STRANGE PRODUCTIONS THROUGH TRANSPORT APPROACH AT COLLIDING ENERGY $\sqrt{s_{NN}}$ = 54.4 GeV/A

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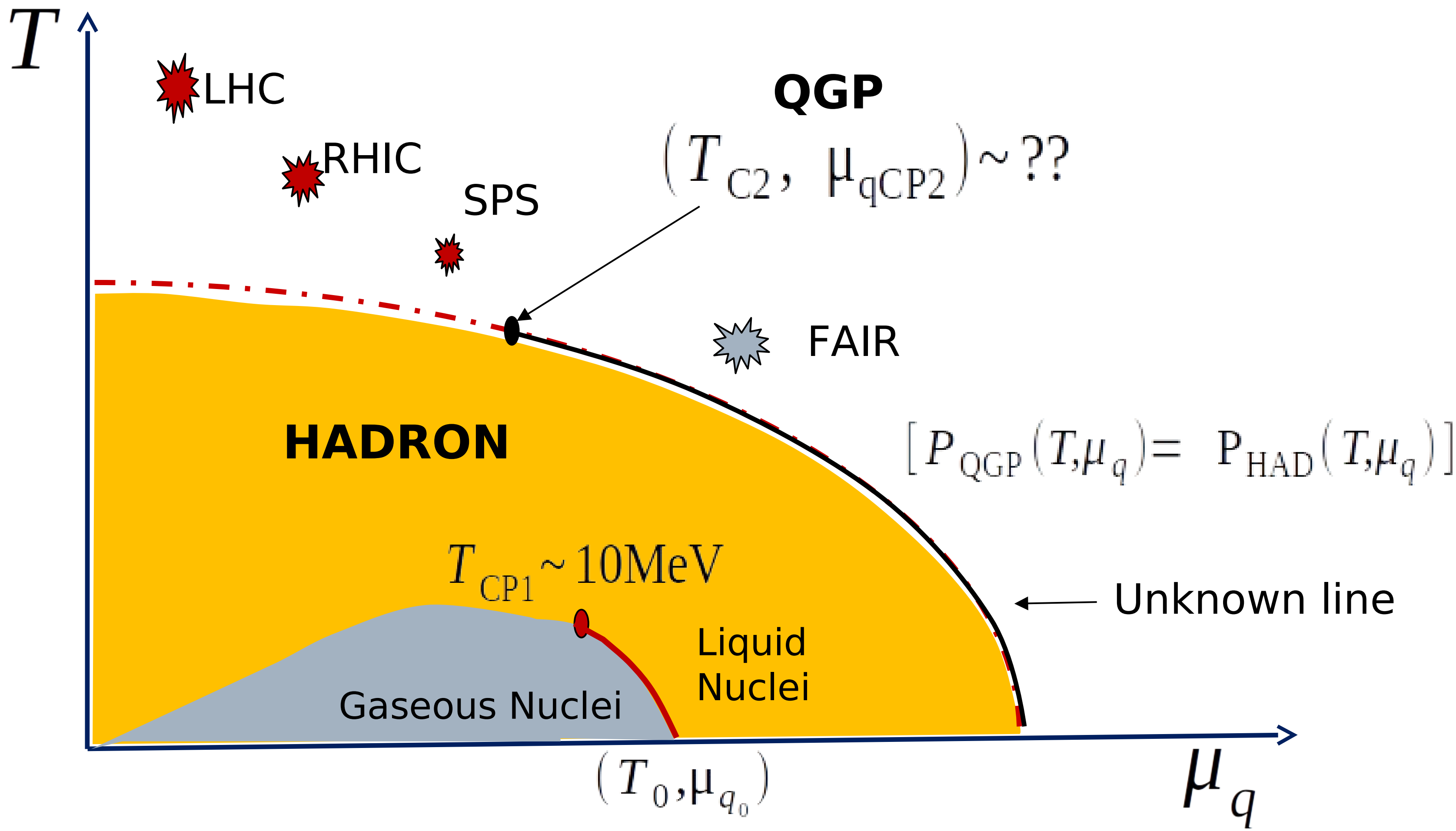
OUTLINE

- ✓ PROBING RELATIVISTIC NUCLEAR COLLISIONS THROUGH STRANGE PRODUCTIONS
- ✓ STUDYING STRANGENESS USING TRANSPORT APPROACH-MOMENTUM INTEGRATED BOLTZMANN EQUATION
- ✓ FORMALISM
- ✓ YIELD RATIO PLOTS
- ✓ SUMMARY AND OUTLOOK

