Excited QCD
Krynica-Zdrój, Feb 5, 2020

News from NA61/SHINE: small and large systems

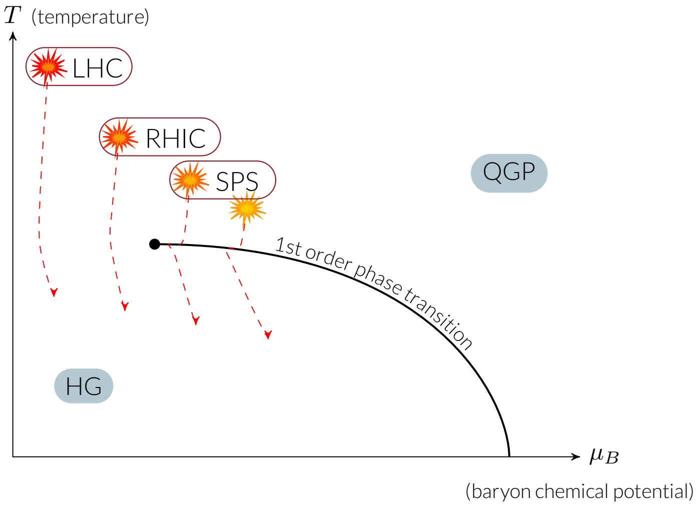
Maciej Lewicki
maciej.lewicki@uwr.edu.pl

University of Wrocław
Institute of Theoretical Physics

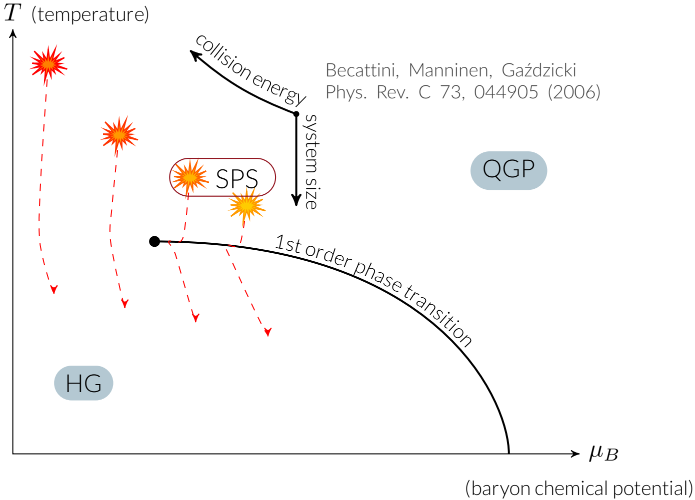
Section 1

Studies of the Onset of Deconfinement

Phase Transitions in QCD



Phase Transitions in QCD



Becattini, Manninen, Gaździcki
Phys. Rev. C 73, 044905 (2006)

Strangeness as a probe of deconfinement

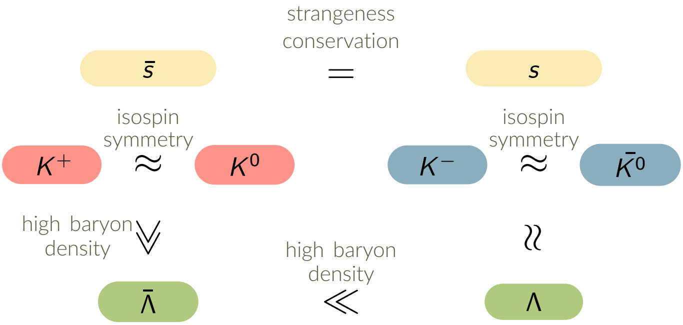
- No strangeness content in colliding nuclei.
- Sensitive to the state of matter created in the fireball.

confined matter		quark-gluon plasma
K mesons	$T_C \approx 150\ \mathrm{MeV}$ $\longrightarrow$ Phase transition	(anti-)strange quarks
$g_K = 4$		$g_s = 12$ 2: $q, \bar{q}$ 2×spin 3×color
$2M \approx 2 \cdot 500\ \mathrm{MeV}$		$2m \approx 2 \cdot 100\ \mathrm{MeV}$

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



strangeness conservation

$\bar{s} = s$

isospin symmetry

$K^+ \approx K^0$

isospin symmetry

$K^- \approx \bar{K}^0$

high baryon density

$\bar{\Lambda} \ll \Lambda$

high baryon density

🟥 – sensitive to strangeness content only

🟦🟩 – sensitive to strangeness content and baryon density

$p + p \rightarrow p + \Lambda + K^+ + \pi^0$ ≈[GeV] 0.94 + 0.94 → 0.94 + 1.12 + 0.49 + 0.14

$p + p \rightarrow p + p + K^+ + K^-$ ≈[GeV] 0.94 + 0.94 → 0.94 + 0.94 + 0.49 + 0.49

The first option is almost 200MeV "cheaper".

