Recent results on dilepton and strangeness production with HADES and perspectives at FAIR

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TU Munich
Motivation

Fundamental problem: how a hadron changes its properties when implanted in a strongly-interacting many body system?

Nucleus $\rho_B \leq \rho_0$

Heavy-ion collisions $\rho_B \leq 2-3\rho_0$
(at 1–2 GeV/u)

Neutron star $\rho_B \leq 3–8\rho_0$
(in the interior)

Vienna University of Technology

Casey Reed, courtesy of Penn State
Motivation

 Restoration of the SB chiral symmetry

 Light vector mesons $\rho$, $\omega$, $\phi$

 - Drop of the order parameter – chiral condensate – by ~30% already at normal nuclear density

 - Early expectations: $m_V \sim \langle q\bar{q} \rangle$
 - Most of modern predictions: significant broadening, no substantial mass shift

[Image: Diagram showing the restoration of the SB chiral symmetry and the behavior of light vector mesons under varying conditions, with references to the work by P. Muehlich et al. in Nucl. Phys. A780:187-205, 2006.]
Penetrating probes

- Vector mesons $J^P = 1^-$, $V \rightarrow e^+e^-$
- Minimal final state interaction
- Small branchings $\sim 10^{-5}$
- Instrumental challenge: $e/h$ separation

- Virtual photon in a hot fireball


- Hadrons interact strongly $\rightarrow$ rescattering


- Particular case of the kaon ($S=+1$)

Note: from $K^+p$ total cross section

Kaon
The HADES experiment

**High Acceptance** Di-Electron Spectrometer
Location: GSI, Darmstadt

Fixed-target experiment,
SIS18, beam $E_{\text{kin}} = 1\text{—}3 \text{ GeV/nucl.}$
Full azimuthal coverage, $18^\circ - 85^\circ$ in polar angle

Sub-detectors:
- MDCs
- RICH, Time-of-flight (TOF and RPCs)
- Pre-Shower detector
- Forward Wall detector at small angles
p+p at 3.5 GeV: reference measurement

ρ–meson contribution ~ contribution of resonances
\[ R \rightarrow \rho + N \rightarrow e^+e^- + N \]

Gap below the omega pole

G. Agakishiev et al. [HADES]

GiBUU model, J. Weil, ECT* Workshop 2013

Interpretation with a transport model
p+p at 3.5 GeV: reference measurement

Gap below the omega pole

Interpretation with a transport model

“Modification” of the the ρ–meson in vacuum
p+p at 3.5 GeV: different models

- Very different treatment of the Δ and bremsstrahlung contributions

HSD model
E. Bratkovskaya et al.,

GiBUU model, J. Weil, ECT* Workshop 2013
Cold nuclear environment: p+Nb at 3.5 GeV

Excess on the left shoulder of the omega-peak, rho-like contribution, observed for slow pairs

G. Agakishiev et al. [HADES]
Vector mesons in cold nuclear matter

- Indication for slow omega’s absorption
- Related to the in-medium width

Nuclear modification factor

\[ R_{pA} = \frac{d\sigma^{pNb}/dp}{d\sigma^{pp}/dp} \times \frac{\langle A_{\text{part}}^{pp} \rangle}{\langle A_{\text{part}}^{pNb} \rangle} \times \frac{\sigma_{\text{reaction}}^{pp}}{\sigma_{\text{reaction}}^{pNb}}. \]

G. Agakishiev et al. [HADES]
Measuring the cocktail components

G. Agakishiev et al. [HADES]

- Exploit main decay branch $P \rightarrow \gamma\gamma$ and photon conversion
Phase space of neutral mesons in pNb

- Test/input for models that interpret $e^+e^-$ data
- Au+Au data → talk by C. Behnke

G. Agakishiev et al. [HADES]
Heavy ions: Ar + KCl at 1.76 GeV

- Excess over the reference spectrum
- Dilepton emission beyond binary NN collisions

G. Agakishiev et al. [HADES]

- First measurement of the omega-meson sub-threshold
Excess yield in Ar + KCl

- First measurement of the omega-meson sub-threshold

G. Agakishiev et al. [HADES]  

- Excess over the reference spectrum
- To be continued with Au+Au data (May 2012), talk by S. Harabasz
Strangeness in medium: mesons

Kaon

- Repulsive in-medium potential,
  moderate increase of the effective mass

Antikaon

- Attractive in-medium potential,
  strong decrease of the effective mass,
  major broadening


A. Ramos, E. Oset
Strangeness in medium: baryons

Λ(1116)
- U ~ -30 MeV (attractive) at saturation density
- Density/momentum dependence?

