



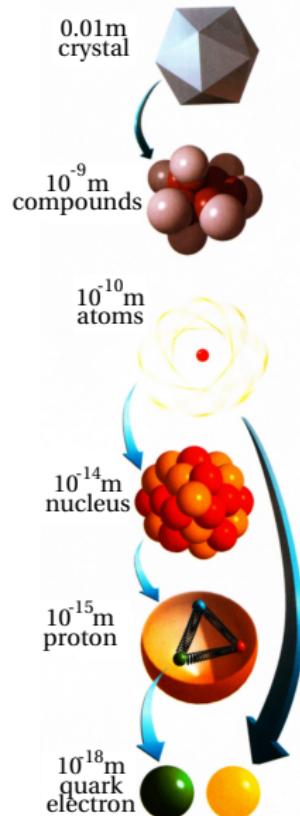
The strange case of Peter

Piotr Podlaski

University of Warsaw, Faculty of Physics

HALF CENTURY OF HIGH-ENERGY PHYSICS

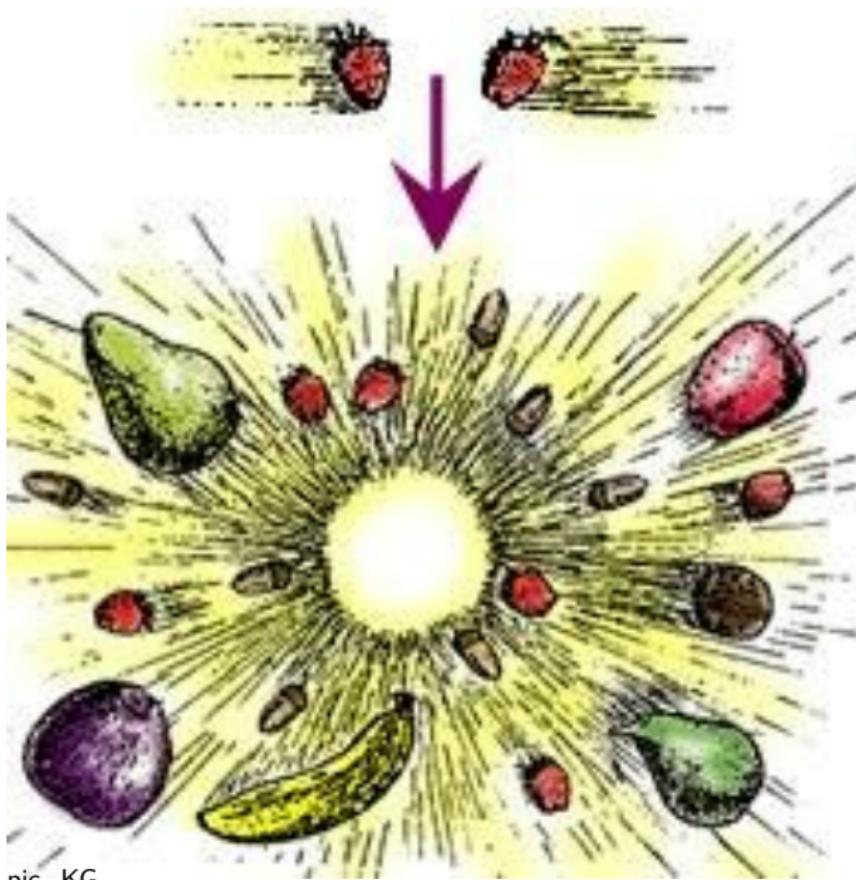
The matter we are interested in...the elementary particles zoo



