Strange Particle Measurements
at the CERN SPS
NA49 and NA61/SHINE Experiments

Outline:
• Experiments
• Motivation
• Evidence for the onset of deconfinement
• Strange particle production measurements
• Fluctuations in particle composition
• Summary

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NA61/SHINE and NA49 experiments

- **Hadron spectrometer**
  
  Five TPCs: two VTPCs(1/2) and GTPC in the B field and two others MTPCs (R/L) outside - allows for precise measurement of q, p and dE/dx

- **Large acceptance (≈ 50%)**

- **Good PID and momentum resolution**
  
  \[
  \sigma(TOF) \sim 60 - 120 \text{ ps} \\
  \sigma(dE/dx)/dE/dx \sim 0.04 \\
  \sigma(m_{inv}) \sim 5 \text{ MeV} \\
  \sigma(p)/p^2 \sim 10^{-4} [\text{GeV/c}]^{-1}
  \]
  
  for 9 Tm magnetic field

NA61/SHINE was approved in 2007. First physics run in 2009. It is successor of NA49 which operated in 1994-2002 and recorded data on p+p, C+C, Si+Si and Pb+Pb at $\sqrt{s_{NN}} = 6.3 - 17.3$ GeV/c

S. Afanasiev et al., NiM A430, 210 (1999)

Phase diagram of strongly interacting matter

- QCD considerations suggest a 1st order phase boundary ending in a Critical End Point (CEP)
- lattice calculations locate CEP in the SPS energy range
  Z.Fodor, S.D.Katz, JHEP 0404,050 (04),
  R.V.Gavai, S.Gupta, PRD 71,114014 (05)
- maximum of Critical End Point signal is expected for freeze-out close to CEP → SPS energy range
**Phase diagram scan – NA49, NA61 experiments**


- **NA49** – scan with energy Pb+Pb at 20\(A\), 30\(A\), 40\(A\), 80\(A\), 158\(A\) GeV and with system size p+p, C+C, Si+Si, Pb+Pb at 158\(A\) GeV

- **NA61** - 2D scan \((T, \mu_B)\) with six SPS beam energies 13\(A\), 20\(A\), 30\(A\), 40\(A\), 80\(A\), 158\(A\) GeV and five different systems p+p, p+Pb, Be+Be, Ar+Ca, Xe+La
  - higher statistics – at least \(10^6\) events per energy and per reaction
  - better centrality selection (PSD detector) and reduction of interactions in the gas inside VTPCs (Helium beam pipe)
  - similar analysis like in NA49 with better precision
Evidence for the onset of deconfinement

- rapid changes in energy dependence of hadron production properties provide evidence for the phase transition
- the LHC and RHIC BES points confirm NA49 measurements and trends

Data:
NA49: C.Alt et al., PRC 77, 024903 (2008)

Theoretical predictions:
M.Gazdzicki, M.Gorenstein, APP B30, 2705 (99)

Evidence for the onset of deconfinement in Pb+Pb collisions at $\sqrt{s_{NN}} \approx 8$ GeV
$K^*(892)$, $\bar{K}^*(892)$ production measured by NA49

T. Anticic et al., PRC 84, 064909 (2011)

- yield of $K^*$ exceeds that of $\bar{K}^*$ by factors of two similar like for $K^+$ and $K^-$ yields (same valence quark composition)
- yield of $K^*$ and $\bar{K}^*$ per wounded nucleon appears to increase from $p+p$ to $C+C$, $Si+Si$ and then decrease for $Pb+Pb$ collisions at 158A GeV
- $<K^*>/<K^+>$, $<\bar{K}^*>/<K>$ ratios decrease with increasing size of colliding nuclei.

Substantial duration of the hadronic stage of the fireball?
**K*(892), \( \bar{K}*(892) \) production measured by NA49**

\[
p+p, \ C+C, \ Si+Si, \ Pb+Pb \ 158A \ GeV
\]

\[
T. \ Anticic \ et \ al., \ PRC \ 84, \ 064909 \ (2011)
\]

- yields of \( K^* \) mesons in central Pb+Pb collisions are about 2.5 lower than the predictions of HGM with parameters fitted to the yields of stable hadrons
- for the yields of several resonance states (\( K^*, \ \bar{K}^*, \ \Lambda, \ \phi \)) measured by NA49 the suppression respect to HGM predictions seems to get stronger with decreasing lifetime of the resonance

**Reduction of \( K^* \) yield by rescattering of decay products during hadronic stage?**
First $K^-$ production measurements by NA61/SHINE

- NA61/SHINE and NA49 spectra agree
- EPOS model reproduces data trends; significant quantitative differences for $K^-$