Σ⁻(1197)
- Ambiguity in the potential value
- Hard to measure experimentally: Σ⁻ → n π⁻
- Calorimetry give a chance (neutron detection)
Appearance of strangeness in a neutron star

- Very high density in the interior
- Production of strangeness is energetically favorable (relieve Fermi pressure of neutrons and electrons)
- Decrease of the pressure softens the matter (→ soft EoS)
- Decrease of the maximum mass of the star

$R \sim 10 - 15 \text{ km}$

$M \sim 1.5 \, M_\odot$
Precise measurement of a pulsar mass via Shapiro delay

$M = 1.97 \pm 0.04 \, M_{\odot}$

Excludes soft EoS and thus strangeness content

“There is still lack of information about the nucleonic EOS at suprasaturation densities as well as on the hyperon interactions in nuclear matter that may allow for an unambiguous answer to whether the mass of the pulsars J1614–2230 or J0348+0432 could rule out exotic degrees of freedom from the interior of compact stars.”

Neutral kaon production in pp reactions at 3.5 GeV

- Exclusive measurement, extraction of production cross sections
- Tune of the resonance model (GiBUU) to exclusive and inclusive data
- Use the tuned model to interpret the pNb data
Kaon production in NN collisions: role of baryonic resonances

K. Tsushima, A. Sibirtsev, A.W. Thomas, G.Q. Li, PRC59 (1999) 369
“Resonance model study of kaon production in baryon baryon reactions for heavy ion collisions”

\[ \begin{align*}
  B_3(p_3) & \rightarrow Y(p_4) \rightarrow K(k) \\
  B_3(p_3) & \rightarrow Y(p_4) \rightarrow K(k)
\end{align*} \]

\[ \begin{align*}
  \pi, \eta, \rho \\
  \pi, \eta, \rho
\end{align*} \]

\[ B = N \text{ or } \Delta \]

<table>
<thead>
<tr>
<th>Resonance ((J^P))</th>
<th>Width (MeV)</th>
<th>Decay channel</th>
<th>Branching ratio</th>
<th>Adopted value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(N(1650)) (\frac{1}{2}^-)</td>
<td>150</td>
<td>(N\pi)</td>
<td>0.60 – 0.80</td>
<td>0.700</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(N\eta)</td>
<td>0.03 – 0.10</td>
<td>0.065</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(\Delta\pi)</td>
<td>0.03 – 0.07</td>
<td>0.050</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(\Lambda K)</td>
<td>0.03 – 0.11</td>
<td>0.070</td>
</tr>
<tr>
<td>(N(1710)) (\frac{1}{2}^+)</td>
<td>100</td>
<td>(N\pi)</td>
<td>0.10 – 0.20</td>
<td>0.150</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(N\eta)</td>
<td>0.20 – 0.40</td>
<td>0.300</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(N\rho)</td>
<td>0.05 – 0.25</td>
<td>0.150</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(\Delta\pi)</td>
<td>0.10 – 0.25</td>
<td>0.175</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(\Lambda K)</td>
<td>0.05 – 0.25</td>
<td>0.150</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(\Sigma K)</td>
<td>0.02 – 0.10</td>
<td>0.060</td>
</tr>
<tr>
<td>(N(1720)) (\frac{3}{2}^+)</td>
<td>150</td>
<td>(N\pi)</td>
<td>0.10 – 0.20</td>
<td>0.150</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(N\eta)</td>
<td>0.02 – 0.06</td>
<td>0.040</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(N\rho)</td>
<td>0.70 – 0.85</td>
<td>0.775</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(\Delta\pi)</td>
<td>0.05 – 0.15</td>
<td>0.100</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(\Lambda K)</td>
<td>0.03 – 0.10</td>
<td>0.065</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(\Sigma K)</td>
<td>0.02 – 0.05</td>
<td>0.035</td>
</tr>
<tr>
<td>(\Delta(1920)) (\frac{3}{2}^+)</td>
<td>200</td>
<td>(N\pi)</td>
<td>0.05 – 0.20</td>
<td>0.125</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(\Sigma K)</td>
<td>0.01 – 0.03</td>
<td>0.020</td>
</tr>
</tbody>
</table>

Note:
these heavy resonances are not produced in the GiBUU code, only cross sections parameterizations are used.