Fermions (matter)			Bosons (forces)		
Quarks	I	II	III	0	0
mass →	2.2 MeV	1.27 GeV	173 GeV	0	125 GeV
charge →	+ $\frac{2}{3}$	+ $\frac{2}{3}$	+ $\frac{2}{3}$	0	0
spin →	+ $\frac{1}{2}$	+ $\frac{1}{2}$	+ $\frac{1}{2}$	1	0
name →	<i>u</i> up	<i>c</i> charm	<i>t</i> top	γ photon	H^0 Higgs boson
	4.7 MeV	95 MeV	4.2 GeV	0	
	- $\frac{1}{3}$	- $\frac{1}{3}$	- $\frac{1}{3}$	0	
	+ $\frac{1}{2}$	+ $\frac{1}{2}$	+ $\frac{1}{2}$	1	
	<i>d</i> down	<i>s</i> strange	<i>b</i> bottom	<i>g</i> gluon	
	<2 eV	<0.19 MeV	<18.2 MeV	91.2 GeV	
	0	0	0	0	
	+ $\frac{1}{2}$	+ $\frac{1}{2}$	+ $\frac{1}{2}$	1	
	<i>e</i> electron neutrino	<i>ν_μ</i> muon neutrino	<i>ν_τ</i> tau neutrino	<i>Z</i> <i>Z boson</i>	
Leptons	511 keV	105.7 MeV	1.777 GeV	80.4 GeV	
	-1	-1	-1	± 1	
	+ $\frac{1}{2}$	+ $\frac{1}{2}$	+ $\frac{1}{2}$	1	
	<i>e</i> electron	<i>μ</i> muon	<i>τ</i> tau	<i>W</i> <i>W boson</i>	

pic. KG

How to study elementary particles and fundamental forces?



pic. KG

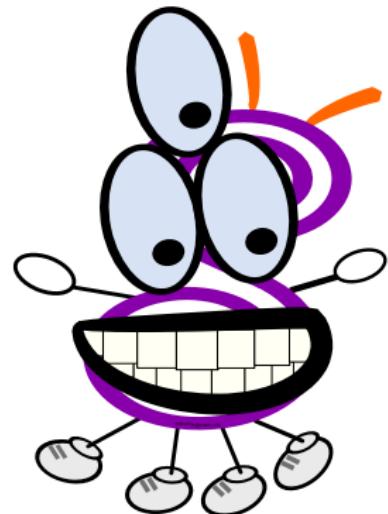
Strangeness – definition

In particle physics:

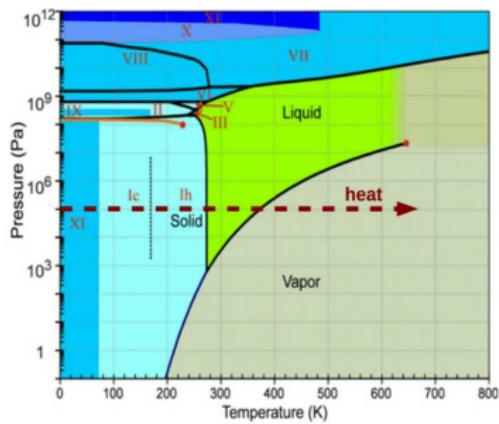
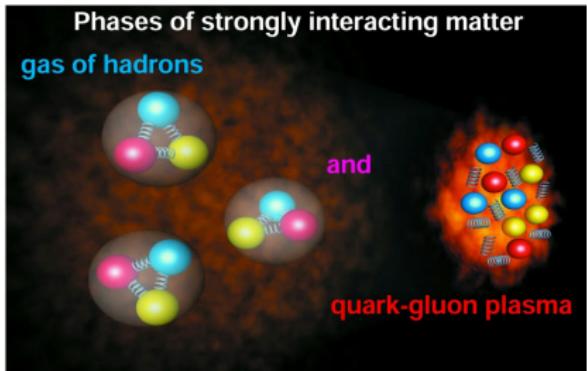
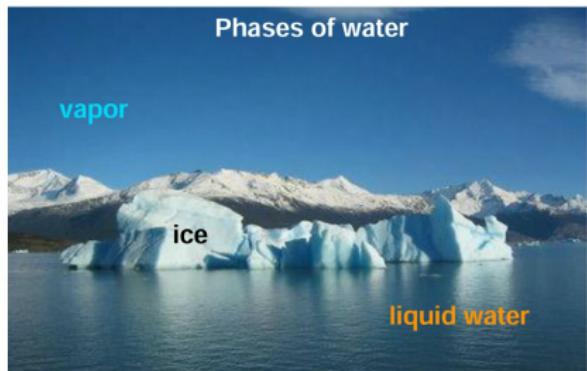
- strangeness ("S") is a property of particles, expressed as a quantum number
- strangeness of a particle is defined as $S = (n_s - n_{\bar{s}})$, where n_s and $n_{\bar{s}}$ are the numbers of strange and anti-strange quarks, respectively.
- Strangeness is conserved in strong interactions.

