The Kaon to Pion Ratio in Heavy Ion Collisions

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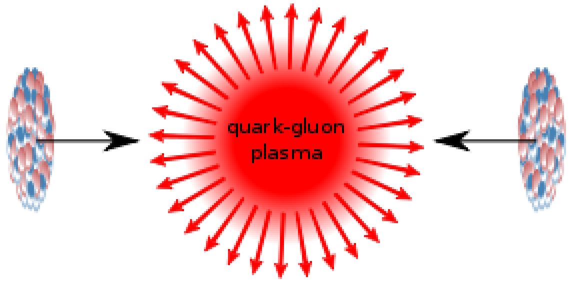
Plan of talk

- Introduction
- Theoretical formulation
- Results
- Summary

Introduction



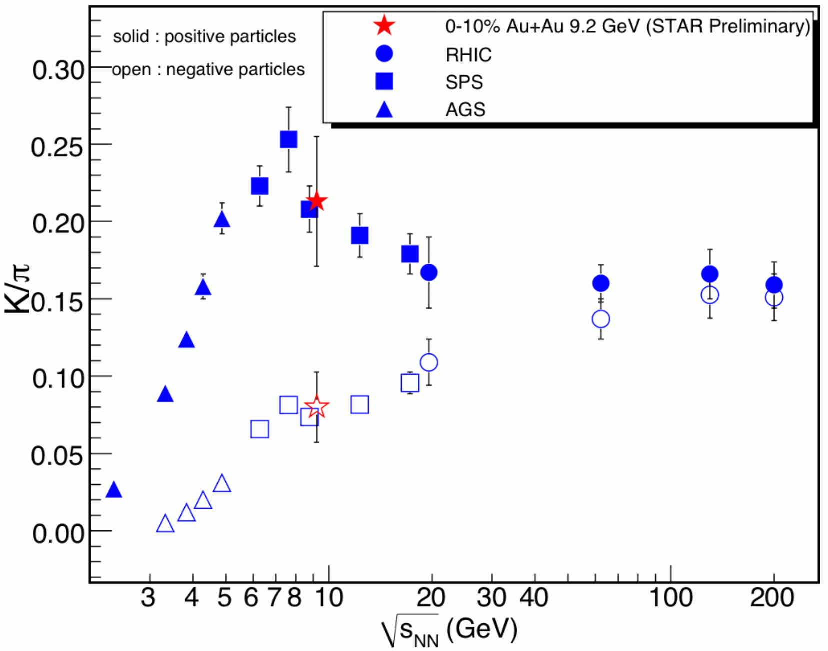
Microseconds after the Big Bang, the infant cosmos consisted of a particle soup. The universe then existed in its most basic form: as a hot sea of quarks and gluons. The analogous minibang can be reproduced in the laboratory by colliding a nucleus with another nucleus at relativistic energies.

Probing the Quark-Gluon Plasma

At high temperatures and/or densities, strongly interacting matter becomes a QGP.

Possible probes:

- J/Ψ suppression
- jet quenching
- dilepton production
- photon production
- strangeness enhancement



C. Alt et.al. (NA49 collab.) PRC 77(2008) 024903
B. I. Abelev et. al. (STAR collab.) arxiv: 0909.4131
I.G. Bearden et. al.(BRAHMS collab.) PRL. 94(2005) 162301
S.F. Afanasiev et.al.(NA49 collab.) PRC 66(2002)054902
M Gazdzicki & M. Gorenstein, Acta. Phys. Poln. B30 (1999)2705

Kaon/Pion ratio proposed as measure of strangeness to entropy ratio.

π is the lightest hadron. It carries maximum entropy and is copiously produced in QGP phase.

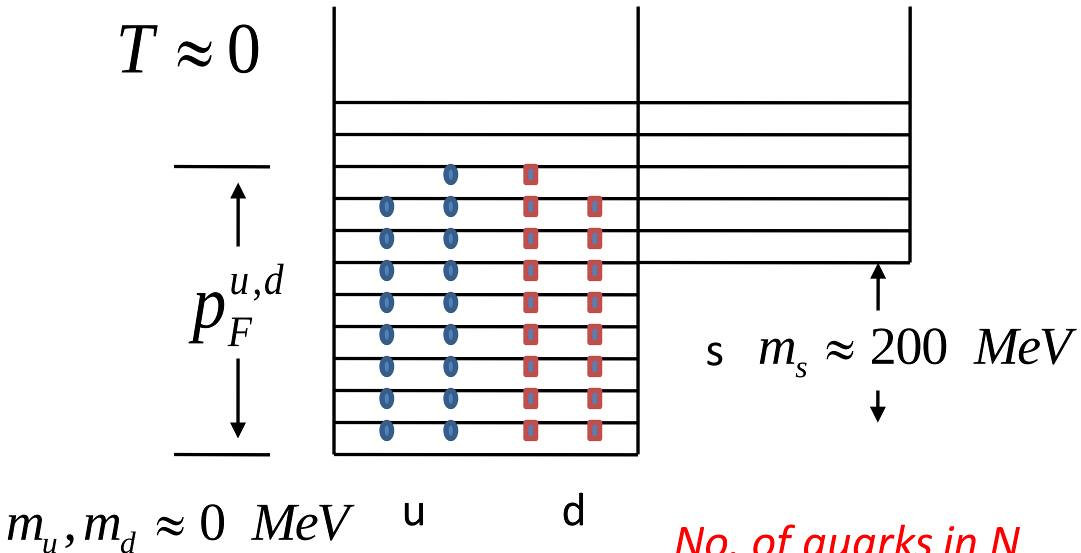
$$\varepsilon = \frac{g}{(2\pi)^3} \int \sqrt{p^2 + m^2}\, f \, d^3 p$$

$$P = \frac{g}{(2\pi)^3} \frac{1}{3} \int \frac{p^2}{\sqrt{p^2 + m^2}} f \, d^3 p$$

$$s = \frac{\varepsilon + P - \mu N}{T} \approx 4 \times \frac{\pi^2}{90} \times g \times T^3$$ For massless particles

The g rises sharply in QGP phase

Strangeness enhancement & K^+ distillation (high density region)



