Recent results from NA61/SHINE

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Outline

• Introduction

• Study of the onset of deconfinement
  - Particle production properties
  - Flow

• Onset of fireball

• Search for critical point

• Strangeness production in p+p at 158 GeV/c:
  - $K^*(892)^0$
  - $\Xi$ production
  - Search for pentaquark

• NA61/SHINE beyond 2020

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See P. Podlaski Tuesday
See A. Tefelska Thursday 4.10PM
See D. Tefelski Thursday, Poster A. Merzlaya
Fixed target experiment located at the CERN SPS accelerator

Beams:
- ions (Be, Ar, Xe, Pb)  
  \( p_{\text{beam}} = 13\text{A} - 150\text{A} \text{ GeV}/c \)
- hadrons (\( \pi, K, p \))  
  \( p_{\text{beam}} = 13 - 400 \text{ GeV}/c \)
- \( \sqrt{s_{NN}} = 5.1 - 16.8 \text{ (27.4)} \text{ GeV} \)

Large acceptance hadron spectrometer – coverage of the full forward hemisphere, down to \( p_T = 0 \)
NA61/SHINE performed the 2D scan in **collision energy and system size** to study the phase diagram of strongly interacting matter.
Uniqueness of heavy ion results from NA61/SHINE

NA61/SHINE recorded unique data for:

- Onset of deconfinement
- Onset of fireball
- Critical point?
Study of the onset of deconfinement: Particle production properties
Onset of deconfinement: step and horn

2D kaon spectra for central (0-10\%) Ar+Sc collisions

Ar+Sc→K±+X

K± spectra in $p_T$ are fitted with

$$\frac{d^2 n}{dp_T dy} = \frac{S_p}{T^2 + T m_K} \exp \left( - \sqrt{\frac{p_T^2 + m_K^2}{T}} - m_K \right)$$
Onset of deconfinement: step

Plateau – **STEP** – in the inverse slope parameter $T$ of $m_T$ spectra in Pb+Pb collisions observed at SPS energies. This is expected for the onset of deconfinement due to mixed phase of HRG and QGP (SMES).

Qualitatively similar energy dependence is seen in $p+p$, $Be+Be$ and $Pb+Pb$ collisions.

Magnitude of $T$ in $Be+Be$ slightly higher than in $p+p$.

$Ar+Sc$ results between $p+p/Be+Be$ and $Pb+Pb$. 

See P. Podlaski Tuesday.
Onset of deconfinement: horn

Rapid changes in $K^+ / \pi^+$ – HORN – were observed in Pb+Pb collisions at SPS energies. This was predicted (SMES) as a signature of onset of deconfinement.

Plateau like structure visible in p+p
Be+Be close to p+p
Ar+Sc is higher than p+p but form of energy dependence is similar to p+p (no horn)
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.

Resonance-string model (UrQMD) fails to reproduce data.
Study of the onset of deconfinement: Flow
Directed flow $v_1$ is considered to be sensitive to 1st order phase transition (softening of EOS). Expected: non-monotonic behavior (positive→negative→positive) of proton $dv_1/dy$ as a function of beam energy - “collapse of proton flow”

Predictions of hydrodynamical model:

Directed flow measured by NA49 at middle SPS energy (“anti-flow” of protons at mid-rapidity):
Centrality dependence of $dv_1/dy$ in Pb+Pb at $\sqrt{s_{NN}} = 7.6$ GeV

NA61/SHINE fixed target setup → tracking and particle identification over wide rapidity range

Flow coefficients are measured relative to the spectator plane estimated with Projectile Spectator Detector (PSD) → unique for NA61/SHINE

Close to mid-rapidity (-0.2 < y < 0.8)
- slope of pion $v_1$ is negative for all centralities
- slope of proton $v_1$ changes sign at centrality of about 50%

More NA61/SHINE flow results:
Klochkov, Selyuzhenkov (QM2018 talk)
Proton directed flow vs rapidity

No evidence for the collapse of proton directed flow in Pb+Pb at 13A GeV/c

Directed flow measured by NA49 at middle SPS energy ("anti-flow" of protons at mid-rapidity):

- Central
- Mid-central
- Peripheral
Spectator-induced electromagnetic effects

EM-repulsion of $\pi^+$ and attraction of $\pi^-$ is the strongest for pions with rapidities close to spectator (beam) rapidity and with low $p_T$

First observation of spectator induced EM effects in small systems at SPS

Similar effect seen in intermediate centrality Ar+Sc (NA61/SHINE) and peripheral Pb+Pb (NA49)
Study of the onset of fireball
Onset of fireball: system size dependence