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^+ ($u\bar{s}$), K^- ($\bar{u}s$), K^0 ($d\bar{s}$), \bar{K}^0 ($\bar{d}s$);
 - ▶ the lightest strange baryon ($M \approx 1.1$ GeV):
 Λ (uds), $\bar{\Lambda}$ ($\bar{u}\bar{d}\bar{s}$);
- strange and anti-strange quarks can also be hidden in strangeness neutral ϕ ($s\bar{s}$) meson.



What happens when strongly interacting matter gets hotter/denser?



pic. MG

Why strangeness is so interesting in heavy ion collisions?

Phase transition $T_c \approx 150$ MeV

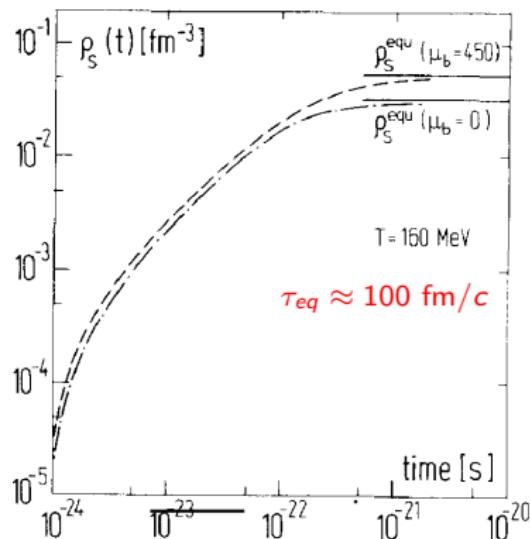
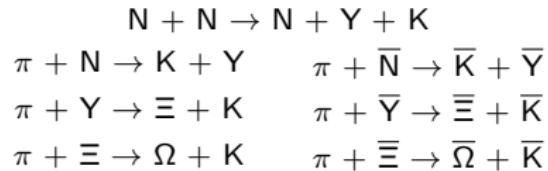
confined matter	\rightarrow	quark-gluon plasma
K mesons	\rightarrow	(anti-)strange quarks
$g_K = 4$	\rightarrow	$g_s = 12$
$2M \approx 2 \cdot 500$ MeV	\rightarrow	$2m \approx 2 \cdot 100$ MeV

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

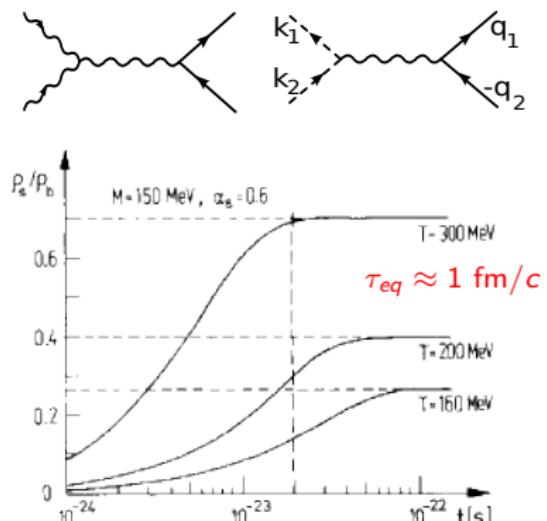
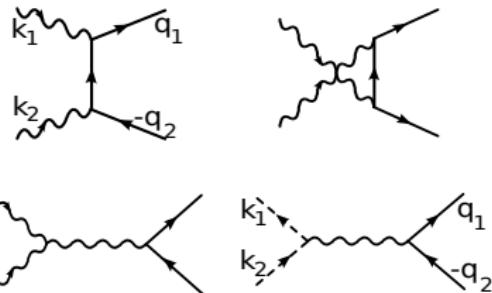
**Thanks to these properties of strange mesons and strange quarks
the strangeness production is sensitive to phase transition!**

A story within Rafelski-Müller Dynamic Model...

