On strangeness from NA61/SHINE

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for the NA61/SHINE collaboration
Outlook

1. Why strangeness?

2. How to measure strangeness production?

3. How NA61/SHINE measures strange hadrons?

4. Strange results...
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 (\( M \approx 0.5 \text{ GeV} \)):
    \( K^+ (u\bar{s}), K^- (\bar{u}s), K^0 (d\bar{s}), \bar{K}^0 (\bar{d}s) \);
  ▶ the lightest strange baryon (\( M \approx 1.1 \text{ GeV} \)):
    \( \Lambda (uds), \Lambda (\bar{u}\bar{d}\bar{s}) \);
- strange and anti-strange quarks can also be hidden in strangeness neutral \( \phi (s\bar{s}) \) meson.
Why strangeness is so interesting in heavy ion collisions?

**Phase transition**

\[ T_c \approx 150 \text{ MeV} \]

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

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 \( (\text{pions, light quarks and gluons}) \).

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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...

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

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

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

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

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

A story within Statistical Model of Early Stage...

In SMES temperature depends on collision energy as follows:

\[
\begin{array}{c|c|c|c|c|c|c}
\hline
\sqrt{s_{\text{NN}}} \ [\text{GeV}] & 0 & 5 & 10 & 15 & 20 & 25 \\
T \ [\text{MeV}] & 100 & 150 & 200 & 250 & 300 \\
\hline
\end{array}
\]

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
A story within Rafelski-Müller Dynamic Model...

strangeness production in confined matter

\[ N + N \rightarrow N + Y + K \]
\[ \pi + N \rightarrow K + Y \quad \pi + \bar{N} \rightarrow \bar{K} + \bar{Y} \]
\[ \pi + Y \rightarrow \Xi + K \quad \pi + \bar{Y} \rightarrow \bar{\Xi} + \bar{K} \]
\[ \pi + \Xi \rightarrow \Omega + K \quad \pi + \bar{\Xi} \rightarrow \bar{\Omega} + \bar{K} \]

strangeness production in QGP

\[ \tau_{eq} \approx 100 \text{ fm/c} \]

\[ \tau_{eq} \approx 1 \text{ fm/c} \]

Rafelski, Müller,

Magdalena Kuich (University of Warsaw)
A story within RM model...

- Crossing the phase transition leads to an increase of the strange to non-strange particle ratio – the **strangeness enhancement**
How to measure strangeness production?
Distribution of strangeness between various hadrons
in A+A collision at high baryon density

\[ \bar{s} = s \]

\[ \text{isospin symmetry} \]

\[ K^+ \approx K^0 \]

\[ \Lambda \ll \bar{K}^0 \]

\[ \text{strangeness conservation} \]

\[ V \ll V \]

\[ \text{high baryon density} \]

\[ \text{sensitive to strangeness content only} \]

\[ \text{sensitive to strangeness content and baryon density} \]
How to measure produced strangeness

Decades ago...

For example NA35

- streamer chambers
- measured:
  - charge
  - momentum
- strange hadrons identified by reconstruction of their decays:
  - \( \Lambda \)
  - \( K^0_s \)

\[
\langle K^0_s \rangle = \frac{1}{2} (\langle K^0 \rangle + \langle K^0 \rangle)
\]

\[
4\langle K^0_s \rangle = 2\langle K^0 \rangle + 2\langle \overline{K^0} \rangle \approx \langle K^0 \rangle + \langle K^+ \rangle + \langle K^- \rangle + \langle \overline{K^0} \rangle
\]

\[
\langle \Lambda \rangle + 4\langle K^0_s \rangle \approx 2\langle N_{ss} \rangle
\]

\[
E_s = \frac{\langle \Lambda \rangle + 4\langle K^0_s \rangle}{\langle \pi \rangle} \approx 2\frac{\langle N_{ss} \rangle}{\langle \pi \rangle}
\]
How to measure produced strangeness

Nowadays...

