Enhanced Strange Hadron Productions in Cu+Cu Collisions at $\sqrt{s_{NN}} = 200GeV$

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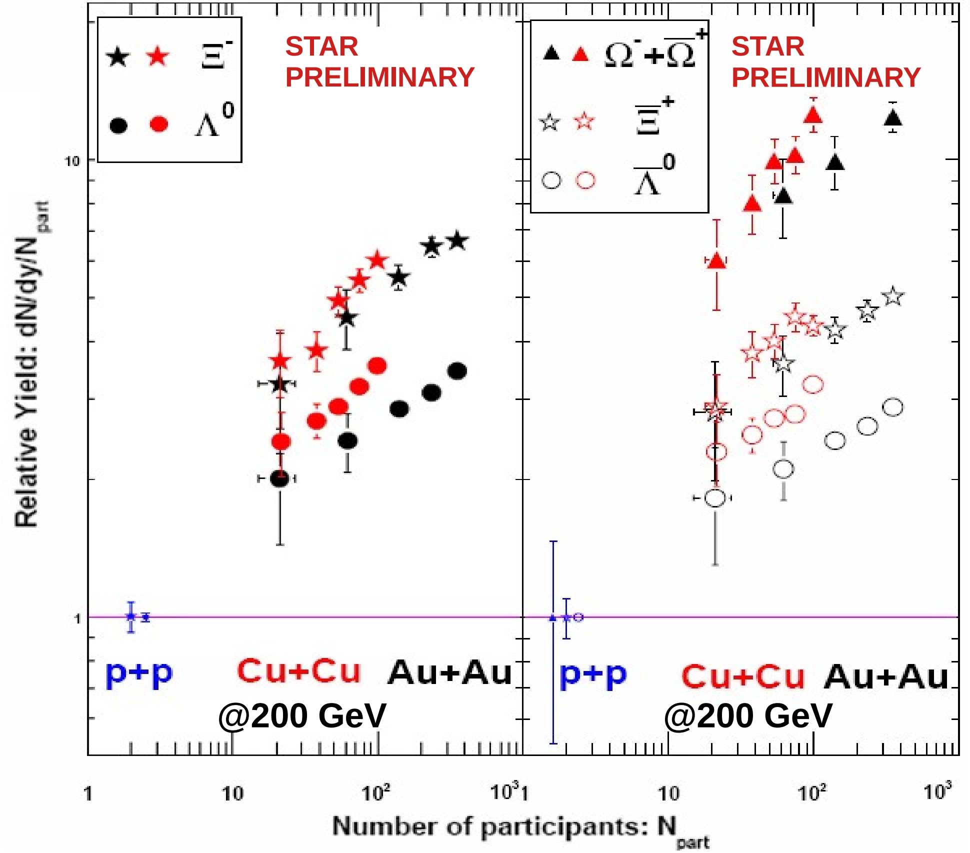
OUTLINE

- Introduction
- Physics Motivation
- Model Based Calculations
- Results
- Outlook and Conclusion

INTRODUCTION



Observations

1) Hyperon yields per participant are strongly enhanced in central collisions.
2) Hyperon yields per participant in Cu+Cu (Medium sized) system is higher than that of Au+Au (Large sized) system at the same energy.

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PHYSICS MOTIVATION

- What is the effect of the system size on the physics of collisions?
- Is $dN_{ch}/d\eta$ a good parameter to estimate collision centrality? Are there any alternative methods to estimate collision centrality?

STRANGE HADRON TRANSPORT IN HEAVY ION COLLISON

- Model is developed using Momentum Integrated Boltzmann equation.
- We solve rate equations for all strange degrees of freedoms simultaneously along with temperature and baryon chemical potential.

ASSUMPTIONS

- We assume that hadronic system is formed after QGP at Tc.
- Non-strange hadrons dominated by pions, are in thermal equilibrium.
- Strange hadrons are slightly away from thermal equilibrium due to their different interaction strength.