Strange definitions

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

$$2 \cdot \langle N_{s\bar{s}} \rangle = \langle \Lambda + \bar{\Lambda} \rangle + \langle K + \bar{K} \rangle + \langle \phi \rangle + \overset{\text{multistrange hyperons}}{\ldots}$$

Strange definitions

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

$$2 \cdot \langle N_{s\bar{s}} \rangle = \langle \Lambda + \cancel{\bar{\Lambda}} \rangle + \langle K + \bar{K} \rangle + \langle \cancel{\phi} \rangle + \overset{\cancel{\text{multistrange hyperons}}}{\dots}$$

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

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

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

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

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

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

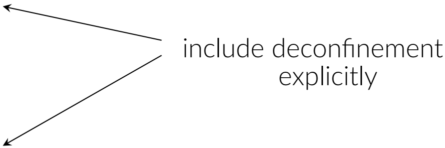
Section 2

Theoretical Models

Models of strangeness production

There are multiple approaches to describe the strangeness production in HIC. I want to briefly introduce some of them:

- 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

Hadron Resonance Gas

→ Assumption of chemical equilibrium.
Density of particle species i:

$$n_i(\mu, T) = \frac{N_i}{V} = -\frac{T}{V}\frac{\partial lnZ_i}{\partial \mu} = \frac{g_i}{2\pi^2}\int \frac{p^2 dp}{e^{\frac{E_i - \mu_i}{T}} \pm 1}, \qquad \mu_i = \mu_B B_i + \mu_S S_i + \mu_{I_3} I_{3,i}$$

Chemical potentials μ_i constrained by conservation laws:

baryon number: $$V \sum_i n_i B_i = Z + N \rightarrow \mu_B$$

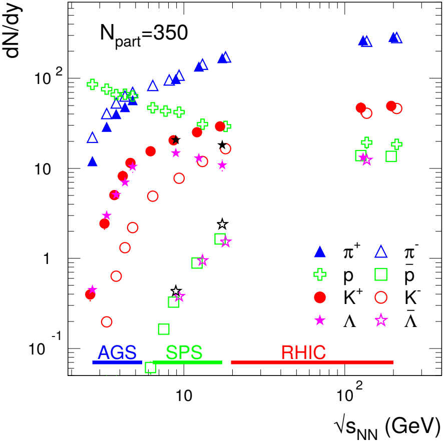
strangeness: $$V \sum_i n_i S_i = 0 \rightarrow \mu_s$$

charge: $$V \sum_i n_i I_{3,i} = \frac{Z - N}{2} \rightarrow \mu_{I_{3,i}}$$

3 equations,
5 unknowns
↓
2 free parameters

Two free parameters (T, μ_B) are fitted to experimental data on particle yields.

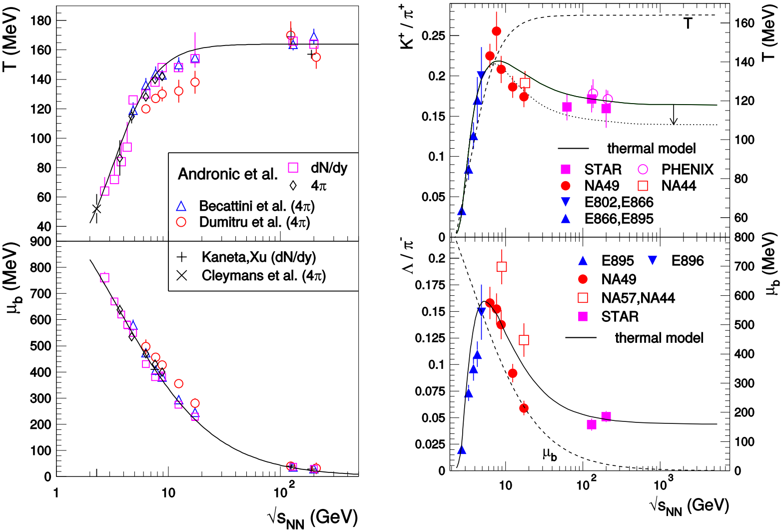
Particle yields – input to HRG model



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

(Andronic, Braun-Munzinger, Stachel; Nucl.Phys.A772:167-199,2006)

Hadron Resonance Gas



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

Statistical Hadronization – γ_s, γ_q

Results on strangess in 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).

Statistical Hadronization – γ_s, γ_q

Results on strangess in HRG were not satisfactory.

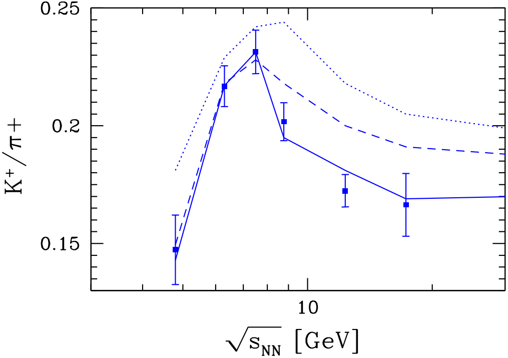
Parameter of "phase-space occupancy" γ_s introduced to improve the fits:

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

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).

Later on γ_q was introduced to tune the fits for ***u***, ***d*** quarks.

Statistical Hadronization – γ_s, γ_q



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

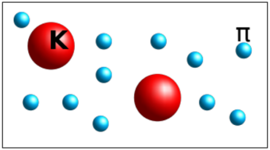
but is it still a statistical model?