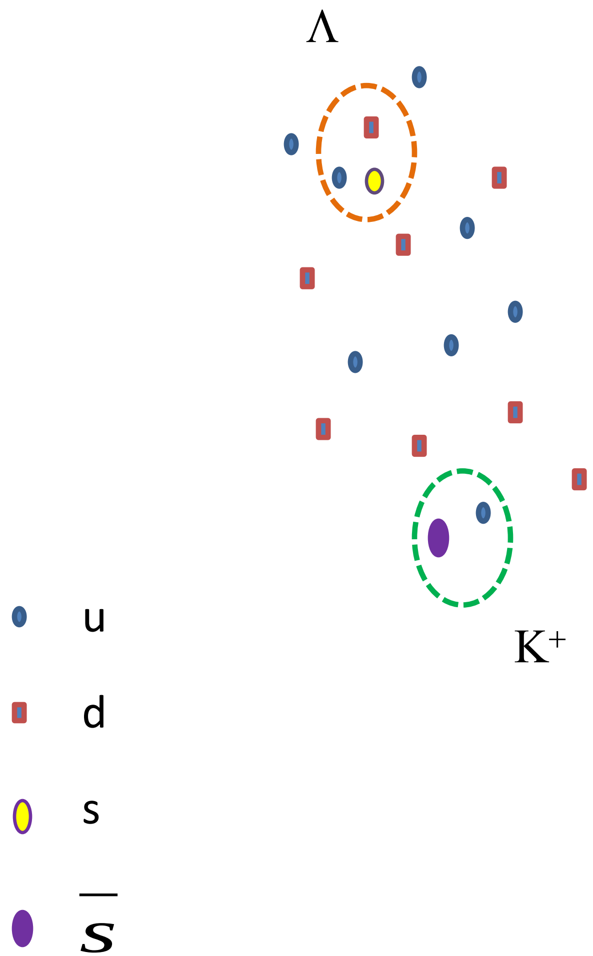
⇨ **Strangeness Enhancement**

No. of quarks in N

$$E_F^{u,d} \cong p_F^{u,d} = \left(\frac{3}{2\times 3}\right)^{1/3} \left(\frac{\rho}{\rho_0}\right)^{1/3} p_F^N \rightarrow 450\,\mathrm{MeV} > \mathrm{m_s} + \mathrm{m_{\bar{s}}}$$

flavour *colour*

Therefore, it is easier to create $s\bar{s}$ than $u\bar{u}$, $d\bar{d}$ pairs.



K⁺ (or Λ) distillation

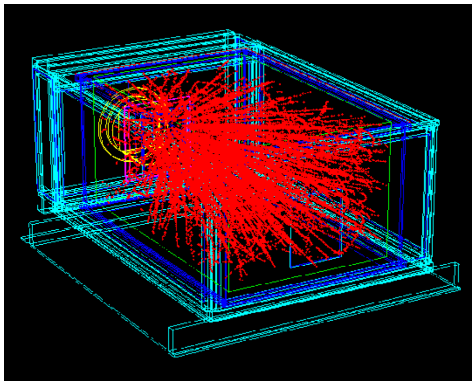
$$K^{+}\left(u\,\bar{s}\right)\text{: easy}$$

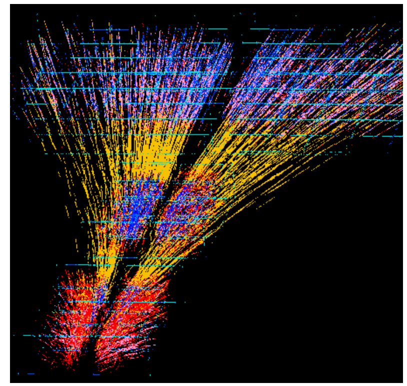
$$K^{-}\left(\bar{u}\,s\right)\text{: not easy}$$

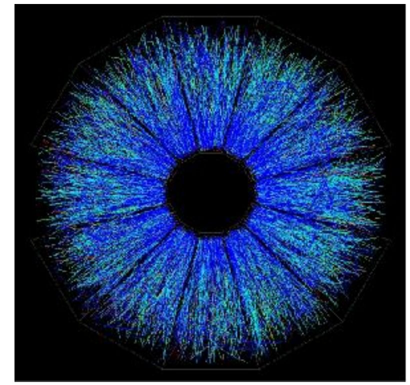
$$\Lambda\left(u\,d\,s\right)\text{: easy}$$

Experiments

AGS ⟶ SPS ⟶ RHIC







Strangeness flavour is the only known observable of the deconfined quark-gluon state of matter which can be studied in the entire available experimental AGS, SPS, RHIC and LHC energy range.

Theoretical studies to explain the horn

- Hadronic kinetic model **Boris Tomasik et al Eur.Phys.J.C49:115120,2007**
- Extended hadron resonance gas model: **S. Gupta et. al. PRC 81(2009), 044907**
- Statistical thermal model **J Cleymans et. al., Phys. Lett B 615(2005)**
  A. Andronic, P. Braun-Munzinger and J. Stachel, Nucl. Phys. A, 772(2006) 167
- Transport models (UrQMD, HSD) **E.L. Bratkovskaya et al.,PRC 69 (2004), 054907**

Ours is a Microscopic approach.

- Similar work by Kaputsa, but with constant cross-section for kaon production. **J. Kaputsa & A. Mekjian,PRD 33 (1986), 1304**

After the collision, the system is in

i) hadronic phase for all c. m. energy
ii) partonic phase beyond a threshold in c. m. energy

Strangeness production in QGP phases

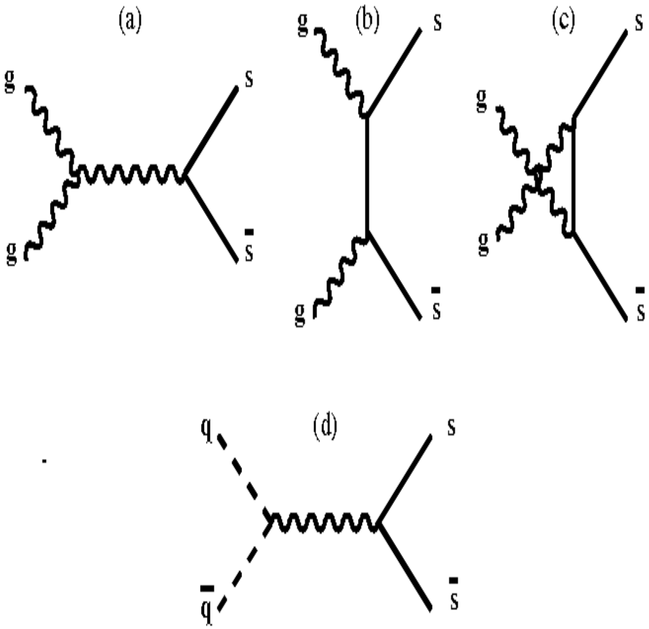
Processes for strange quark formation

i)gluon fusion $$g\ g \rightarrow s\bar{s}$$

$2\text{X}10^{-23}$ s

ii)quark- antiquark annihilation $$q\bar{q} \rightarrow s\bar{s}$$

$2\text{X}10^{-22}$ s



Cross-section for lowest order QCD is

$$\sigma_{q\bar{q}\to s\bar{s}} = \frac{8\pi\alpha_s^2}{27s}\left(1+\frac{2m^2}{s}\right)w(s)$$