CALCULATION FOR RATE EQUATIONS

General form of Boltzmann equation is, $\hat{\mathbf{L}}[f] = \mathbf{C}[f]$

Where, $\hat{\mathbf{L}}$ = Liouville's operator; [f] = Phase Space density; C = Collision term

In relativistic regime, $p^{\mu}\partial_{\mu}[f_a] = C[f_a]$

Assuming the system to be isotropic and homogenous this equation simplifies to

$$E\frac{\partial[f_a]}{\partial t} = C[f_a]$$

Integrating over momenta, we have $\frac{g_a}{(2\pi)^3}\int d^3p\frac{\partial f_a}{\partial t} = \frac{g_a}{(2\pi)^3}\int\frac{d^3p}{E}C[f_a]$

Since, $n_a(t) = \frac{g_a}{(2\pi)^3}\int d^3p\, f_a(E,t)$ we can write, $\frac{dn_a}{dt} = \frac{g_a}{(2\pi)^3}\int\frac{d^3p}{E}C[f_a]$

For a process, a + b <--> c + d , we will have two distinct cross sections for forward and backward reactions. Using classical particle assumption,

CALCULATION FOR RATE EQUATIONS (ctd.)

$$\int d\Pi_a C[f_a] = -\int d\Pi_a \, d\Pi_b \, d\Pi_c \, d\Pi_d \, (2\pi)^4 \delta^4 (p_a + p_b - p_c - p_d) F_{abcd}$$

Where, $F_{abcd} = |\mathcal{M}|^2_{a+b\to c+d} f_a f_b - |\mathcal{M}|^2_{c+d\to a+b} f_c f_d$ and $d\Pi = \frac{g}{(2\pi)^3} \frac{d^3p}{E}$

Finally, assuming that we are only slightly away from thermal equilibrium we can Approximate non thermal cross section equal to thermal. Doing this we have,

$$\frac{dn_a}{dt} = -n_a n_b \langle \sigma_{ab} \, v_{ab} \rangle_{Th} + n_c n_d \langle \sigma_{cd} \, v_{cd} \rangle_{Th}$$

where, v_{ab} and v_{cd} are moller velocities

For expanding system, rate equation becomes

$$\boxed{\frac{dn_a}{dt} + \Gamma_{exp} \, n_a = -n_a n_b \langle \sigma_{ab} \, v_{ab} \rangle_{Th} + n_c n_d \langle \sigma_{cd} \, v_{cd} \rangle_{Th}}$$

Rate of change of number density

Dilution Term

Forward reaction **Backward Reaction**

Net Production term

For detailed calculation please refer to Phys. Rev. D 101, 094004

Note, since we are only interested in numbers, we can use 1+1 Bjorken expansion. In this case, the expansion term Γ_{exp} simplifies to t^{-1}

RATE EQUATIONS OR MOMENTUM INTEGRATED BOLTZMANN EQUATIONS FOR KAONS

$$\begin{aligned}\frac{dn_K}{dt} + \frac{n_K}{t} = {} & n_\pi n_\pi \langle \sigma v \rangle_{\pi\pi \to K\bar{K}} - n_K n_{\bar{K}} \langle \sigma v \rangle_{K\bar{K} \to \pi\pi} + n_\rho n_\rho \langle \sigma v \rangle_{\rho\rho \to K\bar{K}} - n_K n_{\bar{K}} \langle \sigma v \rangle_{K\bar{K} \to \rho\rho} \\ & + n_\pi n_\rho \langle \sigma v \rangle_{\pi\rho \to K\bar{K}} - n_K n_{\bar{K}} \langle \sigma v \rangle_{K\bar{K} \to \pi\rho} + n_\pi n_N \langle \sigma v \rangle_{\pi N \to \Lambda K} - n_\Lambda n_K \langle \sigma v \rangle_{\Lambda K \to \pi N} \\ & + n_\rho n_N \langle \sigma v \rangle_{\rho N \to \Lambda K} - n_\Lambda n_K \langle \sigma v \rangle_{\Lambda K \to \rho N} + n_\pi n_N \langle \sigma v \rangle_{\pi N \to \Sigma K} - n_\Sigma n_K \langle \sigma v \rangle_{\Sigma K \to \pi N} \\ & + n_{\bar{K}} n_N \langle \sigma v \rangle_{\bar{K} N \to K \Xi} - n_K n_\Xi \langle \sigma v \rangle_{K\Xi \to \bar{K} N} + n_p n_{\bar{p}} \langle \sigma v \rangle_{p\bar{p} \to K\bar{K}} - n_K n_{\bar{K}} \langle \sigma v \rangle_{K\bar{K} \to p\bar{p}} \\ & + n_{\bar{K}} n_\Lambda \langle \sigma v \rangle_{\bar{K}\Lambda \to \Omega K} - n_\Omega n_K \langle \sigma v \rangle_{\Omega K \to \bar{K}\Lambda} + n_{\bar{K}} n_\Sigma \langle \sigma v \rangle_{\bar{K}\Sigma \to \Omega K} - n_\Omega n_K \langle \sigma v \rangle_{\Omega K \to \bar{K}\Sigma} \\ & + n_\pi n_\Xi \langle \sigma v \rangle_{\pi\Xi \to K\Omega} - n_\Omega n_K \langle \sigma v \rangle_{\Omega K \to \pi\Xi}\end{aligned}$$