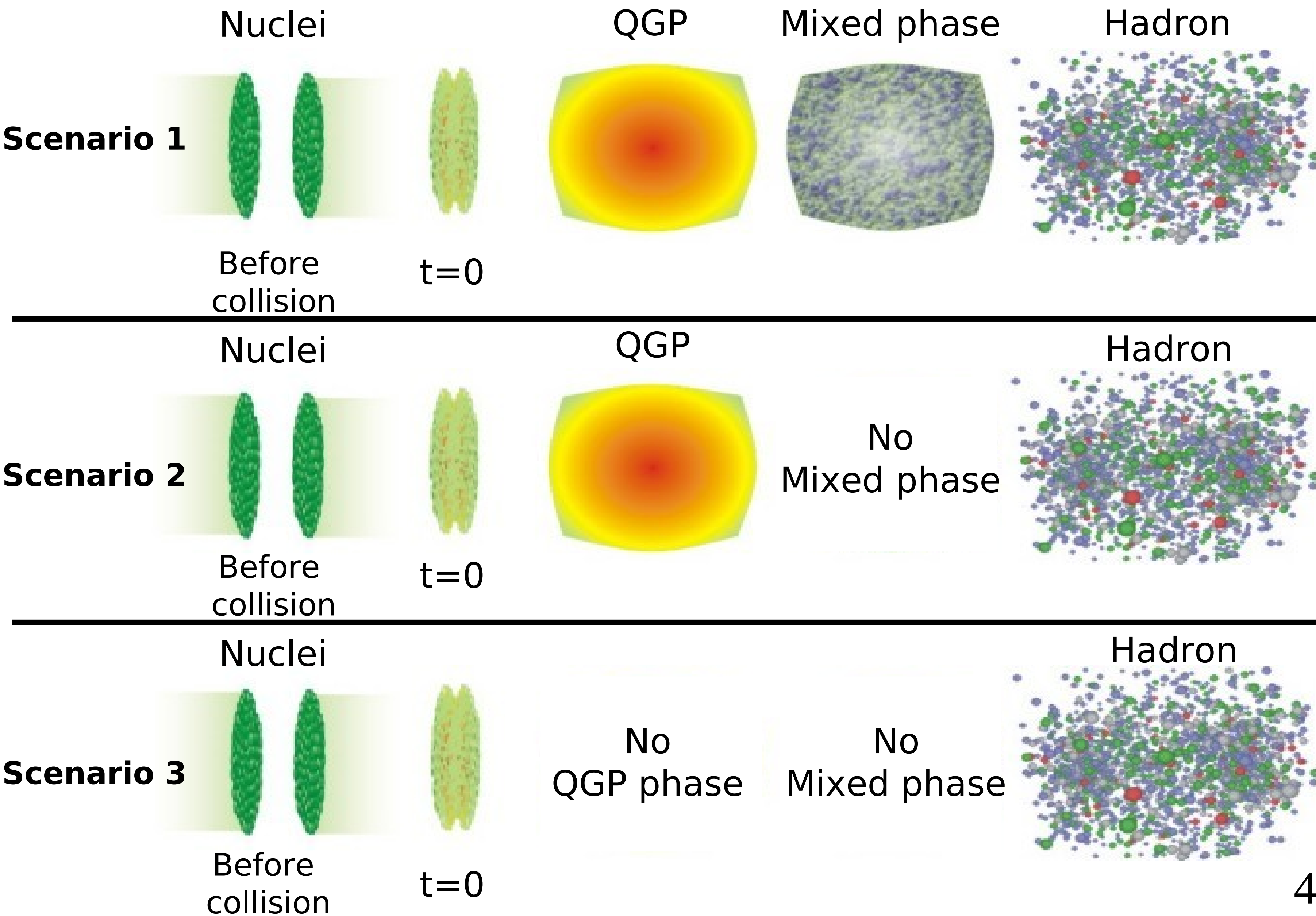
QCD PHASE DIAGRAM : SCHEMATIC AND NOT TO SCALE



Ground state Nuclear matter= $(T_0,\mu_{q_0}) \sim (\ 0,\ 308\ \text{MeV}\ )$

$T_{CP1} = \text{Temp.}\ \ \text{at}\ \ \text{1st CP}$

Heavy Ion Collision & Possible Scenarios



Introduction

How to know whether the desired system is formed or not?

Answer:
- *Direct probes*
- *Indirect probes*

✓ Dimension of the system formed is very small.

✓ Lifetime of system is very small

Hence, Indirect probes are our only recourse

Different types of indirect probes

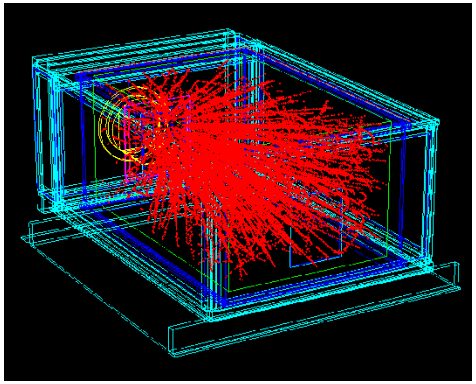
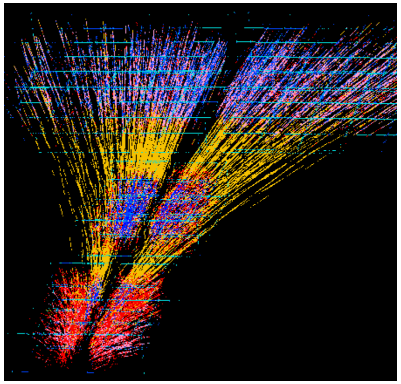
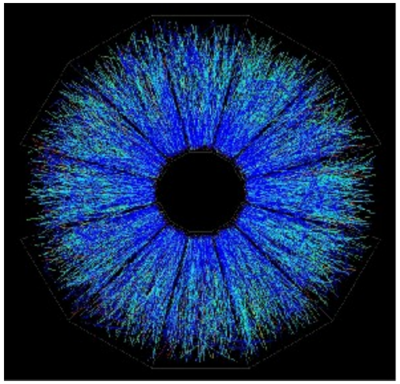
- Electromagnetic probes: radiations
- Strange probes
- Jet quenching
- Heavy Flavor-Charm probes

Here we discuss the strange probe:

- Strangeness production in the collisions
- Strangeness evolution in the medium
- How they serve as a good probe