$$\sigma_{gg\to s\bar{s}} = \frac{2\pi\alpha_s^2}{3s}\left[G(s)\tanh^{-1}w(s) - \frac{7}{8} + \frac{31m^2}{8s}w(s)\right]$$

where $G = 1 + 4m^2/s + m^4/s^2$

$$w(s) = (1 - 4m^2/s)$$

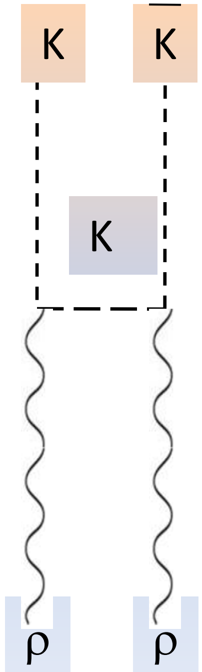
$$s = (p_1 + p_2)^2$$

J. Rafelski & B. Muller, P.R.L.48 (1982) 1066

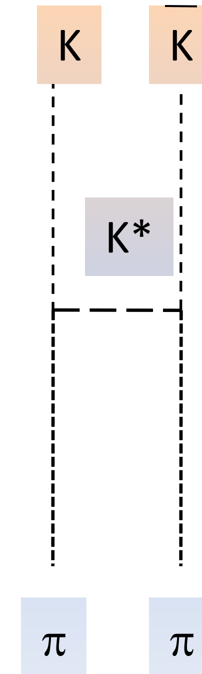
Strangeness production in hadronic phases

i) $MM \rightarrow K\bar{K}$
ii) $MB \rightarrow YK$
iii) $BB \rightarrow BYK$

G. E. Brown, C. M. Ko, Z. G. Wu & L. H. Xia, PRC 43 (1991) 1881



$1. MM \rightarrow K\overline{K}$



- $\pi\pi \rightarrow K\bar{K}$
- $\rho\rho \rightarrow K\bar{K}$
- $\pi\rho \rightarrow K\bar{K}^*$
- $\pi\rho \rightarrow K^*\bar{K}$

$$L_{K^*K\pi} = g_{K^*K\pi} K^{*\mu} \tau \left[K(\partial_\mu \pi) - (\partial_\mu K)\pi \right]$$

$$L_{\rho KK} = g_{\rho KK} \left[K\tau(\partial_\mu K) - (\partial^\mu K)\tau K \right] \rho^\mu$$

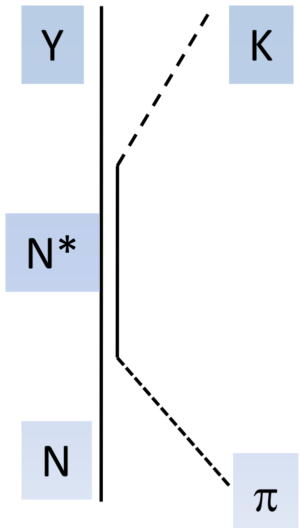
Cross-section calculations for K^+ production

Isospin averaged cross section can be expressed as

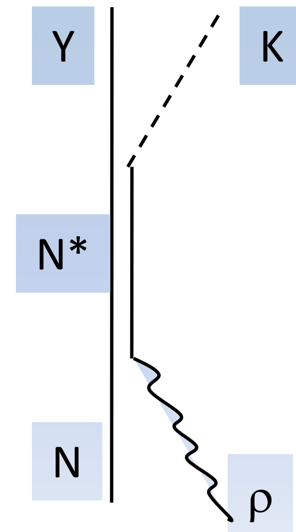
$$\overline{\sigma} = \frac{1}{32\pi} \frac{p^{'}}{sp} \int_{-1}^{+1} dx \; M(s,x)$$

where s is the square of total c.m. energy, p & p' are 3-momenta of meson & kaon in c.m. frame. M(s,x) is the isospin-averaged squared invariant amplitude.

$MB \to YK$



- $\pi N \to \Lambda K$
- $\rho N \to \Lambda K$
- $\pi N \to N K \bar{K}$
- $\pi N \to N \pi K \bar{K}$



Isospin averaged crosssection

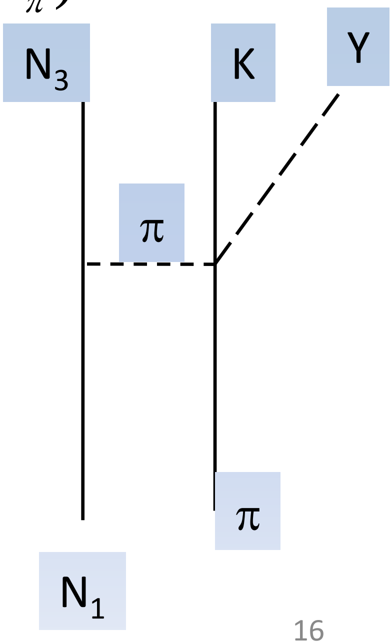
$$\overline{\sigma}_{\pi N \to \Lambda K} = \sum_i \frac{2J_i + 1}{(2s_1+1)(2s_2+1)} \quad \frac{\pi}{k_i^2} \frac{B^{in}{}_i B^{out}{}_i \, \Gamma_i^2}{\left(s^{1/2} - m_i\right)^2 + \Gamma_i^2 / 4}$$

$BB \to BYK$

- $N\,\Delta \to N\,\Lambda\,K$
- $\Delta\,\Delta \to N\,\Lambda\,K$
- $N\,N \to N\,N\,K\,\bar{K}$
- $N\,N \to N\,N\,\pi\,\pi\,K\,\bar{K}$

Isospin averaged cross section

$$\overline{\sigma}_{NN\to N\Lambda K} = \frac{3m_n^2}{2\pi^2 p^2 s} \int_{W_{\min}}^{W_{\max}} dW\, W^2 k \int_{q_-^2}^{q_+^2} dq^2 \frac{f_{\pi NN}^2}{m_\pi^2} F^2(q^2) \frac{q^2}{(q^2 - m_\pi^2)^2}\, \overline{\sigma_0}(W; q^2)$$



$W_{\min} = m_K + m_\Lambda$

$W_{\max} = s^{1/2} - m_N$

$q_\pm^2 = 2\, m_n^2 - 2\, E\, E' \pm 2\, p\, p'$

while $\mathrm{E} = \left(\mathrm{p}^2 + m_N^2\right)^{1/2}$ & p are the energy & momentum of nucleon N_1 in the c.m. system while E' & p' are those of N_3.

$\mathrm{F} = \dfrac{\Lambda^2 - m_\pi^2}{\Lambda^2 - q^2}$; Λ is the cut off parameter $\Lambda = 1\,\mathrm{GeV}$.

In a baryon rich medium K^- gets absorbed due to its interaction with baryons.

