Recent results from the strong interaction programme of the NA61/SHINE experiment

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• Motivation
• The onset of deconfinement
• The onset of fireball
• The critical point
• Open charm measurements
• Future plans (beyond 2020)
• Summary
Motivation

NA61/SHINE programme:

1. Strong interactions
   - Study particle spectra
   - Study properties of the onset of deconfinement
   - Search for the critical point (CP)
   - Charm physics

2. Cosmic rays & neutrinos

Comprehensive 2D scan of p+p, p+A and A+A collisions, as a function of system size and energy

"fluctuation hill"
NA61/SHINE experiment

- Large acceptance hadron spectrometer - coverage of the full forward hemisphere, down to $p_T = 0 \text{ GeV/c}$
- Performs measurements on hadron production in $h+p$, $h+A$, $A+A$ at $13A - 150(8)A$ GeV/c
- Event selection in A+A collisions by measurements of forward energy with PSD
- Recent upgrades:
  - Vertex detector (open charm measurements)
  - FTPC-1/2/3

NA61/SHINE in virtual reality: http://shine3d.web.cern.ch/shine3d/
Onset of deconfinement

- Beginning of the creation of quark-gluon plasma (QGP) in nucleus-nucleus (A+A) collisions with increasing collision energy $\sqrt{s_{NN}}$. 
Onset of deconfinement (energy dependence)

- Rapid changes in $K^+/\pi^+$ (HORN) observed in Pb+Pb collisions predicted by the Statistical Model of Early Stage (SMES) as a signature of the onset of deconfinement.
- "Shadow" of HORN seen for p+p interactions.
- Be+Be close to p+p.
- $\langle K^+\rangle/\langle \pi^+\rangle$ in Ar+Sc between p+p/Be+Be and Pb+Pb.
Onset of deconfinement (energy dependence)

- Changes in $T$ (STEP-like structure), observed in Pb+Pb collisions predicted by SMES model as a signature of the onset of deconfinement
- "Shadow" of STEP seen for p+p interactions
- Be+Be close to p+p
Onset of fireball

- Beginning of the creation of large clusters of strongly interacting matter (SIM) in nucleus-nucleus collisions with increasing mass number $A$. 

ONSET OF FIREBALL
Onset of fireball (system size dependence)

- Rapid changes in $K^+/\pi^+$ and multiplicity fluctuations when moving from light $(p+p, \text{central Be+Be})$ to intermediate and heavy systems (central Pb+Pb)
- Heavy systems closer to predictions of statistical models for large volumes
  → beginning of the creation of large clusters of strongly interacting matter in intermediate systems - onset of fireball?
Onset of fireball
(system size/cluster volume dependence)

Statistical Models with an Ideal
Boltzmann gas within
Canonical Ensemble (CE)
and
Grand Canonical Ensemble (GCE)

M. Gazdzicki, PoS – CPOD2017, 1801.00178
Onset of deconfinement vs onset of fireball

- 2D scan conducted by varying collision energy and system size indicated two thresholds:
  - Onset of deconfinement
  - Onset of fireball

→ four domains of hadron production
Critical point and critical fluctuations

Event-by-event fluctuation measures:

- $\omega[h^-]$: **intensive** (*independent on system volume, dependent on its fluctuations, sensitive to material conservation laws*)

  $\omega[h^-]$: different energy dependence for p+p/Be+Be (increase) and Ar+Sc (constant)

- $\Sigma[P_T,N]$: **strongly intensive** (*independent on system volume and its fluctuations, insensitive to material conservation laws*)

  $\Sigma[P_T,N] = (\langle N \rangle \omega[P_T] + \langle P_T \rangle \omega[N] - 2 \text{cov}(P_T, N)) \frac{1}{\langle N \rangle \omega[P_T]}$

  $P_T = \sum_i^N p_{T_i}$; $\omega[p_T]$ - for inclusive $p_T$ distribution

$\Sigma[P_T,N]$: no fluctuation hill associated with the critical point
Critical point and critical fluctuations

