Dziwność a przejście fazowe silnie oddziałującej materii

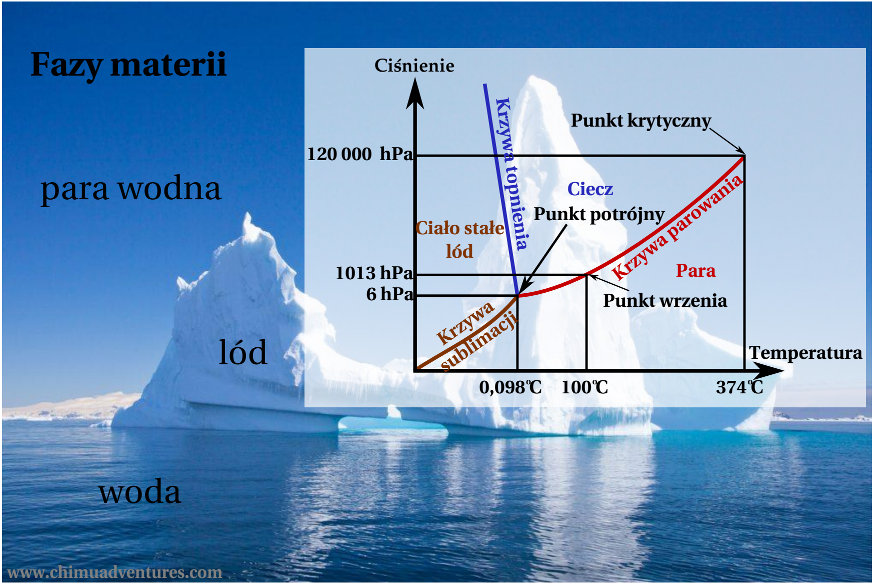
Magdalena Kuich
Zakład Cząstek i Oddziaływań Fundamentalnych

Outlook

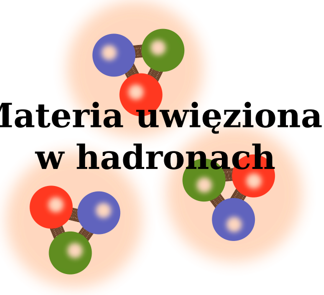
1. Phase transition and its signals
2. Why strangeness?
3. How to measure strangeness production?
4. Strange results...
5. How to understand strangeness?

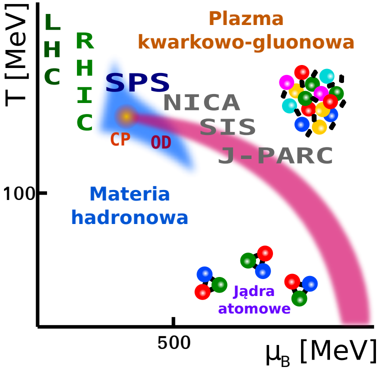
Phase transition of strongly interacting matter

The idea of the phase transition...

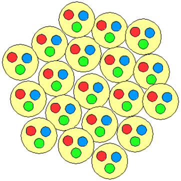


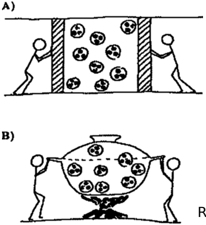
...of the strongly interacting matter

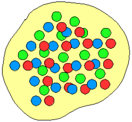




How to probe QGP and onset of deconfinement?