NA49 points obtained from $x_F - p_T$ spectra
EPOS: PRC 74, 044902 (2011)
Fluctuations in particle composition – motivation and measures

• In the vicinity of phase transition distinct fluctuations patterns are expected

• Event-by-event maximum likelihood fits were used to extract relative species abundances

• Studied fluctuation measures:

\[ \omega_i = \frac{<N_i^2>-<N_i>^2}{<N_i>} \]

\[ \sigma_{dyn} = \text{sgn} \left( \sigma_{data}^2 - \sigma_{mix}^2 \right) \sqrt{\left| \sigma_{data}^2 - \sigma_{mix}^2 \right|}, \quad \sigma^2 = \frac{\text{Var}(N_i/N_j)}{\langle N_i/N_j \rangle^2} \]

\[ \nu_{dyn} = \frac{<N_i>.(<N_i>-1)}{<N_i^2>} + \frac{<N_j>.(<N_j>-1)}{<N_j^2>} - 2 \cdot \frac{<N_i N_j>}{<N_i><N_j>} \]

\[ \nu_{dyn} \sim \frac{1}{N_W} \]

\[ \nu_{dyn} \approx \text{sgn} \left( \sigma_{dyn} \right) \sigma_{dyn}^2 \]

Method: C.Alt et al., PRC 79, 044910 (2009)
Identity method

• The identity method allows to obtain second and third moments of identified particle multiplicity distribution corrected for misidentification effect.

Using dE/dx information a particle identity is calculated as:

\[ W_i = \frac{\rho_i(dE/dx)}{\rho(dE/dx)}, \]

where \( \rho_i \) - function fitted to \( i^{th} \) particle type in \( dE/dx \) and \( \rho \) - function fitted to total \( dE/dx \) distribution.

Event quantity \( W_i \) defined as:

\[ W_i = \Sigma w_i, \]

where summation runs over all particles in an event.

\[ \langle W_i \rangle = \langle N_i \rangle \]

• Once detector response (\( \rho_i \)) and \( W_i \) distributions are known the method is used to obtain moments of identified particle multiplicity distributions.

\[ \rho_i, W_i, \ldots \rightarrow \langle N_i^2 \rangle, \langle N_i \cdot N_j \rangle \]

• No event-by-event fits and mixed events required in identity method.

PRC 83,054907
PRC 84,024902
arXiv:nucl-th/1204.6632
Trend of NA49 results at low energies confirmed. Differences between STAR and NA49 results remains.

- $p/\pi$: $\nu_{\text{dyn}} < 0$ due to resonance decay (reproduced by multiplicity scaling model)
  
  \[ \nu_{\text{dyn}} \propto \frac{1}{\langle N_i \rangle} + \frac{1}{\langle N_j \rangle} \]  

- $K/\pi$: $\nu_{\text{dyn}} > 0$ anti-correlation (reproduced by multiplicity scaling model)

Unchanged correlation strength (same physics) with energy?

- $K/p$: $\nu_{\text{dyn}}$ shows a strong dependence on energy, going from positive values at low energies to $\nu_{\text{dyn}} < 0$ at high energies (not reproduced by multiplicity scaling model)

Underlying correlation physics (baryon-strangeness) changing with energy?
Fluctuations of particle composition – dependence on acceptance

- clear difference of NA49 and STAR acceptance for 30A GeV

- identity method can work with low multiplicity and acceptance cuts can be applied
Fluctuations of particle composition – dependence on acceptance

NA49, Pb+Pb, 3.5% most central at $\sqrt{s_{NN}}$: 6.3, 7.6, 8.7, 17.3 GeV

• clear dependence on acceptance cut at low SPS energies for K, $\pi$ and K,p

• no energy dependence of particle composition for “STAR equivalent” acceptance

Differences between NA49 and STAR results can be explained by different acceptance
Multiplicity fluctuations of $\pi$, $K$, $p$

- Increase of $\omega_\pi$ in Pb+Pb collisions due to $N_w$ fluctuations?

- $\omega_K > 1 \rightarrow$ strangeness conservation at least in p+p collisions?

- $\omega_p < 1 \rightarrow$ baryon number conservation at least in p+p collisions?

