NA61/SHINE - UNIQUE MULTIPURPOSE FACILITY:
Hadron production in hadron-nucleus and nucleus-nucleus collisions at high energies
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
Onset of deconfinement: horn

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.

Phys.Rev.C 102 (2020) 1, 011901
Study of the onset of fireball
System size dependence of $K^+ / \pi^+$ and $T$ at 150A GeV/c

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

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**SMASH:** J. Phys. G 47 (2020) 6, 065101 and private communication;
**UrQMD and HRG:** Phys. Rev. C99 (2019) 3, 034909;

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**Be+Be:** Eur. Phys. J. C81 (2021) 1, 73
**Ar+Sc:** NA61/SHINE preliminary
New results on rapidity spectra of protons

"Peak-dip" transition is observed in medium and heavy systems: Ar+Sc and Pb+Pb within SPS energy range.

No such transition for small systems: p+p and Be+Be

- "Peak-dip" transition is observed in medium and heavy systems: Ar+Sc and Pb+Pb within SPS energy range.
- No such transition for small systems: p+p and Be+Be
(Multi-)strange hadron production in $p+p$ interactions at $\sqrt{s} = 17.3$ GeV
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
\( K^*(892)^0 \) meson production in \( p+p \) interactions

- \( K^*(892)^0 \) was reconstructed in \( K^* \to K^+ + \pi^- \) channel
- The resonance yield is affected by regeneration and rescattering processes
- We have observable sensitive to time between chemical and kinetic freezouts \( \Delta t \):
\[
\frac{K^*}{K^\pm}_{\text{kinetic}} = \frac{K^*}{K^\pm}_{\text{chemical}} \cdot e^{-\Delta t/\tau}, \quad \tau = 4.17 \text{ fm/c}
\]
Results on $K^*(892)^0$ mass and width were included in PDG

time between freezeouts at 158 GeV/c estimated to be
$\Delta t \approx 5.3 fm/c$

$\Delta t_{\text{SPS}} \geq \Delta t_{\text{RHIC}} \rightarrow$ lifetime of hadronic phase longer at SPS
and/or regeneration more important at RHIC energies
$\Xi^-$ and $\Xi^+$ production in $p+p$ interactions at 158 GeV/c

- Reconstruction based on decay topology
- $\Xi^{\pm}$ decays into $\pi^{\pm}$ and $\Lambda(\bar{\Lambda})$ with BR$\approx$99.9%
- 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 $\Xi^+$ production in SPS energy range in $p+p$ interactions

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

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

$\Xi^0(1530)$ and $\bar{\Xi}^0(1530)$ production in $p+p$ interactions at 158 GeV/c

- 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 $\Xi^0(1530)$: $\langle \Xi^0(1530) \rangle / \langle \Xi^0(1530) \rangle \approx 0.40 \pm 0.03 \pm 0.05$
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

<table>
<thead>
<tr>
<th>Measured Total Multiplicity</th>
<th>Fitted Total Multiplicity</th>
<th>CE Fitted parameters:</th>
</tr>
</thead>
<tbody>
<tr>
<td>$6 \times 10^{-1}$</td>
<td>$6 \times 10^{-1}$</td>
<td>$T = 104.90 \pm 0.24$ MeV</td>
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<td>$5 \times 10^{-2}$</td>
<td>$5 \times 10^{-2}$</td>
<td>$R = 3.60 \pm 0.15$ fm</td>
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<td>$4 \times 10^{-3}$</td>
<td>$4 \times 10^{-3}$</td>
<td>$\gamma_s = 1$ (fixed)</td>
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<td>$3 \times 10^{-4}$</td>
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<td>$\chi^2$/NDF = 29</td>
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<td>$2 \times 10^{-5}$</td>
<td>$2 \times 10^{-5}$</td>
<td>$\phi$ (1530)</td>
</tr>
<tr>
<td>$1 \times 10^{-6}$</td>
<td>$1 \times 10^{-6}$</td>
<td>$\Xi^-(1530)$</td>
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<tr>
<td>$10^{-6}$</td>
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<td>$T = 193 \pm 17$ MeV</td>
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<tr>
<td>$10^{-5}$</td>
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<td>$R = 1.06 \pm 0.27$ fm</td>
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<tr>
<td>$10^{-4}$</td>
<td>$10^{-4}$</td>
<td>$\gamma_s = 0.434 \pm 0.028$</td>
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<td>$\chi^2$/NDF = 11</td>
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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
No horn structure observed in Ar+Sc data

Unexpected system-size dependence: \((p+p \approx Be+Be) \neq (Ar+Sc \leq Pb+Pb)\)

New results on rapidity spectra of protons

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 \((K^\pm, K^0, \Xi \text{ and } \Xi(1530))\)
Thank you
Backup
In order to obtain the $d\eta/dy$ 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.
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 \textit{Acta Phys. Polon.} \textbf{B30}, 2705 (1999)

Similar structures are visible in recently measured reactions

Magnitude of the $T$ parameter increases with the colliding system size

\begin{itemize}
  \item NA61/SHINE Preliminary
  \item \textbf{Ar+Sc $\rightarrow K^+$ + X}
  \item \textbf{Ar+Sc $\rightarrow K^-$ + X}
  \item Piotr Podlaski (FUW)
  \item Strangeness production from NA61/SHINE
  \item CPOD 2022 23 / 20
  \item Eur.Phys.J.C 81 (2021) 1, 73 (Be+Be)
\end{itemize}