Zimányi School '17
Budapest, Dec 6, 2017

New results on strangeness production from the NA61/SHINE

Maciej Lewicki
mlewicki@ift.uni.wroc.pl

University of Wrocław
Institute of Theoretical Physics

NA61/SHINE on Zimányi School

Today:

- **Krisztina Márton**:
  High pT particles in p+p and p+Pb collisions at CERN SPS energies.
- **Michał Naskręt**:
  Pion spectra in Ar+Sc collisions in the NA61/SHINE collaboration.

Tomorrow:

- **Daria Prokhorova**:
  Pseudorapidity dependence of multiplicity and transverse momentum fluctuations in pp collisions at the SPS energies.
- **Andrey Seryakov**:
  Rapid change of multiplicity fluctuations in system size dependence at SPS energies.

Section 1

Strangeness in Heavy Ion Collisions

Strangeness in HIC

Most strangeness produced in the form of:

- The lightest (anti-)strange mesons ($M \approx 0.5\ \mathrm{GeV}$):
  - K^+ – $(u\bar{s})$
  - K^0 – $(d\bar{s})$
  - K^- – $(\bar{u}s)$
  - $\bar{K}^0$ – $(\bar{d}s)$
- The lightest (anti-)strange baryons ($M \approx 1.1\ \mathrm{GeV}$):
  - Λ – (uds)
  - $\bar{\Lambda}$ – $(\bar{u}\bar{d}\bar{s})$
- Strangeness neutral mesons: ($M \approx 1.0\ \mathrm{GeV}$):
  - ϕ – $(s\bar{s})$

Main strangeness carriers

in A+A collisions at high baryon density

strangeness conservation

$$\bar{s} = s$$

isospin symmetry

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

high baryon density

$$K^{+} \gg \bar{\Lambda} \qquad \bar{K}^{0} \approx \Lambda$$

high baryon density

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

– sensitive to strangeness content only

– sensitive to strangeness content and baryon density

Strange definitions

Strangeness production:

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

The experimental ratio:

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

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

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

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

It is convenient to study the ratio E_S in this form, as the identification of charged hadrons is relatively easy.

Section 2

Strangeness in Phase Transition

Strangeness in phase transition

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

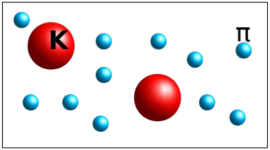
Lightest strangeness carriers close to T_C:

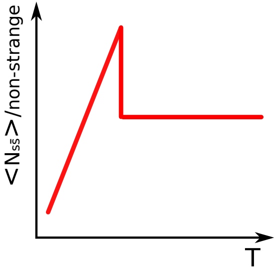
- relatively heavy kaons ($M > T_C$) in the confined phase,
- relatively light strange quarks ($m \lesssim T_C$) in QGP.

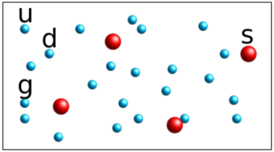
Strangeness in **Statistical Model of Early Stage**

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

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





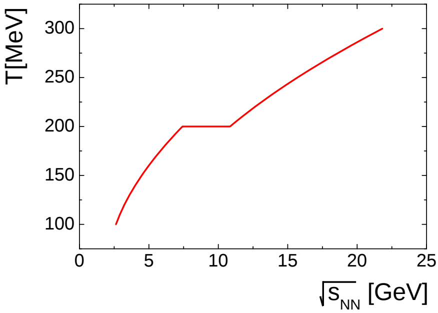


$$\frac{\langle K \rangle}{\langle \pi \rangle} \propto \frac{MT^{3/2}}{T^3}\cdot e^{-M/T}$$

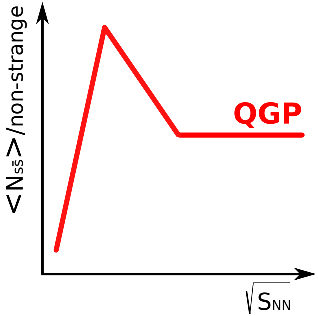
$$\frac{\langle s \rangle}{\langle u+d+g \rangle} \propto \frac{T^3}{T^3} = \mathrm{const}(T)$$