For example NA61/SHINE

- TPCs + ToF
- measured:
  - momenta
  - charges
  - masses
- strange hadrons identified by mass measurement:
  - $K^+$
  - $K^-$

\[
2 \langle K^+ \rangle \approx \langle N_{s\bar{s}} \rangle \\
\frac{\langle K^+ \rangle}{\langle \pi^+ \rangle} \approx \frac{1}{2} \frac{\langle N_{s\bar{s}} \rangle}{\langle \pi^+ \rangle} \\
\frac{\langle K^+ \rangle}{\langle \pi^+ \rangle} \approx \frac{3}{4} \mathcal{E}_s
\]
How NA61/SHINE measures strange hadrons?
NA61/SHINE is a multi-purpose device measuring properties of:

**beam particles**

- **Beam detectors:**
  - position
  - charge
  - mass
  - time

- **TPCs:**
  - electric charge
  - momentum
  - mass ($dE/dx$)

- **ToF:**
  - mass ($tof$)

**produced particles**

**projectile spectators**

- **PSD:**
  - energy of projectile spectators
  - azimuthal angle
Particle identification

via simultaneous measurements of $t_{of}$ and $dE/dx$

- Beautiful particle separation $\rightarrow$ easy identification of K mesons!
Strange results...
Results on strangeness production
From NA61/SHINE today:

- **p+p interactions**
  - all inelastic interactions

- **Be+Be collisions**
  - the most violent collisions

- **Ar+Sc collisions**
  - the most violent collisions
  - CPOD2017 (preliminary)

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


Event selection based on forward energy measurements

- Event (centrality) selection is done using the forward energy ($E_F$) dominated by energy of projectile spectators and measured by Projectile Spectator Detector.
- Examples of event selection using $E_F$ for Ar+Sc:

<table>
<thead>
<tr>
<th>$E_F$ [GeV]</th>
<th>arb. units</th>
<th>$E_F$ [GeV]</th>
<th>arb. units</th>
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<tr>
<td>0.2%</td>
<td>1%</td>
<td>5%</td>
<td></td>
</tr>
<tr>
<td>1%</td>
<td>0.2%</td>
<td>1%</td>
<td></td>
</tr>
</tbody>
</table>

- 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.
$m_T$ spectra and inverse slope parameter

Examples for 75A GeV/c

- $m_T$ spectra at mid-rapidity were fitted with an exponential function

$$\frac{1}{m_T} \frac{d^2 n}{dm_T dy} = A \exp \left( -\frac{m_T}{T} \right)$$

which well describes K spectra for all beam momenta and all reactions

- The energy dependence of the inverse slope parameter was predicted to be sensitive to the phase transition between confined matter and QGP.
A plateau structure in the energy dependence of the inverse slope parameter of $m_T$ – STEP – was observed in Pb+Pb collisions as predicted (SMES) for the phase transition (with a mixed phase).

- p+p and Be+Be are significantly lower than Pb+Pb.
- Be+Be only slightly above p+p.
Collision energy dependence of strangeness production

- 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 $4\pi$ acceptance.
- Ar+Sc results between p+p and Pb+Pb.
Collision energy dependence of strangeness production

Comparison with the models

- Qualitatively, data follow dependence predicted by SMES.
- The dependence predicted by the Rafelski-Müller model is in clear contradiction with the data.
In a version, without chiral symmetry restoration (without CSR), the prediction of PHSD qualitatively resembles predictions of the Rafelski-Müller model.

In the version with CSR, the strange quark mass used in the string decay Schwinger-formula is assumed to decrease with energy density. This leads to enhance strangeness production in the confined phase.
Summary of predictions by models with transition to QGP

- At higher energies all three models with phase transition predict the strange/non-strange particle ratio close to the one for the equilibrium QGP.
- At low collision energies (in the confined matter):
  - RM model predicts the small strangeness production.
  - PHSD cures this problem reducing the strange quark mass in string decays.
  - SMES overcomes it by postulating the statistical particle production at early stage of collisions.
Surprisingly Be+Be is close to p+p.

This is true for all beam momenta.
System size dependence of strangeness production - SMES

- SMES predicts very different system size dependence of $K^+ / \pi^+$ 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.