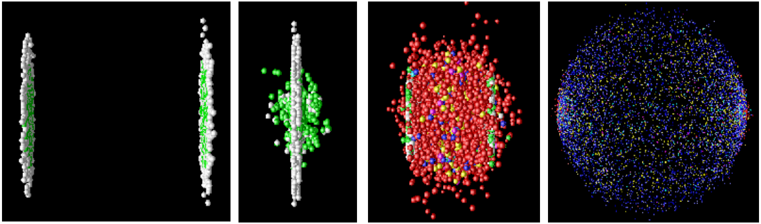




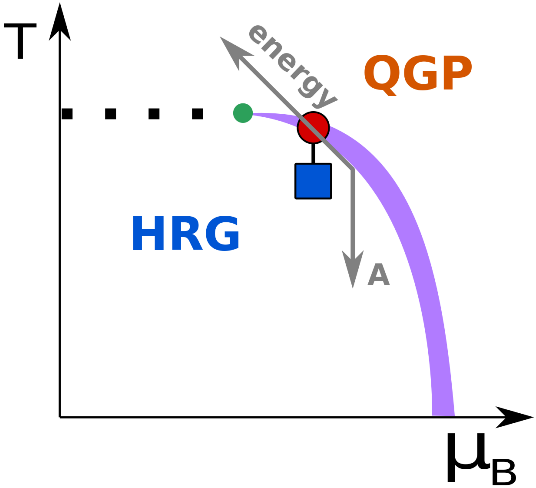


Rys. S. Mrówczyński

THUS... LET'S HAVE A SMALL BANG

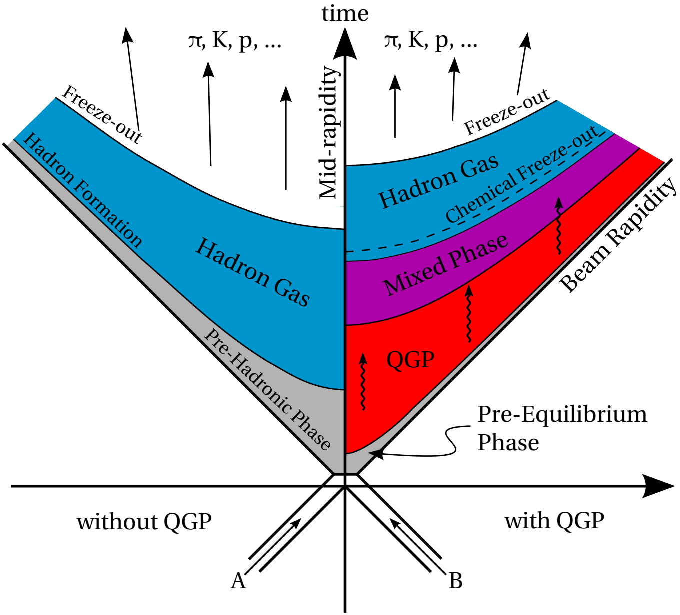


How to explore the phase diagram



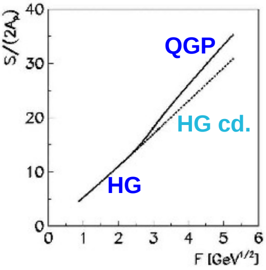
- Increase of the energy of the collision → increase of the T and decrease of the μ_B
- Increase of the system size → decrease of the T

And look at the emitted particles

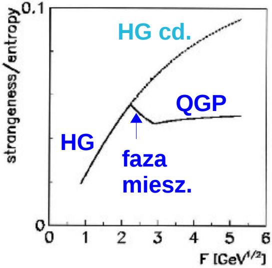


Selected signals of the onset of deconfinement

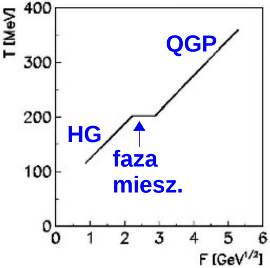
“kink”



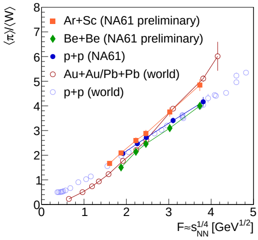
“horn”

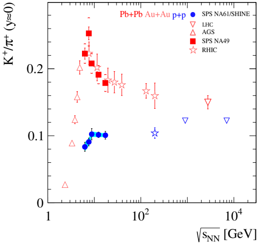


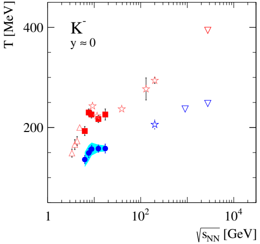
“step”



In theory (↑) and experiment(↓)







Why strangeness?

