_{th}, (c) q, and (d) σ parameters as functions of the center-of-mass energy, each with its corresponding power-law trend (solid line). (e) Shannon entropy as a function of the center-of-mass energy for both the thermal model and the U function. The shaded regions represent uncertainty propagation.

with the following exponents: $\alpha_{T_{\mathrm{th}}} = 0.011(24)$, $\alpha_q = 0.0154(14)$, and $\alpha_\sigma = 0.037(11)$ [1], as shown in Figs. 1(b)-(d).

The Shannon entropy provides a way to quantify the uncertainty and information of the p_T distribution. For the normalized p_T distribution is calculated as [1]

$$\mathcal{H} = -\int_0^\infty \left(\frac{1}{I_0}\frac{dN}{dp_T^2}\right) \ln\left(\frac{1}{I_0}\frac{dN}{dp_T^2}\right) p_T, \tag{3}$$

where $I_0 = \int_0^\infty \left(\frac{dN}{dp_T^2}\right) p_T$. The shape of this quantity is scale-independent and reflects the amount of information contained in the fully normalized p_T distribution [1].

The main result obtained is that the Shannon entropy increases with the center-of-mass energy of the collisions, as shown in Fig. 1(e), indicating that higher-energy collisions generate more information in both the thermal and U function approaches. However, the U function captures more information than the thermal model, as evidenced by the steeper rise in Shannon entropy with increasing center-of-mass energy.

In conclusion, the nonextensive description of string tension fluctuations provides a more accurate representation of the system, enabling the model to capture additional information, particularly in the production of high-p_T particles.

References

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