**System size dependence of strangeness production - PHSD**

PHSD predicts increase of strangeness production with system size at low (<10 GeV) collision energies and decrease at high (>10 GeV) collision energies.

There is a tension between the PHSD prediction and data at high energies.

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Palmese et al., PRC94 (2016) 044912
After all these years of the studying, strangeness production remains strange...
Particle identification via $dE/dx$ measurement in Time Projection Chambers:

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

\[
\beta \gamma = \frac{p}{M c}
\]
Particle identification

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

\[ p = \frac{\beta}{\sqrt{1 - \beta^2}} M c, \]

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

\[ M^2 = \left( \frac{p}{c} \right)^2 \left( \frac{c^2 \text{ tof}^2}{s^2} - 1 \right), \]
Probability of identification

- Identity method is used to determine the probability of the particle identification

\[ P_j = \frac{\rho_j(p, p_T, m^2, dE/dx)}{\rho(p, p_T, m^2, dE/dx)} \]

- The method allows deriving spectra easily in phase-space depending on \( p \) and \( p_T \).
- Can be used in all mentioned identification procedures.
Definition of results

Results stand for primary particles produced in strong and electromagnetic processes. For nucleus-nucleus collisions, the event classes are defined by forward energy measured by PSD. Results for p+p collisions refer to all inelastic interactions.

Corrections:

- Results are corrected for:
  - biases in event selection
  - reconstruction inefficiency
  - weak decays
  - secondary interactions
  - detector geometrical acceptance.

- MC used for corrections: EPOS 1.99 model and GEANT3.2+NA61/SHINE detector simulation.

Uncertainties:

- There are two sources of statistical uncertainties in results:
  - data uncertainties
  - MC corrections uncertainties (insignificant).

- The systematic uncertainties comes from:
  - limited precision of simulation and detector description.
Particle yield extrapolation to full $p_T$ acceptance

Examples for Be+Be

- In order to obtain the $dn/dy$ yields of K mesons, the data is extrapolated with the exponential function in $m_T$ beyond the detector acceptance.
- $dn/(dp_T\,dy)$ spectra were fitted with the corresponding function in $p_T$.
- The function integral outside the acceptance region ($<10\%$) is added to the measured yield.
In order to obtain the $dn/dy$ yields of K mesons, the data is extrapolated beyond the detector acceptance.

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

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

- Shape parameters: $y_0$ and $\sigma$ are fixed to values obtained in NA49's Pb+Pb.
- The amplitude $A$ is the only free parameter.
- Soon, points at mid-rapidity from the $\text{tof} - \text{dE/dx}$ analysis will be added to the spectra.
Models without phase transition

\[ E_s \]

\[ \sqrt{s_{NN}} \text{ (GeV)} \]

- HSD
- SMES
- RQMD
- HGM
- UrQMD

Statistical: SMES
TABLE V. Comparison between measured and fitted particle multiplicities, in the framework of various versions of the SHM, in central Pb-Pb collisions (5%) at a beam energy of 158A GeV. Also shown are the predicted multiplicities of the main hadron species. The A(1520) multiplicity was not used in the fits (see text). For the SHM(γ, γ) model, the multiplicities are those calculated in the γ = 1.6 fit.