EXPERIMENTS

AGS → SPS → RHIC

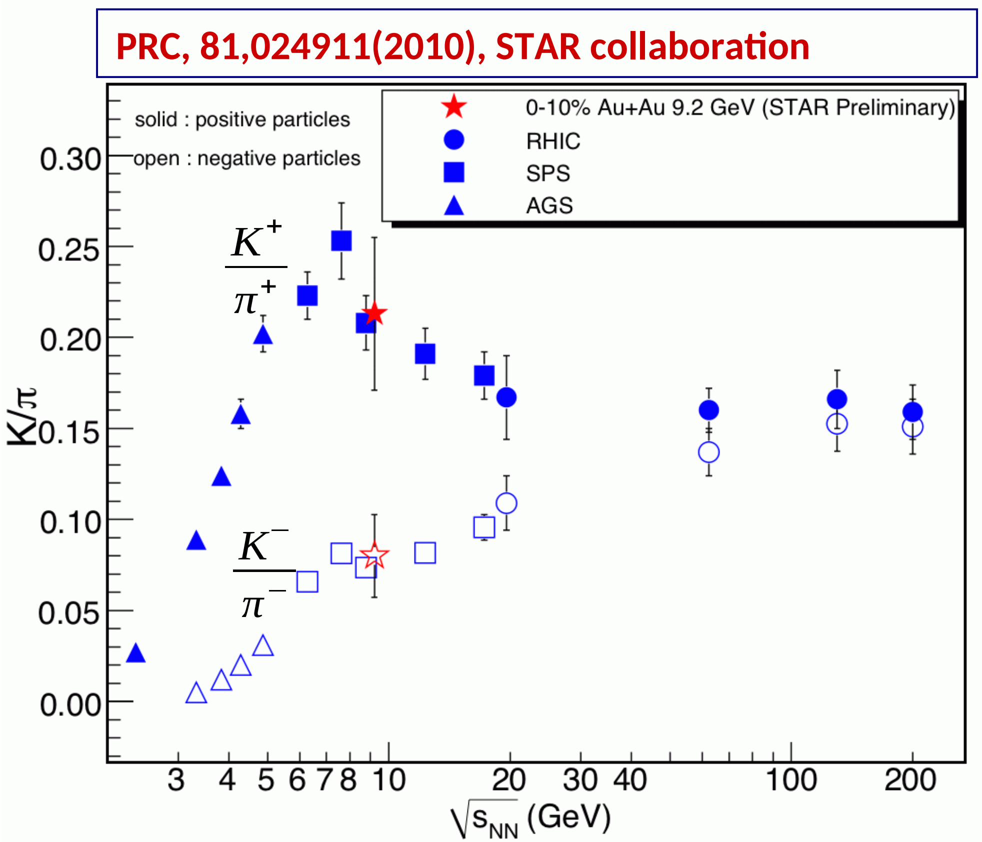
  

	Experiments	E_{beam} (A GeV)	$\sqrt{s_{NN}}$ (GeV)	System	Particles
AGS	E802, E866, E877, E891, E895, E917	2-10.7	2.7-4.9	Au+Au	π, K, p, Λ
SPS	NA45, NA49, NA57, (NA44, WA98)	20-158	6.3-17.3	Pb+Pb	π, K, p, ϕ, Λ, Ξ, Ω,...
RHIC	STAR, PHENIX, BRAHMS, PHOBOS	-	20.0-200.0	Au+Au	π, K, p, ϕ, Λ, Ξ, Ω, ...

Motivation for Studying Strangeness productions

Why was strangeness thought to be
a good probe to diagnose the medium ?

EXPERIMENTAL MOTIVATION BEHIND THE STRANGENESS STUDIES



Strangeness enhancement compared to p-p collision at same energy

$\frac{K^+}{\pi^+}$	p-Be 4% p-Au 10% Si-Au 20%
$\frac{K^-}{\pi^-}$	4% for all

Results from AGS energies

Non-monotonic energy dependence in K^+/π^+ ratio

Monotonic energy dependence in K^-/π^- ratio

What does it say

(1) about formation of QGP medium?

(2) about threshold of QGP production?

Importance of K/π ratio

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

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

$$\mathrm{s} = \frac{\epsilon + P + \mu N}{T} \approx 4.\frac{\pi^2}{90}.g.T^3$$

(For massless particles)

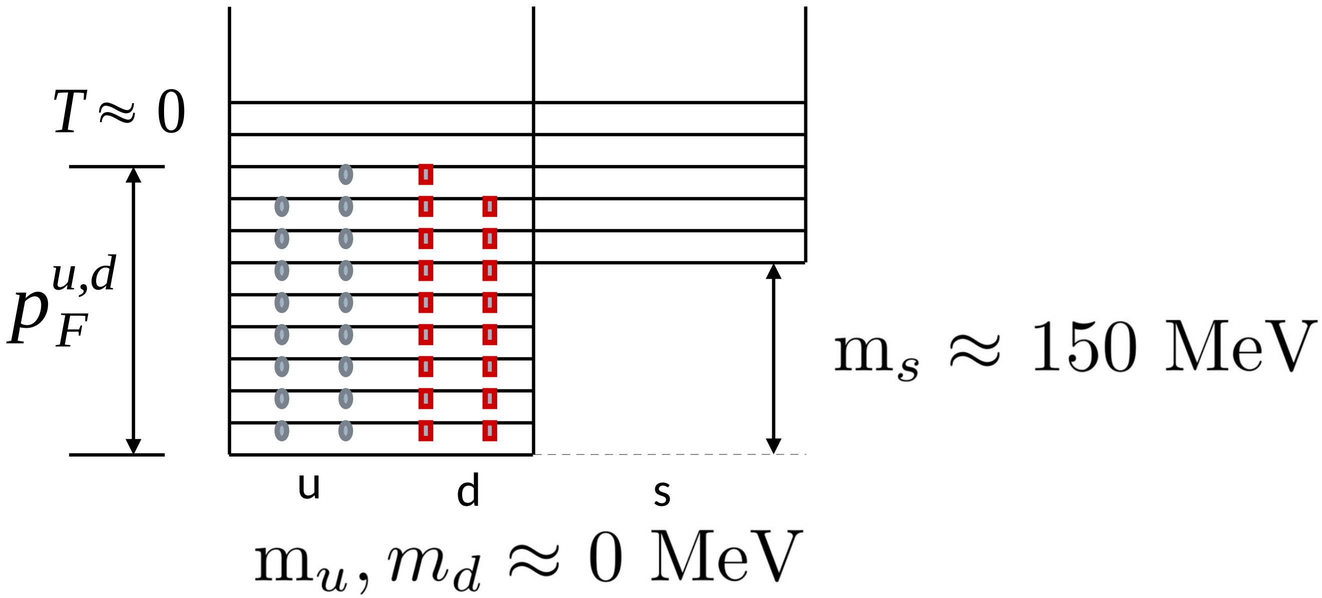
The degrees of freedom g rises sharply in QGP phase

