Experimental studies of the diagram of interacting matter

- Strangeness at SPS energies
- Beam energy and system size scan of $K^{\pm}$ production
- $\langle K^{+} \rangle + \langle K^{-} \rangle \stackrel{?}{=} 2\langle K_S^0 \rangle$

Maciej Lewicki

Institute of Nuclear Physics
Polish Academy of Sciences


+46
CS
MP
JS
RR
AS
JO
CJ
MK
DP
Dariusz Prorok
ZH
Zbigniew Haba
KG
Krzysztof Graczyk
Remigiusz Durka

Strangeness as a probe of deconfinement

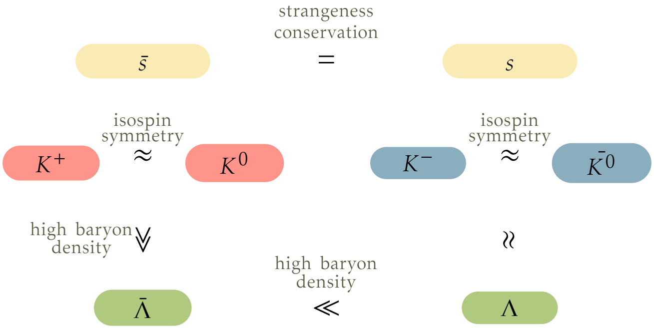
- No strangeness content in colliding nuclei.
- Sensitive to the state of matter created in the fireball.

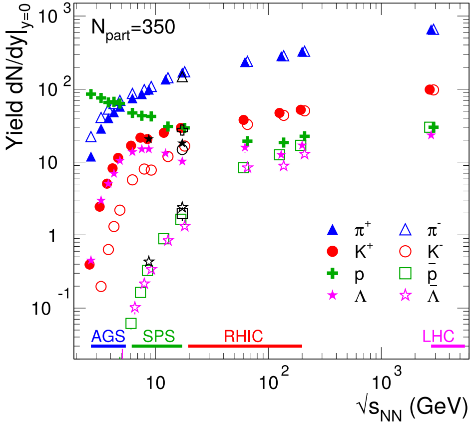
confined matter		quark-gluon plasma
K mesons	$T_C \approx 150$ MeV	(anti-)strange quarks
$g_K = 4$	$\longrightarrow$ Phase transition	$g_s = 12$
$2M \approx 2 \cdot 500$ MeV		$2m \approx 2 \cdot 100$ MeV

Lightest strangeness carriers:

- relatively heavy kaons ($M > T_C$) in the confined phase,
- relatively light strange quarks ($m \lesssim T_C$) in QGP.

Main strangeness carriers in A+A collisions at high μ_B





– sensitive to strangeness content only

– sensitive to strangeness content and baryon density

[Int.J.Mod.Phys.A:29,1430047,2014]

Strange definitions

Strangeness production $\langle N_{s\bar{s}} \rangle$ – number of s-$\bar{s}$ pairs produced in a collision.

$$2 \cdot \langle N_{s\bar{s}} \rangle = \langle \Lambda + \bar{\Lambda} \rangle + \langle K + \bar{K} \rangle + \langle \phi \rangle + \dots$$

Strange definitions

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$$2 \cdot \langle N_{s\bar{s}} \rangle = \langle \Lambda + \bar{\Lambda} \rangle + \langle K + \bar{K} \rangle + \langle \phi \rangle + \ldots$$
$$2 \cdot \langle N_{s\bar{s}} \rangle \approx \langle \Lambda \rangle + \langle K^+ + K^- + K^0 + \bar{K}^0 \rangle$$

Entropy production $\propto$ $\langle \pi \rangle$

The experimental ratio of strangeness to entropy can be defined as:

$$E_S = \frac{\langle \Lambda \rangle + \langle K + \bar{K} \rangle}{\langle \pi \rangle} \approx \frac{2 \cdot \langle N_{s\bar{s}} \rangle}{\langle \pi \rangle}$$

$$\langle N_{s\bar{s}} \rangle \approx \langle K^+ \rangle + \langle K^0 \rangle \approx 2 \cdot \langle K^+ \rangle, \qquad \langle \pi \rangle \approx \frac{3}{2} \Big(\langle \pi^+ \rangle + \langle \pi^- \rangle \Big)$$

$$\frac{\langle N_{s\bar{s}} \rangle}{\langle \pi \rangle} \approx \frac{2}{3} \frac{\langle K^+ \rangle}{\langle \pi^+ \rangle}, \qquad E_S \approx \frac{4}{3} \frac{\langle K^+ \rangle}{\langle \pi^+ \rangle}$$

Models of strangeness production

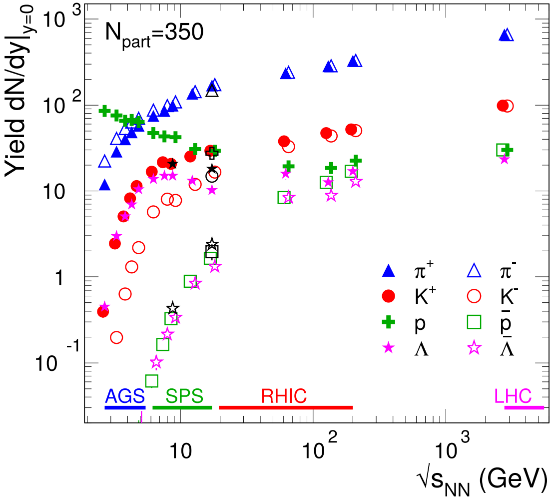
There are multiple approaches to describe the strangeness production in HIC.

