Pion spectra in Ar+Sc collisions in the
NA61/SHINE Collaboration

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The NA61/SHINE detector

- **Fixed target** experiment,
- Located at the SPS accelerator,
- **Large acceptance** spectrometer – coverage of the full forward hemisphere, down to $p_T = 0$,
- Selection of events based on forward energy (projectile spectators) measured in PSD.
Strong interactions programme at NA61/SHINE

The NA61/SHINE performs a 2D scan over system size and collision energy to study the phase diagram of strongly interacting matter in temperature and baryon density.

![Diagram showing system sizes and beam momentums for various interactions with dates for data taking and planned data taking.]

- **Data taken:** Blue squares
- **Large statistics data taken:** Darker blue squares
- **Data taking scheduled:** Red squares
- **Data taking planned:** Grey squares

<table>
<thead>
<tr>
<th>System size</th>
<th>Data taken</th>
<th>Large statistics data taken</th>
<th>Data taking scheduled</th>
<th>Data taking planned</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pb+Pb</td>
<td></td>
<td></td>
<td></td>
<td>2016/18</td>
</tr>
<tr>
<td>Xe+La</td>
<td></td>
<td></td>
<td></td>
<td>2017</td>
</tr>
<tr>
<td>Ar+Sc</td>
<td></td>
<td></td>
<td></td>
<td>2015</td>
</tr>
<tr>
<td>Be+Be</td>
<td></td>
<td></td>
<td></td>
<td>2011/12/13</td>
</tr>
<tr>
<td>p+Pb</td>
<td></td>
<td></td>
<td></td>
<td>2012/14/16/17/18</td>
</tr>
<tr>
<td>p+p</td>
<td></td>
<td></td>
<td></td>
<td>2009/10/11</td>
</tr>
</tbody>
</table>

Beam momentum [A GeV/c]
Strong interactions programme at NA61/SHINE

In this talk news on $4\pi\pi^-$ spectra and mean multiplicity in 5% most violent $^{40}\text{Ar}+^{45}\text{Sc}$ collisions at 13A, 19A, 30A, 40A, 75A and 150A GeV/c beam momentum will be presented.

Figure: shine3d.web.cern.ch/shine3d/
Why?
Why?
Why?
Why?
The $h^-$ method is used to extract $\pi^-$ spectra in Ar+Sc interactions at different beam momenta. Results refer to pions produced by strong interaction processes and in electromagnetic decays of produced hadrons.
The $h^-$ method

- The experimental data undergoes series of **quality cuts**.
- Spectra of negatively charged particles are determined using the selected events and tracks.
- The spectra are **corrected for acceptance, reconstruction efficiency and contamination of particles other than primary $\pi^-$ mesons** by EPOS 1.99 Monte Carlo model\(^1\).
- Mean $\pi^-$ multiplicity in $4\pi$ is estimated by summing up the measured spectra and correcting it for missing acceptance by extrapolation.

\(^1\) Liu et al. *PRC* 74.
The $h^-$ method

Example for $^{40}$Ar+$^{45}$Sc at 19A GeV/c

Raw data

MC corrections

Corrected $\pi^-$ spectrum
Extrapolation to $4\pi$ acceptance

Example for $^{40}\text{Ar}+^{45}\text{Sc}$ at 19A GeV/c

Extrapolation in $p_T$

FITTING GAUSSIANS

Double gaussian fit

Ar+Sc 5%

$\frac{d^2\sigma}{dydp_T}$

$\frac{d\sigma}{dy}$

$\frac{d\sigma}{dy}$

Ar+Sc 5%

Double gaussian fit
Results: $\pi^-$ rapidity spectra

- $\pi^-$ spectra measured in large acceptance: $p_T$ down to 0, in full forward hemisphere.
- Rapidity spectra are approximately gaussian, independently of the collision energy,
- Only statistical uncertainties plotted.
Mean number of wounded nucleons $\langle W \rangle$

- Mean number of wounded nucleons (nucleons interacting inelastically calculated within the Glauber model) $\langle W \rangle$ obtained using **EPOS 1.99**\(^2\) Monte Carlo,
- Systematic and statistical uncertainties plotted. Systematic uncertainties are based on the uncertainty of p+p inelastic collision cross section and the difference between EPOS and Hijing values.
- $\langle W \rangle$ calculated from EPOS is $< 1\%$ smaller than that from Glissando\(^3\),
- 5% most violent events chosen based on the number of projectile spectators. **Event selection based on the full simulation of the PSD response is under way.** Uncertainty coming from the selection is not shown here.

\(^{2}\)Liu et al. *PRC* 74.
Mean number of wounded nucleons $\langle W \rangle$

Example of 5% most violent Ar+Sc collisions
Results: $\langle \pi^- \rangle$ and $\langle W \rangle$

Preliminary results for $4\pi$, 5% event class $\langle \pi^- \rangle$ and $\langle W \rangle$ for Ar+Sc at different SPS momenta.

- Systematic uncertainty of $\langle \pi^- \rangle$ is estimated to be 5% based on previous NA61/SHINE analysis\(^4\).