π is the lightest hadron and is copiously produced in heavy ion collisions. Therefore it is also the measure of entropy of the system

Similarly K is the lightest strange meson and hence representation of strangeness production

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

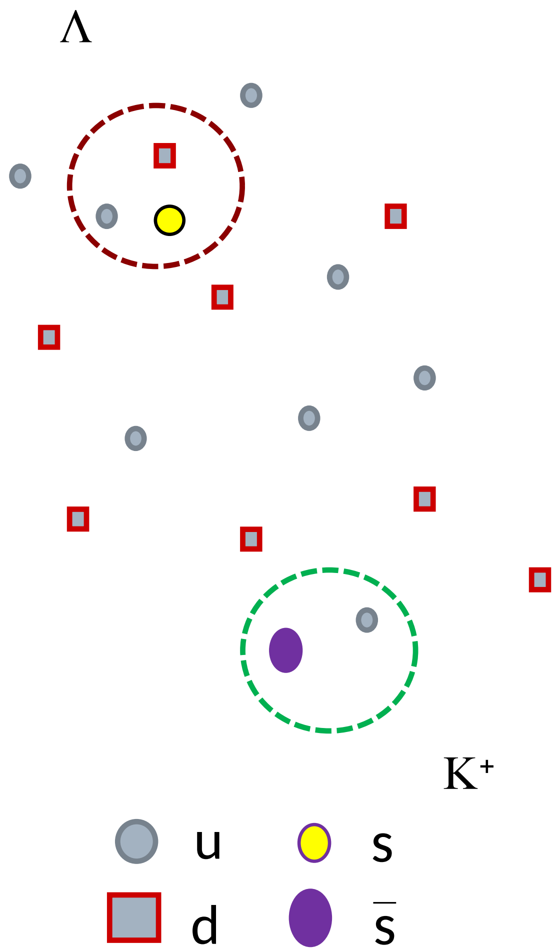
STRANGENESS ENHANCEMENT (HIGH DENSITY REGION)



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

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

K^+ DISTILLATION (HIGH DENSITY REGION)



List of Major Strange Particles

$\Phi\,(s\bar{s})$ $K\,(q\bar{s})$ $\bar{K}\,(\bar{q}s)$ $\Xi\,(qss)$ $\bar{\Xi}\,(\overline{qss})$ $\Omega\,(sss)$ $\bar{\Omega}\,(\overline{sss})$

✔QGP Region is more abundant in u and d quarks than $\bar{u}$ and $\bar{d}$. $\bar{s}$ and s are equal in number

✔Since it is easier to locate u and d than single $\bar{u}$, s is more likely to go to Λ(uds) than $K^-(\bar{u}s)$.

✔Unlike $K^-(\bar{u}s)$, $K^+(u\bar{s})$ has no competition

Hence, Enhancement of K^+ > Enhancement of K^-

WORKING OF OUR MODEL

- 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.
- Non-strange hadron yields are estimated using thermal model.

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.

RATE EQUATIONS OR MOMENTUM INTEGRATED BOLTZMANN EQUATIONS FOR KAONS

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

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

RATE EQUATIONS OR MOMENTUM INTEGRATED BOLTZMANN EQUATIONS FOR HYPERONS

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

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

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

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

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

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**.

EVOLUTION OF TEMPERATURE AND CHEMICAL POTENTIAL

Simultaneously, we solve temperature evolution equation,

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

We get this following Björken expansion by solving energy momentum conservation equation

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

Further, the baryon chemical potential equation is solved

$$\partial_\mu n_b^\mu = 0$$

IMPORTANCE OF CALCULATION: 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(Mollar) 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