Intermittency analysis of 2-nd factorial moments

- $F_2(M)$: second factorial moment for $M^2$ cells in transverse momentum space
  \[
  F_2(M) = \frac{\left\langle \frac{1}{M^2} \sum_{m=1}^{M^2} n_m(n_m - 1) \right\rangle}{\left\langle \frac{1}{M^2} \sum_{m=1}^{M^2} n_m \right\rangle^2}
  \]


- $\Delta F_2(M) = F_2^{\text{data}}(M) - F_2^{\text{mix}}(M)$: correlator after subtraction of non-critical background moments

- $\Delta F_2(M) \sim (M^2)^{\phi_2}$, $\phi_2 = 5/6$ (protons): critical fluctuations

Open charm measurements

Motivation:

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

- Model predictions differ by a factor up to 50 for central Pb+Pb collisions at top SPS energy
- Production in full phase space required to discriminate models
- Different charm carriers in deconfined (c quarks) and confined (D mesons) matter
- Enhancement of $\langle c\bar{c} \rangle$ production predicted by the SMES
- Mesurement of both $J/\psi$ and $\langle c\bar{c} \rangle$ required to calculate probability of $\langle c\bar{c} \rangle$ to $J/\psi$ hadronization

<table>
<thead>
<tr>
<th>Model</th>
<th>Reference</th>
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<tbody>
<tr>
<td>HSD</td>
<td>Linnyk, Bratkovskaya, Cassing, IJMP E17 1367</td>
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<tr>
<td>pQCD</td>
<td>Gavai et al. IJMP A10 2999</td>
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<td>HRG</td>
<td>Braun-Munzinger, J. Stachel, PLB 490, 196</td>
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<td>Quark Coalesc. Stat.</td>
<td>Gavai et al. IJMP A10 2999</td>
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<tr>
<td>SMES</td>
<td>Gazdzicki, Gorenstein, APP B30, 2705</td>
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\[ \langle c\bar{c} \rangle \]

Grzegorz Stefanek

ICHEP 2018, SEOUL

UJK Kielce
The analysis of pilot data on Pb+Pb collisions at 150A Gev/c (low statistics - 140k events) proved the measurement of D⁰ production by Small Acceptance Vertex Detector is possible.

Pb+Pb and Xe+La data with higher statistics are under analysis.

Detailed studies require Large Acceptance VD and high statistics data.
Future plans (beyond 2020)

• Measurement plans:
  - precise open charm studies in Pb+Pb collisions at 150A and 40A GeV/c with Large Acceptance Vertex Detector
  
  - reference measurements of nuclear fragmentation cross-section for cosmic ray experiments (DAMPE, PAMELA, CALET, GAPS) to decrease uncertainties from 20% to 0.5%
  
  - reference measurements of hadron production for neutrino experiments (T2K-II, Hyper-Kamiokande) to decrease systematical uncertainty for neutrino flux from 10% to 3-4%

• NA61/SHINE detector upgrade:
  - construction of Large Acceptance Vertex Detector for D⁰, anti-D⁰ decay reconstruction
  
  - new trigger and data acquisition system
  
  - replacement of the TPC readout electronics to increase data rate to 1 kHz
  
  - upgrade of Projectile Spectator Detector
  
  - new Time-of-Flight detectors
• Changes in hadron production as a function of energy (HORN, STEP) observed in central Pb+Pb collisions (NA49) as signatures of deconfinement

• Shadow of HORN observed in p+p/Be+Be

• STEP structure also observed in light nuclei collisions p+p/Be+Be

• Dependence of particle yield ratios and multiplicity fluctuations on the system size suggests existence of the onset of fireball - the beginning of creation of large clusters

• Four domains of hadron production with two thresholds

• No fluctuation signal attributed to the critical point

• The increase of fluctuations in Si+Si collisions (NA49) from intermittency analysis

• First observation of $D^0$ peak in central Pb+Pb collisions at SPS energies

• New NA61/SHINE results for Ar+Sc, Xe+La and Pb+Pb collisions expected soon

• Ambitious programme of measurements beyond 2020
Thank you for your attention!