Strangeness in **Statistical Model of Early Stage**

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



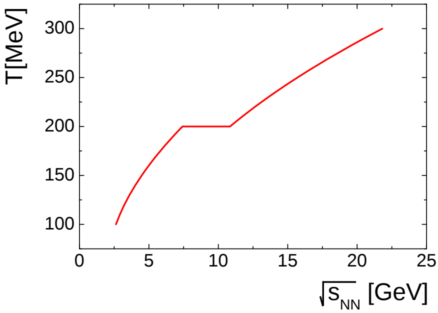
Strange/non-strange particle ratio:



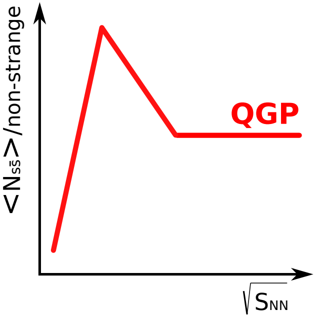
- Crossing the phase transition leads to a decrease of the strange/non-strange particle ratio – the horn-like structure

Strangeness in **Statistical Model of Early Stage**

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



Strange/non-strange
particle ratio:

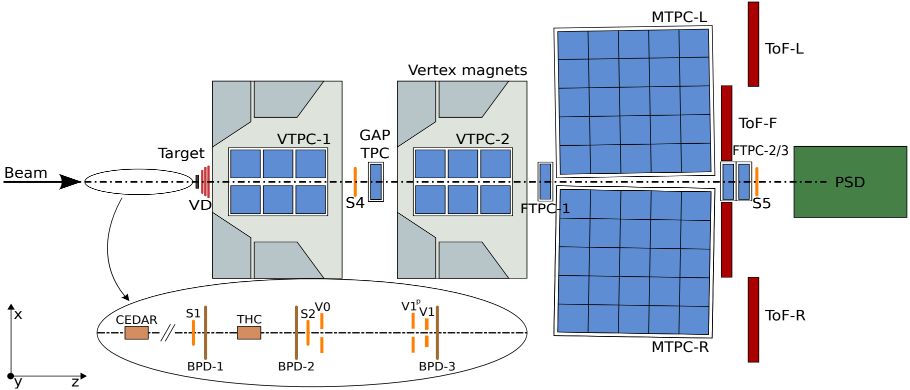


- Crossing the phase transition leads to a decrease of the strange/non-strange particle ratio – the horn-like structure – Marek's horn

Section 3

Strangeness at NA61/SHINE

NA61/SHINE – facility



Beam detectors:

- position
- charge
- mass
- time

TPCs:

- electric charge
- momentum
- dE/dx

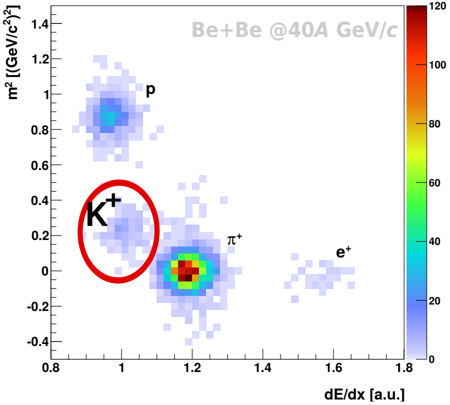
ToF:

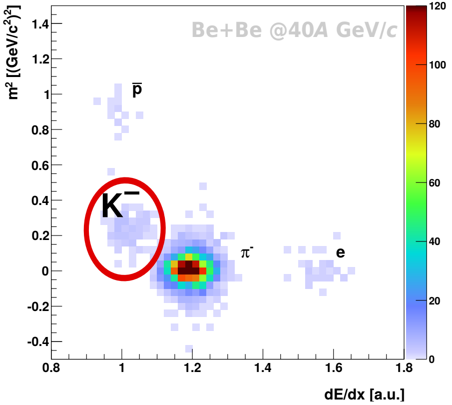
- *tof*

PSD:

- E_F – energy of projectile spectators
- reaction plane

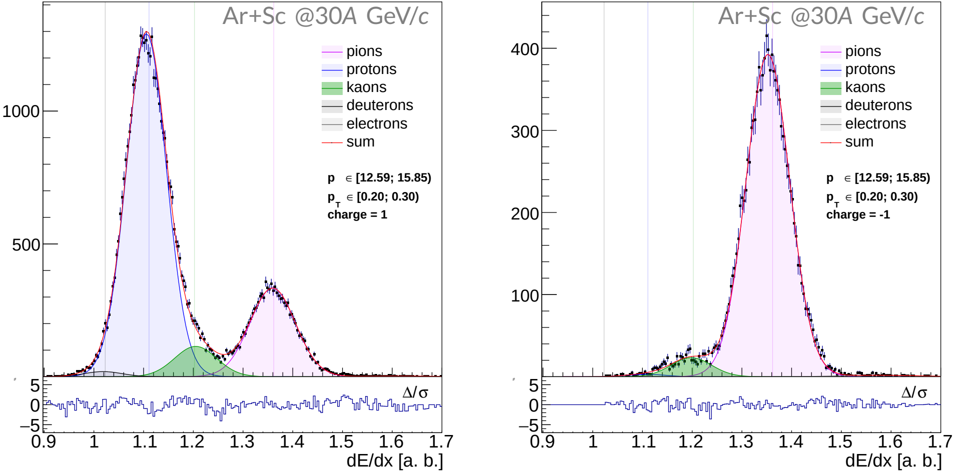
Particle identification — *tof*-dE/dx





Very good separation.
Very efficient PID in mid-rapidity region.

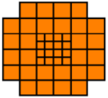
Particle identification — dE/dx

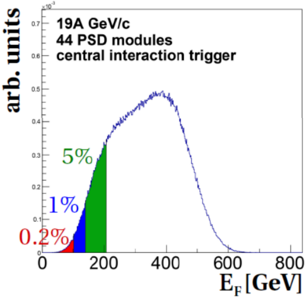


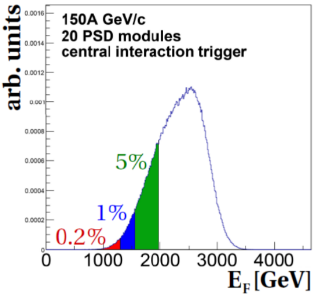
Probability PID.

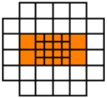
Applicable in forward-rapidity region.

Event selection



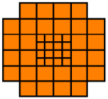


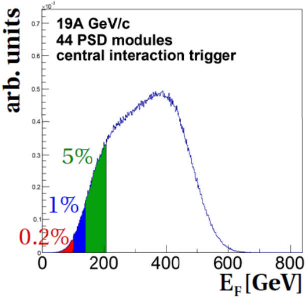


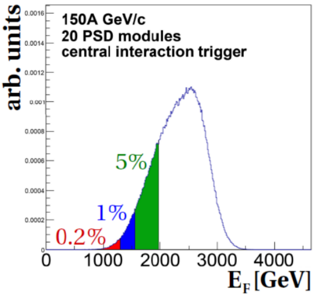


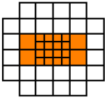
- The PSD is located most downstream on the beam line and measures the projectile spectator energy E_F of the non-interacting nucleons of the beam nucleus.
- The energy measured by the PSD is used to select events classes corresponding to the collision *"violence"* (≈ centrality).

Event selection









- The PSD is located most downstream on the beam line and measures the projectile spectator energy E_F of the non-interacting nucleons of the beam nucleus.
- The energy measured by the PSD is used to select events classes corresponding to the collision *"violence"* ($\approx$ centrality).

See: A. Seryakov presentation

Section 4

Results on Strangeness

Results on strangeness production

Results from **NA61/SHINE** on identified hadrons produced in strong and electromagnetic processes in primary interactions:

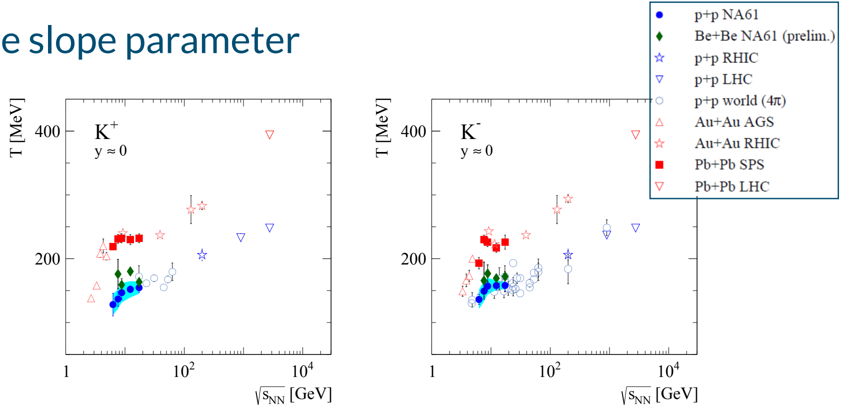
- Ar+Sc [CPOD 2017]
- Be+Be [Nucl. Phys. A 967, 35 (2017)]
- p+p [Eur. Phys. J. C74 (2014) 2794, Eur. Phys. J. C77 (2017) 671]

World data on Pb+Pb, Au+Au, C+C, Si+Si and p+p:

- NA49
  [Phys.Rev. C77, 024903 (2008)], [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]
- p+p world data: [Z. Phys. C65 (1995) 215], [Phys. Rev. C69 (2004) 044903]

Inverse slope parameter

"step" plot



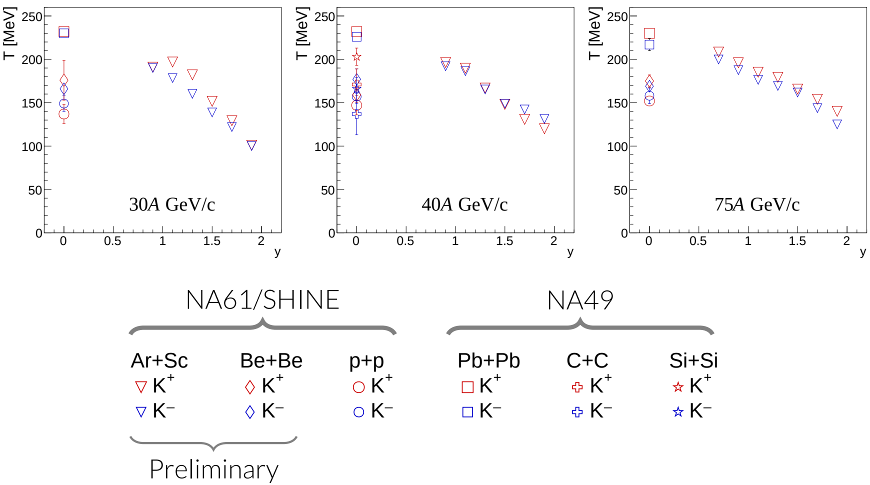
Inverse slope parameter T (vague temperature analogy) – a parameter in fit to transverse mass spectra: $\frac{dN}{m_T dm_T} \cong C \exp\left(-\frac{m_T}{T}\right)$

Especially convenient to study in case of kaons – insignificant effect of collective flow.

- A plateau visible in the phase transition region ($\sqrt{s_{NN}} \approx 10$ GeV).
- Be+Be points slightly above p+p and both significantly lower than heavy ions.
- Predicted by **SMES**.

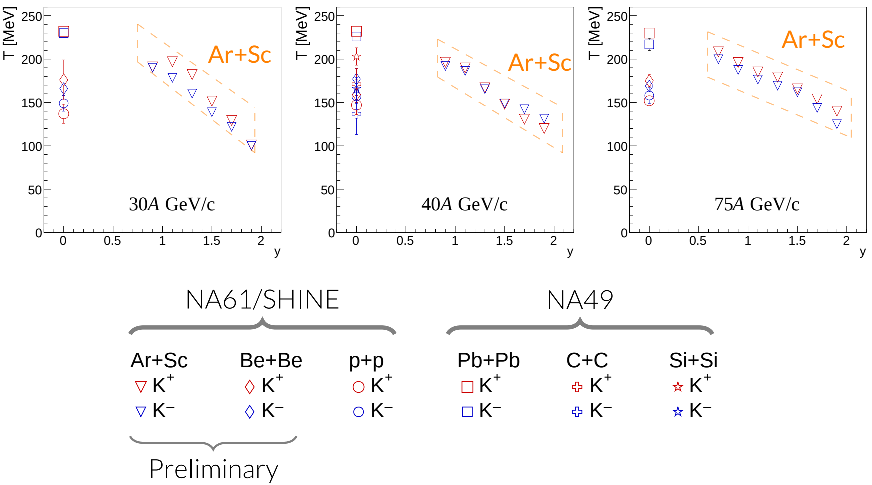
Inverse slope parameter

Extrapolation of Ar+Sc points to $T(y \approx 0)$ falls close to Pb+Pb, while smaller systems show significantly smaller values.