- Completely detached from the resonance model(s) used for dilepton data interpretation
Neutral kaons: effect of the potential in pNb at 3.5 GeV

- Maximal effect of the potential at $10^\circ < \theta_{\text{LAB}} < 20^\circ$
- Build the ratio of two spectra (A/B)

$F = -\nabla U \Rightarrow$ kinematics of particles.
Neutral kaons: effect of the potential in pNb at 3.5 GeV

- Ongoing analyses: measure particles that might be relevant for neutron stars (hyperons)
Rapidity distribution in pNb: scattering and secondary processes

- Very different behaviour of two species, reflecting different interaction with nucleonic environment
- Important constraints/input for transport
Antikaon–nucleon interaction

- $\Lambda(1405)$ is crucial for understanding of the free and in–medium $\bar{K}N$ interaction.
- Predicted as a $\bar{K}N$ bound state.
- Within coupled channel approach generated as a $\bar{K}N$ bound state and a $\Sigma\pi$ resonance.
$\Sigma^+\pi^-$ channel

$\Sigma^-\pi^+$ channel

First measurement of $\Lambda(1405)$ in p+p reactions in charged decay mode.
Mass distribution peaked below 1405 MeV/c$^2$.

G. Agakishiev et al. [HADES]
Different reactions $\rightarrow$ different lineshapes

**Pion beam program:**

HADES has a unique opportunity to measure $\Lambda(1405)$ in two different reactions:

- **p+p at 4.3 GeV/c**

- **$K^-+d$ at 0.7–0.85 GeV/c**

- **$\gamma+p$ at 1.6–1.8 GeV/c**

- **$\pi^-+p$ at 1.69 GeV/c**

- **p+p at 3.65 GeV/c**

Hypothesis of a Kaonic Cluster

**Strong force** mediated by **virtual** pion

**“Super-strong nuclear force”** mediated by **real** antikaon

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HADES search for a simplest strange cluster in pp reactions

Most theoretical works predict existence of the bound state.

\[
\begin{align*}
B(ppK^-) & \approx 14-80 \text{ MeV} \\
\Gamma(ppK^-) & \approx 40-110 \text{ MeV/}c^2
\end{align*}
\]

main decay channel “ppK−” → pΛ ⇒ search in pp → pΛK+ at 3.5 GeV

$p + p \xrightarrow{3.5\text{GeV}} p + K^+ + \Lambda$

$p + p \xrightarrow{3.5\text{GeV}} N^{*++} + p$
$\quad \xrightarrow{} \Lambda + K^+$
$\quad \xrightarrow{} \Sigma^0 + K^+$

$p + p \xrightarrow{3.5\text{GeV}} ppK^- + K^+$
$\quad \xrightarrow{} \Lambda + p$
$\quad \xrightarrow{} \Sigma^0 + p$
pΛK⁺ analysis with HADES

\[ p + p \xrightarrow{3.5 \text{GeV}} p + K^+ + \Lambda \]

\[ p + p \xrightarrow{3.5 \text{GeV}} N^{*+} + p \]
\[ \xrightarrow{\Lambda + K^+} \Sigma^0 + K^+ \]

\[ p + p \xrightarrow{3.5 \text{GeV}} "ppK^-" + K^+ \]
\[ \xrightarrow{\Lambda + p} \Sigma^0 + p \]

N^{*+}(1650)
N^{*+}(1720)
N^{*+}(1900)
N^{*+}(2190)
pΛK⁺ analysis with HADES

\[ p + p \overset{3.5\text{GeV}}{\rightarrow} p + K^+ + \Lambda \]

\[ p + p \overset{3.5\text{GeV}}{\rightarrow} N^{*+} + p \]
\[ \quad \overset{\Lambda + K^+}{\rightarrow} \Lambda + K^+ \]
\[ \quad \overset{\Sigma^0 + K^+}{\rightarrow} \Sigma^0 + K^+ \]

\[ p + p \overset{3.5\text{GeV}}{\rightarrow} \,^\prime p p K^-\prime + K^+ \]
\[ \quad \overset{\Lambda + p}{\rightarrow} \Lambda + p \]
\[ \quad \overset{\Sigma^0 + p}{\rightarrow} \Sigma^0 + p \]
Search for kaonic cluster signal