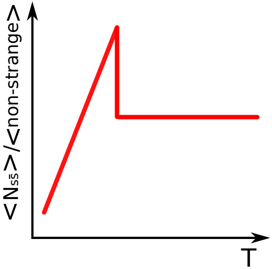
(J. Rafelski; Eur.Phys.J.ST 155 (2008) 139-166)

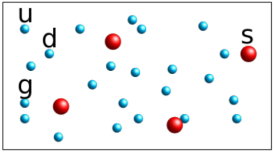
Strangeness in **Statistical Model of Early Stage**

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

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







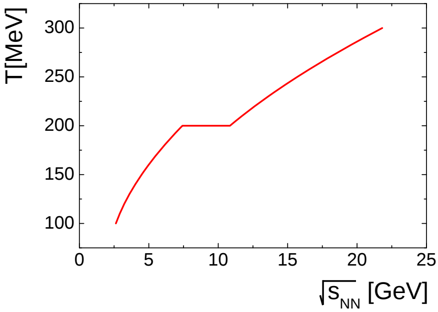
$$\frac{\langle K \rangle}{\langle \pi \rangle} \propto \frac{MT^{3/2}}{T^3} \cdot e^{-M/T}$$

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

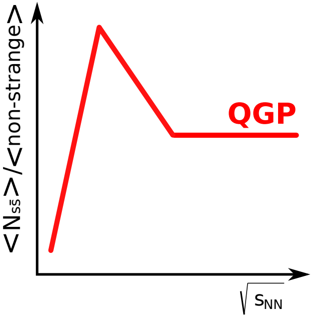
Gaździcki, Gorenstein, Acta Phys.Polon. B30 (1999) 2705

Strangeness in **Statistical Model of Early Stage**

Temperature dependence
on collision energy in **SMES**:



Strange/non-strange
particle ratio:



- Crossing the phase transition leads to a decrease of the strange/non-strange particle ratio – the horn-like structure – Mareks' horn.

Dynamical Approach by Rafelski-Müller

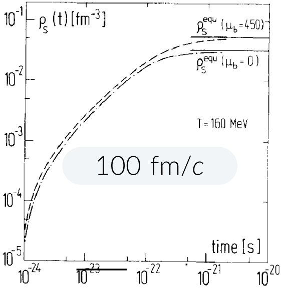
strangeness production in confined matter

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

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

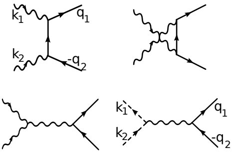
$$\pi + Y \rightarrow \Xi + K \qquad \pi + \overline{Y} \rightarrow \overline{\Xi} + \overline{K}$$

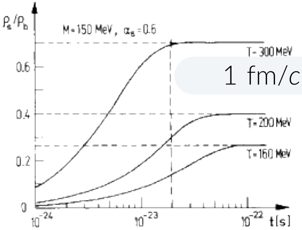
$$\pi + \Xi \rightarrow \Omega + K \qquad \pi + \overline{\Xi} \rightarrow \overline{\Omega} + \overline{K}$$



100 fm/c

strangeness production in QGP

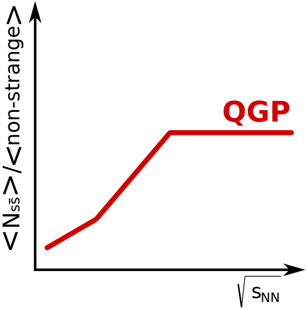




1 fm/c

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

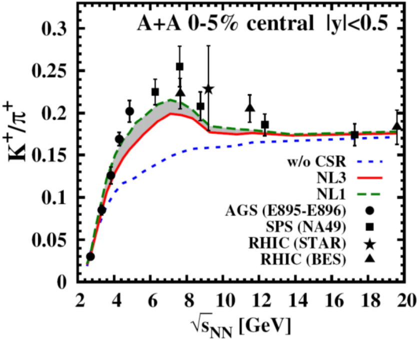
Rafelski-Müller Dynamical Approach



- Equilibrium value reached in QGP ← fast strangeness production.
- No enhancement in the confined phase ← slow strangeness production in whole hadronic region.
- Deconfinement happens in the collisions of heavy ions, but not in p+p interactions.
  → explanation for system size dependence (*A*+*A* vs *p*+*p*).

PHSD model with & without **C**hiral **S**ymmetry **R**estoration

in the confined phase

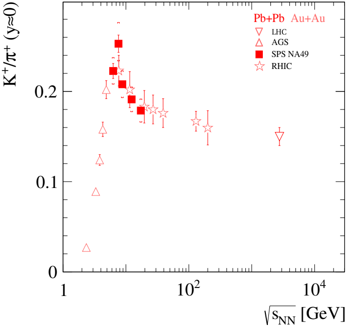


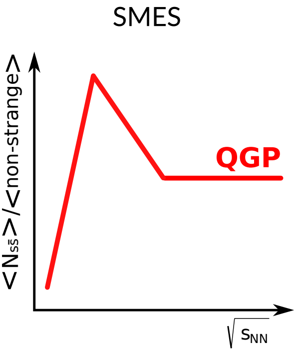
- Implements the onset of deconfinement.
- Without CSR – prediction of PHSD qualitatively resembles predictions of the Rafelski-Müller model.
- With CSR – enhanced strangeness production in the confined phase.
  The strange quark mass used in the string decay Schwinger-formula in assumed to decrease with energy density, while still in the confined phase.