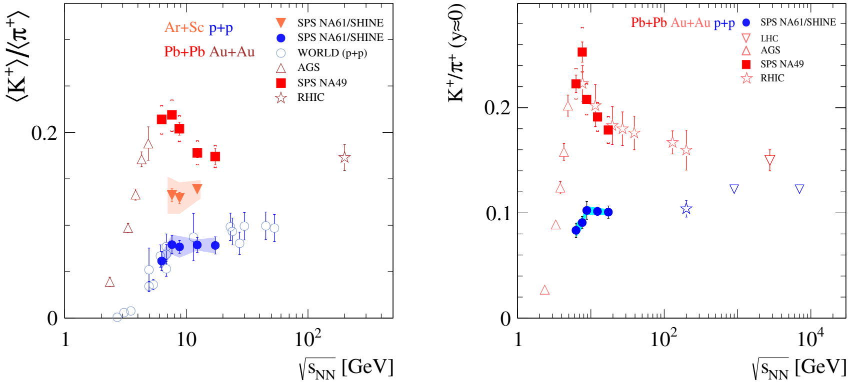
Inverse slope parameter

Extrapolation of Ar+Sc points to $T(y \approx 0)$ falls close to Pb+Pb,
while smaller systems show significantly smaller values.



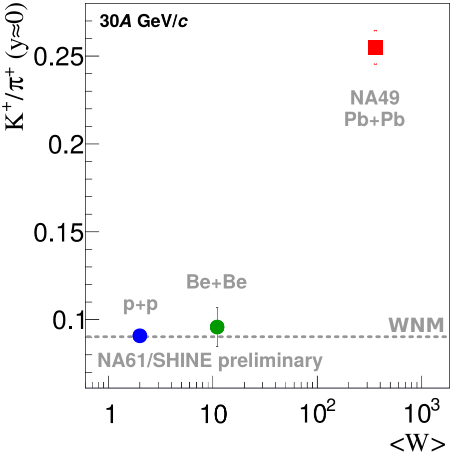
Energy dependence

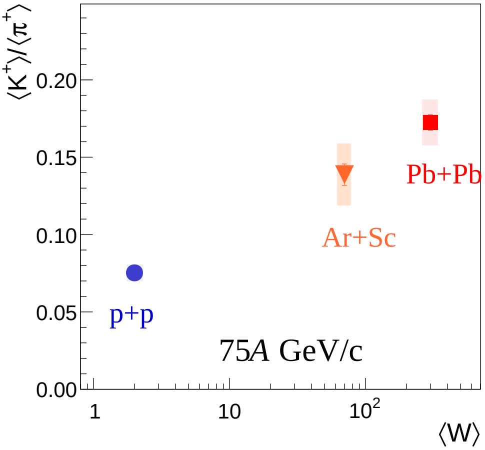
"horn" plot



- Rapid change in strangeness production observed in Pb+Pb – the horn.
- Step-like energy dependence in p+p data.
- Ar+Sc placed in between light and heavy systems.

System size dependence

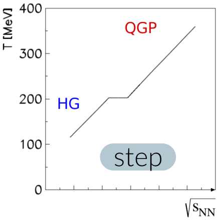




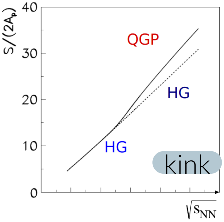
- Be+Be resembles closely the p+p data.
- Ar+Sc close to Pb+Pb

→ Qualitative difference between ^{7}Be+^{9}Be and ^{40}Ar+^{45}Sc.

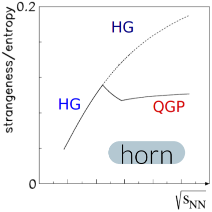
Summary



Plateu in "temperature" dependence on collision energy.



Enhancement of entropy production in QGP phase (per participating nucleon).