Some examples include:

- Statistical Models:
  - Hadron Resonance Gas
  - Statistical Hadronization Model
  - **Statistical Model of Early Stage**
- Dynamical Models:
  - Rafelski-Müller toy model
  - **Parton-Hadron String Dynamics**

include deconfinement explicitly

Particle yields – input to HRG model



The energy dependence of experimental hadron yields at mid-rapidity for various species produced in central nucleus-nucleus collisions.

[A. Andronic, Int.J.Mod.Phys.A:29,1430047,2014]

Hadron Resonance Gas

Recipe for intepreting K^+/π^+ within HRG:

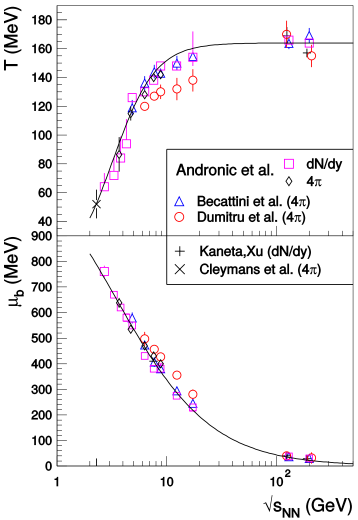
1. Fit V, T, μ_B to experimentally measured yields
2. Parametrize the T, μ_B dependence on s_{NN}
3. Compare to the experimentally measured $K^+/\pi+$

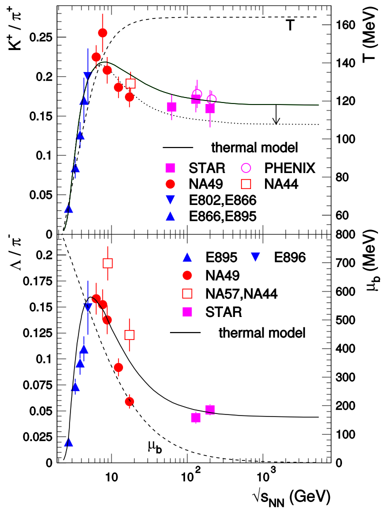
Expected:

- Smoother than data
- Approximately reproduces experimental data (because it was the input)

Notable:

- Fitted T, μ_B evolve smoothly with s_{NN}
- Addition of σ meson and heavier resonances "enhances" the horn-like shape in the K^+/π^+ dependence on s_{NN} (dotted line)





(Andronic, Braun-Munzinger, Stachel; Nucl.Phys. A834 (2010) 237C-240C)

No equilibrium? — dynamical Approach by Rafelski-Müller

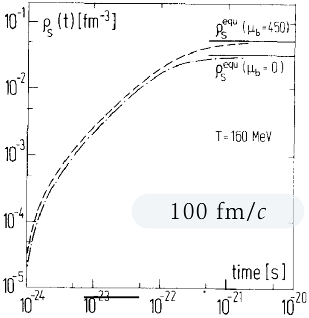
strangeness production in confined matter

$$N + N \rightarrow N + Y + K$$

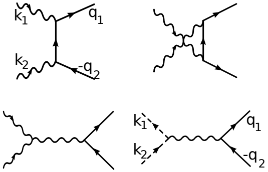
$$\pi + N \rightarrow K + Y \qquad \pi + \overline{N} \rightarrow \overline{K} + \overline{Y}$$

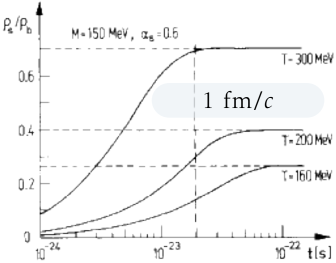
$$\pi + Y \rightarrow \Xi + K \qquad \pi + \overline{Y} \rightarrow \overline{\Xi} + \overline{K}$$

$$\pi + \Xi \rightarrow \Omega + K \qquad \pi + \overline{\Xi} \rightarrow \overline{\Omega} + \overline{K}$$



strangeness production in QGP





(Rafelski, Müller, Phys. Rev. Lett. 48 (1982) 1066)

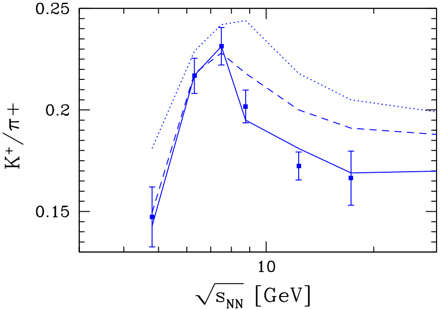
Statistical Hadronization – γ_s, γ_q

Results on strangeness in equilibrium HRG were not satisfactory.

Parameter of "phase-space occupancy" γ_s introduced to improve the fits:

$$\langle\frac{N_s}{V}\rangle = \langle\rho_s\rangle = \int \frac{d^3p}{(2\pi)^3}\frac{1}{\lambda_s^{-1}\gamma_s^{-1}e^{E(p)/T}+1}, \quad \langle\frac{N_{\bar{s}}}{V}\rangle = \langle\rho_{\bar{s}}\rangle = \int \frac{d^3p}{(2\pi)^3}\frac{1}{\lambda_s\gamma_s^{-1}e^{E(p)/T}+1}$$

Due to larger mass of s quark it requires more time to saturate and so it doesn't reach equilibrium value.
→ $\gamma_s < 1$ at lower collision energies (AGS, SPS).
→ $\gamma_s = 1$ at higher energies (from RHIC).



dotted: $\gamma_q, \gamma_s = 1$
dashed: $\gamma_q = 1, \gamma_s < 1$
solid: $\gamma_q, \gamma_s < 1$

but is it still a statistical model?