- Decrease of $\omega_p$ with energy in Pb+Pb collisions but increase in p+p interactions

- EPOS model agrees with p+p data
Summary

• Onset of deconfinement in central Pb+Pb, NA49 measurements are confirmed:
  - results from RHIC agree with relevant NA49 data
  - first LHC data confirm the interpretation

• $K^*(892)$, $\bar{K}^*(892)$ productions in central C+C, Si+Si, Pb+Pb and inelastic p+p coll.:  
  - observed suppression of $K^*$ yields in central Pb+Pb collisions as well as the decrease of $<K^*>/ <K^+>$, $<\bar{K}^*>/ <K^->$ with increasing size of the colliding nuclei may suggest a substantial duration of the hadronic stage of the fireball

• $K^-$ production was measured by NA61 in p+p collisions as a function of $y$, $p_T$

• Fluctuations of particle composition:
  - differences between NA49 (Pb+Pb) and STAR (Au+Au) results can be explained by different acceptance
  - $K/\pi$ and $p/\pi$ fluctuations as a function of energy can be described by a simple multiplicity scaling model whereas $K/p$ fluctuations show a deviation from the model. It can be a hint of changing of underlying correlation physics
  - multiplicity fluctuations in p+p collisions mainly reflect conservation laws; they are reproduced by EPOS model
Additional Slides
Evidence for the onset of deconfinement

- $\pi$ yield related to entropy production
- Steeper increase in A+A suggests 3-fold increase of initial d.o.f

- $E_s$ related to strangeness/entropy ratio
- Plateau consistent with prediction for deconfinement
Onset of deconfinement: the toy model of the horn

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

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

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

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

\[ \approx gV \left( \frac{MT}{2\pi} \right)^{3/2} e^{-M/T} \quad \text{for heavy particles} \]
Fluctuation measures studied by NA49

- scaled variance \( \omega \) of the multiplicity distribution \( P(n) \)

\[
\omega = \frac{Var(n)}{<n>} = \frac{<n^2> - <n>^2}{<n>}
\]

- \( \Phi_x \) measure of fluctuations of observable \( x \) (\( <p_T>, <\Phi>, Q \))

\[
\Phi_x = \sqrt{\frac{<Z^2>}{<N>}} - \sqrt{<Z^2>}; \\
Z = x - <x>, \\
Z = \sum_{i=1}^{N} (x_i - <x>)
\]

- \( F_2 \) factorial moments of low mass \( \pi^+\pi^- \) pair number fluctuations in \( p_T \) space

- \( \sigma_{dyn} \) measure of particle ratio fluctuations (\( K/\pi, p/\pi, K/p \))

\[
\sigma_{dyn} = \text{sign}(\sigma_{data}^2 - \sigma_{mix}^2) \sqrt{|\sigma_{data}^2 - \sigma_{mix}^2|}; \\
\sigma_{dyn}^2 = \nu_{dyn}
\]


- \( \omega \) affected by \( N_w \) fluctuations
- \( \Phi_x \) strongly intensive fluctuation measure
  independent of \( N_w \) and its fluctuations
- \( F_2 \) factorial moments of low mass \( \pi^+\pi^- \) pair number fluctuations in \( p_T \) space
  proper mass window and multiplicity are required
  mixed events used as the reference
  power-law behavior from \( \sigma \) mode expected
- \( \sigma_{dyn} \) measure of particle ratio fluctuations (\( K/\pi, p/\pi, K/p \))
  mixed events used as the reference
  \( \sigma_{dyn}^2 \sim 1/N_w \), sensitive to fluctuations
**Particle ratio fluctuations (standard method)**

- event-by-event PID based on energy loss $dE/dx$ in MTPCs
- inclusive probability density function + event-by-event maximum likelihood fit to extract relative species abundances $\Theta_m$

\[ L = \prod_{i=1}^{n} \left\{ \sum_{m} \Theta_m F_m(\vec{p}_i) f_m(\vec{p}_i, (dE/dx)_i) \right\} \]

- acceptance different for different species and depends on beam energy; it has to be taken into account for model comparisons

- reference sample of mixed events which preserve multiplicity distribution quantify effect of finite-number statistics and $dE/dx$ resolution

- dynamical fluctuations:

\[ \sigma_{\text{dyn}} = \text{sign} \left( \sigma_{\text{data}}^2 - \sigma_{\text{mix}}^2 \right) \sqrt{|\sigma_{\text{data}}^2 - \sigma_{\text{mix}}^2|}, \quad \sigma^2 = \frac{\text{Var}(K/\pi)}{\left(\langle K/\pi \rangle \right)^2} \]
Identity method

2 particle example

Available information:
- inclusive distribution of PID variable, $\rho_j(x)$
- mean multiplicities: $\langle N_p \rangle = \int \rho_p(x) dx$, $\langle N_k \rangle = \int \rho_k(x) dx$, ...

The Problem:
- how to find the moments of multiplicity distributions?