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

Collision energy dependence of strangeness production

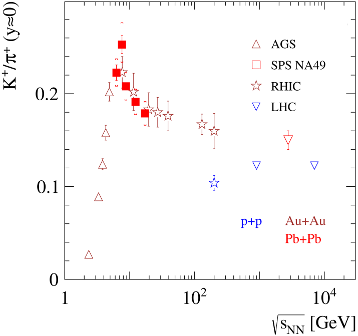
"horn" plot

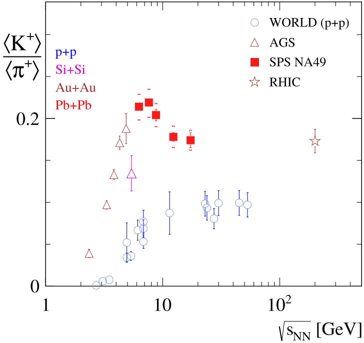




- Qualitatively, heavy-ion data follows dependence predicted by **SMES**.

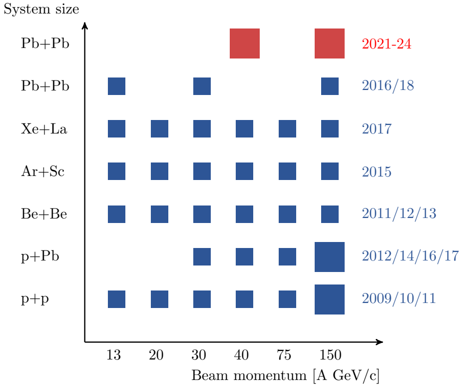
Before NA61/SHINE

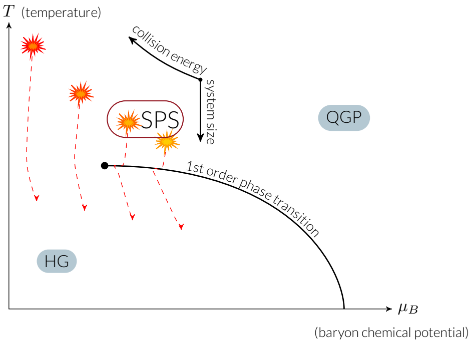




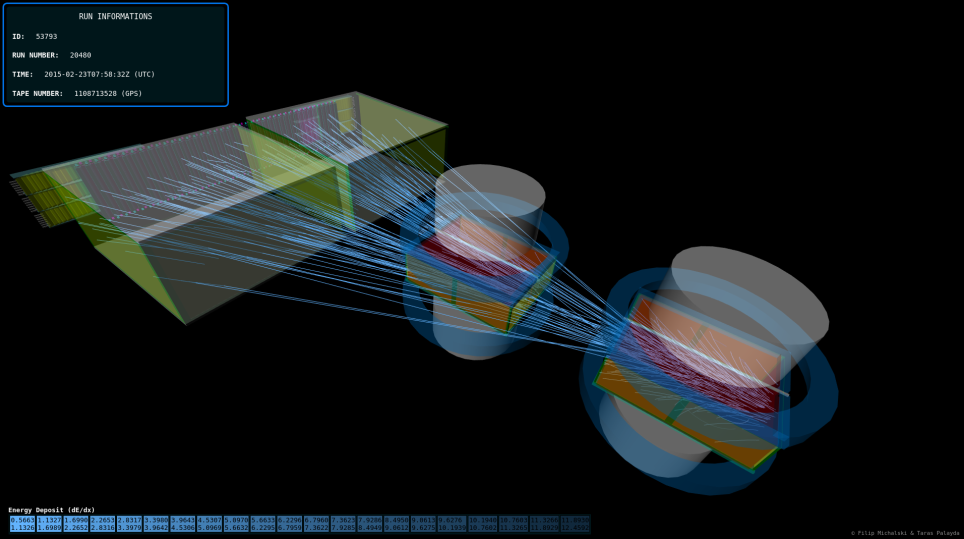
- No precise baseline of p+p collisions.
- No data on system size dependence of particle production at SPS energies – vicinity of the onset of deconfinement.

NA61/SHINE 2D scan





- Unique, two-dimensional scan in collision energy and nuclear mass number of colliding nuclei.
- Unique range in the phase diagram of strongly interacting matter.