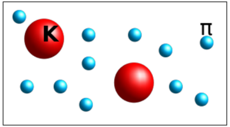
Similarly, γ_q factor can be introduced to reflect the undersaturation of u, d quarks.

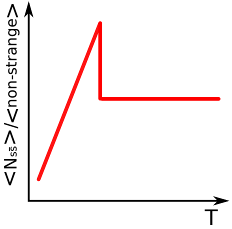
(J. Rafelski; Eur.Phys.J.ST 155 (2008) 139-166)

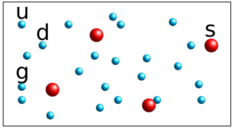
Strangeness in Statistical Model of Early Stage

$$\langle n \rangle = \frac{gV}{(2\pi)^3} \int d^3p \frac{1}{e^{E/T} \pm 1} \approx gV \left(\frac{MT}{2\pi}\right)^{3/2} e^{-M/T} \quad \text{for heavy particles}$$

$$\approx gV \frac{2\pi^2}{4 \cdot 45} T^3 \quad \text{for light particles}$$



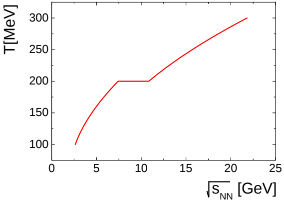




$$\frac{\langle K \rangle}{\langle \pi \rangle} \propto \frac{MT^{3/2}}{T^3} \cdot e^{-M/T}$$

$$\frac{\langle s \rangle}{\langle u + d + g \rangle} \propto \frac{T^3}{T^3} = \text{const}(T)$$

Temperature dependence on collision energy in SMES



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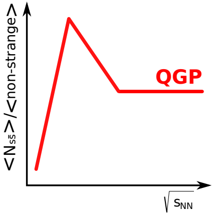
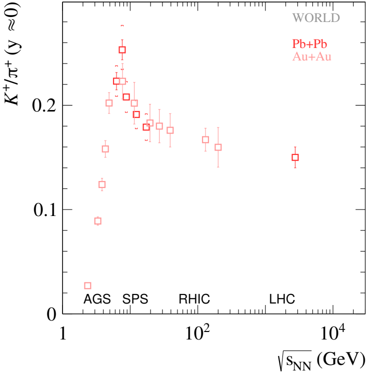
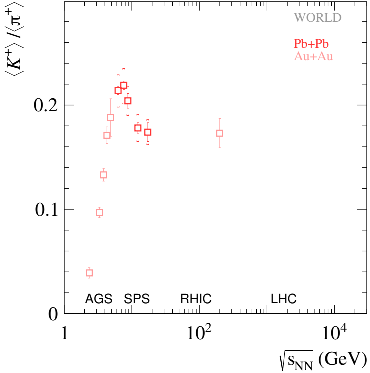


Strange/non-strange particle ratio:

Mareks' horn: [Gaździcki, Gorenstein, Acta Phys.Polon. B30 (1999) 2705]

$K^+/\pi+$ ratio dependence on collision energy





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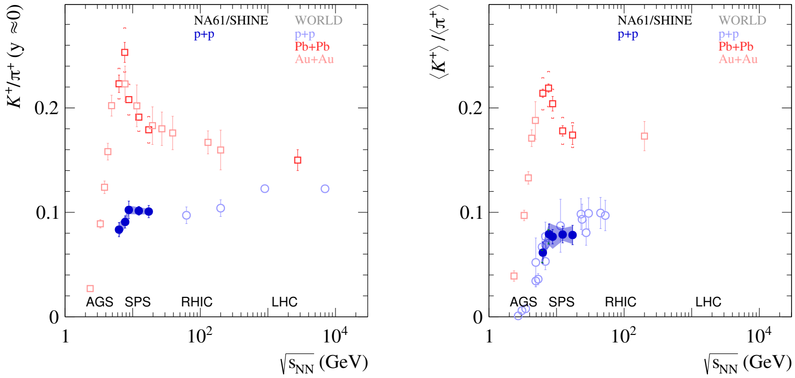
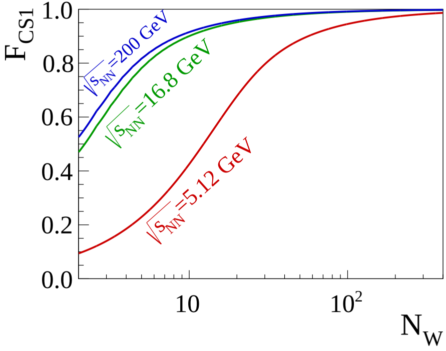
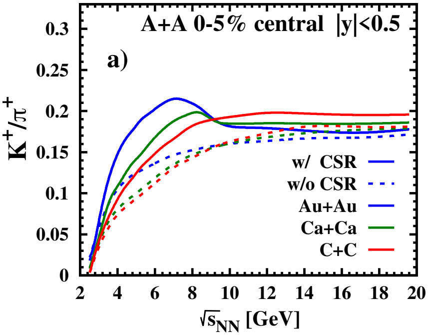