<table>
<thead>
<tr>
<th>Particle</th>
<th>Reference</th>
<th>Measurement</th>
<th>SHM(γ) fit A</th>
<th>SHM(γ) fit B</th>
<th>SHM(SCV)</th>
<th>SHM(TC)</th>
<th>SHM(γ, γ)</th>
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<tr>
<td>N°</td>
<td>[1]</td>
<td>362 ± 1.5</td>
<td>363.6</td>
<td>362.0</td>
<td>364.2</td>
<td>362.6</td>
<td></td>
</tr>
<tr>
<td>π⁺</td>
<td>[1]</td>
<td>619 ± 1.7</td>
<td>551.5</td>
<td>502.7</td>
<td>503.4</td>
<td>578.7</td>
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</tr>
<tr>
<td>π⁻</td>
<td>[1]</td>
<td>639 ± 1.7</td>
<td>583.5</td>
<td>534.1</td>
<td>595.3</td>
<td>612.5</td>
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<tr>
<td>π⁰</td>
<td></td>
<td></td>
<td>638.2</td>
<td>576.2</td>
<td>585.4</td>
<td>661.9</td>
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<tr>
<td>K⁺</td>
<td>[1]</td>
<td>103 ± 1.5</td>
<td>103.5</td>
<td>106.7</td>
<td>99.98</td>
<td>102.3</td>
<td></td>
</tr>
<tr>
<td>K⁻</td>
<td>[1]</td>
<td>103 ± 1.9</td>
<td>103.5</td>
<td>106.7</td>
<td>99.98</td>
<td>102.3</td>
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<td>K⁰</td>
<td>[1]</td>
<td>51.9 ± 1.9</td>
<td>59.37</td>
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<td>Κ⁺</td>
<td>[28]</td>
<td>814 ± 4</td>
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<td>η</td>
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<td>ρ⁻</td>
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<td>K⁺⁺</td>
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<td>K⁻⁻</td>
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<td>Λ⁺</td>
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<td>14.78</td>
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<td>Ω</td>
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<td>0.62 ± 0.09</td>
<td>0.4499</td>
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<td>Ω⁺</td>
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<td>Π(1520)</td>
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TABLE I. Comparison between measured and fitted particle multiplicities, in the framework of SIH(pγ) model, in central Au-Au collisions (5%) at a beam energy of 11.64 GeV. Also shown are the predicted multiplicities of the main hadron species.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Measurement</th>
<th>Fit A</th>
<th>Fit B</th>
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<td>$N_p$</td>
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<td>$363 \pm 10$</td>
<td>$361.7 \pm 36.6$</td>
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<td>$p/\pi^+$</td>
<td>[9,25]</td>
<td>$1.23 \pm 0.13$</td>
<td>$1.277 \pm 1.224$</td>
</tr>
<tr>
<td>$\sigma^-$</td>
<td>[9,40]</td>
<td>$134.0 \pm 93.0$</td>
<td>$140.0 \pm 146.0$</td>
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<tr>
<td>$\sigma^+$</td>
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<td>$176.9 \pm 182.2$</td>
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</tr>
<tr>
<td>$\rho$</td>
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<tr>
<td>$K^-$</td>
<td>[39]</td>
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<td>$18.80 \pm 18.81$</td>
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<td>$3.890 \pm 3.539$</td>
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<td>$K^0$</td>