strangeness production in confined matter

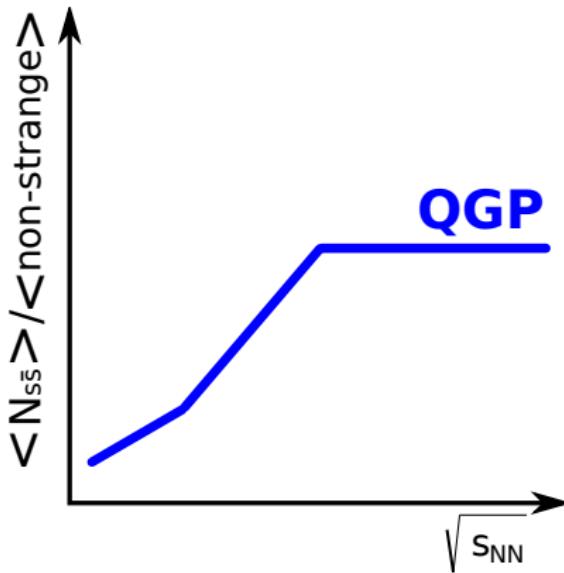


strangeness production in QGP



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

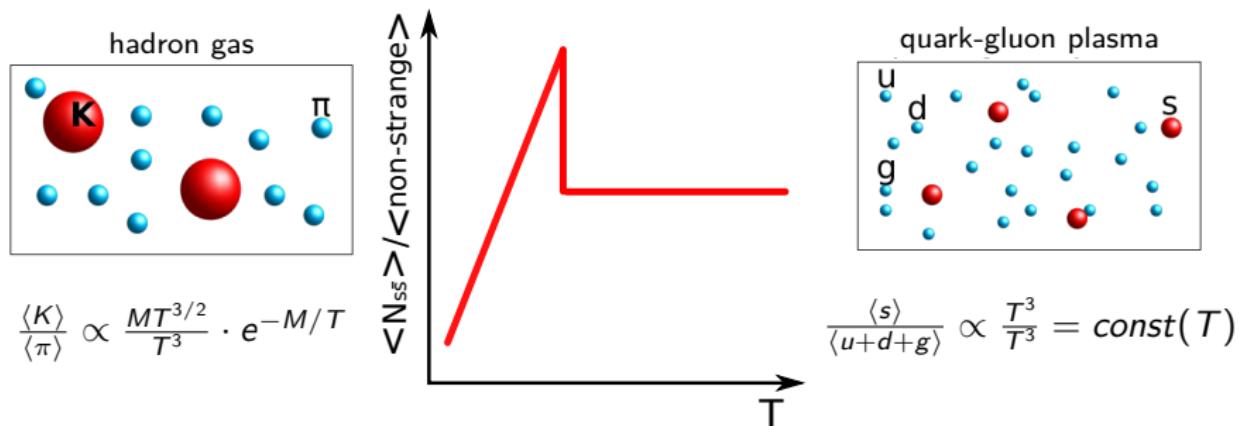
A story within RM model...



- Crossing the phase transition leads to an increase of the strange to non-strange particle ratio – the **strangeness enhancement**

Glendenning, Rafelski, Phys. Rev. C31 (1985) 823

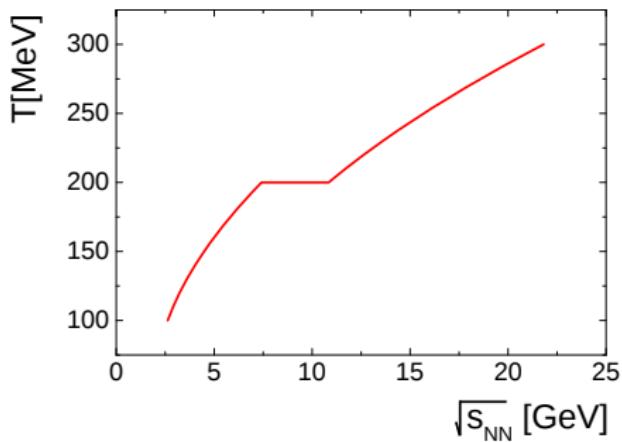
A story within Statistical Model of Early Stage...



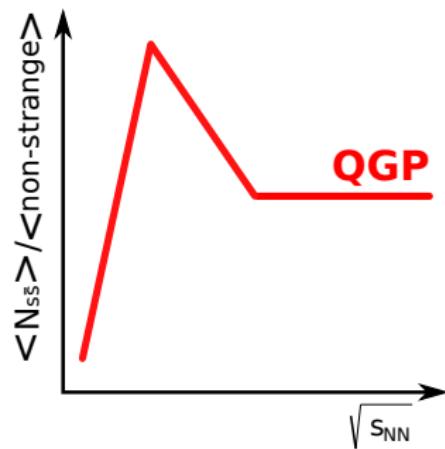
Ga  dzicki, Gorenstein, Acta Phys.Polon. B30 (1999) 2705

A story within Statistical Model of Early Stage...