<table>
<thead>
<tr>
<th>$p_{\text{lab}}$ [A GeV/c]</th>
<th>$\langle \pi^- \rangle$</th>
<th>$\langle W \rangle$</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>$38.46 \pm 1.92$</td>
<td>$66.63 \pm 0.50$</td>
</tr>
<tr>
<td>19</td>
<td>$48.03 \pm 2.40$</td>
<td>$66.68 \pm 1.02$</td>
</tr>
<tr>
<td>30</td>
<td>$59.72 \pm 2.98$</td>
<td>$66.72 \pm 0.50$</td>
</tr>
<tr>
<td>40</td>
<td>$66.28 \pm 3.31$</td>
<td>$66.64 \pm 0.57$</td>
</tr>
<tr>
<td>75</td>
<td>$86.12 \pm 4.30$</td>
<td>$66.66 \pm 0.52$</td>
</tr>
<tr>
<td>150</td>
<td>$108.92 \pm 5.44$</td>
<td>$66.88 \pm 0.50$</td>
</tr>
</tbody>
</table>

\(^4\)N. Abgrall et al. *EPJ C* 74.3, p. 1.
The Fermi statistical model predicts linear increase of $\langle \pi \rangle / \langle W \rangle$ with the Fermi energy measure

$$F = \left[ \frac{(\sqrt{s_{NN}} - 2m_N)^3}{\sqrt{s_{NN}}} \right]^{1/4}$$

An increase of the slope of $\langle \pi \rangle / \langle W \rangle$ – **KINK** – at the onset of deconfinement is predicted by the SMES\(^5\) due to the larger number of effective degrees of freedom in comparison to HRG.

\(^5\)Gazdzicki and Gorenstein. APP B30.
Estimation of \( \langle \pi \rangle \) from \( \langle \pi^- \rangle \)

As for the NA61 Ar+Sc, Be+Be and p+p data we only have the \( \langle \pi^- \rangle \) value, the multiplicities of \( \langle \pi^+ \rangle \) and \( \langle \pi^0 \rangle \) are as:

\[
\langle \pi \rangle_{N+N} = 3 \langle \pi^- \rangle_{N+N} \\
\langle \pi \rangle_{Ar+Sc} = 3 \langle \pi^- \rangle_{Ar+Sc} \\
\langle \pi \rangle_{Be+Be} = 3 \langle \pi^- \rangle_{Be+Be}
\]

This approach is motivated by the fact that the NA61/SHINE acceptance is the largest for \( \pi^- \).
At high SPS energies Be+Be approximately follows p+p, whereas Ar+Sc follows Pb+Pb.

At low SPS energies no simple systematic is observed. The reason might be physical or due to systematic bias in $\langle W \rangle$ estimate. Full simulation of fragmentation process and PSD response is needed.
Summary

- Preliminary results on $\pi^-$ multiplicities in 5% most violent collisions of Ar+Sc at $p_{\text{lab}} = 13\text{A}, 19\text{A}, 30\text{A}, 40\text{A}, 75\text{A}, 150\text{A}$ GeV/c are presented.

- At high SPS energies Ar+Sc follows Pb+Pb.

- At low SPS energies no simple systematic is observed.

- Full simulation of fragmentation process and PSD response is urgently needed.
Thank you for your attention.
Event classes

Event (centrality) classes are chosen using the forward energy, $E_F \approx$ energy of projectile spectators. $E_F$ is measured by the PSD zero-degree calorimeter. This is an important feature of NA61/SHINE.

Example for Ar+Sc at 13A GeV/c
**PID methods in NA61/SHINE**

- \( dE/dx \) method estimates multiplicities of \( \pi^{\pm}, K^{\pm}, p \) and \( \bar{p} \) using energy loss measurements in TPCs,

- \( \text{tof-}dE/dx \) method estimates multiplicities of \( \pi^{\pm}, K^{\pm}, p \) and \( \bar{p} \) using energy loss and particle time of flight measurements in ToFs,

- \( h^- \) method estimates multiplicities of \( \pi^- \) based on the fact that the majority of negatively charged hadrons produced in p+p and A+A collisions are \( \pi^- \).
Results: $\langle \pi^- \rangle / \langle W \rangle$ ratio

- No increase with system size,
- Systematic and statistical uncertainties plotted.
Results: $\langle \pi^- \rangle / \langle W \rangle$ ratio

- Data suggests monotonic increase with system size at 150A GeV/c. Ar+Sc and Be+Be measurements in line.
- Systematic and statistical uncertainties plotted.
Isospin correction

In order to compare results obtained for different systems, the isospin correction should be taken into account. To this end phenomenological formulas are used

\[
\langle \pi^- \rangle_{N+N} = \langle \pi^- \rangle_{p+p} + \frac{1}{3}
\]

\[
\langle \pi^- \rangle_{Au+Au}^I = \frac{\langle \pi^- \rangle_{Au+Au} + \langle \pi^+ \rangle_{Au+Au}}{2}
\]

The correction is only applied to measurements where its effect is the strongest. This assumption is based on the compilation of the world data presented in\(^6\) and the model presented therein.

Where needed, the data is corrected for slight differences in beam momentum.

\(^6\)Golokhvastov. Physics of Atomic Nuclei 64.1, p. 84.