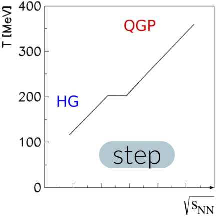


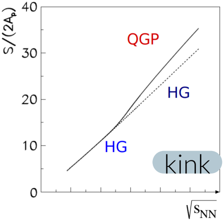
Suppresion of strangeness production in QGP phase.

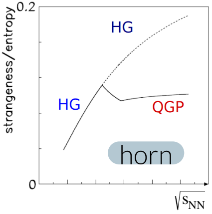
Predictions of the **Statistical Model of the Early Stage**.

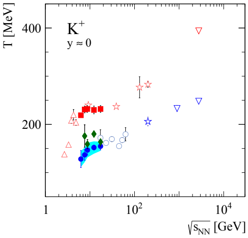
"Step" and "horn" discussed in presented analysis.

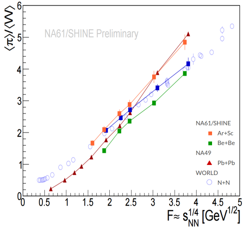
Summary

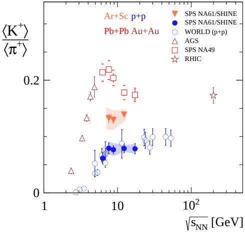








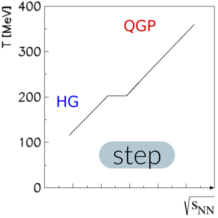


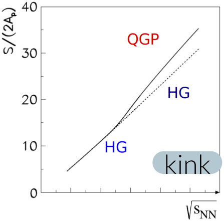


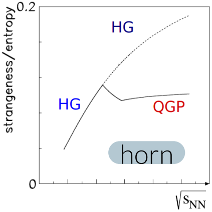
Experimental results – confirming **SMES** predictions.

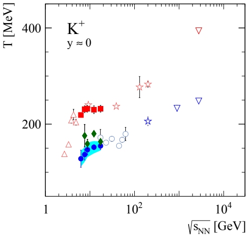
Signatures of PT happen all at the same $\sqrt{s_{NN}}$.

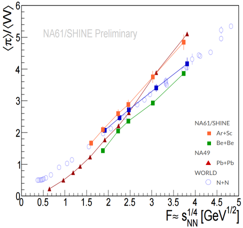
Summary

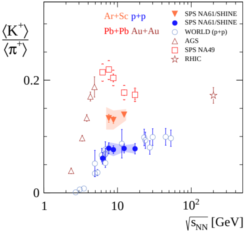






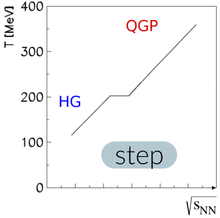


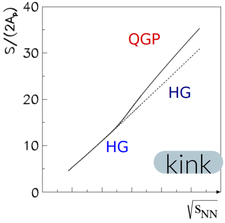


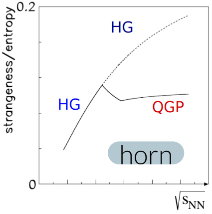


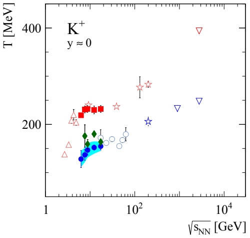
Non-trivial behavior of intermediate systems: Be+Be and Ar+Sc

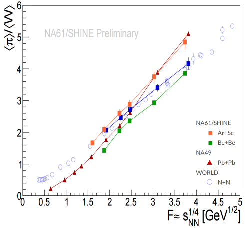
Summary

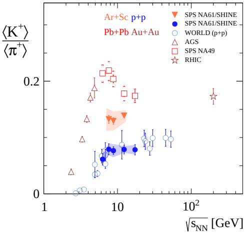










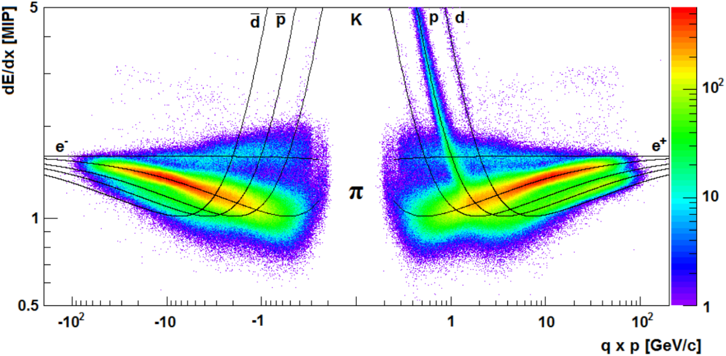


Kink – see presentation by M. Naskręt


"That's all Folks!"