In SMES temperature depends on collision energy as follows:



Then, the strange/non-strange particle ratio looks as follows:

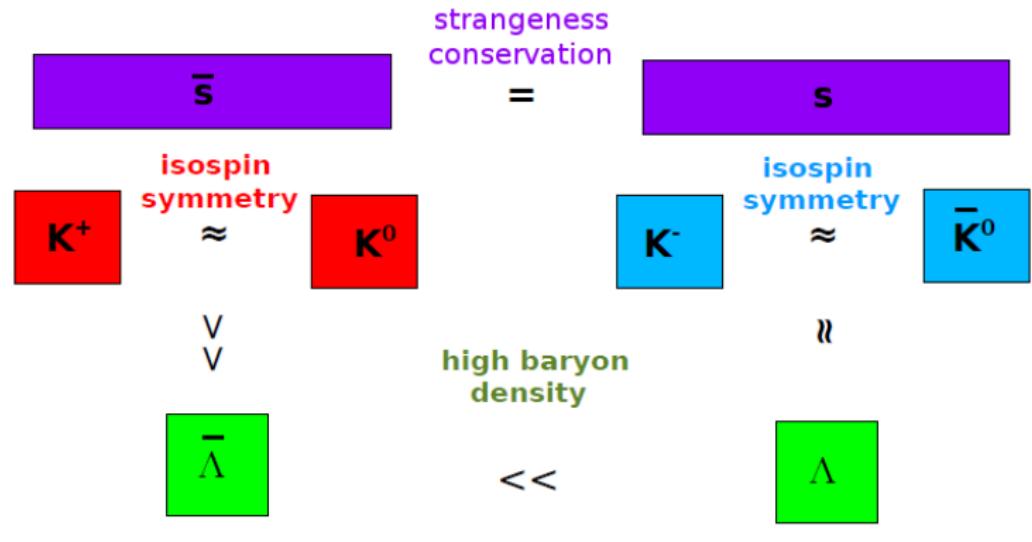


- Crossing the phase transition leads to a decrease of the strange/non-strange particle ratio – the **horn-like structure**

How to measure strangeness production?

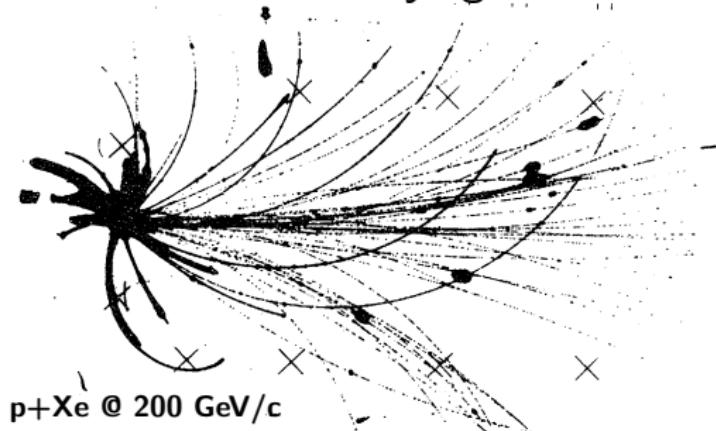
Distribution of strangeness between various hadrons