System size dependence in statistical and dynamical models





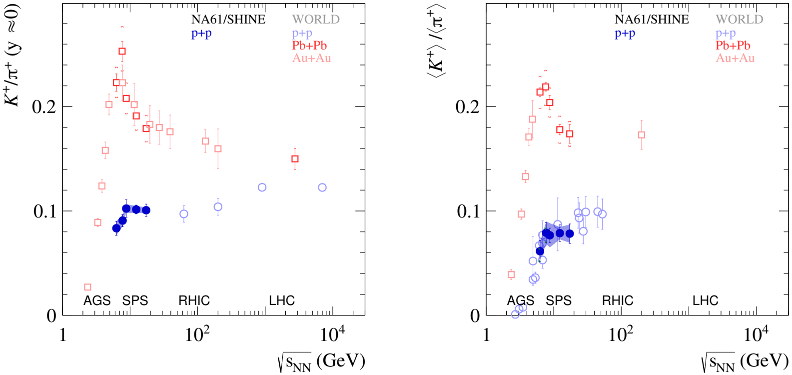
- Arises due to differences between GC and C formulation.
- Local conservation of quantum numbers severely reduces the phase space available for particle production.

(Tounsi, Redlich; Nucl.Phys.A 715 (2003) 565c-568c)

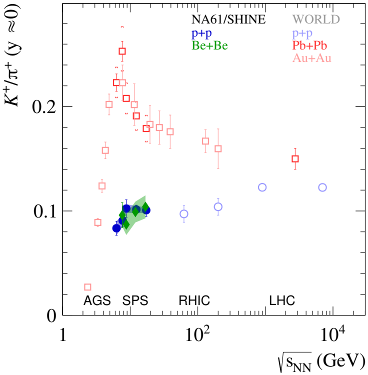
- PHSD features the onset of deconfinement.
- Predicts increase of strangeness production with system size at low collision energies (<10 GeV) and decrease at high collision energies (>10 GeV).

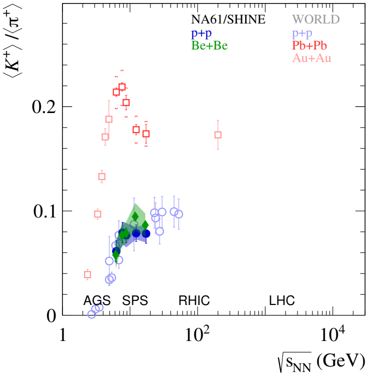
(Palmese et al. , PRC94 (2016) 044912)

System size dependence of strangeness production

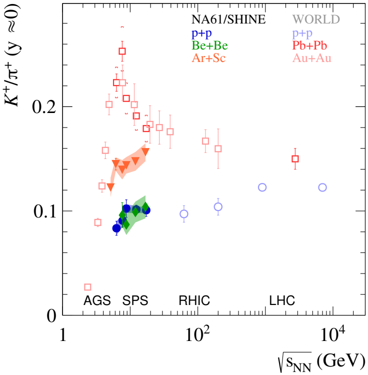


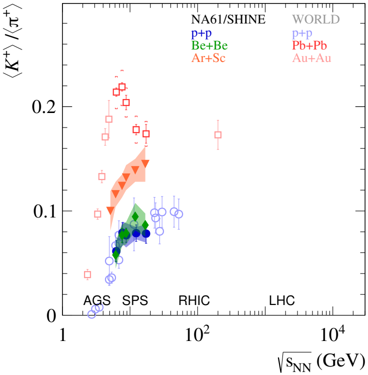
System size dependence of strangeness production





System size dependence of strangeness production



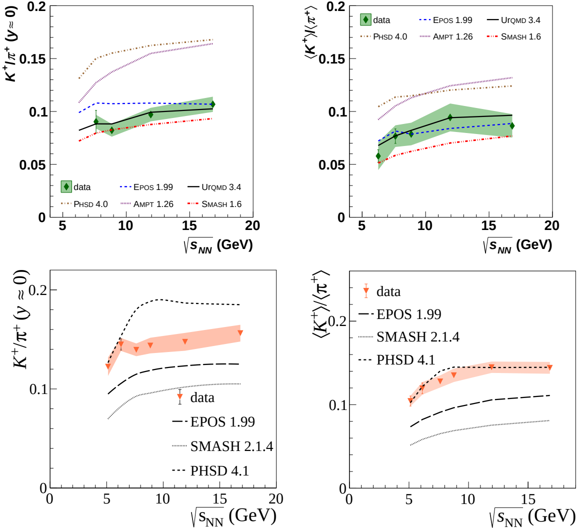


$p{+}p \approx$ **Be+Be** $\neq$ **Ar+Sc** $\ll$ **Pb+Pb**

- No horn-like structure in Ar+Sc
- Be+Be close to $p{+}p$ in K^+/π^+

- Good measure of the strangeness to entropy ratio...
- ...which is different in the confined phase (hadrons) and the QGP (quarks, anti-quarks and gluons).
- → probe of the **onset of deconfinement**.

Be+Be, Ar+Sc: K^+/π^+ ratio vs models



- K^+/π^+ ratio in midrapidity:

  — reasonably well described for Be+Be by UrQMD and SMASH,

  — none of the models works well for Ar+Sc.

- $\langle K^+\rangle/\langle\pi^+\rangle$:

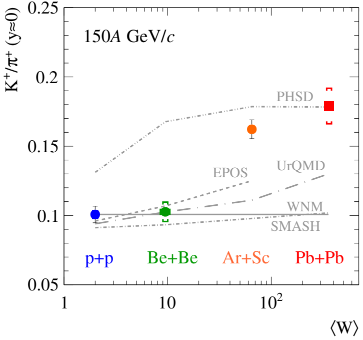
  — Be+Be data well reproduced by UrQMD and EPOS, underestimated by SMASH and overestimated by AMPT and PHSD,

  — only PHSD reproduces the Ar+Sc measurements.