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<td>$11.68 \pm 11.68$</td>
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<td>$\eta$</td>
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<td>$8.073 \pm 6.310$</td>
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</tr>
<tr>
<td>$\omega$</td>
<td></td>
<td>$8.870 \pm 3.659$</td>
<td></td>
</tr>
<tr>
<td>$\phi$</td>
<td></td>
<td>$0.3297 \pm 0.3489$</td>
<td></td>
</tr>
<tr>
<td>$\eta'$</td>
<td></td>
<td>$0.2997 \pm 0.2437$</td>
<td></td>
</tr>
<tr>
<td>$\rho$</td>
<td></td>
<td>$7.707 \pm 10.39$</td>
<td></td>
</tr>
<tr>
<td>$\rho^0$</td>
<td></td>
<td>$9.164 \pm 12.55$</td>
<td></td>
</tr>
<tr>
<td>$\rho^+$</td>
<td></td>
<td>$8.517 \pm 11.49$</td>
<td></td>
</tr>
<tr>
<td>$K^{*+}$</td>
<td></td>
<td>$3.555 \pm 3.512$</td>
<td></td>
</tr>
<tr>
<td>$K^{*-}$</td>
<td></td>
<td>$6.179 \pm 0.145$</td>
<td></td>
</tr>
<tr>
<td>$K^{0*}$</td>
<td></td>
<td>$3.706 \pm 3.801$</td>
<td></td>
</tr>
<tr>
<td>$K^{*0}$</td>
<td></td>
<td>$0.5555 \pm 0.4628$</td>
<td></td>
</tr>
<tr>
<td>$\rho$</td>
<td></td>
<td>$172.2 \pm 17.14$</td>
<td></td>
</tr>
<tr>
<td>$\rho^0$</td>
<td></td>
<td>$0.02851 \pm 0.02465$</td>
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</tr>
<tr>
<td>$\Delta^{*+}$</td>
<td></td>
<td>$25.39 \pm 24.31$</td>
<td></td>
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<tr>
<td>$\Delta^{*-}$</td>
<td></td>
<td>$0.093071 \pm 0.00222$</td>
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</tr>
<tr>
<td>$\Lambda$</td>
<td>[23,24], see text</td>
<td>$18.1 \pm 1.9$</td>
<td>$19.82 \pm 20.71$</td>
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<tr>
<td>$\Xi^-$</td>
<td></td>
<td>$0.01601 \pm 0.01645$</td>
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</tr>
<tr>
<td>$\Sigma^-$</td>
<td></td>
<td>$4.840 \pm 4.784$</td>
<td></td>
</tr>
<tr>
<td>$\Sigma^0$</td>
<td></td>
<td>$5.457 \pm 5.453$</td>
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</tr>
<tr>
<td>$\Xi^0$</td>
<td></td>
<td>$5.163 \pm 5.106$</td>
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</tr>
<tr>
<td>$\Xi^- $</td>
<td></td>
<td>$0.003445 \pm 0.00321$</td>
<td></td>
</tr>
<tr>
<td>$\Sigma^+$</td>
<td></td>
<td>$0.002793 \pm 0.00259$</td>
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</tr>
<tr>
<td>$\Xi^+$</td>
<td></td>
<td>$0.003115 \pm 0.00288$</td>
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<tr>
<td>$\Xi^0$</td>
<td></td>
<td>$0.56067 \pm 0.5564$</td>
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</tr>
<tr>
<td>$\Xi^+$</td>
<td></td>
<td>$0.54670 \pm 0.5387$</td>
<td></td>
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<tr>
<td>$\Xi^0$</td>
<td></td>
<td>$0.002133 \pm 0.00248$</td>
<td></td>
</tr>
<tr>
<td>$\Omega$</td>
<td></td>
<td>$0.007292 \pm 0.002380$</td>
<td></td>
</tr>
<tr>
<td>$\Omega$</td>
<td></td>
<td>$0.01352 \pm 0.01459$</td>
<td></td>
</tr>
<tr>
<td>$\Xi(1520)$</td>
<td></td>
<td>$0.000365 \pm 0.00056$</td>
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</tr>
<tr>
<td>$\Phi(1020)$</td>
<td></td>
<td>$0.7720 \pm 0.6401$</td>
<td></td>
</tr>
<tr>
<td>$\Theta(1540)$</td>
<td></td>
<td>$1.86 \pm 2.20$</td>
<td></td>
</tr>
<tr>
<td>$\Theta(1540)$$^*$</td>
<td></td>
<td>$2.71 \times 10^{-5} \pm 1.87 \times 10^{-5}$</td>
<td></td>
</tr>
</tbody>
</table>