- $K^-p \rightarrow \Lambda\pi^0$ •$K^-p \rightarrow \sigma\pi^0,$ •$K^-n \rightarrow \sigma p$
- $K^-p \rightarrow \bar{K}^0 n,$ •$K^-n \rightarrow K^-n$

Rate calculations for strangeness production

$$a_1(p_1)+a_2(p_2)\rightarrow a_3(p_1^{'})+a_4(p_2^{'}), \quad \text{where} \quad a_1 \neq a_2$$

$$R(T)=\int\frac{d^3p_1}{(2\pi)^3}F(p_1)\int\frac{d^3p_2}{(2\pi)^3}F(p_2)v_{rel}\sigma(M)$$

Where,

$$F(p)=\exp[-(E-\mu)/T],$$

$$v_{rel}=\left|\vec{v}_1-\vec{v}_2\right|, \qquad m^2=E^2-\vec{p}^{\,2}$$

Evolution of Strangeness

<u>Assumption</u>:

•Non-strange quarks & hadrons are in thermal equilibrium.

•Strange quarks & hadrons are not in equilibrium.

The time evolution of the strangeness in either partonic/hadronic phase is governed by **momentum integrated Boltzmann Equation**

$$\frac{dn_i}{d\tau} = R_i(\mu_B, T)[1 - \frac{n_i n_j}{n_i^{eq} n_j^{eq}}] - \frac{n_i}{\tau}$$

$$\frac{dn_j}{d\tau} = R_j(\mu_B, T)[1 - \frac{n_j n_i}{n_j^{eq} n_i^{eq}}] - \frac{n_j}{\tau}$$

The evolution of the kaons in mixed phase

$$\begin{aligned}
\frac{dn_{K^+}}{d\tau} &= R_{K^+}(\mu_B, T_c)[1 - \frac{n_{K^+} n_{K^-}}{n^{eq}_{K^+} n^{eq}_{K^-}}] - \frac{n_{K^+}}{\tau} + \\
& \frac{1}{f_H}\frac{df_H}{d\tau}\left(\delta n_{\bar{s}} - n_{K^+}\right), \\
\frac{dn_{K^-}}{d\tau} &= R_{K^-}(\mu_B, T_c)[1 - \frac{n_{K^+} n_{K^-}}{n^{eq}_{K^+} n^{eq}_{K^-}}] - \frac{n_{K^-}}{\tau} + \\
& \frac{1}{f_H}\frac{df_H}{d\tau}\left(\delta n_{s} - n_{K^-}\right).
\end{aligned}$$

Where in the mixed phase,

$$\begin{aligned}
f_Q(\tau) &= \frac{1}{r-1}(r\frac{\tau_H}{\tau} - 1) \\
f_H(\tau) &= 1 - f_Q(\tau)
\end{aligned}$$

J. Kaputsa & A. Mekjian,PRD 33 (1986), 1304

Space-time Evolution

The partonic/hadronic system evolves in space-time. $\partial_\mu T^{\mu\nu} = 0$

The net baryon number is conserved. $\partial_\mu (n_B u^\mu) = 0$

The baryon chemical potential at freeze out is taken from the parameterization of μ_B with $\sqrt{s_{NN}}$

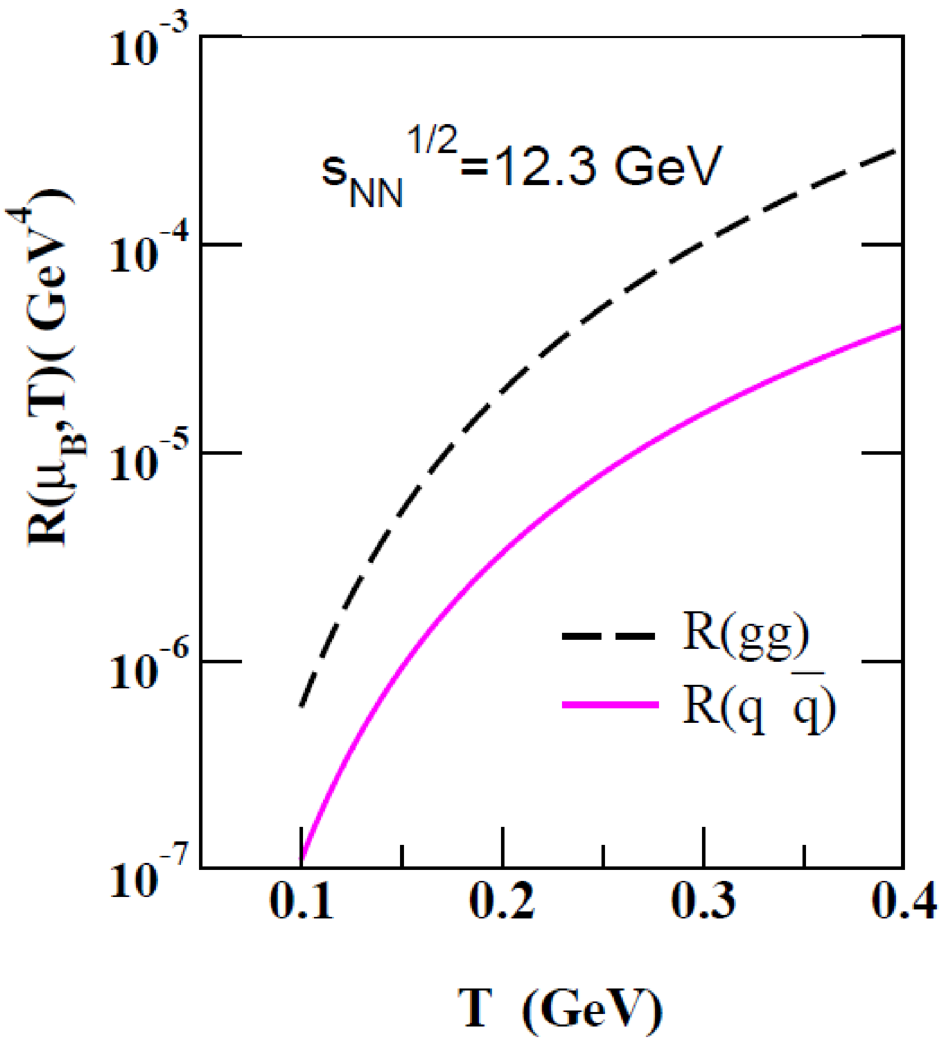
O. Ristea for BRAHMS collab. Romanian Reports in Physics, 56(2004) 659.

The initial baryonic chemical potential is obtained from net baryon number conservation equation.