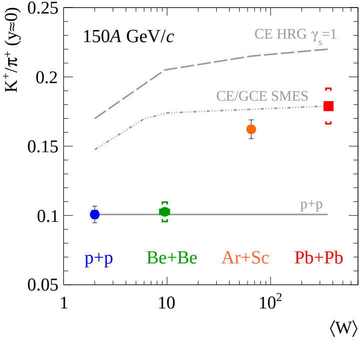
Eur.Phys.J.C 81 (2021) 1, 73
Eur.Phys.J.C 84 (2024) 4, 416

K^+/π^+ and T vs the system size at 150A GeV/c

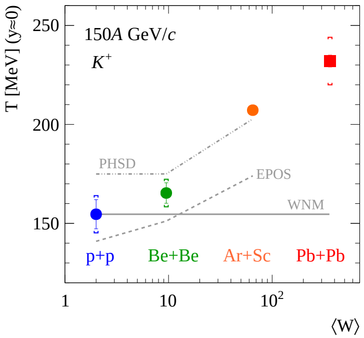
dynamical models



statistical models



dynamical models



- **Beginning of the creation of large clusters of strongly interacting matter?**

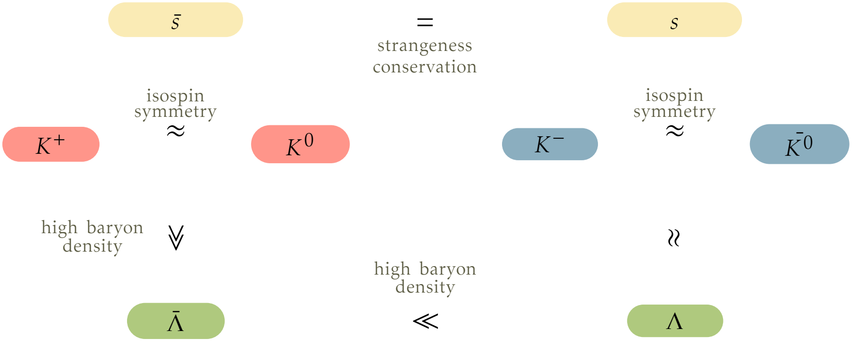
  Rapid change of observables when going from small ($p+p$, Be+Be) to intermediate (Ar+Sc) and large ones (Pb+Pb).

- None of the models reproduce K^+/π^+ ratio nor T for whole $\langle W \rangle$ range

PHSD: Eur.Phys.J.A 56 (2020) 9, 223, arXiv:1908.00451 and private communication;
SMASH: J.Phys.G 47 (2020) 6, 065101 and private communication;
UrQMD and HRG: Phys. Rev. C99 (2019) 3, 034909
SMES: Acta Phys. Polon. B46 (2015) 10, 1991 - recalculated

p+p: Eur. Phys. J. C77 (2017) 10, 671
Be+Be: Eur. Phys. J. C81 (2021) 1, 73
Ar+Sc: NA61/SHINE preliminary
Pb+Pb: Phys. Rev. C66, 054902 (2002)

The new story: excess of charged over neutral kaons



– sensitive to strangeness content only

– sensitive to strangeness content and baryon density

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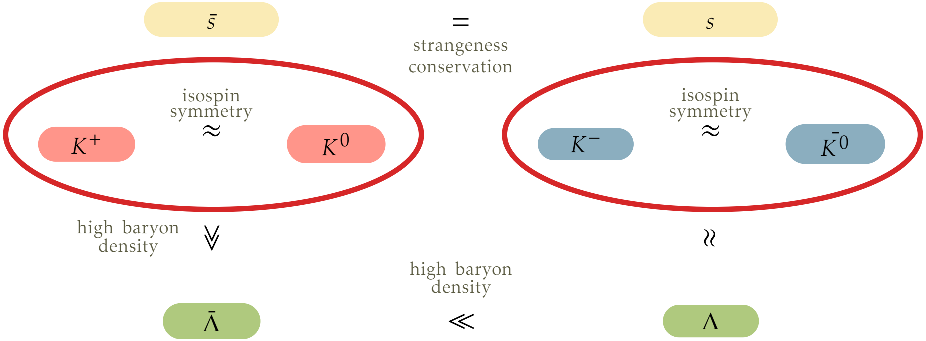

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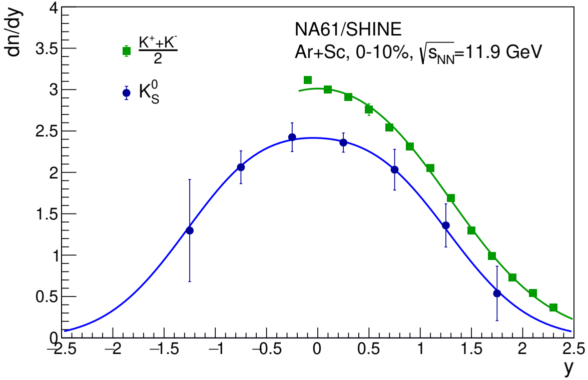
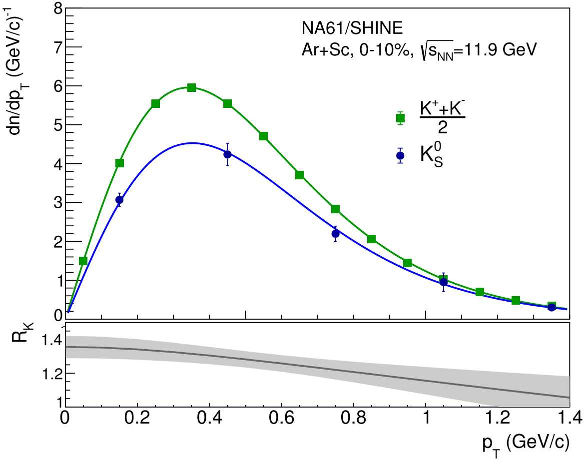