Partial wave analysis with the Bonn–Gatchina framework

http://pwa.hiskp.uni-bonn.de/
A.V. Anisovich, V.V. Anisovich, E. Klempt, V.A. Nikonov and A.V. Sarantsev

Coherent sum of baryonic resonances reproduces the spectrum well.

Not much room for the kaonic cluster in pp at 3.5 GeV.

Resonances considered in the solution

<table>
<thead>
<tr>
<th>Notation in PDG</th>
<th>old</th>
<th>Mass GeV/c²</th>
<th>Width GeV/c²</th>
<th>$\Gamma_{\pi K}/\Gamma_{All}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>N(1650) $\frac{1}{2}^-$</td>
<td>N(1650)S₁₁</td>
<td>1.655</td>
<td>0.150</td>
<td>3-11%</td>
</tr>
<tr>
<td>N(1710) $\frac{1}{2}^+$</td>
<td>N(1710)P₁₁</td>
<td>1.710</td>
<td>0.200</td>
<td>5-25%</td>
</tr>
<tr>
<td>N(1720) $\frac{3}{2}^+$</td>
<td>N(1720)D₁₃</td>
<td>1.720</td>
<td>0.250</td>
<td>1-15%</td>
</tr>
<tr>
<td>N(1875) $\frac{3}{2}^-$</td>
<td>N(1875)D₁₃</td>
<td>1.875</td>
<td>0.220</td>
<td>?</td>
</tr>
<tr>
<td>N(1880) $\frac{1}{2}^+$</td>
<td>N(1880)P₁₁</td>
<td>1.870</td>
<td>0.235</td>
<td>?</td>
</tr>
<tr>
<td>N(1895) $\frac{1}{2}^-$</td>
<td>N(1895)S₁₁</td>
<td>1.895</td>
<td>0.090</td>
<td>?</td>
</tr>
<tr>
<td>N(1900) $\frac{3}{2}^+$</td>
<td>N(1900)P₁₃</td>
<td>1.900</td>
<td>0.250</td>
<td>0-10%</td>
</tr>
</tbody>
</table>
Heavy ion collisions at HADES

May 2012: Au+Au at 1.23 GeV/u

Flow of strangeness w.r.t. reaction plane

- Reconstruct event–by–event reaction geometry.
- Look at the preferred direction of strangeness emission.
- Infer potentials from the comparison with models.
Experiments with pion beams (2014)

Why pion beam?

- Continue studies started in pp/pA.
- Light projectile — favorable kinematics for in-medium effects.
- Simpler production mechanisms ($\pi N \rightarrow N^* \rightarrow e^+e^- + N$; $\pi N \rightarrow N^* \rightarrow YK$).
- Light and heavy targets (C, Cu, W).

GiBUU simulations

J. Weil, ECT* Workshop 2013
Hadron properties in dense matter at 2–8 GeV/nucl. EoS at high baryonic densities

- Vector mesons: production above the threshold
- No dilepton measurements in this energy range
- Multistrange baryons (Ξ, Ω)
- Bridge to CBM, NA61

V. V. Begun et al.
Detector performance tested with Au+Au at 1.23 GeV
Detector upgrade: lead–glass calorimeter

Motivation
1. Pseudoscalar meson reconstruction.
2. Better $e/\pi$–separation at high momenta.

Feasibility study: $\eta$–meson in CC and NiNi at 8 GeV/nucl.
Measurements of elementary collisions are a vital reference for pA and AA. Rich physics case by itself.

Resonances are ubiquitous. Does it change at SIS–100 energies? How to model the particle production in the transition region?

Dileptons&strangeness: same transport frameworks but different underlying models. Unified description?

Pion beam program: elementary channels and in-medium effects.

SIS–100: measurements at densities relevant for neutron stars.
The HADES Collaboration

Extra slides
How well the resonance model works for $K^0$ in pp?