$$\begin{aligned}\frac{dn_{\bar{K}}}{dt} + \frac{n_{\bar{K}}}{t} = {} & n_\pi n_\pi \langle \sigma v \rangle_{\pi\pi \to K\bar{K}} - n_K n_{\bar{K}} \langle \sigma v \rangle_{K\bar{K} \to \pi\pi} + n_\rho n_\rho \langle \sigma v \rangle_{\rho\rho \to K\bar{K}} - n_K n_{\bar{K}} \langle \sigma v \rangle_{K\bar{K} \to \rho\rho} \\ & + n_\pi n_\rho \langle \sigma v \rangle_{\pi\rho \to K\bar{K}} - n_K n_{\bar{K}} \langle \sigma v \rangle_{K\bar{K} \to \pi\rho} - n_{\bar{K}} n_N \langle \sigma v \rangle_{\bar{K} N \to \Lambda\pi} + n_\Lambda n_\pi \langle \sigma v \rangle_{\Lambda\pi \to \bar{K} N} \\ & - n_{\bar{K}} n_N \langle \sigma v \rangle_{\bar{K} N \to \Sigma\pi} + n_\Sigma n_\pi \langle \sigma v \rangle_{\Sigma\pi \to \bar{K} N} - n_{\bar{K}} n_N \langle \sigma v \rangle_{\bar{K} N \to K\Xi} + n_K n_\Xi \langle \sigma v \rangle_{K\Xi \to \bar{K} N} \\ & - n_{\bar{K}} n_\Lambda \langle \sigma v \rangle_{\bar{K}\Lambda \to \pi\Xi} + n_\pi n_\Xi \langle \sigma v \rangle_{\pi\Xi \to \bar{K}\Lambda} - n_{\bar{K}} n_\Sigma \langle \sigma v \rangle_{\bar{K}\Sigma \to \pi\Xi} + n_\pi n_\Xi \langle \sigma v \rangle_{\pi\Xi \to \bar{K}\Sigma} \\ & + n_p n_{\bar{p}} \langle \sigma v \rangle_{p\bar{p} \to K\bar{K}} - n_K n_{\bar{K}} \langle \sigma v \rangle_{K\bar{K} \to p\bar{p}} - n_{\bar{K}} n_\Lambda \langle \sigma v \rangle_{\bar{K}\Lambda \to \Omega K} + n_\Omega n_K \langle \sigma v \rangle_{\Omega K \to \bar{K}\Lambda} \\ & - n_{\bar{K}} n_\Sigma \langle \sigma v \rangle_{\bar{K}\Sigma \to \Omega K} + n_\Omega n_K \langle \sigma v \rangle_{\Omega K \to \bar{K}\Sigma}\end{aligned}$$

The first term in the LHS **rate of change of number density**, second term is the **dilution term due to expansion**. Terms in the RHS are the **production/annihilation terms**.

RATE EQUATIONS OR MOMENTUM INTEGRATED BOLTZMANN EQUATIONS FOR HYPERONS

$$\frac{dn_\Lambda}{dt}+\frac{n_\Lambda}{t}=n_\pi n_N\langle\sigma v\rangle_{\pi N\to\Lambda K}-n_\Lambda n_K\langle\sigma v\rangle_{\Lambda K\to\pi N}+n_\rho n_N\langle\sigma v\rangle_{\rho N\to\Lambda K}-n_\Lambda n_K\langle\sigma v\rangle_{\Lambda K\to\rho N}$$
$$-n_\Lambda n_\Lambda\langle\sigma v\rangle_{\Lambda\Lambda\to N\Xi}+n_N n_\Xi\langle\sigma v\rangle_{N\Xi\to\Lambda\Lambda}-n_\Lambda n_\Sigma\langle\sigma v\rangle_{\Lambda\Sigma\to N\Xi}+n_N n_\Xi\langle\sigma v\rangle_{N\Xi\to\Lambda\Sigma}$$
$$-n_{\bar K}n_\Lambda\langle\sigma v\rangle_{\bar K\Lambda\to\pi\Xi}+n_\pi n_\Xi\langle\sigma v\rangle_{\pi\Xi\to\bar K\Lambda}+n_{\bar K}n_N\langle\sigma v\rangle_{\bar K N\to\Lambda\pi}-n_\Lambda n_\pi\langle\sigma v\rangle_{\Lambda\pi\to\bar K N}$$
$$+n_p n_{\bar p}\langle\sigma v\rangle_{p\bar p\to\Lambda\bar\Lambda}-n_\Lambda n_{\bar\Lambda}\langle\sigma v\rangle_{\Lambda\bar\Lambda\to p\bar p}+n_K n_\Omega\langle\sigma v\rangle_{K\Omega\to\bar K\Lambda}-n_{\bar K}n_\Lambda\langle\sigma v\rangle_{\bar K\Lambda\to K\Omega}$$