Change between $p+p \approx Be+Be$ and $Ar+Sc$, $Pb+Pb$ results

- $p+p$ data are corrected for experimental biases, systematic uncertainty $\sim 0.1$ [EPJ.C76:635]
- 0-1% $Be+Be$ data is uncorrected, experimental bias is $\sim 10-15$
- 0-0.2% $Ar+Sc$ data is uncorrected, experimental bias is $\sim 5-7$%
Search for critical point

Expected: non-monotonic behavior of CP signatures
Critical point: Proton intermittency as signal of CP

Second order phase transition → scale invariance → characteristic dependence of fluctuations on size $\delta$ of subdivision intervals of momentum space $\Delta$

$M = \Delta/\delta$ – number of intervals

$$F_2(M) = \frac{\left\langle \frac{1}{M^2} \sum_{m=1}^{M^2} n_m(n_m-1) \right\rangle}{\left\langle \frac{1}{M^2} \sum_{m=1}^{M^2} n_m \right\rangle^2}$$

where:

$n_m$ – particle number in bin $i$, $\langle \ldots \rangle$ - averaging over events

at critical point power law dependence is expected

$$F_2(M) = F_2(\Delta) M^{\phi_2}$$
Critical point: Proton intermittency in Ar+Sc and Be+Be at 150A GeV/c

Ar+Sc, 5-10%

Ar+Sc, 10-15%

Be+Be, 0-12%

\[ M^2 \] – numbers of bins in \((p_x, p_y)\) space

\[ F_2(M^2) \] moment are higher in data than in mixed events in Ar+Sc collisions - detailed investigation of significance of this result is in progress.

No signal visible in Be+Be.
Critical point: Strongly intensive measures $\Sigma[P_T,N]$

So far there are no prominent structures which could be related to critical point

System size dependence of $\Sigma[P_T,N]$ at 150/158A GeV/c: NA49 and NA61/SHINE points show consistent trends

Strangeness production in p+p at 158 GeV/c.

$K^*(892)^0$
$K^*(892)^0$ production in inelastic $p+p$ collisions

$K^*(892)^0$ p+p collisions can be described by HRG

\[ <K^*(892)> = 0.03812 \pm 0.00538 \pm 0.00372 \]
System size dependence of $K^*(892)^0$ to $K^\pm$ ratio at 158$A$ GeV/$c$

Time between chemical and kinetic freeze-out ($\Delta t$):
- $3.8 \pm 1.1$ fm/$c$ for $K^*(892)^0/K^+$
- $3.3 \pm 1.2$ fm/$c$ for $K^*(892)^0/K^-$

$\Delta t$ at SPS $>$ $\Delta t$ at RHIC ($2\pm1$ fm/$c$, STAR, PR C71, 064902, 2005) suggesting that:
- regeneration effects play significant role for higher energies
- regeneration may happen also at SPS $\rightarrow$ obtained $\Delta t$ is the lower limit of time between freeze-outs
Strangeness production in p+p at 158 GeV/c.
Ξ production
\( \Xi \) production in inelastic \( p+p \) collisions at 158 GeV/c
$\Xi$ production in inelastic $p+p$ collisions at 158 GeV/$c$

UrQMD fails to describe $\Xi^+ / \Xi^-$ ratio – known problem of string models

EPOS describes rapidity distributions of $\Xi^+ , \Xi^-$ and their ratio, but not shape of transverse momentum spectrum.
Strangeness production in p+p at 158 GeV/c. 
Search for $\Xi^-$(1860) pentaquark
\( \Xi^-(1860) \) pentaquark search in NA61/SHINE - motivation

NA49 indication for \( \Xi^- (1860) \) pentaquark

(NA49, PRL 92, 042003, 2004)

Anti-decuplet of baryons (\( J^P = 1/2^+ \))
predicted in chiral soliton model
Diakonov, Petrov, Polyakov, ZP A359, 305, 1997

\[ \Xi^- \pi^- \]
\[ \Xi^- \pi^+ \]
\[ \Xi^+ \pi^- \]
\[ \Xi^+ \pi^+ \]
\( \Xi^- (1860) \) pentaquarks search in NA61/SHINE

**NA49:**
- 6M events
- resonance with mass of \( 1.862^{+/-0.002} \) GeV/c\(^2\)
- width below the detector resolution.
- the significance was estimated to be 4.0 sigma.

**NA61/SHINE:**
- 33M events
- Same analysis as NA49
- No \( \Xi^- (1860) \) pentaquark signal
- \( \Xi (1530) \) well visible
NA61/SHINE beyond 2020
NA61/SHINE program for 2021-2024

- What is the mechanism of open charm production?
- How does the onset of deconfinement impact open charm production?
- How does the formation of quark gluon plasma impact $J/\psi$ production?