$$\frac{K^+ + K^-}{2\ K^0_S} \quad \text{for } \frac{dn}{dy} \text{ at } y \approx 0 = 1.233 \pm 0.055$$

$$\frac{K^+ + K^-}{2\ K^0_S} \quad \text{for integrated in } y > 0 = 1.347 \pm 0.116$$

- ~four additional charged K mesons per central Ar+Sc collision (extrapolating to 4π)

(Eur.Phys.J.C 84 (2024) 4, 416)
(arxiv:2312.06572)

Why is it surprising?

Strong interactions are **independent of flavor** in the limit of massless quarks.

$$m_u = 2.16^{+0.49}_{-0.26}\ \text{MeV}, \qquad m_d = 4.67^{+0.48}_{-0.17}\ \text{MeV} \quad \text{and} \quad m_s = 93.4^{+8.6}_{-3.4}\ \text{MeV}$$

Assuming the two colliding nuclei are made of an **equal number of protons and neutrons**:

$\longrightarrow$ equal number of valence $\boldsymbol{u}$ and $\boldsymbol{d}$ quarks *in the initial state*

$\longrightarrow$ closely equal abundances of $\boldsymbol{u}$ and $\boldsymbol{d}$ ($\boldsymbol{\bar{u}}$ and $\boldsymbol{\bar{d}}$) quarks *in the final state*

These symmetries should (?) translate to particle production:

$$K^+(u\bar{s}) \text{ and } K^0(d\bar{s}), \qquad K^-(s\bar{u}) \text{ and } \overline{K^0}(s\bar{d})$$

What can affect the particles yields?

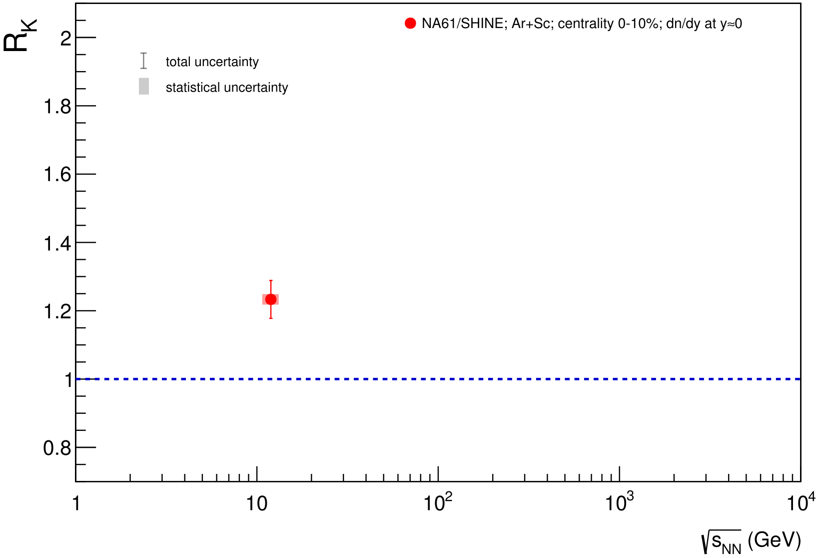
- Ar+Sc: 39 protons and 46 neutrons — 5.5% excess of ***d*** over ***u*** quarks
- Uncertainty of the mean K_S^0 lifetime $\longrightarrow$ inadequate correction for the losses
- Mass difference of quarks
- Mass difference of kaons: $m_{K^+} = m_{K^-} = 493.677 \pm 0.016$ MeV, $m_{K^0} = m_{\overline{K^0}} = 497.611 \pm 0.013$ MeV
- $\phi(1024)$ meson — decays twice as frequently to **charged kaons** as into **neutral ones**

All of the above (and more) studied quantitatively by Bryliński et al in **arxiv:2312.07176**:

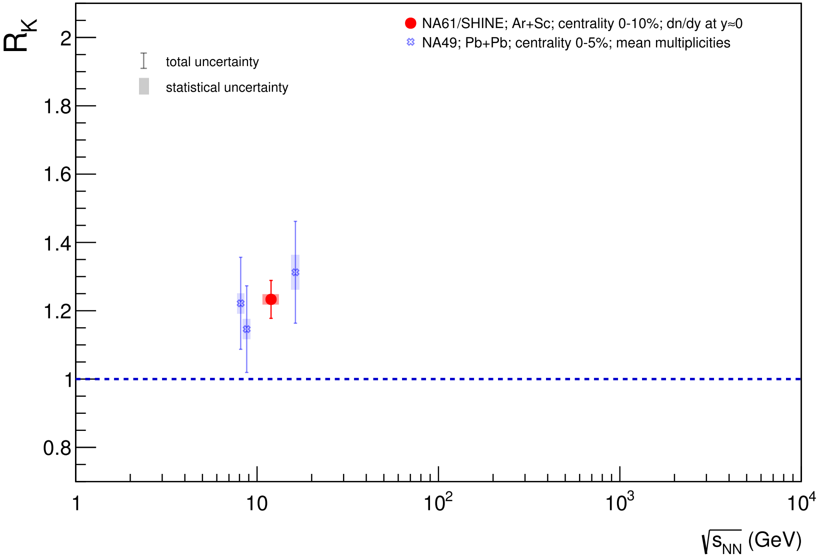
$\longrightarrow$ "at **energies larger than 10 GeV**, the mass difference between charged and neutral kaons, implying isospin symmetry-breaking processes, increases the $\boldsymbol{R_K}$ **ratio by about 0.03**"