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

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

Cross Sections

$\pi N \to \Lambda K$

$\pi N \to \Sigma K$

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

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

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

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

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

M-B TYPE

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

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

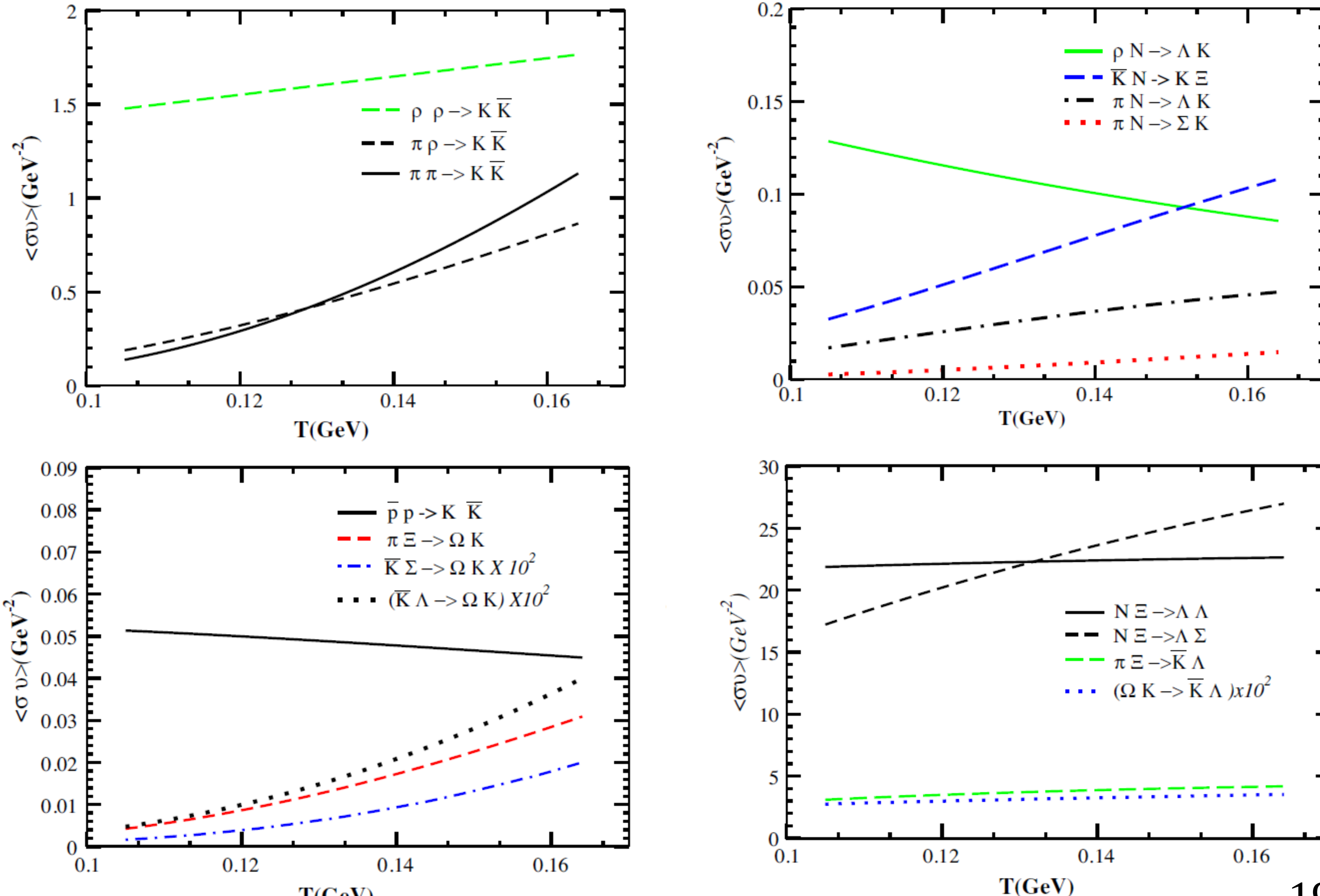
$N\bar{N} \to \Xi\bar{\Xi}$ $N\bar{N} \to \Omega\bar{\Omega}$