To answer these questions mean number of charm quark pairs, $\langle c\bar{c}\rangle$, produced in A+A collisions has to be known. Up to now corresponding experimental data does not exist and only NA61/SHINE can perform this measurement in the near future.
Detector upgrade during LS2

Construction of Vertex Detector (VD) for $D^0$, $\bar{D}^0$ decay reconstruction

Replacement of the TPC read-out electronics to increase data rate to 1 kHz

New trigger and data acquisition system

New Time-of-Flight detectors

Upgrade of Projectile Spectator Detector

See D. Tefelski Thursday
Summary

• 2D scan in system size and collision energy was completed in 2017 with Xe+La data

• Analysis ongoing for p+p, Be+Be, Ar+Sc, Xe+La and Pb+Pb data

• No horn in Ar+Sc collisions

• Unexpected system size dependence: (p+p ≈ Be+Be) ≠ (Ar+Sc ≠ Pb+Pb)

• No convincing indication of CP, proton intermittency signal in Ar+Sc is under scrutiny

• No $\Xi^-(1860)$ pentaquark signal in p+p at 158 GeV/c

• Plans to extend NA61/SHINE program with measurements of open charm production in 2021-2024
Critical point: Strongly intensive measures $\Delta$ and $\Sigma$

\[
\Delta[P_T, N] = \frac{1}{\omega[P_T]} \langle N \rangle \omega[P_T] - \langle P_T \rangle \omega[N] \\
\Sigma[P_T, N] = \frac{1}{\omega[P_T]} \langle N \rangle \omega[P_T] + \langle P_T \rangle \omega[N] - 2 \left( \langle P_T N \rangle - \langle P_T \rangle \langle N \rangle \right)
\]

\[
\omega[P_T] = \frac{\langle P_T^2 \rangle - \langle P_T \rangle^2}{\langle P_T \rangle} \\
\omega[P_T] = \frac{\overline{P_T^2} - \langle P_T \rangle^2}{\langle P_T \rangle} \\
\omega[N] = \frac{\langle N^2 \rangle - \langle N \rangle^2}{\langle N \rangle}
\]

$\Delta = \Sigma = 0$ for no fluctuations

$\Delta = \Sigma = 1$ for Independent Particle Model

- $\Delta[P_T, N]$ uses only first two moments: $\langle N \rangle, \langle P_T \rangle, \langle P_T^2 \rangle, \langle N^2 \rangle$
- $\Sigma[P_T, N]$ uses also correlation term: $\langle P_T N \rangle - \langle P_T \rangle \langle N \rangle$

thus $\Delta$ and $\Sigma$ can be sensitive to several physics effects in different ways
Motivation of $K^*$ measurement

$K^*$ lifetime ($\approx 4 \text{ fm/c}$) comparable with time between freeze-outs →

Some resonances may decay inside fireball; momenta of their decay products can be modified due to elastic scatterings → problems with experimental reconstruction of resonance via invariant mass →

**Suppression of observed $K^*$ yield**

Assuming no regeneration processes (Fig.) time between freeze-outs can be determined from (STAR, PR C71, 064902, 2005):

$$ \frac{K^*}{K} \text{(kinetic)} = \frac{K^*}{K} \text{(chemical)} \cdot e^{-\frac{\Delta t}{\tau}} $$

use Pb+Pb or Au+Au ratio use p+p ratio

$\Delta t$ – time between kinetic and chemical freeze-outs

$\tau$ – $K'(892)^0$ lifetime = $4.17 \text{ fm/c}$; PDG, PR D98, 030001, 2018
$\pi^-$ spectra from 2D-scan

$\pi^-$ spectra measured in large acceptance: $p_T$ down to 0, in full forward hemisphere

- Rapidity spectra $\approx$ gaussian, independently of collision energy and system size
- Large acceptance allows to obtain $4\pi$ multiplicity (Eur.Phys.J C74 (2014) no.3, 2794)
- $m_T$ spectra in $p+p$ are exponential, in larger systems (central collisions) deviate from the exponential shape
Onset of deconfinement: kink

The increase of $\langle \pi \rangle/\langle W \rangle$ with collision energy is stronger for heavier than for lighter systems at high SPS energies.

Statistical model with phase transition (SMES - Acta Phys. Pol. B30 (1999) 2705) predicts a steepening of the rate of increase – KINK – of $\langle \pi \rangle/\langle W \rangle$ in QGP due to the larger number of degrees of freedom in comparison to HRG.

$\langle \pi \rangle$ – mean multiplicity in full acceptance
$\langle W \rangle$ – mean number of wounded nucleons
Clear mass hierarchy of $v_2$ - radial flow

Difference between $v_2$ for $\pi^+$ and $\pi^-$ is small

Significant mass dependence of $v_1$

Difference between $v_1$ for $\pi^+$ and $\pi^-$ is sensitive to electromagnetic effects.