Warning! Other effects may apply (e.g. available phase space)

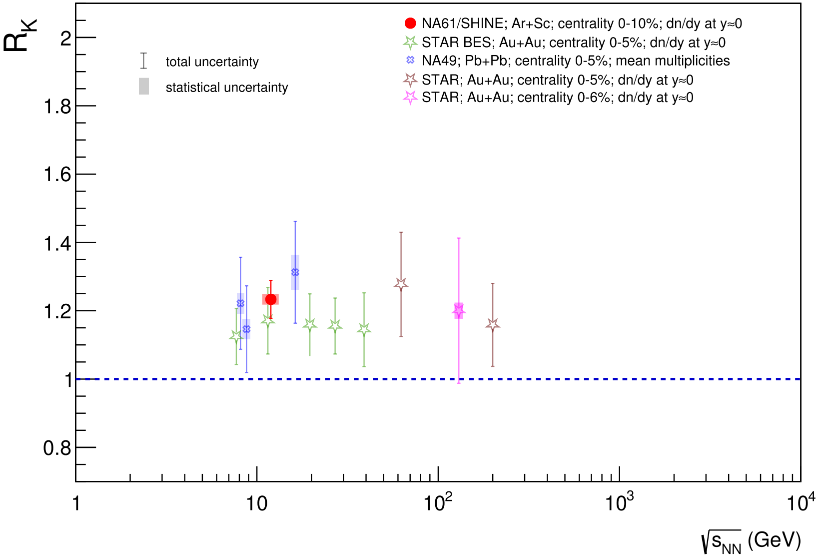
Significance of the measurement



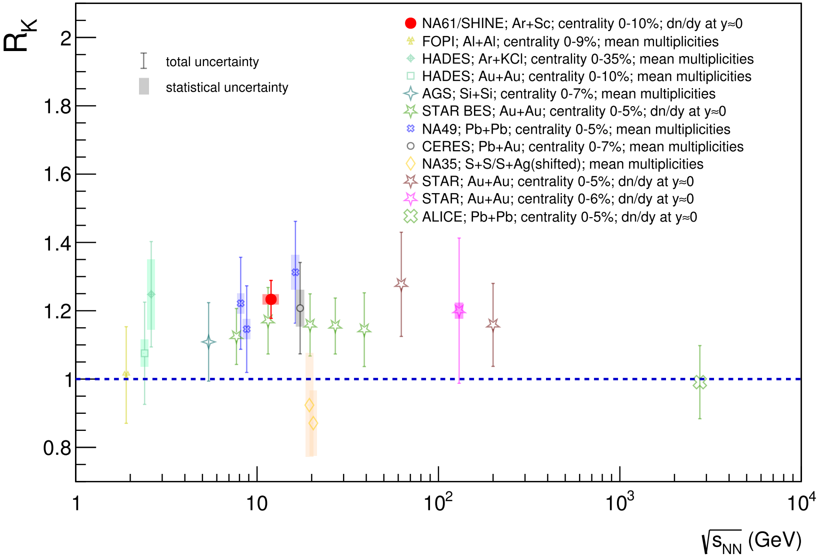
Significance of the measurement



Significance of the measurement



Significance of the measurement



Summary

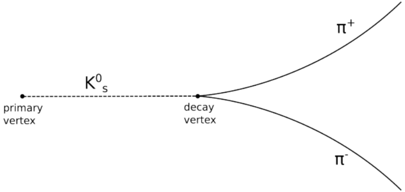
- Studying the properties of hadron production at SPS energies remains an interesting and poorly modelled topic

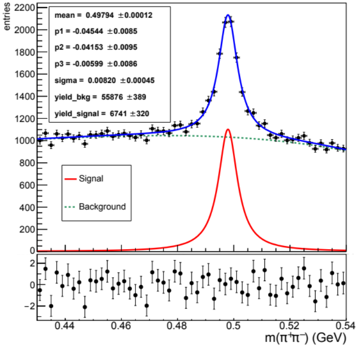
- New data from NA61/SHINE system size scan show unexpected features:
  - No ***horn*** in ^{40}Ar+^{45}Sc!
  - **Threshold-like behavior** when going from small (p+p, Be+Be) to intermediate (Ar+Sc) and large systems (Pb+Pb) visible in K^+/π^+ ratio
  - The significant **excess of charged kaons over neutral ones** (measured in Ar+Sc collisions at $\sqrt{s_{NN}} = 11.9$ GeV)

- Good amount of work ahead of Ludwik and his group in Wrocław!