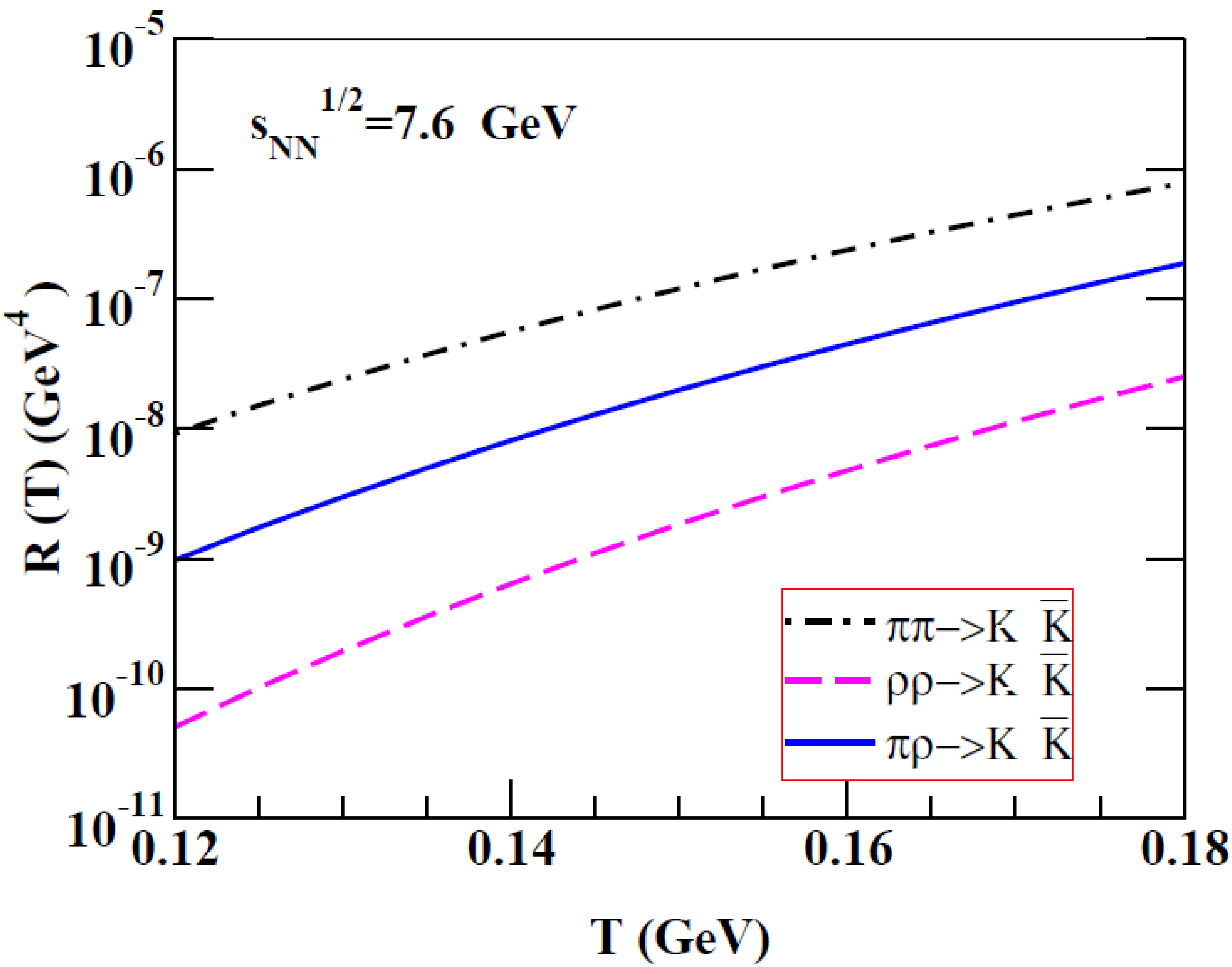
The initial temperature of the system formed after nuclear collisions have been taken using measured hadronic multiplicity by using

$$T_i^3 = \frac{2\pi^4}{45\zeta(3)} \frac{1}{\pi R^2 \tau_i} \frac{90}{4\pi^2 g_{eff}} \frac{dN}{dy}$$