in A+A collision at high baryon density

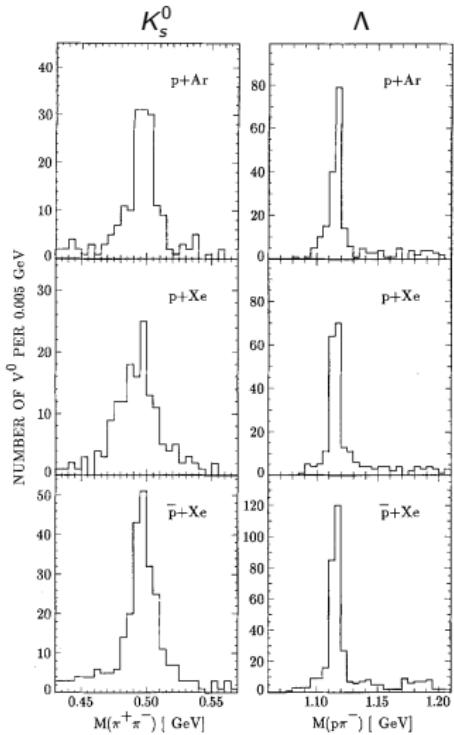


How to measure produced strangeness

Almost a half century ago... NA5



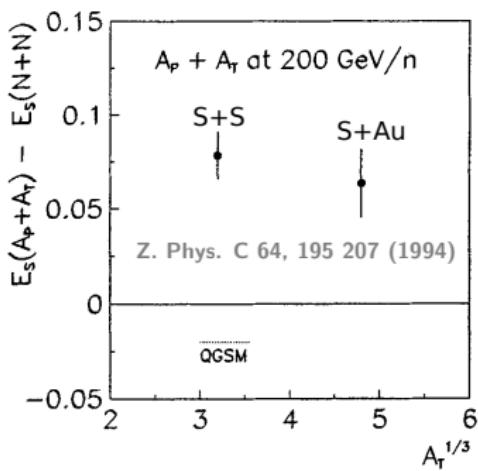
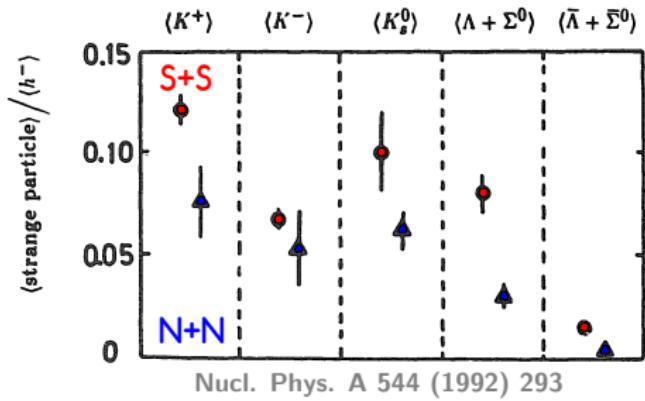
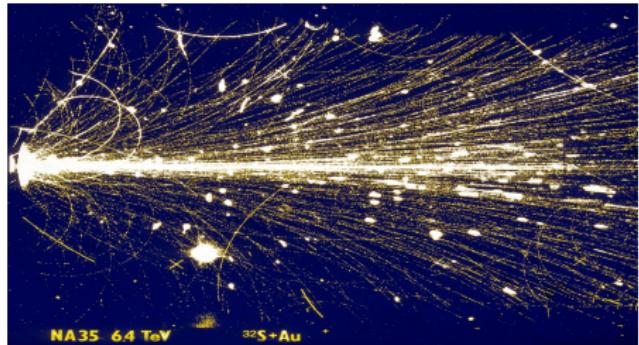
Baseline measurements for the strangeness production in $p+p$ and $p+A$ collisions @ 200 GeV/c



Z. Phys. C50 (1991) 31

How to measure produced strangeness

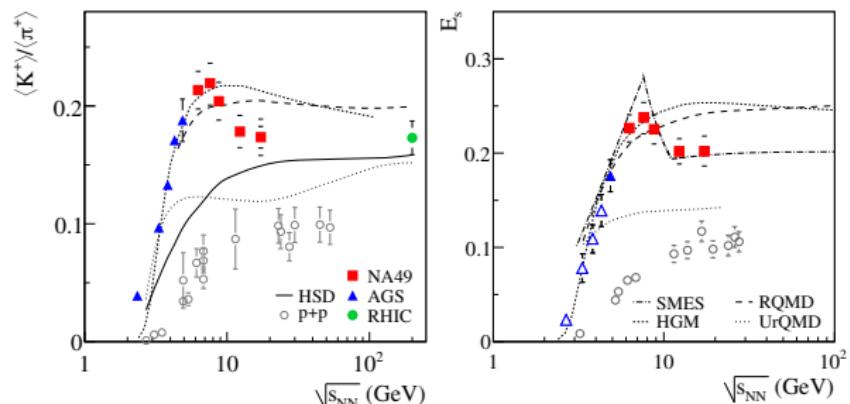
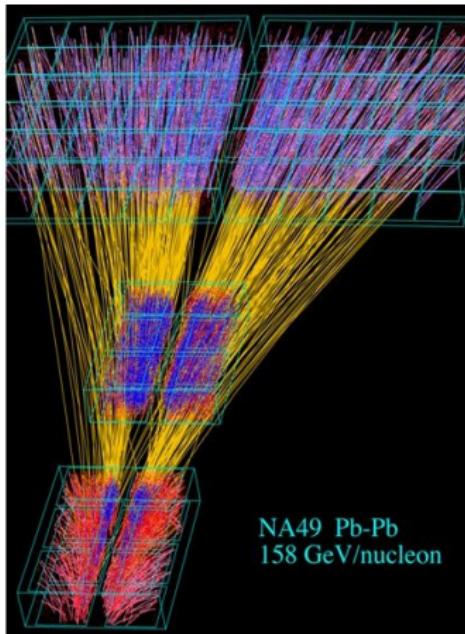
Decades ago... NA35