TABLE II. Comparison between measured and fitted particle multiplicities, in the framework of SIH(pγ) model, in central Pb-Pb collisions (7.2%) at a beam energy of 504 GeV. Also shown are the predicted multiplicities of the main hadron species.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Measurement</th>
<th>Fit A</th>
<th>Fit B</th>
</tr>
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<tbody>
<tr>
<td>$N_p$</td>
<td>[2]</td>
<td>$349 \pm 1.5$</td>
<td>$350.5 \pm 350.5$</td>
</tr>
<tr>
<td>$\pi^+$</td>
<td>[2]</td>
<td>$239 \pm 0.7 \pm 17$</td>
<td>$228.4 \pm 228.5$</td>
</tr>
<tr>
<td>$\pi^-$</td>
<td>[2]</td>
<td>$275 \pm 0.7 \pm 20$</td>
<td>$256.5 \pm 256.8$</td>
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<tr>
<td>$\pi^0$</td>
<td></td>
<td>$265.8 \pm 251.9$</td>
<td></td>
</tr>
<tr>
<td>$K^+$</td>
<td>[2]</td>
<td>$55.3 \pm 1.6 \pm 2.8$</td>
<td>$49.83 \pm 48.33$</td>
</tr>
<tr>
<td>$K^-$</td>
<td>[2]</td>
<td>$16.1 \pm 0.2 \pm 0.8$</td>
<td>$17.11 \pm 20.72$</td>
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<tr>
<td>$K^0$</td>
<td></td>
<td>$3.357 \pm 3.483$</td>
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<tr>
<td>$\eta$</td>
<td></td>
<td>$23.74 \pm 21.60$</td>
<td></td>
</tr>
<tr>
<td>$\phi$</td>
<td></td>
<td>$15.48 \pm 12.90$</td>
<td></td>
</tr>
<tr>
<td>$\eta'$</td>
<td></td>
<td>$2.571 \pm 2.814$</td>
<td></td>
</tr>
<tr>
<td>$\rho$</td>
<td></td>
<td>$1.411 \pm 1.341$</td>
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</tr>
<tr>
<td>$\rho'$</td>
<td></td>
<td>$20.24 \pm 22.68$</td>
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</tr>
<tr>
<td>$\rho^0$</td>
<td></td>
<td>$23.69 \pm 26.05$</td>
<td></td>
</tr>
<tr>
<td>$\rho^*$</td>
<td></td>
<td>$22.14 \pm 25.11$</td>
<td></td>
</tr>
<tr>
<td>$\rho^*$</td>
<td></td>
<td>$3.710 \pm 3.816$</td>
<td></td>
</tr>
<tr>
<td>$K^{*+}$</td>
<td></td>
<td>$13.65 \pm 13.45$</td>
<td></td>
</tr>
<tr>
<td>$K^{*-}$</td>
<td></td>
<td>$4.006 \pm 3.668$</td>
<td></td>
</tr>
<tr>
<td>$K^{0*}$</td>
<td></td>
<td>$14.21 \pm 14.20$</td>
<td></td>
</tr>
<tr>
<td>$K^{*0}$</td>
<td></td>
<td>$3.710 \pm 3.816$</td>
<td></td>
</tr>
<tr>
<td>$\rho$</td>
<td></td>
<td>$138.0 \pm 137.0$</td>
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</tr>
<tr>
<td>$\rho^0$</td>
<td></td>
<td>$0.3650 \pm 0.3803$</td>
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</tr>
<tr>
<td>$\Delta^{*+}$</td>
<td></td>
<td>$26.90 \pm 25.23$</td>
<td></td>
</tr>
<tr>
<td>$\Delta^{*-}$</td>
<td></td>
<td>$0.07781 \pm 0.07428$</td>
<td></td>
</tr>
<tr>
<td>$\Lambda$</td>
<td></td>
<td>$38.02 \pm 40.25$</td>
<td></td>
</tr>
<tr>
<td>$\Lambda$</td>
<td></td>
<td>$0.3392 \pm 0.3501$</td>
<td></td>
</tr>
<tr>
<td>$\Xi^+$</td>
<td></td>
<td>$9.905 \pm 9.933$</td>
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</tr>
<tr>
<td>$\Xi^0$</td>
<td></td>
<td>$10.91 \pm 10.80$</td>
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</tr>
<tr>
<td>$\Xi^0$</td>
<td></td>
<td>$10.48 \pm 10.40$</td>
<td></td>
</tr>
<tr>
<td>$\Xi^- $</td>
<td></td>
<td>$0.1005 \pm 0.1106$</td>
<td></td>
</tr>
<tr>
<td>$\Xi^+$</td>
<td></td>
<td>$0.08620 \pm 0.09491$</td>
<td></td>
</tr>
<tr>
<td>$\Xi^0$</td>
<td></td>
<td>$0.09334 \pm 0.0123$</td>
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</tr>
<tr>
<td>$\Xi^0$</td>
<td></td>
<td>$2.422 \pm 2.422$</td>
<td></td>
</tr>
<tr>
<td>$\Xi^0$</td>
<td></td>
<td>$2.378 \pm 2.361$</td>
<td></td>
</tr>
<tr>
<td>$\Xi^0$</td>
<td></td>
<td>$0.07920 \pm 0.09372$</td>
<td></td>
</tr>
<tr>
<td>$\Xi^0$</td>
<td></td>
<td>$0.08446 \pm 0.09967$</td>
<td></td>
</tr>
<tr>
<td>$\Omega$</td>
<td></td>
<td>$0.1587 \pm 0.1709$</td>
<td></td>
</tr>
<tr>
<td>$\Omega$</td>
<td></td>
<td>$0.02667 \pm 0.02989$</td>
<td></td>
</tr>
<tr>
<td>$\Xi(1520)$</td>
<td></td>
<td>$2.167 \pm 1.751$</td>
<td></td>
</tr>
<tr>
<td>$\Xi(1540)$</td>
<td></td>
<td>$2.84 \pm 3.02$</td>
<td></td>
</tr>
<tr>
<td>$\Xi(1540)$$^*$</td>
<td></td>
<td>$0.0008 \pm 0.0019$</td>
<td></td>
</tr>
</tbody>
</table>