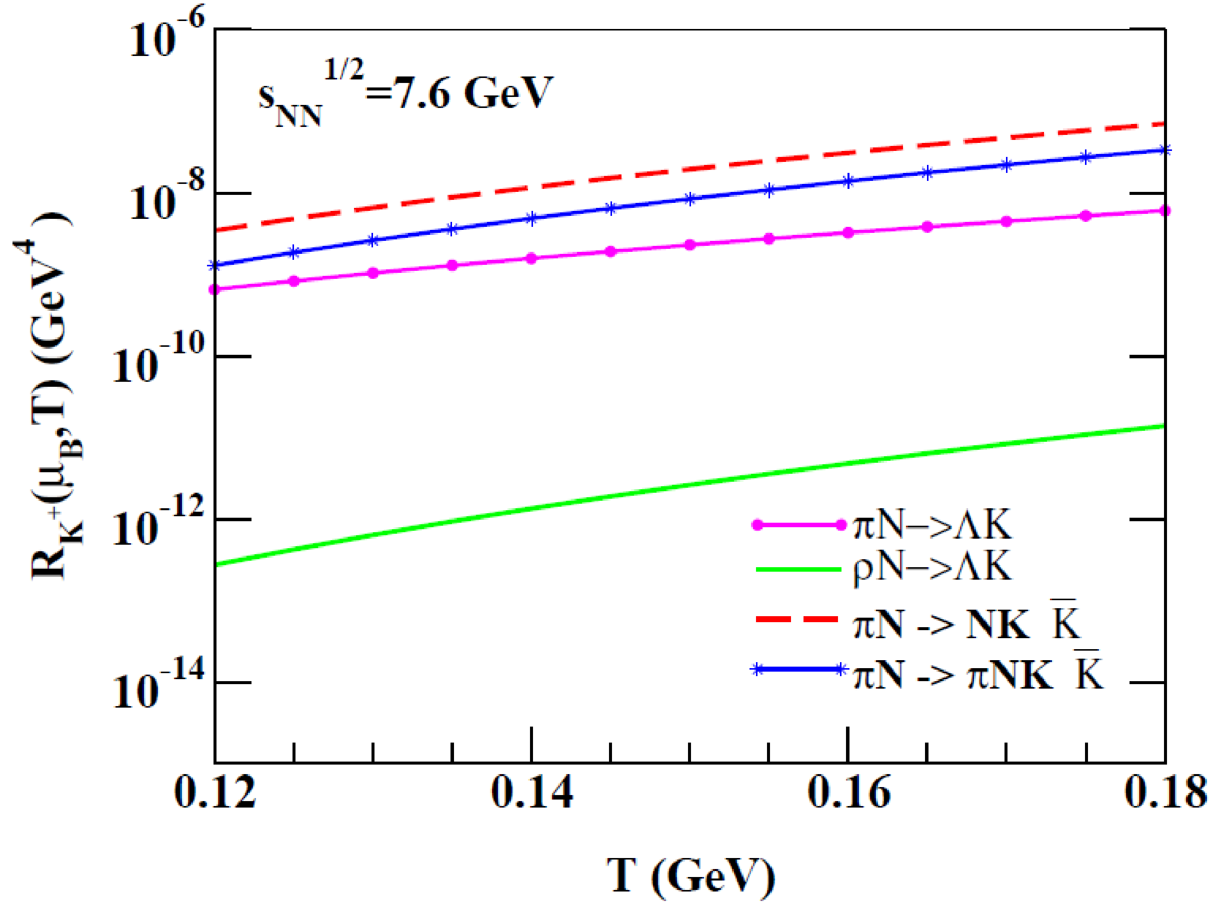
Rate of production of strange quarks



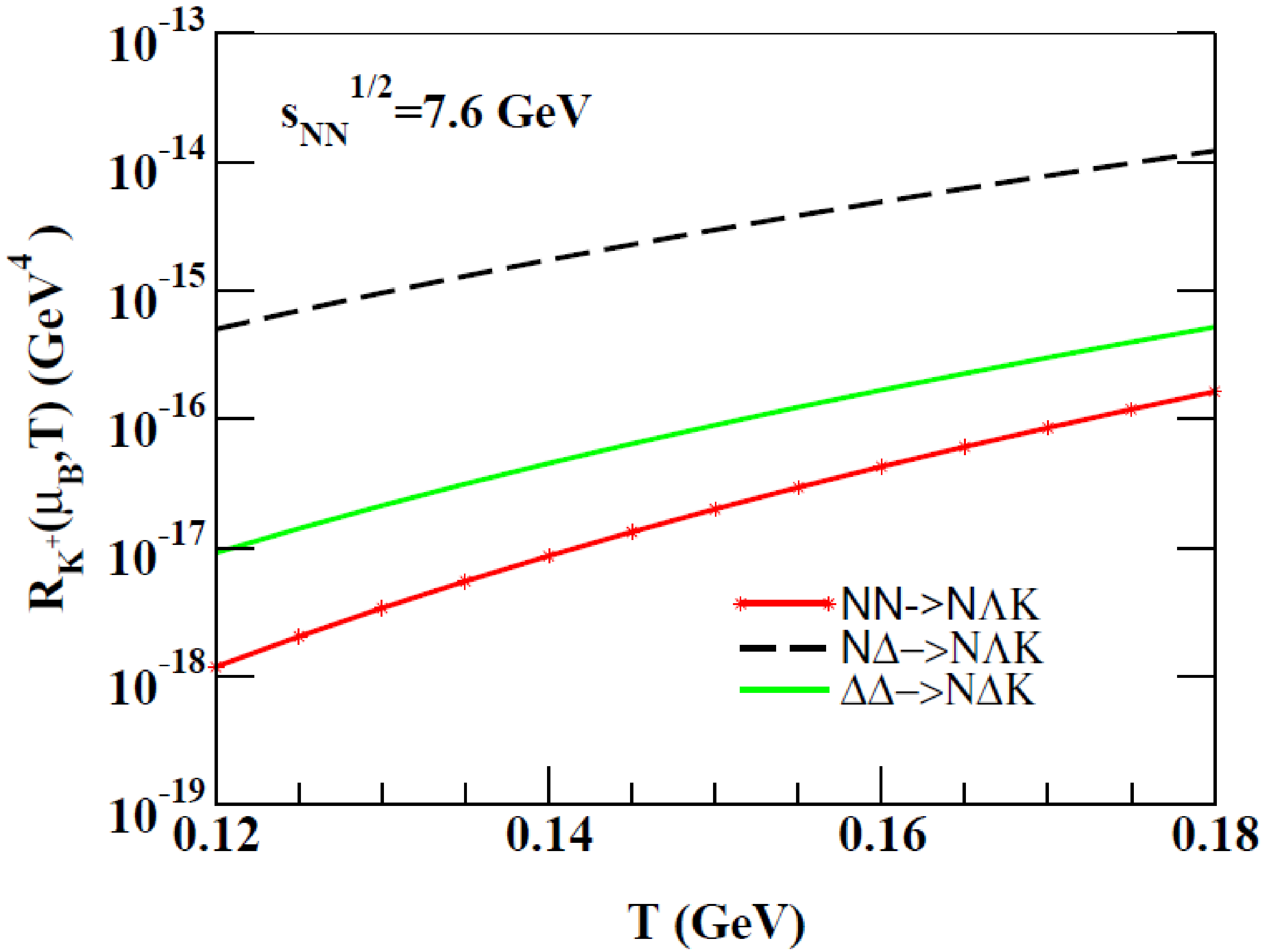
Rate of kaon production from MM interaction



Rate of kaon production from MB interaction



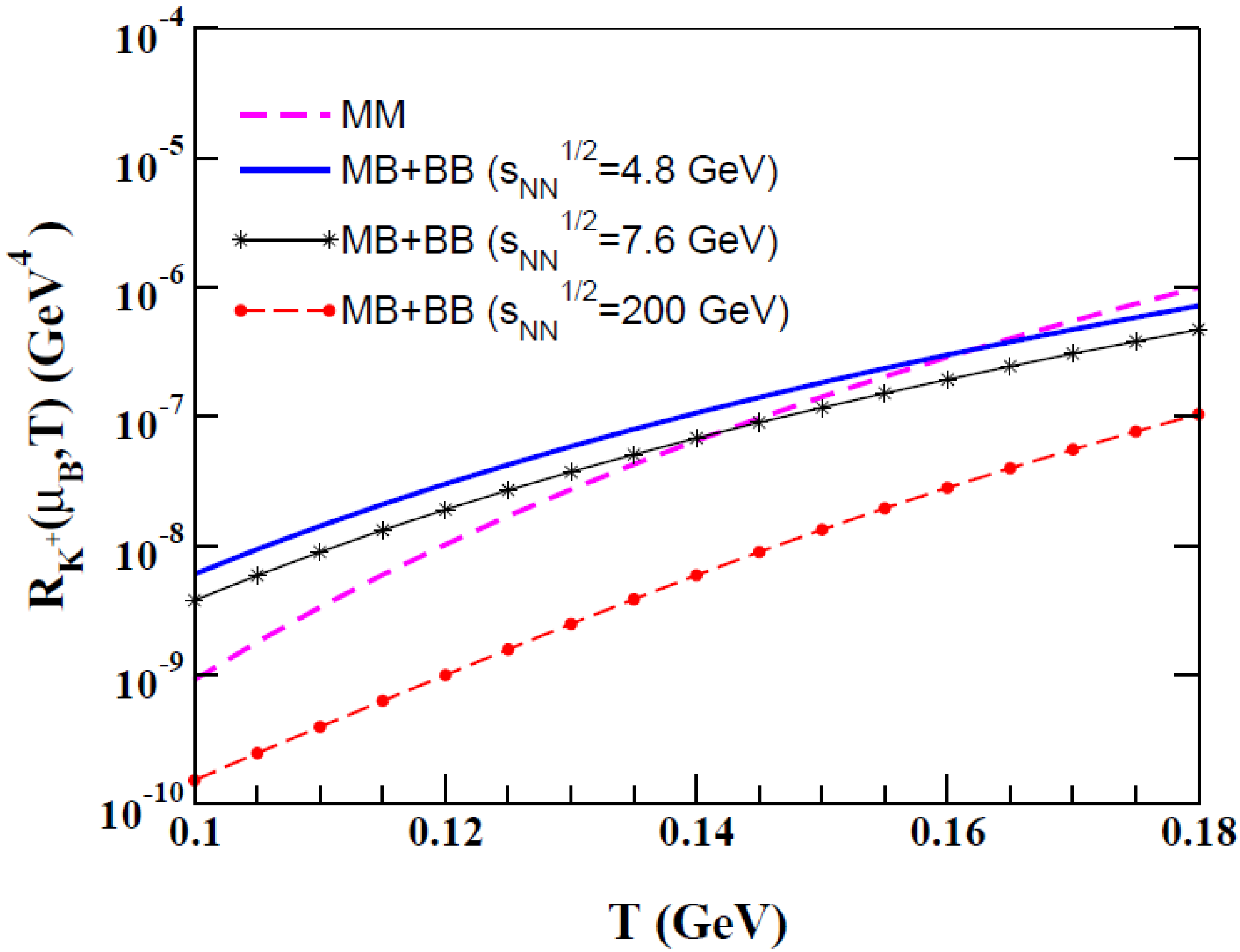
Rate of kaon production from BB interaction