The first indication for the **strangeness enhancement!**

How to measure produced strangeness

Years ago... NA49



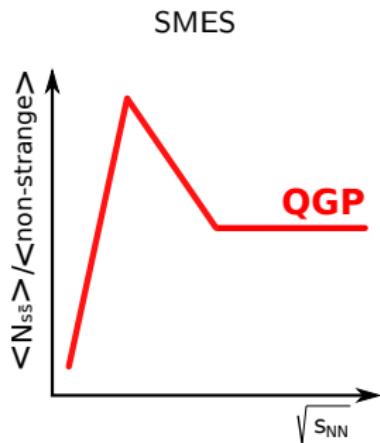
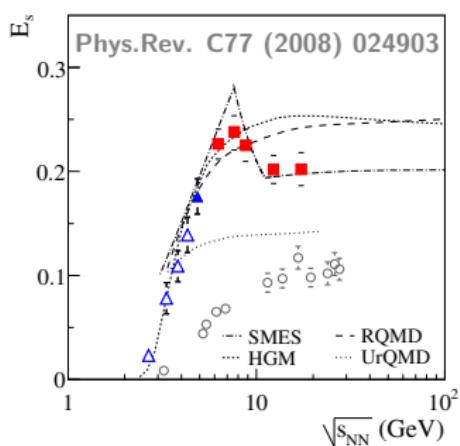
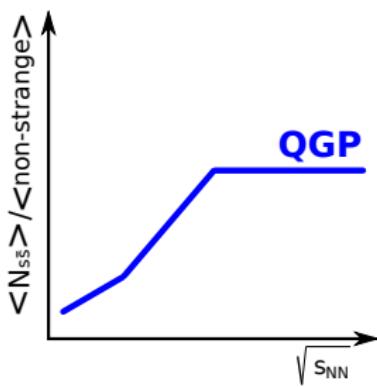
Phys.Rev. C77 (2008) 024903

The first **beam energy scan** of Pb+Pb collisions
and **the evidence of the onset of deconfinement?**

Collision energy dependence of strangeness production

Comparison with the models

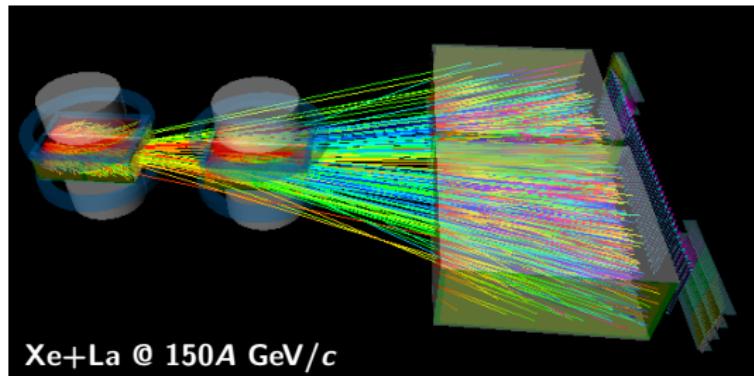
Rafelski-Müller model



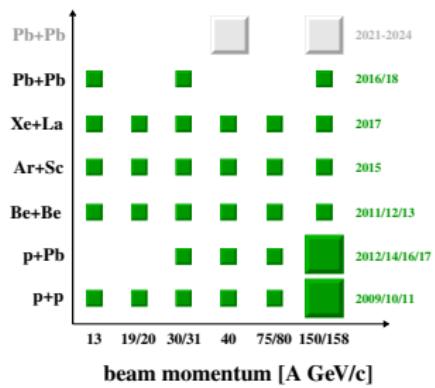
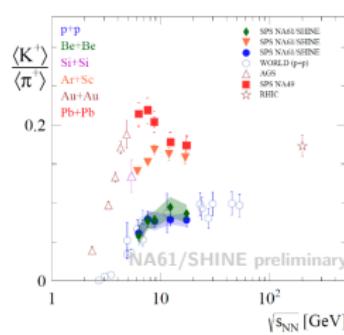
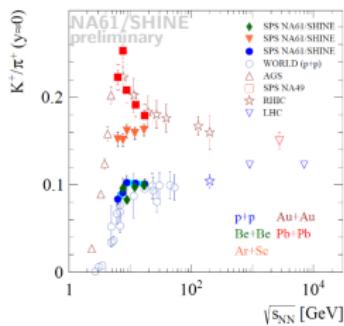
- Qualitatively, data from the NA49 experiment follow dependence predicted by SMES.
- The dependence predicted by the Rafelski-Müller model is in contradiction with the data.
- The evidence of the onset of deconfinement was observed in the SPS energy range?