cays, while in Au-Au collisions at AGS the weak decays of $\Lambda$, $\Sigma$, $\Xi$, $\Omega$, and $K^{*0}$ are included.
The effect of the uncertainties on masses, widths, and branching ratios of the involved hadrons on the fit parameters has been studied by the method described in Ref. [14] and found to be negligible throughout.

In order to cross-check our results and verify their robustness, we have performed the analysis with two independent numerical programs, henceforth referred to as A and B,
strange quark-pair suppression in string decays

- According to the **Schwinger-formula**, the probability to form a massive $s\bar{s}$ in a string-decay is suppressed in comparison to light flavor $(u\bar{u}, d\bar{d})$

\[
P(s\bar{s})/P(u\bar{u}) = P(s\bar{s})/P(d\bar{d}) = \gamma_s = \exp\left(-\pi \frac{m_s^2 - m_q^2}{2\kappa}\right)\]

- **Considering a hot and dense medium**, the above formula remains the same but **effective quark masses** should be employed. This dressing is due to a scalar coupling with the **in-medium quark condensate** $\langle q\bar{q}\rangle$ according to:

\[
m_s^* = m_s^0 + (m_s^0 - m_s^0)\frac{\langle q\bar{q}\rangle}{\langle q\bar{q}\rangle_V} \quad m_q^* = m_q^0 + (m_q^0 - m_q^0)\frac{\langle q\bar{q}\rangle}{\langle q\bar{q}\rangle_V}
\]

→ need to evaluate the **scalar quark condensate in the medium**!

W. Cassing et al., PRC 93 (2016) 014902; A. Palmese et al., PRC94 (2016) 044912
The scalar quark condensate $\langle q\bar{q} \rangle$ is viewed as an order parameter for the restoration of chiral symmetry at high baryon density and temperature. It can be expressed in line with the Hellman-Feynman theorem by:

$$\frac{\langle q\bar{q} \rangle}{\langle q\bar{q} \rangle_V} = 1 - \frac{\Sigma}{f^2_m^2} \rho_S - \sum_h \frac{\sigma_h \rho_h^s}{f^2_m^2 m^2_\pi}$$

where $\rho_s$ is the scalar density obtained e.g. according to the non-linear $\sigma - \omega$ model, $\Sigma_\pi \approx 45$ MeV is the pion-nucleon $\Sigma$-term, and $f_\pi$ and $m_\pi$ are the pion decay constant and pion mass, given by the Gell-Mann-Oakes-Renner relation.