RUN INFORMATIONS

ID: 53793

RUN NUMBER: 20480

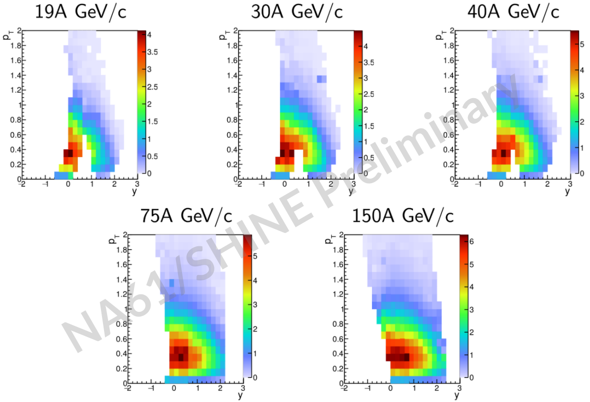
TIME: 2015-02-23T07:58:32Z (UTC)

TAPE NUMBER: 1108713528 (GPS)

Energy Deposit (dE/dx)

0.5663	1.1327	1.6990	2.2653	2.8317	3.3980	3.9643	4.5307	5.0970	5.6633	6.2296	6.7960	7.3623	7.9286	8.4950	9.0613	9.6276	10.1940	10.7603	11.3266	11.8930
1.1326	1.6989	2.2652	2.8316	3.3979	3.9642	4.5306	5.0969	5.6632	6.2295	6.7959	7.3622	7.9285	8.4949	9.0612	9.6275	10.1939	10.7602	11.3265	11.8929	12.4592

Ar+Sc: K^+ spectra in y and p_T



10% most central events recorded for Ar+Sc interactions.

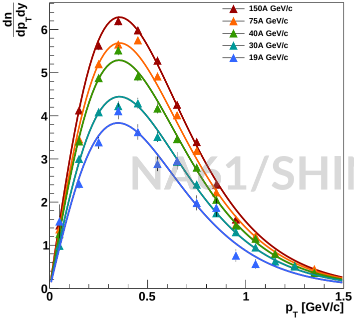
Traits of fixed target experiments:

- Acceptance in rapidity covering whole forward hemisphere.
- Acceptance in p_T down to **0.0 GeV/c**

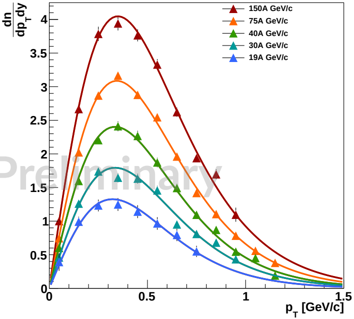
(P. Podlaski [for NA61/SHINE Collaboration], SQM Bari 2019, sqm2019.ba.infn.it/)

Ar+Sc: p_T spectra at mid-rapidity

Ar+Sc $\longrightarrow K^+ + \mathrm{X}$



Ar+Sc $\longrightarrow K^- + \mathrm{X}$

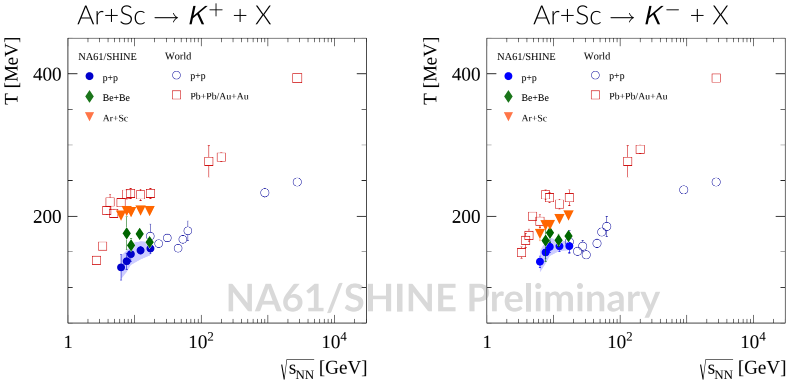


- Spectra fitted with exponential function:

$$\frac{1}{p_T}\frac{dn^2}{dp_T\ dy} = \frac{dn/dy}{T\cdot(m_K+T)} \cdot e^{-(m_T-m_K)/T}$$

(P. Podlaski [for NA61/SHINE Collaboration], SQM Bari 2019, sqm2019.ba.infn.it/)

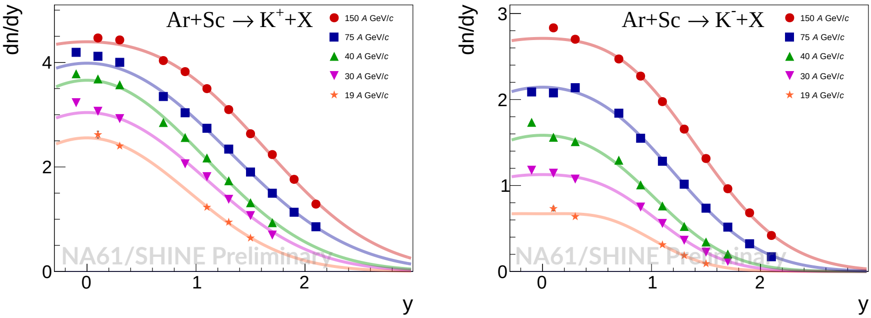
System size dependence of inverse slope parameter


Ar+Sc → K^+ + X

Ar+Sc → K^- + X

- Ar+Sc in between light and heavy systems. Be+Be very close to p+p.
- Sensitive to both: thermal and collective motion in the transverse direction.
- Transverse flow modifies the Boltzmann p_T-spectrum of hadrons.
- Kaons only weakly affected by re-scattering and resonance decays during the post-hydrodynamic hadron cascade at SPS and RHIC energies.
- Reflects temperature of the freeze-out surface and not the early-stage fireball.