$$\frac{dn_\Sigma}{dt}+\frac{n_\Sigma}{t}=n_\pi n_N\langle\sigma v\rangle_{\pi N\to\Sigma K}-n_\Sigma n_K\langle\sigma v\rangle_{\Sigma K\to\pi N}-n_\Lambda n_\Sigma\langle\sigma v\rangle_{\Lambda\Sigma\to N\Xi}+n_N n_\Xi\langle\sigma v\rangle_{N\Xi\to\Lambda\Sigma}$$
$$-n_\Sigma n_\Sigma\langle\sigma v\rangle_{\Sigma\Sigma\to N\Xi}+n_N n_\Xi\langle\sigma v\rangle_{N\Xi\to\Sigma\Sigma}-n_{\bar K}n_\Sigma\langle\sigma v\rangle_{\bar K\Sigma\to\pi\Xi}+n_\pi n_\Xi\langle\sigma v\rangle_{\pi\Xi\to\bar K\Sigma}$$
$$+n_{\bar K}n_N\langle\sigma v\rangle_{\bar K N\to\Sigma\pi}-n_\Sigma n_\pi\langle\sigma v\rangle_{\Sigma\pi\to\bar K N}+n_p n_{\bar p}\langle\sigma v\rangle_{p\bar p\to\Sigma\bar\Sigma}-n_\Sigma n_{\bar\Sigma}\langle\sigma v\rangle_{\Sigma\bar\Sigma\to p\bar p}$$

The first term in the LHS **rate of change of number density**, second term is the **dilution term due to expansion**. Terms in the RHS are the **production/annihilation terms**.

RATE EQUATIONS OR MOMENTUM INTEGRATED BOLTZMANN EQUATIONS FOR HYPERONS (Ctd.)

$$\begin{aligned}\frac{dn_\Xi}{dt}+\frac{n_\Xi}{t} &= n_\Lambda n_\Lambda\langle\sigma v\rangle_{\Lambda\Lambda\to N\Xi} - n_N n_\Xi\langle\sigma v\rangle_{N\Xi\to\Lambda\Lambda} + n_\Lambda n_\Sigma\langle\sigma v\rangle_{\Lambda\Sigma\to N\Xi} - n_N n_\Xi\langle\sigma v\rangle_{N\Xi\to\Lambda\Sigma}\\ &+ n_\Sigma n_\Sigma\langle\sigma v\rangle_{\Sigma\Sigma\to N\Xi} - n_N n_\Xi\langle\sigma v\rangle_{N\Xi\to\Sigma\Sigma} + n_{\bar{K}} n_N\langle\sigma v\rangle_{\bar{K}N\to K\Xi} - n_K n_\Xi\langle\sigma v\rangle_{K\Xi\to\bar{K}N}\\ &+ n_{\bar{K}} n_\Lambda\langle\sigma v\rangle_{\bar{K}\Lambda\to\pi\Xi} - n_\pi n_\Xi\langle\sigma v\rangle_{\pi\Xi\to\bar{K}\Lambda} + n_{\bar{K}} n_\Sigma\langle\sigma v\rangle_{\bar{K}\Sigma\to\pi\Xi} - n_\pi n_\Xi\langle\sigma v\rangle_{\pi\Xi\to\bar{K}\Sigma}\\ &+ n_p n_{\bar{p}}\langle\sigma v\rangle_{p\bar{p}\to\Xi\bar{\Xi}} - n_\Xi n_{\bar{\Xi}}\langle\sigma v\rangle_{\Xi\bar{\Xi}\to p\bar{p}} + n_\Omega n_K\langle\sigma v\rangle_{\Omega K\to\pi\Xi} - n_\pi n_\Xi\langle\sigma v\rangle_{\pi\Xi\to\Omega K}\end{aligned}$$