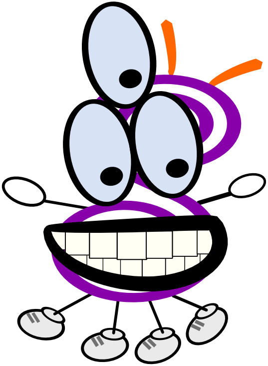
Strangeness

In particle physics:

- strangeness ("S") is a property of particles, expressed as a quantum number
- strangeness of a particle is defined as $S = (n_s - n_{\bar{s}})$, where n_s and $n_{\bar{s}}$ are the numbers of strange and anti-strange quarks, respectively.
- Strangeness is conserved in strong interactions.

In heavy ion physics:

- **produced strangeness** means a number of pairs of strange and anti-strange particles, $N_{s\bar{s}}$
- the most popular hadrons which carry strangeness are:
  - the lightest (anti-)strange mesons ($M \approx 0.5$ GeV): K^+ (u$\bar{\mathrm{s}}$), K^- ($\bar{\mathrm{u}}$s), K^0 (d$\bar{\mathrm{s}}$), $\overline{\mathrm{K}^0}$ ($\bar{\mathrm{d}}$s);
  - the lightest strange baryon ($M \approx 1.1$ GeV): Λ (uds), $\overline{\Lambda}$ ($\bar{u}\bar{d}\bar{s}$);
- strange and anti-strange quarks can also be hidden in strangeness neutral ϕ ($s\bar{s}$) meson.



Why strangeness is so interesting in heavy ion collisions?

Phase transition
$T_c \approx 150$ MeV

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

Close to T_c kaons are heavy ($M > T_c$), whereas strange quarks are light ($m \lessapprox T_c$).
The most popular non-strange particles are light (pions, light quarks and gluons).

Thanks to these properties of strange mesons and strange quarks the strangeness production is sensitive to phase transition!

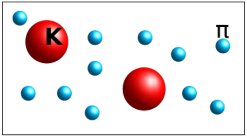
A story within Statistical Model of Early Stage...

$$\langle n \rangle = \frac{gV}{(2\pi)^3} \int d^3p \frac{1}{e^{E/T} \pm 1}$$

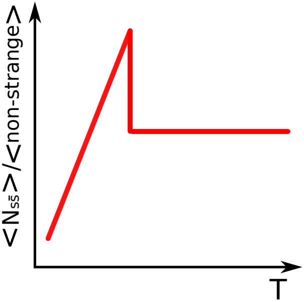
$$\approx AgVT^3 \quad \text{for light particles}$$

$$\approx gV \left(\frac{MT}{2\pi}\right)^{3/2} e^{-M/T} \quad \text{for heavy particles}$$

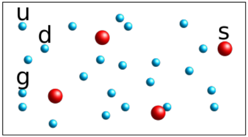
hadron gas



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



quark-gluon plasma



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

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

A story within Statistical Model of Early Stage...

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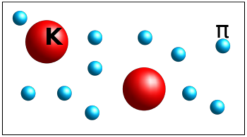

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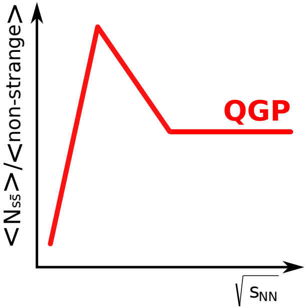

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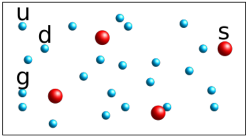

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Gaździcki, Gorenstein, Acta Phys.Polon. B30 (1999) 2705

How to measure strangeness production?