How to measure produced strangeness

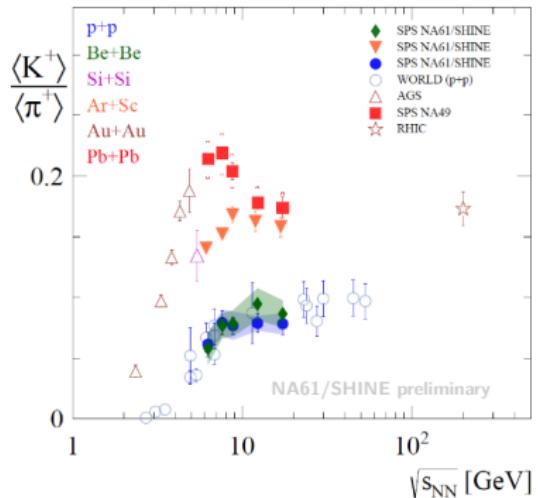
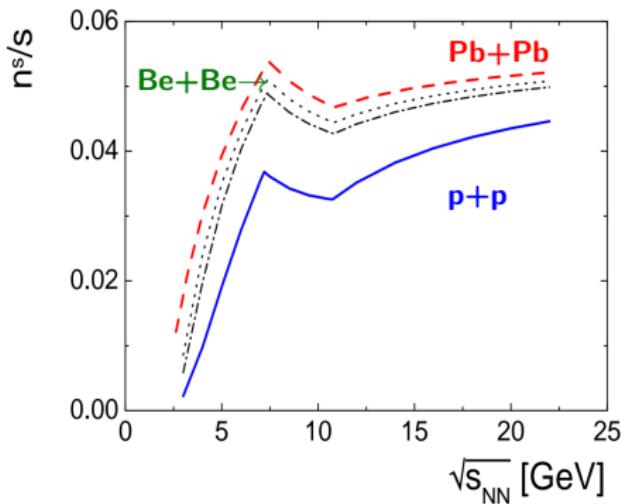
Nowadays... NA61/SHINE



2D scan in **beam energy** and **system size**



System size dependence of strangeness production



- 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, Ga  dzicki, Gorenstein, Acta Phys.Polon. B46 (2015) 10

Still many mysteries in strangeness production to solve...

chiral symmetry restoration

quark-gluon plasma

crossover

onset of deconfinement

onset of fireball

phase transition



Long live Peter Seyboth!

Strangeness production estimation: $\langle N_{s\bar{s}} \rangle$

$$\langle K_s^0 \rangle = \frac{1}{2}(\langle K^0 \rangle + \langle \bar{K^0} \rangle)$$

$$4\langle K_s^0 \rangle = 2\langle K^0 \rangle + 2\langle \bar{K^0} \rangle \approx \langle K^0 \rangle + \langle K^+ \rangle + \langle K^- \rangle + \langle \bar{K^0} \rangle$$

$$\langle \Lambda \rangle + 4\langle K_s^0 \rangle \approx 2\langle N_{s\bar{s}} \rangle$$

$$E_s = \frac{\langle \Lambda \rangle + 4\langle K_s^0 \rangle}{\langle \pi \rangle} \approx 2 \frac{\langle N_{s\bar{s}} \rangle}{\langle \pi \rangle}$$

$$2\langle K^+ \rangle \approx \langle N_{s\bar{s}} \rangle$$

$$\frac{\langle K^+ \rangle}{\langle \pi^+ \rangle} \approx \frac{1}{2} \frac{\langle N_{s\bar{s}} \rangle}{\langle \pi^+ \rangle}$$

$$\frac{\langle K^+ \rangle}{\langle \pi^+ \rangle} \approx \frac{3}{4} E_s$$