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

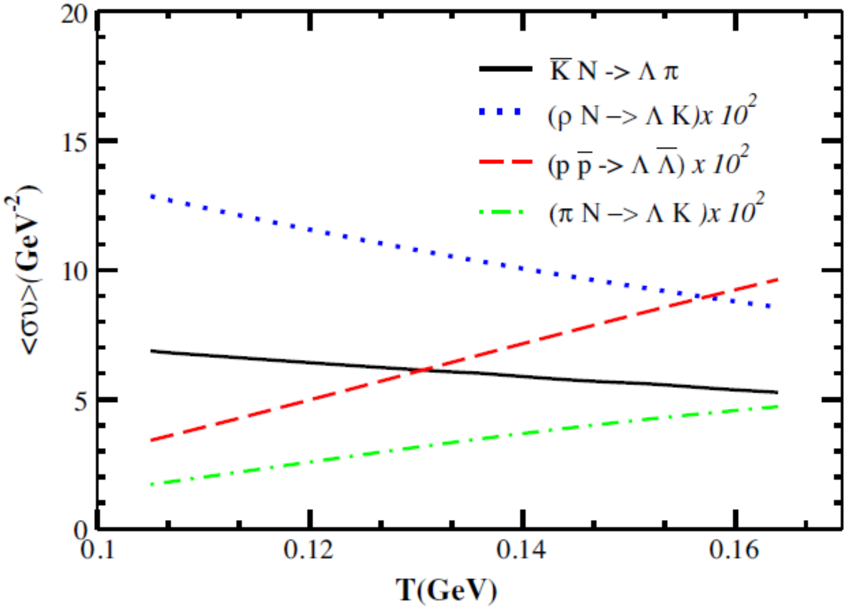
$\Sigma\Sigma \to N\Xi$

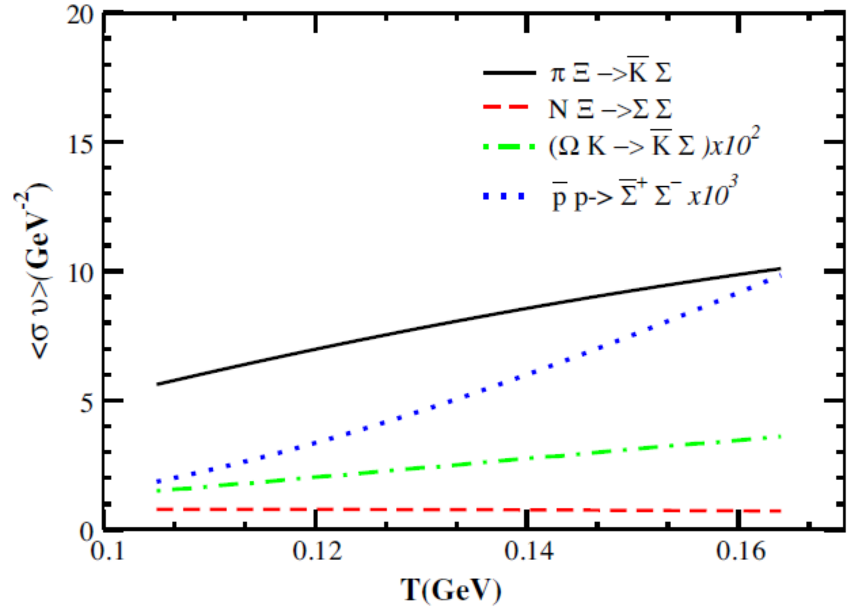
B-B TYPE

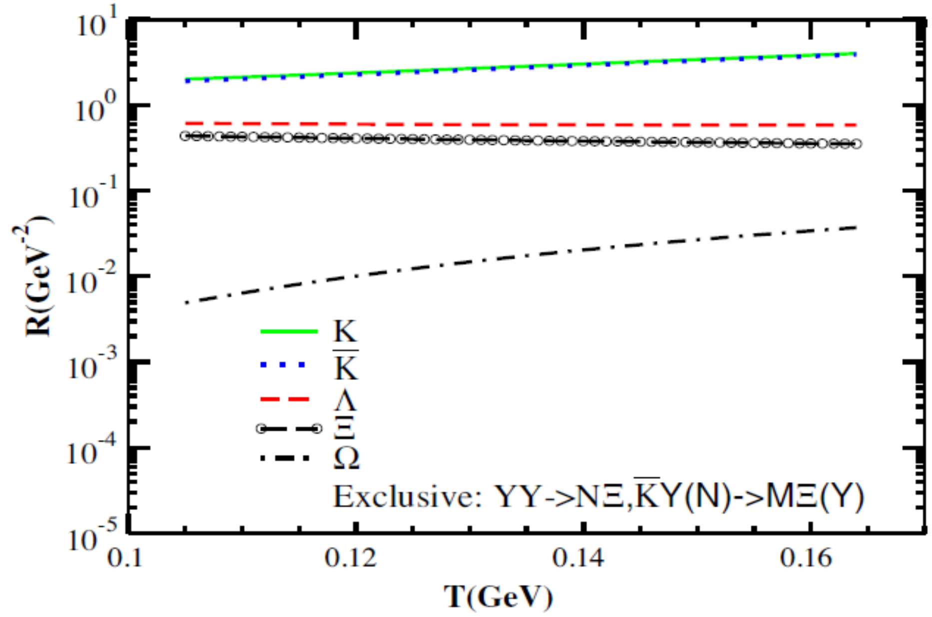
INTERACTION RATES



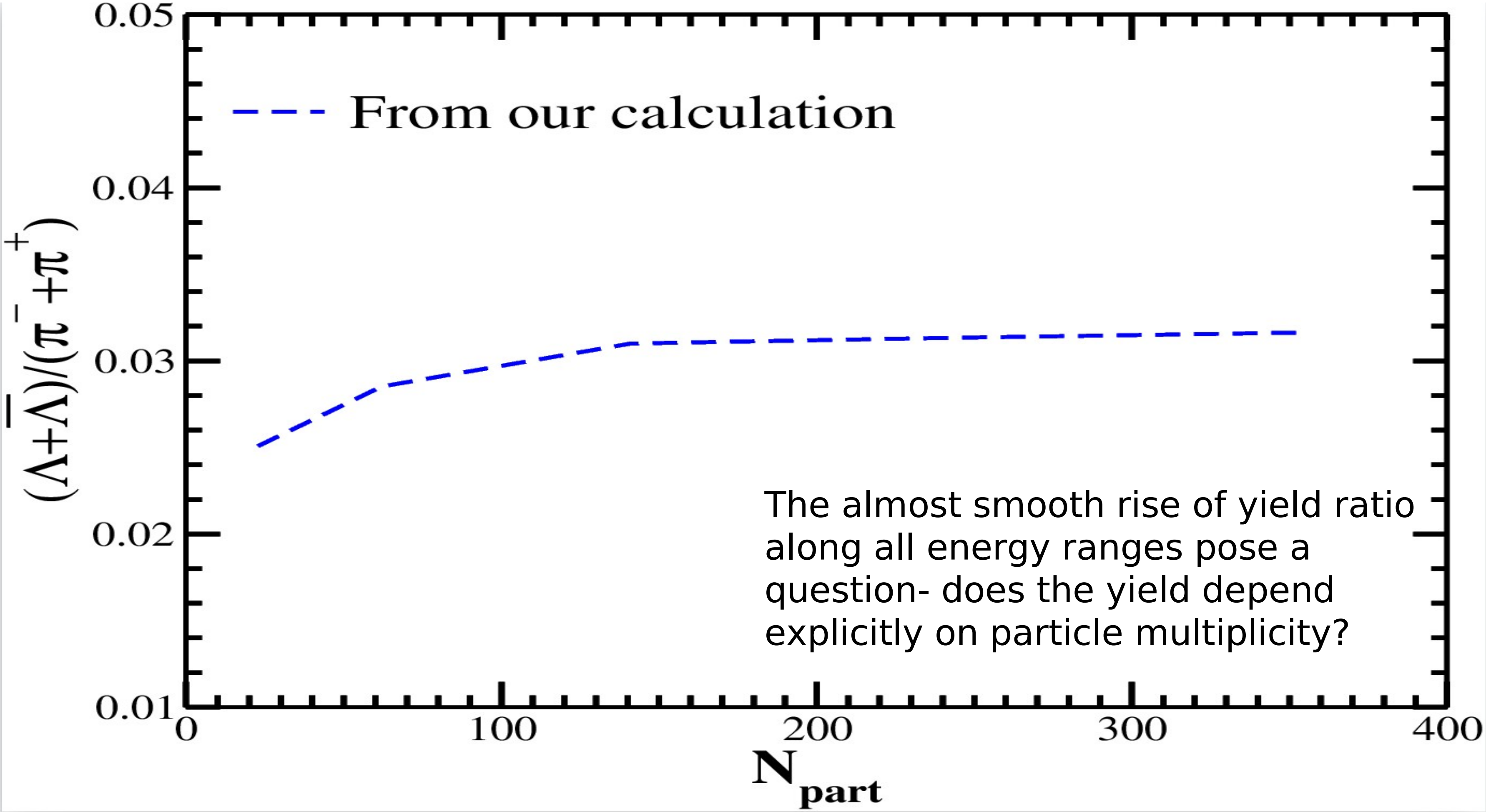
INTERACTION RATES







RESULTS



Yield Ratios of Strange Lambdas to Entropy vs. Centrality for Au-Au Collisions at 54.4 AGeV.