Backup Slides

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: $E_0, \; K, \; X_A, \; a$

Truncated mean $\langle dE/dx \rangle_{Tr}$ distribution

The basic peak shape is assumed to be a sum of asymmetric Gaussians:

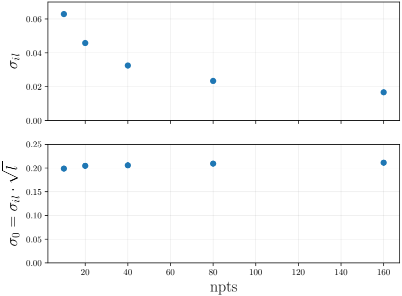
$$\left\langle \frac{dE}{dx} \right\rangle_{total} = \sum_{i=d,p,K,\pi,e} N_i \frac{1}{\sum_l n_l} \sum_l \frac{n_l}{\sqrt{2\pi}\sigma_{i,l}} \exp\left[-\frac{1}{2} \left(\frac{x - x_i}{(1 \pm \delta)\, \sigma_{i,l}} \right)^2 \right]$$

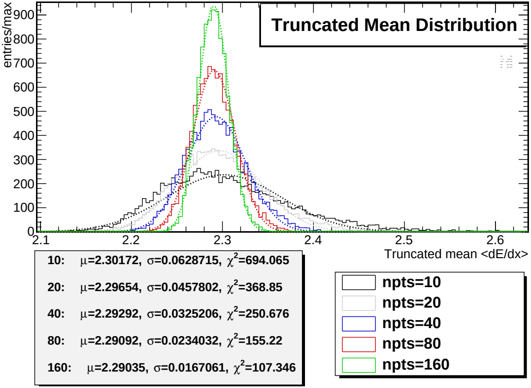
with widths $\sigma_{i,l}$

($l \equiv \mathrm{npts} \equiv$ # of clusters):

$$\sigma_{i,l} = \frac{\sigma_0}{\sqrt{l}} \left(\frac{x_i}{x_1} \right)^{\alpha}$$

(l^{β} arbitrary fixed at $\beta = -\frac{1}{2}$)





Fitting rapidity distribution

Two symmetrically placed gaussians are used to construct the fitting function:

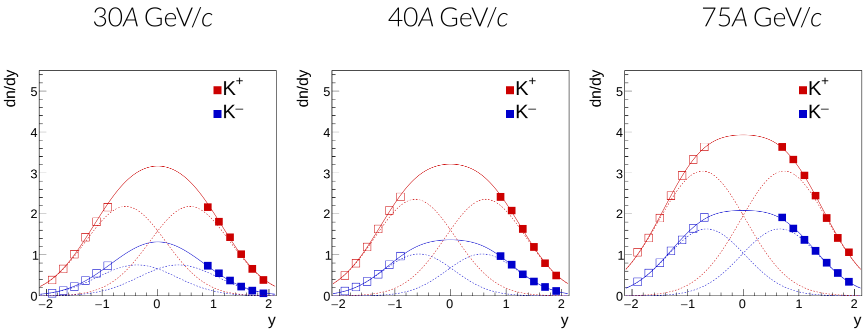
$$f_{fit}(y) = \frac{A}{\sigma_0\sqrt{2\pi}} \exp\left(-\frac{(y-y_0)^2}{2\sigma_0^2}\right) + \frac{A}{\sigma_0\sqrt{2\pi}} \exp\left(-\frac{(y+y_0)^2}{2\sigma_0^2}\right)$$

Shape parameters: y_0 and σ are fixed to values obtained in NA49's Pb+Pb.

The amplitude A is the only free parameter.

Varying the shape parameters provides an estimate of a systematic error.

Rapidity Distribution



Pb+Pb spectra shape fits **Ar+Sc** data surprisingly well.

Measurements of *tof* will add data in $y \approx 0$ region in the near future.

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:

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

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