$$\begin{aligned}\frac{dn_\Omega}{dt}+\frac{n_\Omega}{t} &= n_p n_{\bar{p}}\langle\sigma v\rangle_{p\bar{p}\to\Omega\bar{\Omega}} - n_\Omega n_{\bar{\Omega}}\langle\sigma v\rangle_{\Omega\bar{\Omega}\to p\bar{p}} + n_\pi n_\Xi\langle\sigma v\rangle_{\pi\Xi\to\Omega K} - n_\Omega n_K\langle\sigma v\rangle_{\Omega K\to\pi\Xi}\\ &+ n_{\bar{K}} n_\Lambda\langle\sigma v\rangle_{\bar{K}\Lambda\to K\Omega} - n_K n_\Omega\langle\sigma v\rangle_{K\Omega\to\bar{K}\Lambda} + n_{\bar{K}} n_\Sigma\langle\sigma v\rangle_{\bar{K}\Sigma\to K\Omega} - n_K n_\Omega\langle\sigma v\rangle_{K\Omega\to\bar{K}\Sigma}.\end{aligned}$$

The first term in the LHS **rate of change of number density**, second term is the **dilution term due to expansion**. Terms in the RHS are the **production/annihilation terms**.

TEMPERATURE EVOLUTION

By solving energy momentum conservation equation assuming Björken expansion,

$$\partial_\mu T^{\mu\nu} = 0$$

we obtain the temperature evolution equation,

$$\frac{\partial}{\partial\tau}\left[T^{\frac{4}{(1+c_s^2)}}\tau\right] = 0 \text{ or } T^a\tau = \text{const} = k_2 \text{ and } a = \frac{4}{(1+c_s^2)}$$

Where, T is temperature of system
τ is elapsed time, and
c_s is the velocity of sound which is kept at 1 / 5

CALCULATION OF PRODUCTION TERM: A MICROSCOPIC APPROACH

This approach takes care of interaction of most probable hadronic channels

The RHS of the rate equation contains the rate of production of species of interest at any time. The rate is give by,

$$\langle \sigma v \rangle = \frac{T^4}{4} \mathcal{C}_{ab}(T) \int_{z_0}^{\infty} dz [z^2 - (m_a/T + m_b/T)^2] \times [z^2 - (m_a/T - m_b/T)^2] \sigma K_1(z),$$

Sigma is the cross section and v is the relative velocity (Moller) between two incoming channels. The above expression is for channel ab→ cd

where $\mathcal{C}_{ab}(T)$ is given by

$$\mathcal{C}_{ab}(T) = \frac{1}{m_a^2 m_b^2 K_2(m_a/T) K_2(m_b/T)}$$

K_2 is the modified bessel function of the second kind.