- All exclusive channels are overestimated by the model.
Exclusive analyses (done by J.-C. Berger-Chen) set further constraints, sensitive to the contribution of resonances $\Delta(1232)$, $\Sigma(1385)$ in final states.
Outlook: $K^*(892)$

Analysis by Dimitar Mihaylov

- Short-lived kaon-pion resonance
- In–nucleus decay possible

![Graphs showing data for $p+p$ and $p+Nb$ interactions]
Strange baryons in medium

Momentum dependency of the in-medium energy

$\Lambda(1116)$

$\Sigma^-(1197)$
Resonance model: channel decomposition

**Original** resonance model

$pp \rightarrow p\pi^+\Lambda K^0$ (black), $pp \rightarrow p\pi^+\Lambda K^0$ (red), $pp \rightarrow p\pi\Sigma K^0$ (green).

FIG. 36. $K^0$ transverse momentum spectra in $p + p$ collisions (black circles) and GiBUU transport model simulations within the original resonance model by Tsushima et al. [3]. Blue line shows the total contribution of all $K^0$ production channels included in the model. Individual contributions are: $pp \rightarrow p\Sigma^+ K^0$ (black), $pp \rightarrow p\pi^+\Lambda K^0$ (red), $pp \rightarrow p\pi\Sigma K^0$ (green).
How to observe the kaon in-medium potential

General idea: look at the kinematics of escaped kaons

**FOPI π+A, ANKE p+A**

**HADES Ar+KCl**

$K^0_S \rightarrow \pi^+\pi^-$

$\rho \approx 2-3 \cdot \rho_0$ @ SIS18 1-3 AGeV

$\pi^{-} + A \rightarrow A + \pi^{-}$

$\nu \rightarrow \nu + \pi^0$

$U_{opt} = +20 \pm 5$ MeV extracted from comparison with transport

$U_{opt} = +39$ MeV fit the data best


**Original** resonance model

**FIG. 37.** $K_S^0$ rapidity distribution in $p+p$ collisions (black circles) and GiBUU transport model simulations within the original resonance model by Tsushima *et al.* [3]. Blue line shows the total contribution of all $K^0$ production channels included in the model. Individual contributions are: $pp \rightarrow p\Sigma^+ K^0$ (black), $pp \rightarrow p\pi^+ \Lambda K^0$ (red), $pp \rightarrow p\pi\Sigma K^0$ (green).
Modified resonance model

FIG. 38. $K^0$ transverse momentum spectra in $p + p$ collisions (black circles) and GiBUU transport model simulations within the tuned and modified resonance model. Blue line shows the total contribution of all $K^0$ production channels included in the model. Individual contributions are: $pp \rightarrow p\Sigma^+ K^0$ (black), $pp \rightarrow p\pi^+ \Lambda K^0$ (red), $pp \rightarrow p\pi\Sigma K^0$ (green), $pp \rightarrow N\pi\pi Y K^0$ (cyan). In the last reaction $N$ denotes proton or neutron and $Y$ denotes $\Lambda$ or $\Sigma$. 
Modified resonance model

FIG. 39. $K_S^0$ rapidity distribution in $p + p$ collisions (black circles) and GiBUU transport model simulations within the tuned and modified resonance model. Blue line shows the total contribution of all $K_S^0$ production channels included in the model. Individual contributions are: $pp \rightarrow p\Sigma^+ K^0$ (black), $pp \rightarrow p\pi^+ \Lambda K^0$ (red), $pp \rightarrow p\pi \Sigma K^0$ (green), $pp \rightarrow N\pi\pi Y K^0$ (cyan). In the last reaction $N$ denotes proton or neutron and $Y$ denotes $\Lambda$ or $\Sigma$. 
TABLE V. Cross sections for $K^0$ production channels in p+p collisions at $E_{kin.} = 3.5$ GeV. All values are in $\mu$b. The numbers in brackets are scaling factors that should be applied to the values given by the resonance model (Tsushima et al.).