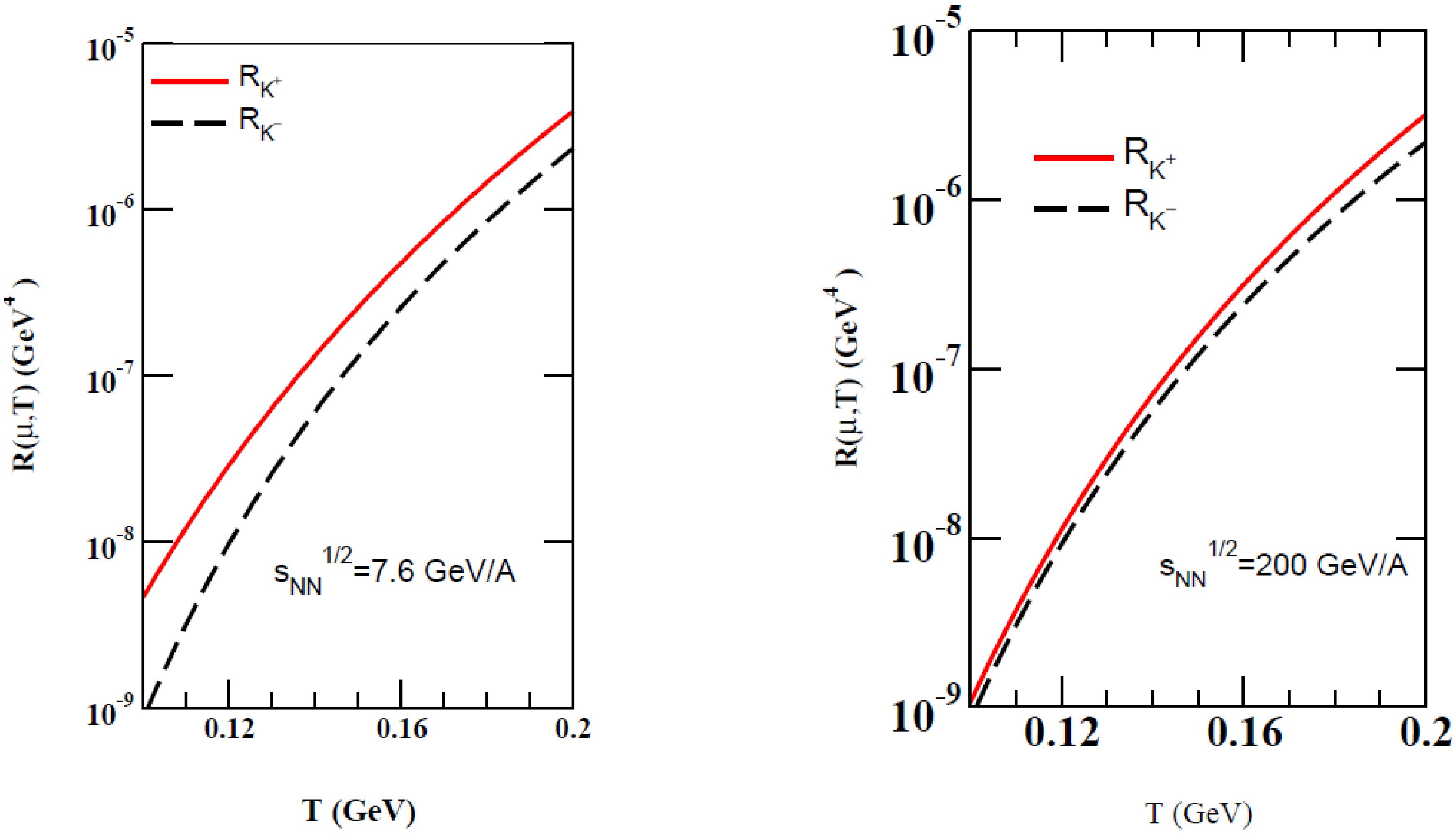
Rate of kaon production from MM, MB, BB interaction