Distribution of strangeness between various hadrons

in A+A collision at high baryon density

strangeness conservation

$\bar{s} = s$

isospin symmetry

$K^+ \approx K^0$

isospin symmetry

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

$K^+ \gg \bar{\Lambda}$

$K^- \approx \Lambda$

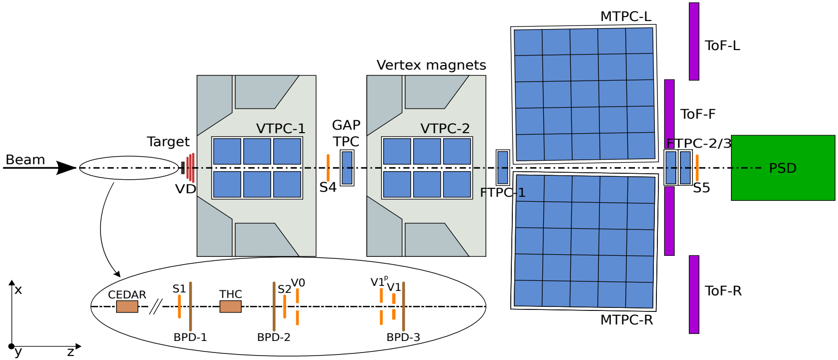
high baryon density

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

sensitive to strangeness content only

sensitive to strangeness content and baryon density

NA61/SHINE spectrometer



NA61/SHINE is a multi-purpose device measuring properties of:

beam particles

Beam detectors:
→ position
→ charge
→ mass
→ time

produced particles

TPCs:
→ electric charge
→ momentum
→ mass (dE/dx)

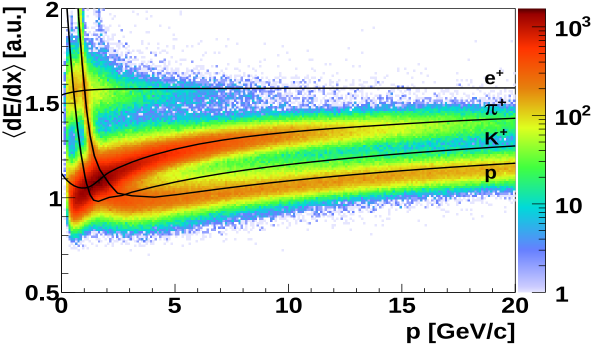
ToF:
→ mass (*tof*)

projectile spectators

PSD:
→ energy of projectile spectators
→ azimuthal angle

Particle identification

via dE/dx measurement in Time Projection Chambers:

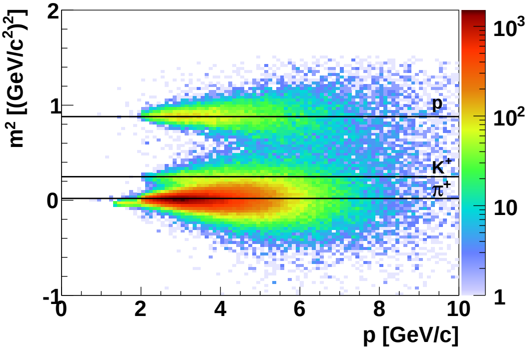


$$\left\langle -\frac{dE}{dx} \right\rangle = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} ln \left(\frac{2m_e c^2 \beta^2 \gamma^2 W_{max}}{I^2} \right) - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

$$\beta\gamma = \frac{p}{Mc}$$

Particle identification

via time (*tof*) measurement in Time of Flight detectors:



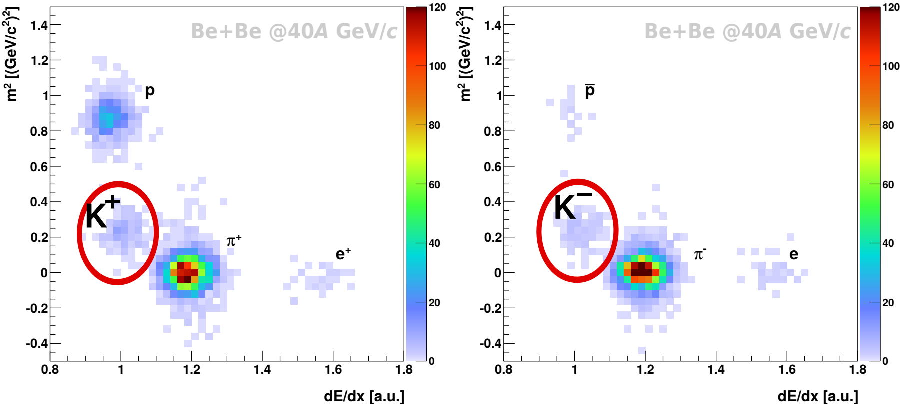
$$p = \frac{\beta}{\sqrt{1-\beta^2}} Mc,$$