<table>
<thead>
<tr>
<th>Reaction, $p + p \rightarrow$</th>
<th>Tsushima resonance model</th>
<th>Exclusive measurement</th>
<th>Inclusive measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p + \Sigma^+ + K^0$</td>
<td>37.8</td>
<td>26.2 (0.69)</td>
<td>26.5 (0.70)</td>
</tr>
<tr>
<td>$p + \pi^+ + \Lambda + K^0$</td>
<td>75.9</td>
<td>44.5 (0.59)</td>
<td>31.9 (0.42)</td>
</tr>
<tr>
<td>$p + \pi^+ + \Sigma^0 + K^0$</td>
<td>24.6</td>
<td>11.5 (0.47)</td>
<td>17.7 (0.72)</td>
</tr>
<tr>
<td>$p + \pi^0 + \Sigma^+ + K^0$</td>
<td>10.9</td>
<td>n/a</td>
<td>7.8 (0.72)</td>
</tr>
<tr>
<td>$n + \pi^+ + \Sigma^+ + K^0$</td>
<td>5.5</td>
<td>n/a</td>
<td>3.9 (0.72)</td>
</tr>
<tr>
<td>$\Delta^{++} + \Lambda(1405) + K^0$</td>
<td>n/a</td>
<td>n/a</td>
<td>5.3</td>
</tr>
<tr>
<td>$\Delta^{++} + \Sigma(1385)^0 + K^0$</td>
<td>n/a</td>
<td>n/a</td>
<td>3.5</td>
</tr>
<tr>
<td>$\Delta^+ + \Sigma(1385)^+ + K^0$</td>
<td>n/a</td>
<td>n/a</td>
<td>2.3</td>
</tr>
</tbody>
</table>
FIG. 43. $K^0_S$ momentum spectra in $p+$Nb collisions (black circles) and GiBUU transport model simulations. Black solid line shows the total contribution of all $K^0_S$ sources besides $pp$ and $np$ collisions: $\Delta N$- (dash-dotted line), $\pi N$-reactions (dotted line) and a contribution from $K^+ N$-scattering accompanied with a charge exchange (dashed line).
**FIG. 54.** Nuclear modification factor $R_{pA}(p) \propto \sigma_{pN_b}^{K^0}/\sigma_{pp}^{K^0}$ (experimental data).

**FIG. 55.** Nuclear modification factor $R_{pA}(p) \propto \sigma_{pN_b}^{K^0}/\sigma_{pp}^{K^0}$ as simulated with the GiBUU transport model. The in-medium ChPT KN potential is OFF. Only statistical uncertainties are shown.

**FIG. 56.** Nuclear modification factor $R_{pA}(p) \propto \sigma_{pN_b}^{K^0}/\sigma_{pp}^{K^0}$ as simulated with the GiBUU transport model. The in-medium ChPT KN potential is ON. Only statistical uncertainties are shown.
KN scattering: effect on $p_t$ distributions in pNb

All plots: GiBUU simulations

- Spectra in each rapidity bin are normalized to the same area.
- Shape of $p_t$-spectra is not sensitive to the KN scattering.
All plots on this slide: KaoS K\(^+\) data, pAu/pC. \( \theta \) is the lab. polar angle.

- At all energies **the very same pattern**:
  - \( R_{pA} < 1 \) for small angles
  - \( R_{pA} > 1 \) for higher angles

- Interpretation:
  - rescattering of forward kaons (both K\(^+\) and K\(^0\) via charge exchange)
  - to larger polar angles
  - slightly amplifying with the momentum

Bands show stat. uncertainties only.
Kaon production anisotropy

$pp \rightarrow pK^0\Sigma^+$

M. Abdel-Bary et al.
Free KN scattering

is known rather well:

\[ p_K = 800 \text{ MeV/c} \]

Picture: M. Effenberger, PhD. Giessen, 1999.

\[ K^+ + p \]

For \( L = 0 \) VM exchange:

## Comparison with KaoS results

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Colliding system</th>
<th>Number of participants (minimum bias)</th>
<th>Total cross section at 3.5 GeV, mb</th>
</tr>
</thead>
<tbody>
<tr>
<td>KaoS (K⁺)</td>
<td>p + ¹⁹⁷Au</td>
<td>3.1</td>
<td>1616</td>
</tr>
<tr>
<td></td>
<td>p + ¹²C</td>
<td>2.1</td>
<td>243.4</td>
</tr>
<tr>
<td>HADES (K⁰)</td>
<td>p + ⁹³Nb</td>
<td>2.4</td>
<td>848</td>
</tr>
<tr>
<td></td>
<td>p + p</td>
<td>2</td>
<td>43.3</td>
</tr>
</tbody>
</table>