- Baryon dominance at lower $\sqrt{s_{NN}}$

- At low temperature baryonic contribution is more



Total kaon production rate

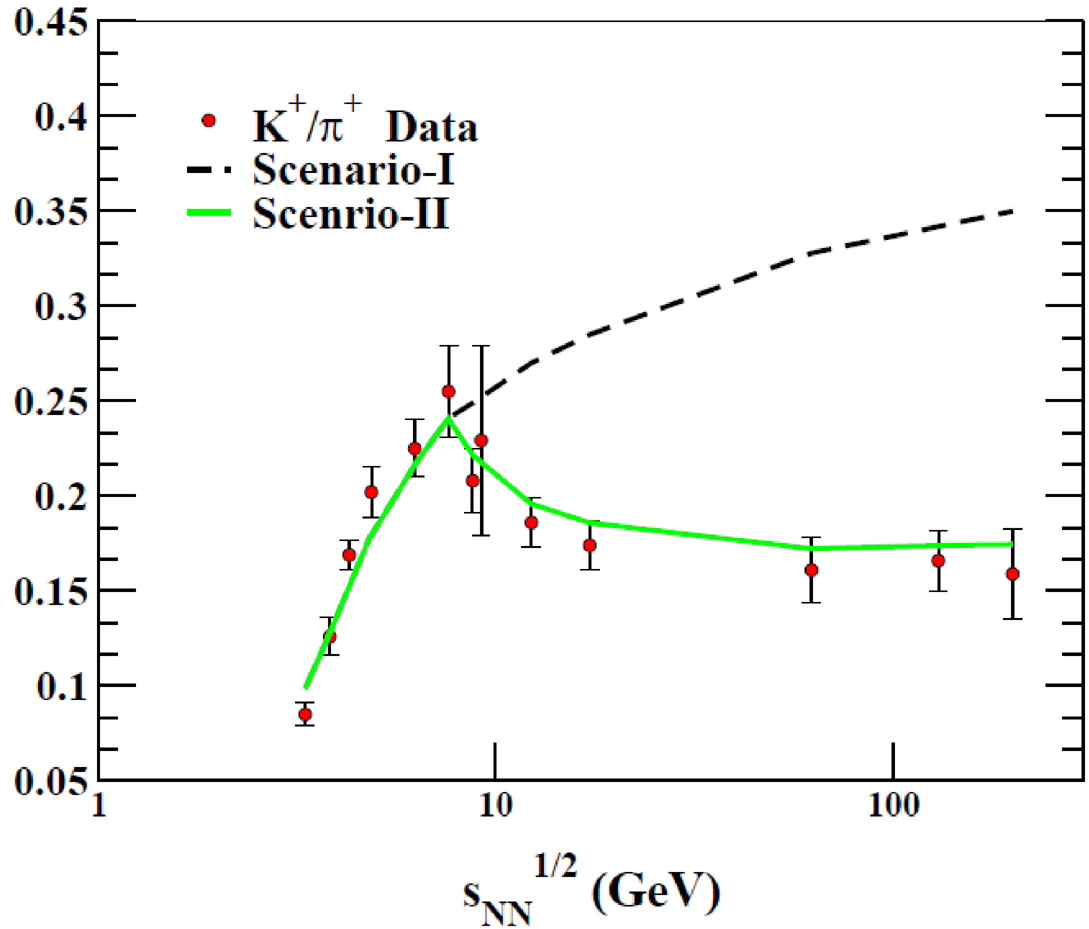


K^+/π^+ ratio

Non-monotonic behaviour of K^+/π^+ ratio can be understood due to

- Large entropy production
- Release of colour degrees of freedom

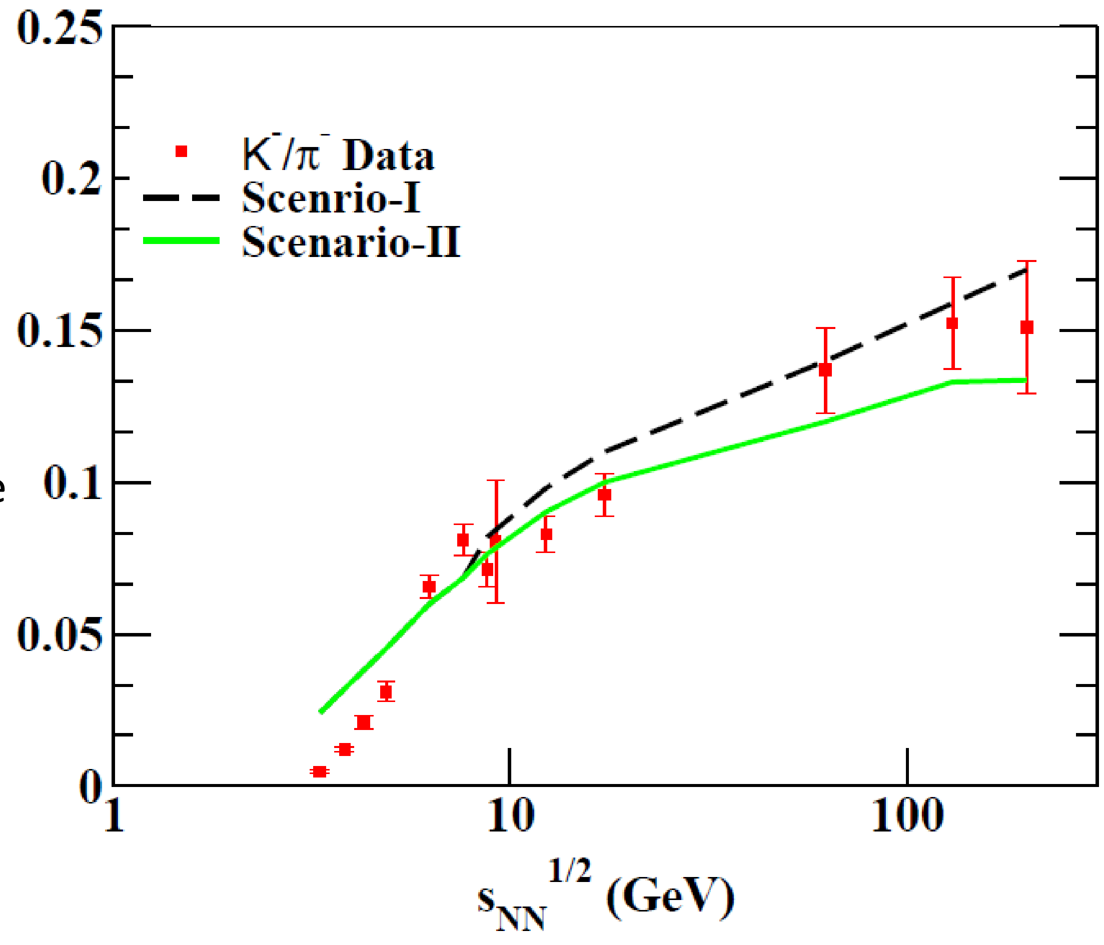
Beyond a threshold in $\sqrt{s_{NN}}$



K^-/π^- ratio

K^-/π^- ratio seems to differentiate little between the two scenarios

However, they both saturate at higher $\sqrt{s_{NN}}$



Summary

- A microscopic approach has been employed to study the kaon/pion ratio.
- The momentum integrated Boltzmann Equation used to study the evolution of strangeness.
- We got a non-monotonic horn like structure for K^+/π^+ when a partonic state is assumed at high c. m. energy .
- However a monotonic rise in K^+/π^+ is observed for a pure hadronic matter.
- The horn is due to release of colour degrees of freedom.
- K^-/π^- data is unable to differentiate between the two initial conditions

Collaborators

J. K. Nayak

Jan-e Alam

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