$$M^2 = \left(\frac{p}{c}\right)^2 \left(\frac{1}{\beta^2} - 1\right),$$

$$M^2 = \left(\frac{p}{c}\right)^2 \left(\frac{c^2 tof^2}{s^2} - 1\right)$$

Particle identification

via simultaneous measurements of *tof* and *dE/dx*

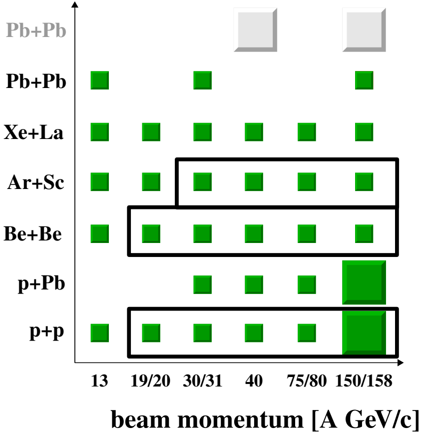


- Beautiful particle separation → easy identification of K mesons!

Strange results...

Results on strangeness production
From NA61/SHINE today:

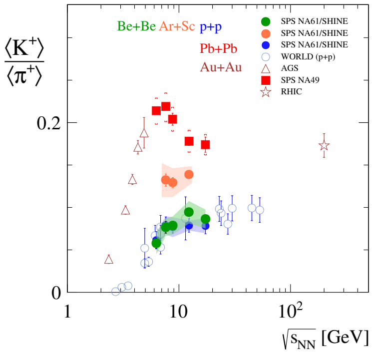
- **p+p interactions**
  - all inelastic interactions
  - Eur. Phys. J. C74 (2014) 2794
  - Eur. Phys. J. C77 (2017) 671
- **Be+Be collisions**
  - the most violent collisions
  - Nucl. Phys. A967 (2017) 35 (preliminary)
  - CPOD2018 (preliminary)
- **Ar+Sc collisions**
  - the most violent collisions
  - PoS CPOD2017 (2018) 057 (preliminary)

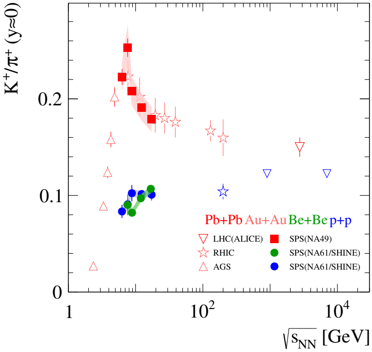


World results on p+p, Au+Au and Pb+Pb:

- **NA49**: Phys. Rev. C77 (2008) 024903; Phys. Rev. C66 (2002) 054902; Phys. Rev. C86 (2012) 054903; Eur. Phys. J. C68 (2010) 1; Eur. Phys. J. C45 (2006) 343;
- **ALICE**: Phys. Lett. B736 (2014) 196; Eur. Phys. J. C71 (2011) 1655; Phys. Rev. Lett. (2012) 109;
- **STAR**: Phys. Rev. C79 (2009) 034909; Phys. Rev. C96 (2017) 044904;
- **BRAHMS**: Phys. Rev. C72 (2005) 014908;
- **E866 and others**: Phys. Lett. B490 (2000) 53-60, Z. Phys. C65 (1995) 215; Phys. Rev. C69 (2004) 044903;