W. Cassing et al., PRC 93 (2016) 014902; A. Palmese et al., PRC94 (2016) 044912
Chiral symmetry restoration in the hadronic medium

- pion-nucleon $\Sigma$-term: 45 MeV

Yi-Bo Yang et al., arXiv 1511.09089

$\rightarrow$ in

$$\frac{\langle q\bar{q} \rangle}{\langle q\bar{q} \rangle_V} = 1 - \frac{\sum \pi}{f_\pi^2 m_\pi^2} \rho_S - \sum_h \frac{\sigma_h \rho_S^h}{f_\pi^2 m_\pi^2}$$

the leading terms are fixed within some uncertainty!

$\rightarrow$ no new 'parameters'!

W. Cassing et al., PRC 93 (2016) 014902; A. Palmese et al., PRC94 (2016) 044912
Strangeness enhancement in the hadronic phase

Insert in:

\[
\frac{P(s\bar{s})}{P(u\bar{u})} = \frac{P(s\bar{s})}{P(d\bar{d})} = \gamma_s = \exp\left(-\pi \frac{m_s^2 - m_q^2}{2\kappa}\right)
\]

- As a consequence of the **chiral symmetry restoration (CSR)**, the strangeness production probability increases with the energy density \(\varepsilon\).

In the QGP phase, the string decay doesn’t occur anymore and this effect is therefore suppressed.

Some dependence on the nuclear EoS!

W. Cassing et al., PRC 93 (2016) 014902; A. Palmese et al., PRC94 (2016) 044912
Comparison to data at AGS: 10.7 A GeV

looks quite good with CSR!

A. Palmese et al., PRC94 (2016) 044912
Excitation function of hadron ratios

→ low sensitivity to the nuclear EoS

A. Palmese et al., PRC94 (2016) 044912
Excitation function of hadron ratios

→ low sensitivity to the nuclear EoS

A. Palmese et al., PRC94 (2016) 044912
Predictions: Dependence on the system size

\[ \frac{K^+}{\pi^+} \]

\[ \frac{K^-}{\pi^-} \]

\[ \frac{(\Lambda + \Sigma^0)}{\pi} \]

\[ \sqrt{s_{NN}} \text{ [GeV]} \]

A. Palmese et al., PRC94 (2016) 044912

\( \Rightarrow \) no 'horn' for C+C
Predictions: Dependence on centrality

A. Palmese et al., PRC94 (2016) 044912
Detailed balance on the level of $2 \leftrightarrow n$: treatment of multi-particle collisions in transport approaches

**Generalized off-shell collision integral for $n \leftrightarrow m$ reactions:**

$$I_{\text{coll}} = \sum_{n} \sum_{m} I_{\text{coll}}[n \leftrightarrow m]$$

$$I_{\text{coll}}[n \leftrightarrow m] =$$

$$\frac{1}{2} N_n^m \sum_{\nu} \sum_{\lambda} \left( \frac{1}{(2\pi)^4} \right)^{n+m-1} \int \left( \prod_{j=2}^{n} d^4 p_j \ A_j(x, p_j) \right) \left( \prod_{k=1}^{m} d^4 p_k \ A_k(x, p_k) \right)$$

$$\times A_i(x, p) \ W_{n,m}(p, p_j; i, \nu \mid p_k; \lambda) \ (2\pi)^4 \delta^4(p^\mu + \sum_{j=2}^{n} p_j^\mu - \sum_{k=1}^{m} p_k^\mu)$$

$$\times \left[ \tilde{f}_i(x, p) \prod_{k=1}^{m} f_k(x, p_k) \prod_{j=2}^{n} \tilde{f}_j(x, p_j) - f_i(x, p) \prod_{j=2}^{n} f_j(x, p_j) \prod_{k=1}^{m} \tilde{f}_k(x, p_k) \right].$$

$$\tilde{f} = 1 + \eta f$$

**is Pauli-blocking or Bose-enhancement factors:**

$\eta = 1$ for bosons and $\eta = -1$ for fermions

$$W_{n,m}(p, p_j; i, \nu \mid p_k; \lambda)$$

**is a transition probability**
Impact of 3-body reactions on baryon annihilation

158 AGeV

80 AGeV

missing still some multistrange baryons and antibaryons !?
Impact of 3-body reactions on baryon annihilation

40 AGeV

20 AGeV

no exp. information on multistrange antibaryons