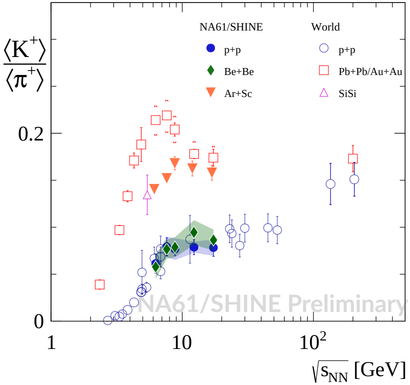
Ar+Sc: *y* spectra

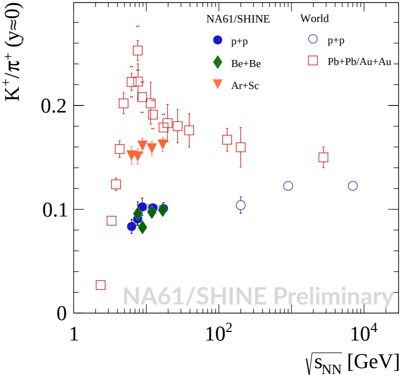


Spectra fitted with a sum of symmetric Gaussians:

$$f_{fit}(y) = A \times \left(\frac{1}{\sigma_0\sqrt{2\pi}} \exp\left(-\frac{(y-y_0)^2}{2\sigma_0^2}\right) + \frac{1}{\sigma_0\sqrt{2\pi}} \exp\left(-\frac{(y+y_0)^2}{2\sigma_0^2}\right)\right)$$

System size dependence of strangeness production





- Ar+Sc placed in between light and heavy systems.
- Be+Be very close to p+p.

Canonical strangeness suppression

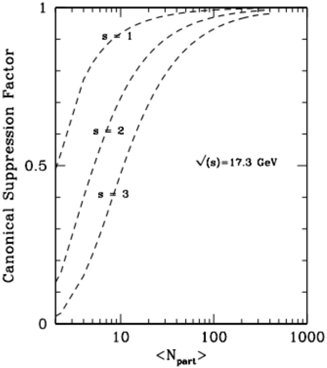


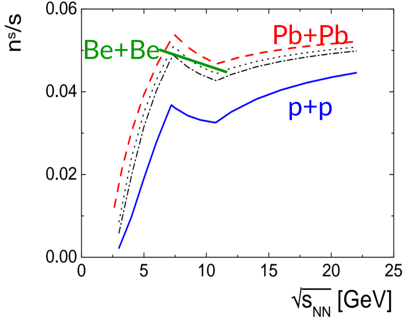
FIG. 1. Canonical suppression factor for three values of particle strangeness: $s = 1, 2, 3$, at top CERN-SPS energy.

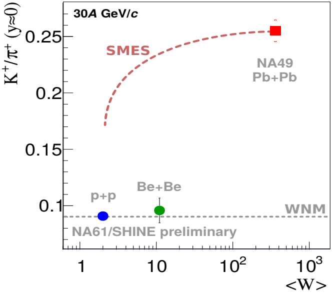
Arises due to differences between GC and C formulation.

Local conservation of quantum numbers severely reduces the phase space available for particle production.

(Tounsi, Redlich; 2001, arXiv:hep-ph/0111159)

System size dependence of strangeness production - SMES

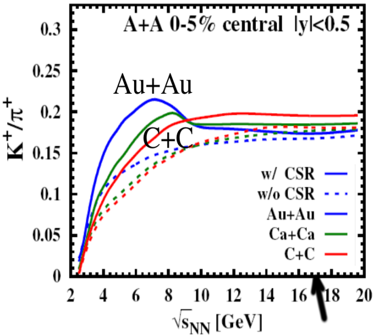


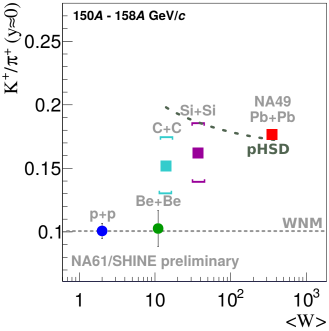


- **SMES** predicts very different system size dependence of K^+/π^+ ratio than the one measured by the NA61/SHINE experiment.
- System size dependence predicted by **SMES** is due to diminishing effect of the canonical strangeness suppression with increasing volume within statistical models.