Collision energy dependence of strangeness production

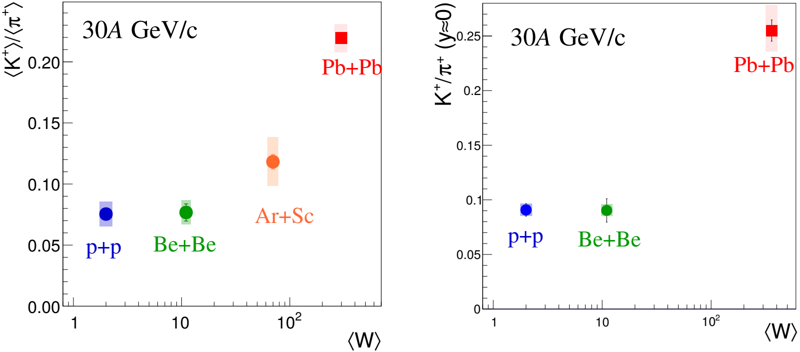




Note different energy scales

- Rapid change in strangeness production – **HORN** – was observed in Pb+Pb collisions as predicted (SMES) for the phase transition.
- Plateau-like structure is visible in p+p at mid-rapidity as well as in the 4π acceptance.
- Monotonic increase in Be+Be results at mid-rapidity as well as in the 4π acceptance.
- Ar+Sc – monotonic rise or not???

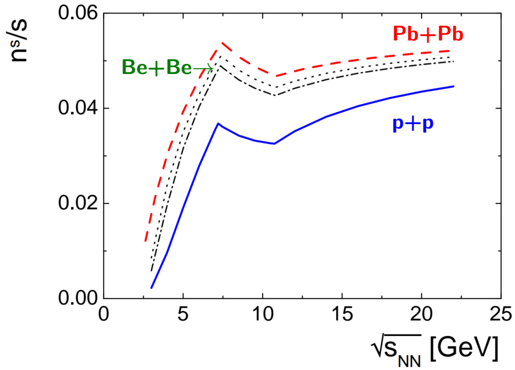
System size dependence of strangeness production - SMES



Note different vertical scales

- p+p and Be+Be results on $K^+/\pi^+(y \approx 0)$ and $\langle K^+\rangle/\langle\pi^+\rangle$ ratio are very similar.
- Ar+Sc results between p+p/Be+Be and Pb+Pb.
- Clear **JUMP** between light and heavy systems.

How about the model???



- 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

How to understand strangeness?

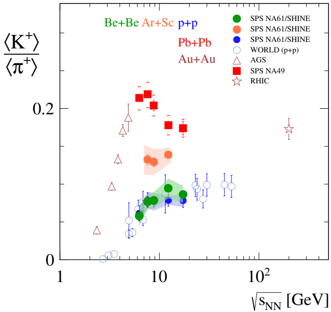
Onset of deconfinement in heavy ion collisions

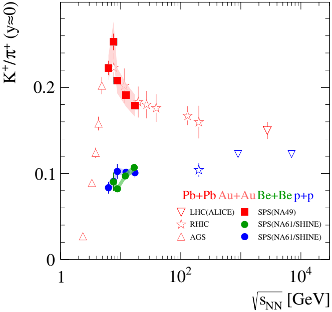
↑ ONSET OF DECONFINEMENT ↑

Pb+Pb close to equilibrium

Pb+Pb

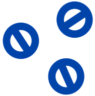
Be+Be
p+p



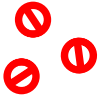


FIREBALL

SMALL CLUSTERS



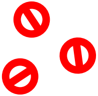
↑ ONSET OF DECONFINEMENT? ↑



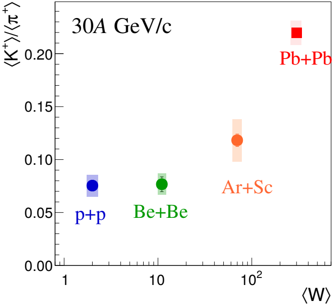
p+p and Be+Be far from equilibrium

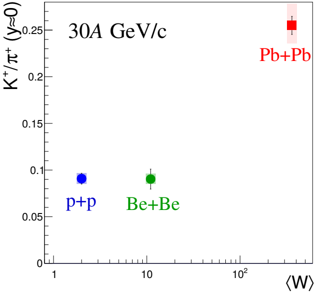
Beginning of quark-gluon plasma in nucleus-nucleus collisions with increasing collision energy.
In small system onset of deconfinement was not expected.