SUMMARY AND OUTLOOK

- Yield Ratios of Strange Hadrons to Entropy is measured and plotted at Au-Au Collisions at 54.4 AGeV(Preliminary).
- Efforts have been made to explain the Yield ratio of Lambda to Entropy vs. Centrality using Strange hadron transport model.
- Similar efforts are being made to explain data for other particles like Cascade and Omega.
- Efforts will be made in the future to extend this work to FAIR energies.

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Dr. Anand K. Dubey
for detailed research and discussions


THANK YOU

BACKUP

Strangeness production in hadronic scenario

Non linear chiral Lagrangian $SU(3)_L x SU(3)_R$ describing the interaction of pseudo scalar mesons (π, K, η)and baryons; nucleons (N)and Hyperons (Y)

$$L=\frac{1}{4}f^2\, Tr\, \partial^\mu \Sigma\, \partial_\mu \Sigma^+ + \frac{1}{2} f^2\, \Lambda \left[M_q \left(\Sigma - 1 \right) + h.c. \right] + Tr\, \bar{B}\, \gamma^\mu \left(i\gamma^\mu \partial_\mu - m_B \right) B$$
$$+ iTr\, \bar{B}\, \gamma^\mu \left[V_\mu , B \right] + D\, Tr\, \bar{B} \gamma^\mu , \gamma^5 \left\{ A_\mu , B \right\} + D\, Tr\, \bar{B} \gamma^\mu , \gamma^5 \left\{ A_\mu , B \right\}$$
$$+ a_1 Tr\, \bar{B} \left(\xi M_q \xi + h.c. \right) B + a_2 Tr\, \bar{B}\, B \left(\xi M_q \xi + h.c. \right) + a_3 Tr \left[M_q \Sigma + h.c. \right] Tr\, \bar{B}\, B$$

B is the Baryon Octet with degenerate mass m_B.

$$\Sigma = \exp\left(\frac{2 i\pi}{f} \right),\ \xi = \sqrt{\Sigma} = \exp\left(\frac{i\pi}{f} \right)$$

G.Q. Li etal. NPA,594(1995)439.

π:*Pseudo Scalar Meson Octet*

f:*Pseudo Scalar Meson Decay Cons* tan *t*

$f_\pi = same\ for\ all\ in\ SU\left(3\right)_V\ \ Limit = 93\ \ MeV$

V_μ *is the vector meson current and*

A_μ *is the axial vector meson current and are given by*

$$V_\mu = \frac{1}{2}\left(\xi^+ \partial_\mu \xi + \xi\ \partial_\mu \xi^+\right),\ A_\mu = \frac{i}{2}\left(\xi^+ \partial_\mu \xi - \xi\ \partial_\mu \xi^+\right)$$

M_q *current quark mass matrix*

with diagonal term $= diag\left\{M_q, M_q, M_s\right\}$,

Mass difference between u and d-quarks are neglected

Expanding Σ up to order of $\dfrac{1}{f^2}$ and keeping explicitly the kaon fields only,

The first two terms in the Lagrangian reduces to

$$\partial^\mu \overline{K}\, \partial_\mu K - \Lambda\left(m_q + m_s\right) K\, \overline{K} + \ldots\ldots$$

where $K = \begin{pmatrix} K^+ \\ K^0 \end{pmatrix}$, $\overline{K} = \begin{pmatrix} K^- & \overline{K^0} \end{pmatrix}$

$\ldots\ldots$ for other mesons .

For the third and fourth terms in the Lagrangian, when we assume only nucleaon and kaon (KN) interaction, then they reduces to

$$\bar{N}(i\gamma^{\mu}\partial_{\mu} - m_B)N - \frac{3i}{8f^2}\bar{N}\gamma^0 N\bar{K}\overleftrightarrow{\partial}_t K + \cdots,$$

where ……for other baryons.

$$N = \begin{pmatrix} p \\ n \end{pmatrix} \quad \text{and} \quad \bar{N} = (\bar{p} \quad \bar{n}),$$

The last three terms (7th, 8th and 9th) in the Lagrangian reduces to

$$\mathrm{Tr}\,\bar{B}(\xi M_q \xi + \mathrm{h.c.})B = 2m_q\bar{N}N - \frac{\bar{N}N}{2f^2}(m_q + m_s)\bar{K}K + \cdots,$$

$$\mathrm{Tr}\,\bar{B}B(\xi M_q \xi + \mathrm{h.c.}) = 2m_s\bar{N}N - \frac{\bar{N}N}{f^2}(m_q + m_s)\bar{K}K + \cdots,$$

$$[\mathrm{Tr}\,M_q\Sigma + \mathrm{h.c.}]\,\mathrm{Tr}\,\bar{B}B = 2(2m_q + m_s)\bar{N}N - \frac{2\bar{N}N}{f^2}(m_q + m_s)\bar{K}K + \cdots.$$

Scalar attraction for K^+ and K^-

Kaplan-Nelson term

Total Lagrangian with

$$\mathcal{L} = \bar{N}(i\gamma^{\mu}\partial_{\mu} - m_N)N + \partial^{\mu}\bar{K}\partial_{\mu}K - \left(m_K^2 - \frac{\Sigma_{KN}}{f^2}\bar{N}N\right)\bar{K}K$$

$$- \frac{3i}{8f^2}\bar{N}\gamma^0 N\bar{K}\overleftrightarrow{\partial}_t K + \cdots,$$