(Poberezhnyuk, Gaździcki, Gorenstein, Acta Phys.Polon. B46 (2015) 10)

System size dependence of strangeness production - PHSD

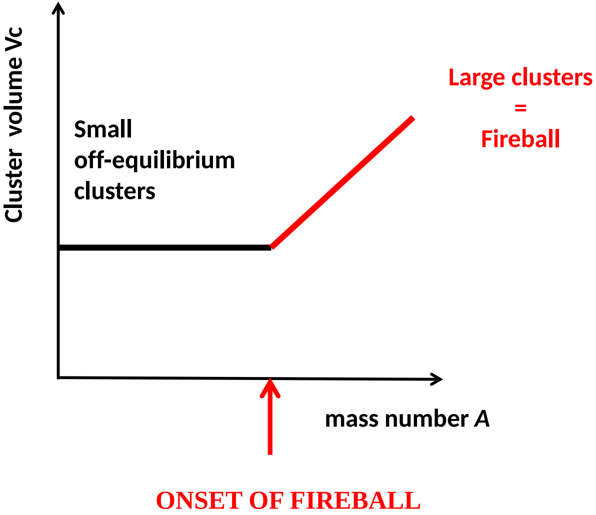




- **PHSD** predicts increase of strangeness production with system size at low collision energies (<10 GeV) and decrease at high collision energies (>10 GeV).
- **PHSD** predictions in disagreement with data at high energies.

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

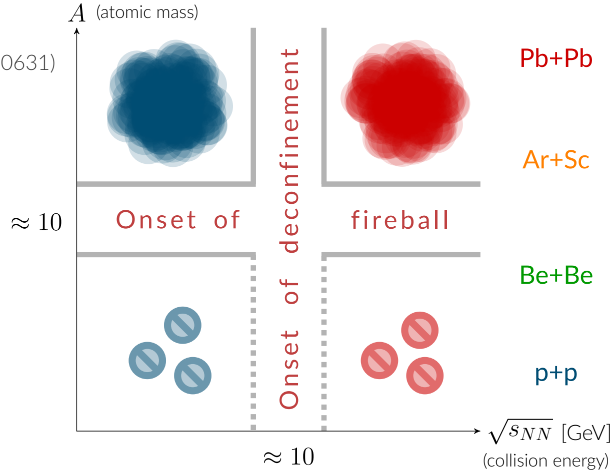
Cluster formation



Beginning of the creation of large clusters of strongly interacting matter in nucleus-nucleus collisions with increasing mass number A.

The Two Onsets

(M.L, L. Turko; arXiv:2002.00631)



- **Onset of deconfinement:**
  beginning of creation of QGP with increasing collision energy ($\sqrt{s_{NN}}$).
- **Onset of fireball:**
  beginning of creation of large clusters of strongly interacting mater in A+A collisions with increasing nuclear mass number (A).

Thank you for your attention!

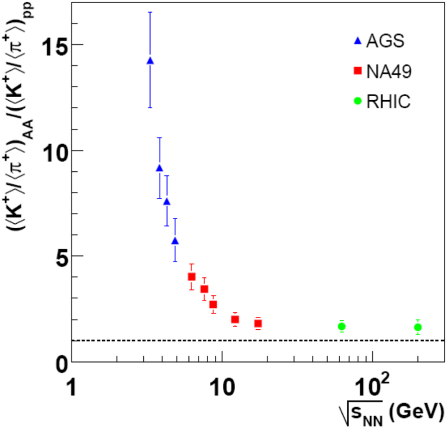
"It was easier to know it than to explain why I know it." said Sherlock.
- Arthur Conan Doyle [1]

---

[1] as reminded by J.R. Pelaez in Phys. Rept. **658**, 1 (2016)

Backup Slides

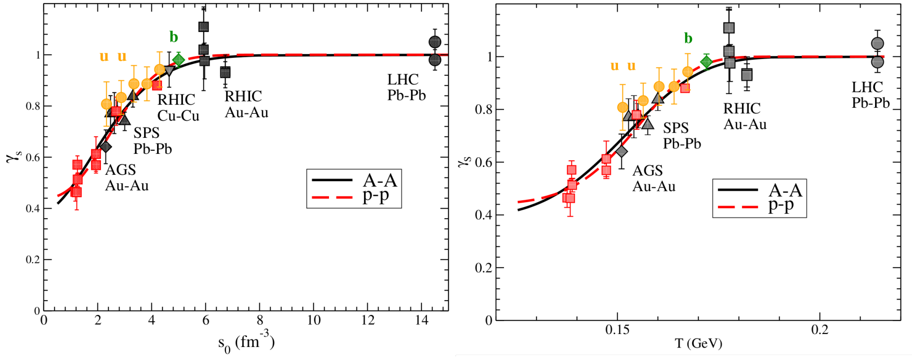
Dynamical approach debunked with low energy data



At low energies (AGS), where transition to QGP is not expected, $\langle K^+\rangle/\langle\pi^+\rangle$ ratio measured in A+A in comparison with p+p was even higher than at SPS and RHIC energies.

(Gazdzicki, Gornestein, Seyboth; Acta Phys.Polon. B42 (2011) 307-351)

Statistical Hadronization – γ_s, γ_q



Smooth parameter evolution as an argument behind using suppressed phase-space occupancy.