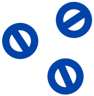
Onset of fireball - new threshold in ion-ion collisions?



↑ **ONSET OF FIREBALL** ↑



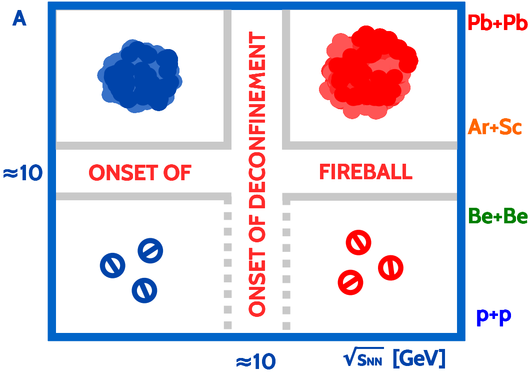




↑ **ONSET OF FIREBALL** ↑

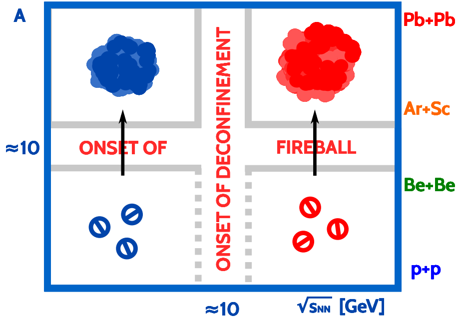
Beginning of creation of large clusters of strongly interacting mater in nucleus-nucleus collision with increasing nuclear mass number

Two threshold behaviours in strangeness production?



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

Possible explanations of the onset of fireball



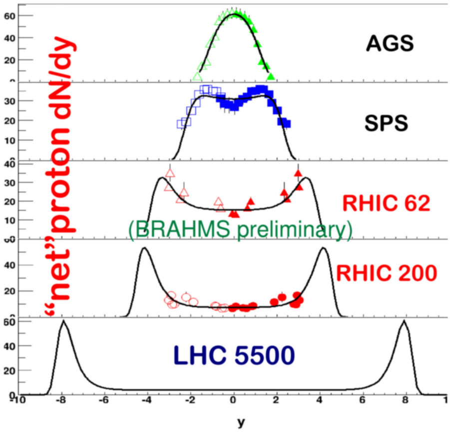
Percolation approach:
With increasing nuclear mass density of clusters (strings, partons...) increases in transverse plane. Thus probability to overlap many elementary clusters may rapidly increase (percolation). This approach does not explain equilibrium properties of large clusters.
Physica A96 (1979) 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

After all these years of studying, strangeness production remains strange...

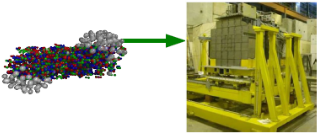
Thank you.

Transparency

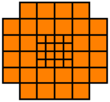


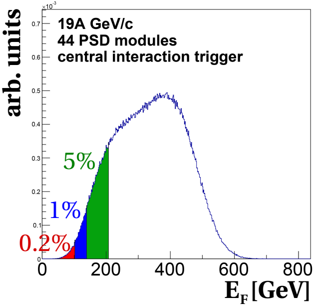
Event selection based on forward energy measurements

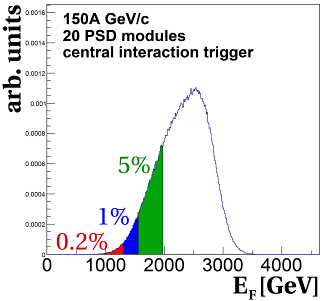
PSD

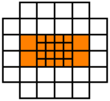


- **Event (centrality) selection** in nucleus-nucleus is done using **the forward energy**(E_F) dominated by energy of projectile spectators and measured by PSD.
- Examples of event selection using E_F for Ar+Sc:









- Due to different magnetic field setting and PSD position for various beam momenta, selection of PSD modules for E_F calculation depends on reaction
- The module selection is based on anti-correlation between energy deposit in a module and track multiplicity in TPC