Backup Slides

K_S^0 identification



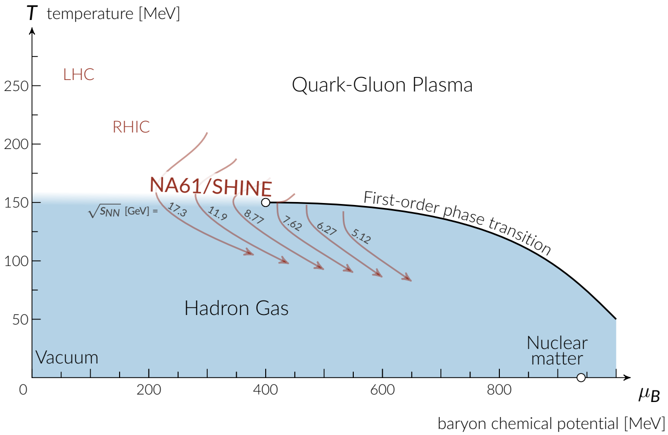


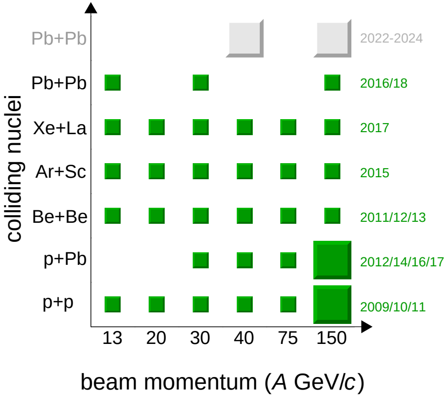
$y \in (0.5, 1.0)$, $p_T \in (1.2, 1.5)$ GeV$/c$

- Reconstruction based on decay topology
- K_S^0 decays into π^+ and π^- with BR $\approx$ 69.2%
- Breit-Wigner function is used to describe signal

NA61/SHINE strong interactions program

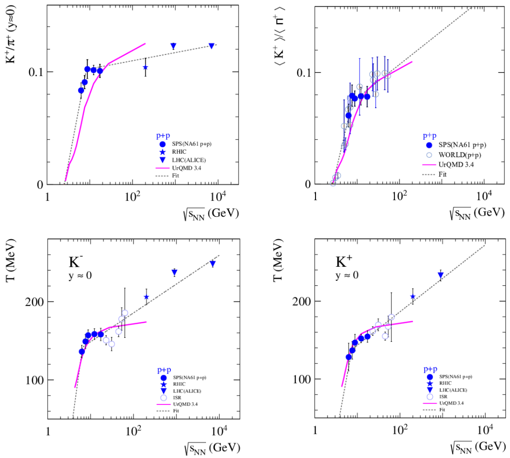
Exploring the phase diagram of strongly interacting matter with a 2D scan in collision energy and system size





$$\sqrt{s_{NN}} \approx 5 - 17 \text{ GeV}$$

K^+/π^+ ratio and inverse slope parameter in p+p

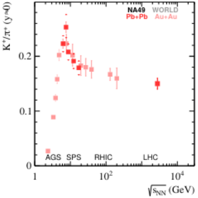


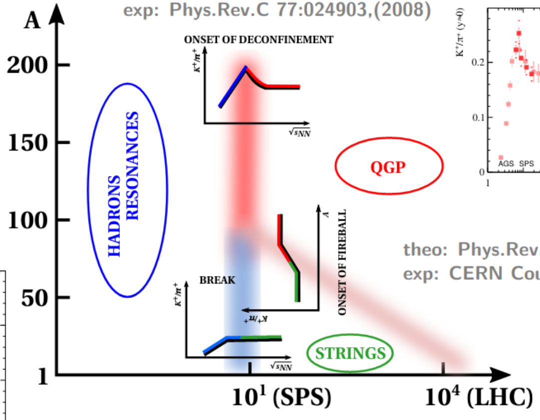
- Rates of increase of K^+/π^+ and T change sharply in p+p collisions at SPS energies
- Models assuming change from resonances to string production mechanism follow similar trend

Phys.Rev.C 102 (2020) 1, 011901

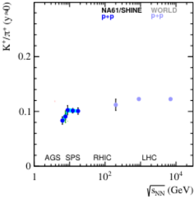
Uniqueness of ion results from NA61/SHINE

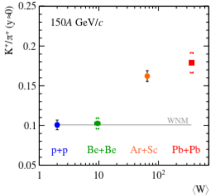
theo: Acta Phys.Polon.B 46 (2015) 10, 1991
exp: Phys.Rev.C 77:024903,(2008)





theo: Phys.Rev.D 90 025031 (2014)
exp: CERN Courier, Sep 23rd, 2019





theo: Phys.Part.Nucl. 51 (2020) 3, 337-339
exp: Phys.Rev.C 102 (2020) 1, 011901

Model comparisons

- **EPOS** – the reaction proceeds from the excitation of strings according to Gribov-Regge theory to string fragmentation into hadrons.
- **UrQMD** starts with a hadron cascade based on elementary cross sections for resonance production which either decay (mostly at low energies) or are converted into strings which fragment into hadrons (mostly at high energies).
- **AMPT** – uses the heavy ion jet interaction generator (HIJING) for generating the initial conditions, Zhang's parton cascade for modeling partonic scatterings and the Lund string fragmentation model or a quark coalescence model for hadronization.
- **PHSD** is a microscopic offshell transport approach that describes the evolution of a relativistic heavy-ion collision from the initial hard scatterings and string formation through the dynamical deconfinement phase transition to the quark-gluon plasma as well as hadronization and the subsequent interactions in the hadronic phase.
- **SMASH** uses the hadronic transport approach where the free parameters of the string excitation and decay are tuned to match the experimental measurements in inelastic p+p collisions.

Selection of events in all model calculations follows the procedure for central collisions corresponding to the experimental results (selection based on forward spectator energy).