Centrality selection

- Unique challenge – especially for small ions.
- p+p: elastic or inelastic
- Pb+Pb: centrality ↔ multiplicity
- Neither works for "intermediate" systems: ^{40}Ar+^{45}Sc, ^{7}Be+^{9}Be.
  → multiplicity depends on physics of interest,
  → may introduce bias

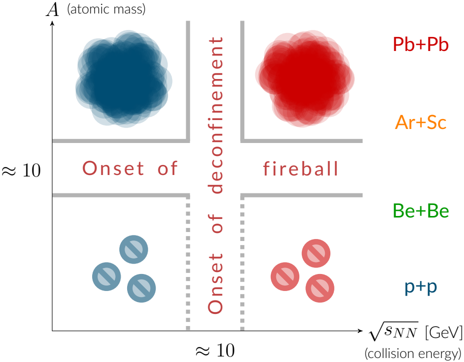
In NA61/SHINE: measurement of forward energy E_F of collision spectators in a modular calorimeter (Projectile Spectator Detector).

The most central collisions deposit the smallest energy E_F.

Precise, reproducible, unbiased.

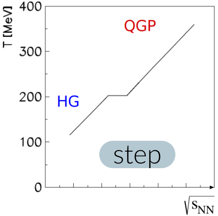
Can be only done with fixed-target experiments.

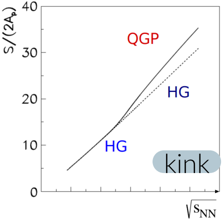
The Two Onsets

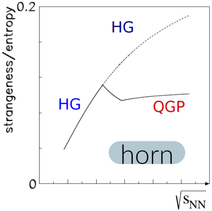


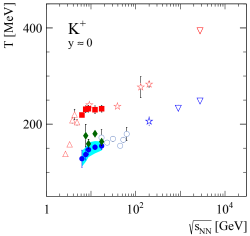
- **Percolation approach:**
  Increasing nuclear mass → density of clusters (strings, partons...) increases
  → Probability of cluster overlapping increases.
  → Conservation laws act on the whole cluster.
  This approach does not explain equilibrium properties of large clusters.
  Physica A96 (1979) 131-135; Phys. Lett. B97 (1980) 128-130; Nucl. Phys. B390 (1993) 542-558; Phys. Rev. Lett 77 (1996) 3736-3738; Phys. Rev. C72 (2005) 024907
- **AdS/CFT correspondence:**
  AdS (gravity) - formation of a black hole horizon, the information trapping takes place when critical values of model parameters are reached.
  CFT (QCD) - only starting from a sufficiently large nuclear mass number the formation of the trapping surface in A+A collisions is possible.
  Prog. Part. Nucl. Phys. (2009) 62; Phys. Rev. D79 (2009) 124015

Predictions of SMES

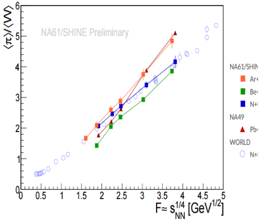




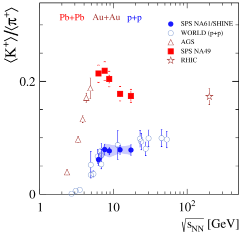




Plateau in "temperature"



Enhancement of entropy

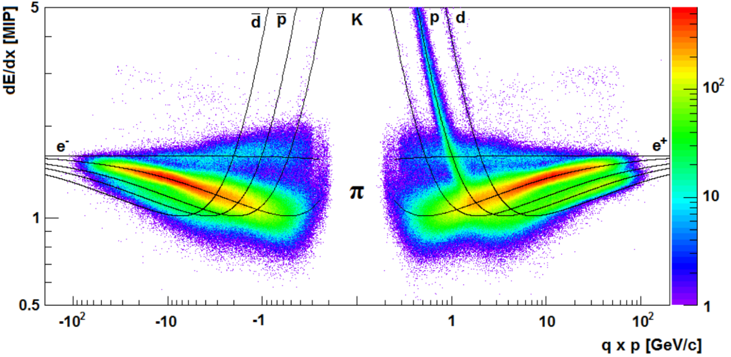


Suppresion of strangeness

Experimental results – confirming **SMES** predictions.

Signatures of PT happen all at the same $\sqrt{s_{NN}}$.

dE/dx distribution



Functions are fitted to experimental data by considering the parameters depending on the absorbing material as free fit parameters:

$$\left\langle -\frac{dE}{dx} \right\rangle_{trunc} = E_0 \frac{1}{\beta^2} \left(K + \ln(\gamma) - \beta^2 - \delta(\beta, X_A, a) \right)$$

E_0 contains all the constant factors.

K adjusts for the shape of the curve around the minimum.

Parameters fitted to the data: E_0, K, X_A, a

Strangeness suppression in Q-state

g_W^s, g_Q^s – numbers of internal *dof* of (anti)strangeness carriers in W-, Q-state.

The entropy carried by strange (and antistrange) particles:

$$S_s = \frac{g_s}{g} S$$

For massless particles of j-th species:

$$S_j = 4N_j, \qquad N_s + N_{\bar{s}} = \frac{S}{4}\frac{g_s}{g}$$

And the strangeness to entropy ratio:

$$\frac{N_s + N_{\bar{s}}}{S} = \frac{1}{4}\frac{g_s}{g}$$

Estimate (for massless *dof*):

$$\text{Q-state: } g_Q^s/g_Q \approx 0.22, \quad \text{W-state: } g_W^s/g_W \approx 0.5$$

Numerical calculations with true masses considered:

energy dependent