$$z_0 = \max(m_a + m_b, m_c + m_d)/T$$

M-M TYPE

$\pi\pi \to K\bar{K}$ $\quad$ $\rho\rho \to K\bar{K}$

$\pi\rho \to K\bar{K}^*$ $\quad$ $\pi\rho \to K^*\bar{K}$

Cross Sections

M-B TYPE

$\pi N \to \Lambda K$

$\pi N \to \Sigma K$

$\rho N \to \Lambda K$ $\quad$ $\rho N \to \Sigma K$

$\bar{K}\ \mathrm{N} \to \Lambda\pi$ $\quad$ $\bar{K}\ \mathrm{N} \to \Sigma\pi$

$\bar{K}\ \mathrm{N} \to K\Xi$ $\quad$ $\bar{K}\ \Lambda \to \pi\Xi$

$\bar{K}\ \Sigma \to \pi\Xi$ $\quad$ $\bar{K}\ \Lambda \to K^0\Omega^-$

$\bar{K}\ \Sigma \to K^0\Omega^-$

B-B TYPE

$N\bar{N} \to K\bar{K}$

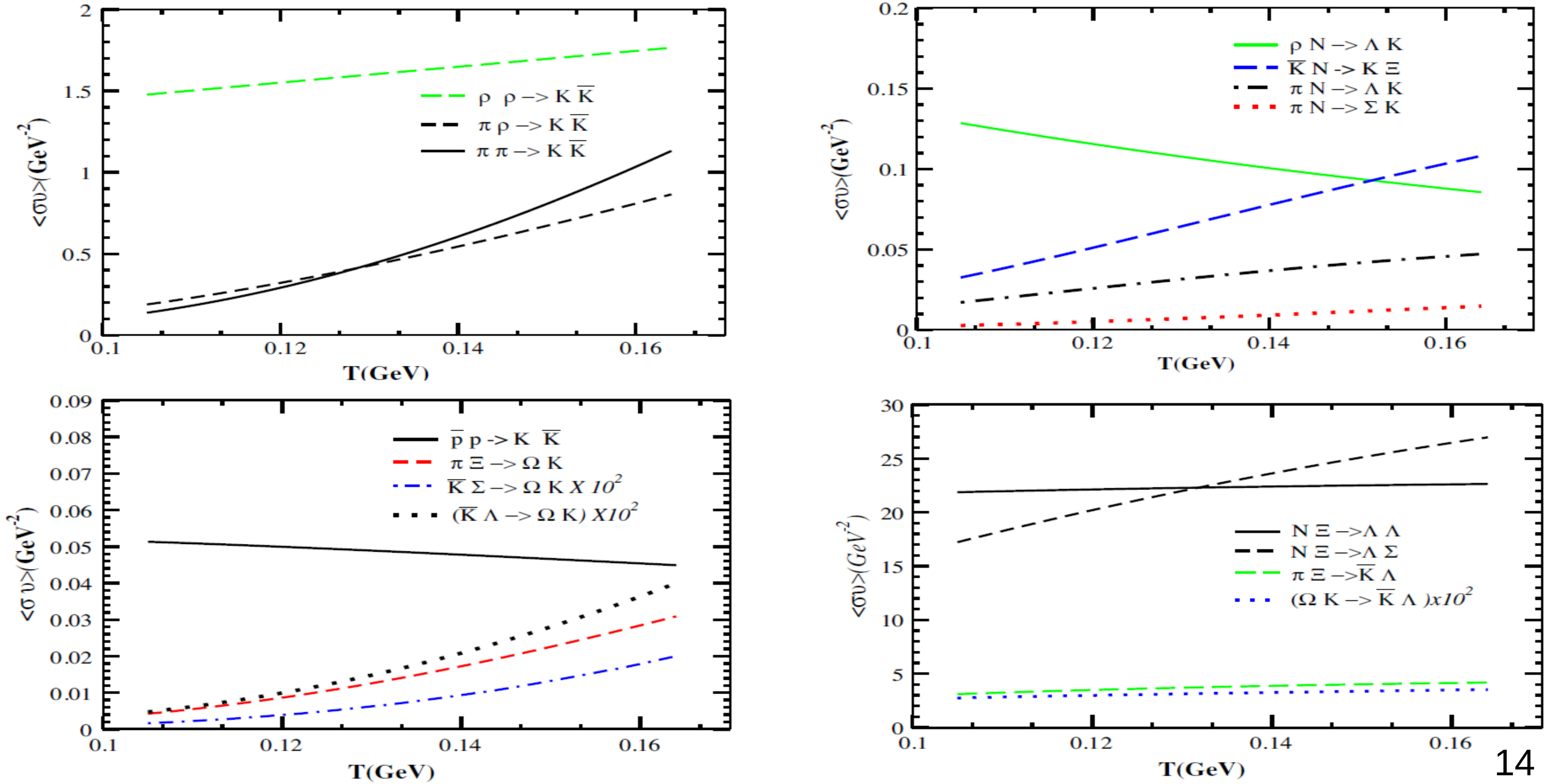
$N\bar{N} \to \Lambda\bar{\Lambda}$ $\quad$ $N\bar{N} \to \Sigma\bar{\Sigma}$

$N\bar{N} \to \Xi\bar{\Xi}$ $\quad$ $N\bar{N} \to \Omega\bar{\Omega}$

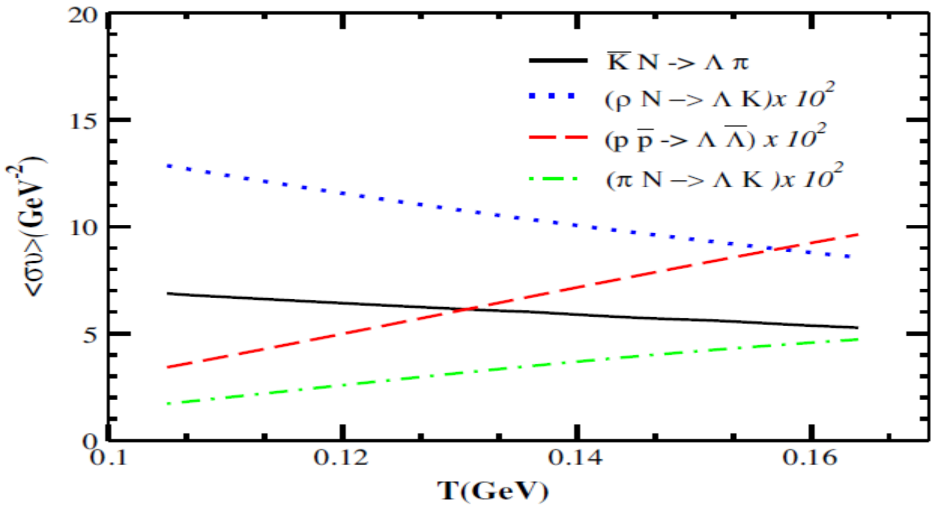
$\Lambda\Lambda \to N\Xi$ $\quad$ $\Lambda\Sigma \to N\Xi$