Repulsive vector potential for K^+

Attractive potential for K^-

Weinberg-Tomozawa term

Kaon mass term is given by $m_K^2 = \Lambda(m_q + m_s)$

Nucleon mass term is given by $m_N = m_B - 2[a_1 m_q + a_2 m_s + a_3(2m_q + m_s)]$

$$\Sigma_{KN} \equiv \frac{1}{2}(m_q + m_s)\langle N|\bar{u}u + \bar{s}s|N\rangle = -\frac{1}{2}(m_q + m_s)(a_1 + 2a_2 + 4a_3).$$

a_1, a_2 fixed from baryon mass splitting

a_3, uncertain since strangeness content of the nucleon is unknown

Hence Σ_{KN} is taken relating to $\Sigma_{\pi N}$ whose value is known $(= 45\ \text{MeV})$

G. Brown et al., NPA, 596(1996)503: J. Gasser etal. Phys. Lett. B, 253 (1991)252

Strangeness production in hadronic scenario

Meson-meson, meson-baryon and baryon-baryon interaction

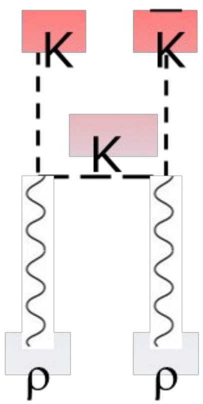
$$MM \rightarrow K\bar{K}$$ and others…

$$MB \rightarrow YK$$

$$BB \rightarrow BYK$$

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

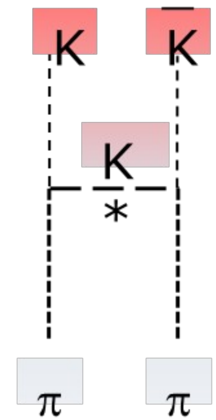
1. $MM \rightarrow K\bar{K}$



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

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

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

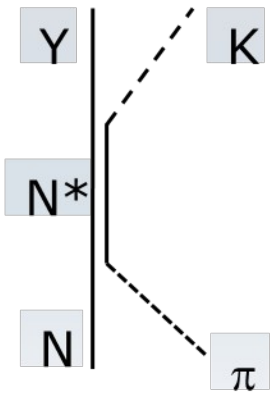


Isospin averaged cross section

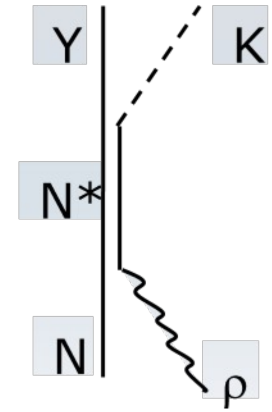
$$\bar{\sigma} = \frac{1}{32 \cdot \pi} \cdot \frac{p'}{sp} \cdot \int dx \ M\left(s,x\right)$$

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

2. $MB \rightarrow YK$



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



Isospin averaged cross-section

$$\bar{\sigma}_{\pi N \rightarrow \Lambda K} = \sum_i \frac{2J_i + 1}{(2s_1+1)(2s_2+1)} \frac{\pi}{k_i^2} \text{ㅎ} \frac{B^{in_i} B^{out_i} \Gamma_i^2}{\left(s^{1/2} - m_i\right)^2 + \Gamma_i^2/4}$$

3. *BB* → *BYK* and others

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

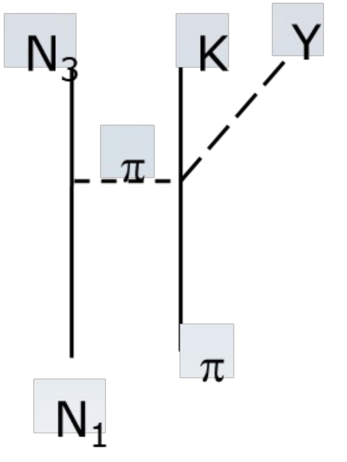
Isospin averaged cross section

$$\bar{\sigma}_{NN \rightarrow N\Lambda K} = \frac{3\ m_n^2}{2\ \pi^2\ p^2\ s} \int_{W_{\min}}^{W_{\max}} dW\ W^2\ k \int_{q_-^2}^{q_+^2} dq^2 \frac{f_{\pi NN}^2}{m_\pi^2} F^2(q^2) \frac{q^2}{(q^2 - m_\pi^2)^2}\ \text{ㅎ}\ \bar{\sigma}_0(W;q^2)$$

$$W_{\min} = m_K + m_\Lambda$$
$$W_{\max} = s^{1/2} - m_N$$
$$q_\pm^2 = 2\ m_n^2 - 2\ E\ E' \pm 2\ p\ p'$$

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

$$F = \frac{\Lambda^2 - m_\pi^2}{\Lambda^2 - q^2}\ ;\ \Lambda \text{ is the cut off parameter } \Lambda = 1 \text{ GeV}.$$

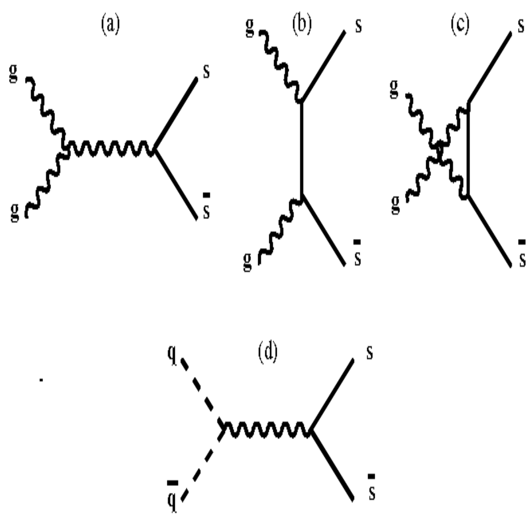


Strangeness production

in a partonic scenario

In a hadronic scenario

In partonic scenario



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

Gluon gluon fusion $gg \rightarrow s\bar{s}$

Quark and anti-quark annihilation $q\bar{q} \rightarrow s\bar{s}$

Cross-section up to lowest order QCD

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

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

Where, $G = 1 + 4m^2/s + m^4/s^2$ $\quad s = (p_1 + p_2)^2$

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

Strange production in different scenarios….