The strategy:
- for each measurement $x$ and particle $j$ in an event one defines
  $$w_j(x) = \frac{\rho_j(x)}{\sum_j \rho_j(x)}$$
- for each event one constructs:
  $$W_j = \sum_i w_j(x_i)$$
- finally one calculates moments of $W$ distribution

The idea:
- find moments of the multiplicity distributions from known moments of $W$ quantities
The Identity Method relates corresponding moments of $W$ and multiplicity distributions through a set of linear equations. An example for the second moments:

\[
\begin{pmatrix}
\langle N_p^2 \rangle \\
\langle N_k^2 \rangle \\
\langle N_p N_k \rangle
\end{pmatrix} =
\begin{pmatrix}
\overline{w}_{pp}^2 & \overline{w}_{pk}^2 & 2\overline{w}_{pp}\overline{w}_{pk} \\
\overline{w}_{kp}^2 & \overline{w}_{kk}^2 & 2\overline{w}_{kp}\overline{w}_{kk} \\
\overline{w}_{pp}\overline{w}_{kp} + \overline{w}_{pk}\overline{w}_{kk} & \overline{w}_{pp}\overline{w}_{kk} + \overline{w}_{pk}\overline{w}_{kp} & \overline{w}_{pp}\overline{w}_{kk} + \overline{w}_{pk}\overline{w}_{kp}
\end{pmatrix}^{-1}
\begin{pmatrix}
\langle W_p^2 \rangle - b_p \\
\langle W_k^2 \rangle - b_k \\
\langle W_p W_k \rangle - b_{pk}
\end{pmatrix}
\]

3 equations, 3 unknowns (unique solution)

\[
b_i = \sum_{j=\pm k} \langle N_j \rangle (\overline{w}_{ij}^2 - \overline{w}_{ij}^2), \quad b_{pk} = \sum_{j=\pm k} \langle N_j \rangle (\overline{w}_{pkj} - \overline{w}_{pj}\overline{w}_{kj})
\]

\[
\overline{w}_{ij} = \frac{\int w_i(m)\rho_j(m)dm}{\int \rho_j(m)dm}, \quad \overline{w}_{ij}^2 = \frac{\int w_i^2(m)\rho_j(m)dm}{\int \rho_j(m)dm}, \quad \overline{w}_{ikj} = \frac{\int w_i(m)w_k(m)\rho_j(m)dm}{\int \rho_j(m)dm}
\]

- Advantages:
  - Event-by-Event fits of PID variable is not needed
  - Also no need for event mixing
  - Mathematically proven

M. Gazdzicki et al., PRC 83, 054907 (2011)
M. I. Gorenstein, PRC 84, 024902 (2011), second moments
Identity method

Graph showing distributions of different particles.
Particle ratio fluctuations

- Increase of $|\sigma_{\text{dyn}}|$ towards peripheral collisions for all three ratios

- Similar trend in RHIC STAR data for $(K^+ + K^-)/(\pi^+ + \pi^-)$ at $\sqrt{s_{\text{NN}}} = 62$ and 200 GeV

  B.I. Abelev et al., PRL 103, 092301 (2009)

- UrQMD predicts similar behaviour with $N_w$

- Scaling with multiplicities, $\sigma_{\text{dyn}} \propto \sqrt{\frac{1}{\langle A \rangle} + \frac{1}{\langle B \rangle}}$ works for all three ratios

  V. Koch, T. Schuster PRC 81, 034910 (2010)

Unchanged correlation strength (same physics) with system size?
Particle ratio fluctuations

- $p/\pi$: $\sigma_{\text{dyn}} < 0$ correlation due to resonance decay \textit{S.Jeon,V.Koch PRL 83, 5435 (99)}
- reproduced by hadronic transport models (UrQMD, HSD)

Scaling with multiplicities: $\sigma_{\text{dyn}} \propto \sqrt{\frac{1}{\langle A \rangle} + \frac{1}{\langle B \rangle}}$

\textit{Scaling: V.Koch, T.Schuster PRC 81, 034910 (2010)}

- $K/\pi$: $\sigma_{\text{dyn}} > 0$ anti-correlation
- UrQMD and HSD models are contradictory; neither describes data well

Unchanged correlation strength (same physics) with energy?
Is the underlying correlation physics (baryon-stangeness) changing with energy?

- $\sigma_{\text{dyn}}$ shows a strong dependence on $\sqrt{s_{\text{NN}}}$, going from positive values at low energies to $\sigma_{\text{dyn}} < 0$ at high energies.

- Ratio for positive charges $K^+/p^+$, has no resonance contribution.

- Neither hadronic models (UrQMD, HSD) nor scaling with multiplicities describe data.

Theory:  
V. Koch, A. Majumder, J. Randrup PRL 95, 182301 (05)