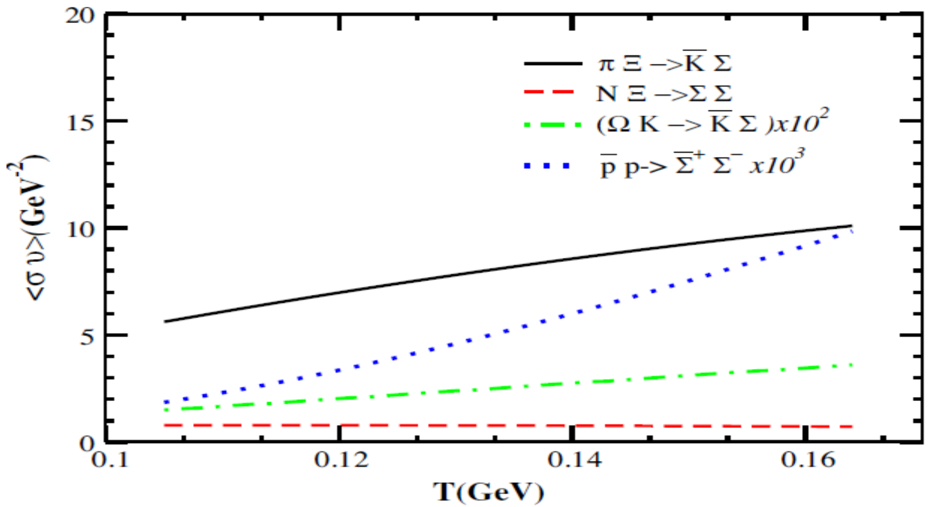
$\Sigma\Sigma \to N\Xi$

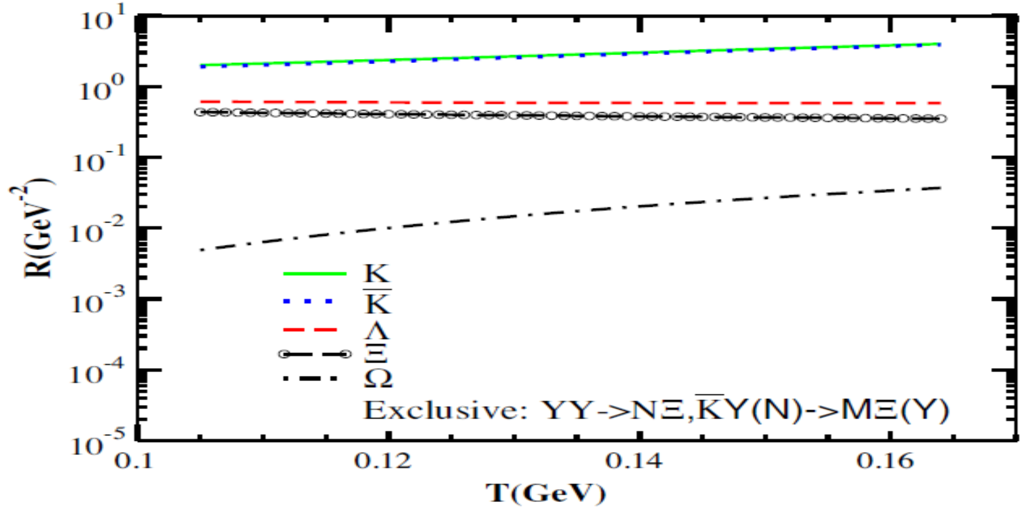
AVERAGED CROSS SECTION TIMES VELOCITY ESTIMATION



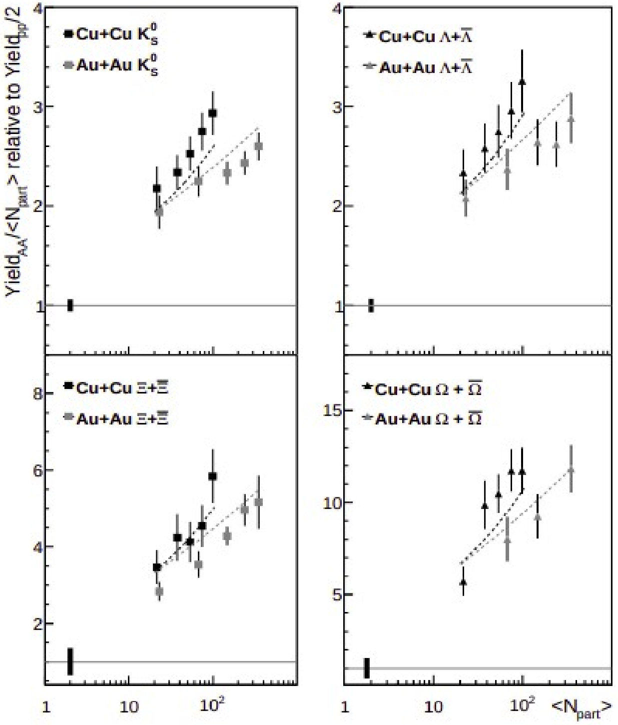
AVERAGED CROSS SECTION TIMES VELOCITY ESTIMATION (ctd.)



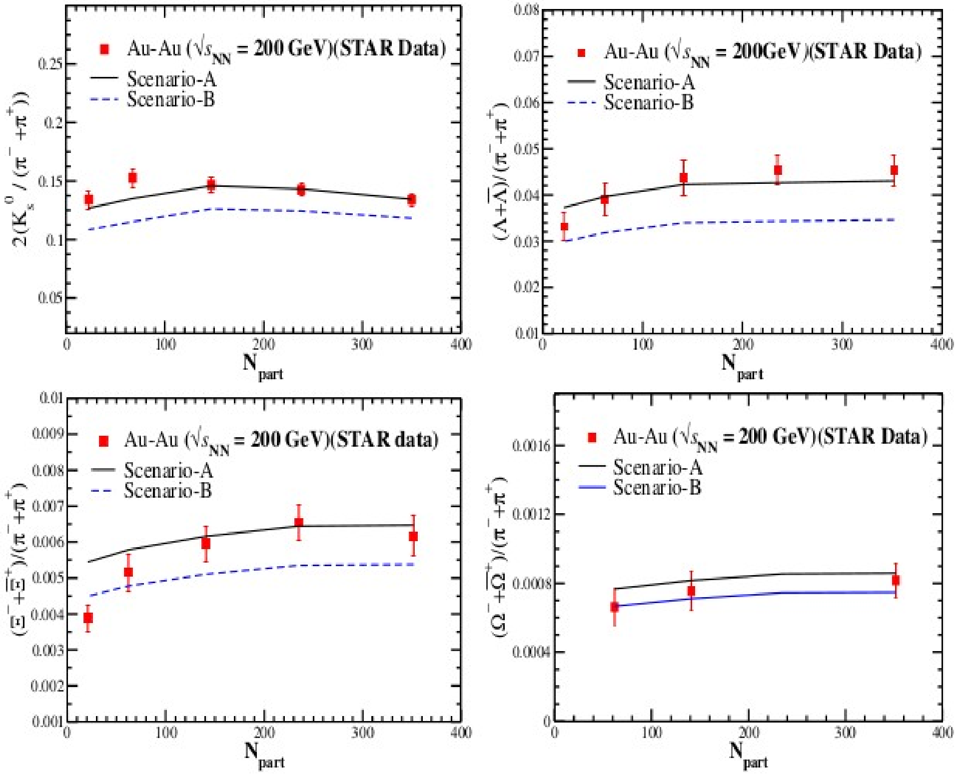




RESULTS



G. Agakishiev et al., for STAR Collaboration,
PRL 108, 072301 (2012)



Ghosh, Purabi & Agarwalla, Santosh & Nayak, Jajati. (2022).
Hyperon productions from Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV.

Differences in the initial conditions like higher temperature and enhanced strangeness is supposed to explain the increase in yields for Cu+Cu vis-a-vis Au+Au system.

The exact nature of difference is still under study.

SUMMARY AND OUTLOOK

- Strange yields from Cu-Cu system are higher than Au-Au system even for the same centrality. This change is explained by change in initial conditions from our model.
- In future we wish to study this difference in detail and ascertain if glauber model is effective tool for measurement of particle centrality in itself.

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