Results on system size dependence of strangeness production in the 
CERN SPS energy range from NA61/SHINE

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NA61/SHINE - UNIQUE MULTIPURPOSE FACILITY:
Hadron production in hadron-nucleus and nucleus-nucleus collisions at high energies
NA61/SHINE physics program

**Strong interaction physics:**
- study properties of the **onsets of deconfinement and fireball**
- search for the **critical point** of strongly interacting matter
- direct measurements of **open charm**

**Neutrino and cosmic ray physics:**
- measurements for neutrino programs at J-PARC and Fermilab
- measurements of nuclear fragmentation cross section for cosmic ray physics
Study of the onset of deconfinement
$K^\pm$ spectra in Ar+Sc collisions

- 10% most central $^{40}\text{Ar}+^{45}\text{Sc}$ collisions
- $p_T$ spectra fitted with exponential dependence
- Rapidity spectra fitted with sum of two gaussians to obtain mean multiplicities $\langle K^+ \rangle$, $\langle K^- \rangle$
Onset of deconfinement: step

Plateau in the inverse slope parameter $T$ of $m_T$ spectra of $K^\pm$ spectra in Pb+Pb was predicted within SMES due to mixed phase of hadron gas and QGP *Acta Phys. Polon.* **B30**, 2705 (1999)

Similar structures are visible in recently measured reactions

Magnitude of the $T$ parameter increases with the colliding system size
Rapid change in the energy dependence of $K^+/\pi^+$ ratio in Pb+Pb collisions indicated the onset of deconfinement in the SPS energy range, as predicted within SMES.

Plateau like structure visible in light systems ($p+p$ and Be+Be).

Ar+Sc systematically higher, shows dependence on collision energy qualitatively similar to $p+p$ and Be+Be (no horn structure).
Onset of deconfinement: $p+p$ data

- Rates of increase of $K^+/\pi^+$ and $T$ change sharply in $p+p$ collisions at SPS energies.
- The fitted change energy is $\approx 7$ GeV - close to the energy of the onset of deconfinement $\approx 8$ GeV.
- Models assuming change from resonances to string production mechanism show similar trend.

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Study of the onset of fireball
System size dependence of $K^+ / \pi^+$ and $T$ at 150A GeV/c

- **dynamical models**
  - $K^+ / \pi^+$
  - $T$ [MeV]

- **statistical models**
  - $K^+ / \pi^+$
  - $T$ [MeV]

None of the models reproduce $K^+ / \pi^+$ ratio or $T$ in the whole $\langle W \rangle$ range.


- Ar+Sc: NA61/SHINE preliminary
(Multi-)strange hadron production in $p+p$ interactions at $\sqrt{s} = 17.3$ GeV
$K^0_S$ meson production in $p+p$ interactions at 158 GeV/c

- Results on $K^0_S$ production were recently published in Eur.Phys.J.C 82 (2022), 96
- Mean multiplicity: $\langle K^0_S \rangle = 0.162 \pm 0.001 \pm 0.011$
- Model predictions deviate by up to 20% from the measurements
Reconstruction based on decay topology

- $\Xi^\pm$ decays into $\pi^\pm$ and $\Lambda(\bar{\Lambda})$ with BR$\approx99.9\%$
- A set of quality cuts is imposed onto $\Xi$ candidates to improve SNR
- Breit–Wigner function is used to describe signal
The only existing results on $\Xi^-$ and $\bar{\Xi}^+$ production in SPS energy range in $p+p$ interactions

Strong suppression of $\bar{\Xi}^+$: $\langle \bar{\Xi}^+ \rangle/\langle \Xi^- \rangle = 0.24 \pm 0.01 \pm 0.05$

Transport models fail to describe the results on $\Xi$ production in $p+p$ collisions

Strangeness enhancement factors

\[ E_{\Xi_s} = \frac{2}{\langle W \rangle} \frac{dn/dy(A + A)}{dn/dy(p + p)} \]

NA61/SHINE results give new base-line for strangeness enhancement study in SPS energy range
Reconstruction based on decay topology

$\Xi^0(1530)$ decays into $\Xi$ and $\pi$ exclusively

A set of quality cuts is imposed onto $\Xi$ candidates to improve SNR

Breit–Wigner function is used to describe signal
The first results on $\Xi^0(1530)$ production in $p+p$ in SPS energy range

The second result results on $\Xi^0(1530)$ production in $p+p$ (other measurement was provided by ALICE at 7 TeV Eur.Phys.J.C 75 (2015) 1)

Suppression of $\bar{\Xi}^0(1530)$: $\langle \bar{\Xi}^0(1530) \rangle / \langle \Xi^0(1530) \rangle \approx 0.40 \pm 0.03 \pm 0.05$
HRG model and $p+p$ data

Fit done with different variants of HRG (THERMAL_FIST1.3):

- Canonical Ensemble with fixed $\gamma_s = 1$
- Canonical Ensemble with fitted $\gamma_s$

- Statistical model fails when strangeness saturation parameter $\gamma_s$ is fixed
- The fit with free $\gamma_s$ finds $\gamma_s = 0.434 \pm 0.028$
- Disagreement between model predictions and data is slightly reduced by allowing for out-of-equilibrium strangeness production
Many new measurements for the study of the onset of deconfinement
No horn structure observed in Ar+Sc data
Unexpected system-size dependence: \((p+p \approx Be+Be) \neq (Ar+Sc \leq Pb+Pb)\)
Unique results on multi-strange baryons production in \(p+p\) interactions in SPS energy range
Present transport models do not describe well the NA61/SHINE results on strange particles production \((K^\pm, K^0, \Xi\) and \(\Xi(1530)\))
Thank you
Backup
In order to obtain the $dn/dy$ yields, the data is extrapolated beyond the detector acceptance.

Exponential dependence in $p_T$ is assumed:

$$f(p_T) = S \cdot p_T \cdot \exp\left(-\frac{\sqrt{p_T^2 + m_K^2} - m_K}{T}\right)$$

To obtain mean multiplicity of produced particles rapidity distribution is fitted with following function:

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

$A$, $y_0$ and $\sigma_0$ parameters are fitted.