Number of participants estimated with a nuclear overlap model
http://www-linux.gsi.de/~misko/overlap/interface.html


KaoS data provided by W. Scheinast

\[ R_{pA}(p) = \frac{d\sigma_{pA}/dp}{d\sigma_{pp}/dp} \cdot \frac{N_{pA}^{pp}}{N_{pA}^{part}} \cdot \frac{\sigma_{pp}}{\sigma_{tot}} \]

Analogous scaling used for comparison between two nuclear targets, e.g. pAu/pC
$R_{pA}$: HADES vs KaoS ($K^0$ vs $K^+$) at 3.5 GeV

- Single scaling factor $K^+/K^0 \approx 1.1$ (from GiBUU).
- Ratios $\sim 1$, cross-check of the data.
- “Line splitting” due to KN scattering and isospin effects.
$R_{pA}:$ HADES vs KaoS ($K^0$ vs $K^+$) at 3.5 GeV

KaoS: pAu/pC

- $K^+/K^+$
- Ratios ~1, cross-check of the data.
- "Line splitting" due to KN scattering and isospin effect.
- Single scaling factor $K^+/K^0 = 1.1$ (from GiBUU).

GiBUU SIM: pn/pp

- $K_0^+/K^+$
- Preliminary

pAu(KaoS)/pNb(HADES)

- Preliminary

pNb(HADES)/pC(KaoS)

- Preliminary
Extending the model with 5–body final states

\[ p + p \rightarrow p + \pi^+ + \Sigma^+ + \pi^- + K^0 \]

\[ \sqrt{s} \approx 2.90 \text{ GeV} \]

\[ p + p \text{ at } 3.5 \text{ GeV} \]

\[ \sqrt{s} \approx 3.18 \text{ GeV} \]

» Well enough energy to produce 5–body final states.

<table>
<thead>
<tr>
<th>number of particles in fin. state</th>
<th>final state</th>
<th>what is added to the model</th>
</tr>
</thead>
<tbody>
<tr>
<td>5–body</td>
<td>( p , \pi^+ \Lambda , \pi^0 , K^0 )</td>
<td>( \Delta^{++} \Sigma(1385) , K^0 )</td>
</tr>
<tr>
<td></td>
<td>( p , \pi^+ , \Sigma^+ , \pi^- , K^0 )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( p , \pi^+ , \Sigma^0 , \pi^0 , K^0 )</td>
<td>( \Delta^{++} \Lambda(1405) , K^0 )</td>
</tr>
<tr>
<td></td>
<td>( p , \pi^+ , \Sigma^- , \pi^+ , K^0 )</td>
<td></td>
</tr>
</tbody>
</table>
K*(892) angular distributions

Analysis by Dimitar Mihaylov

$K^{*+}$
$K_s^0$
$\pi^-$
$\pi^+$

Primary Vertex (PV)
Secondary Vertex (SV)

$p+p$
$p+\text{Nb}$
Exclusive analysis

Analysis by Jia-Chii Berger-Chen
FIG. 28. Invariant mass $p, \pi^+$ with the $\Lambda$-cut in $\text{MM}(p, \pi^+, \pi^+, \pi^-)$.

FIG. 29. Invariant mass $p, \pi^+$ with the $\Sigma^0$-cut in $\text{MM}(p, \pi^+, \pi^+, \pi^-)$. 

Analysis by Jia-Chii Berger-Chen
Variables used

1. Transverse (to the beam direction) momentum \( p_t \)
   - Lorentz invariant under a boost along the beam axis.

2. Rapidity
   \[
   y = \frac{1}{2} \ln \frac{E + p_z}{E - p_z}
   \]
   - Easily transformed under such a boost: \( y' \rightarrow y + c \)
   - Transverse momentum and rapidity fix the kinematics of a particle (up to azimuthal angle).
   - Invariant phase space element \( \sim dp_t^2 dy \)
K^0 in pp: experimental data versus resonance model by Tsushima et al.*

- Absolute normalization (all plots in this talk).
- Resonance model overestimates the inclusive yield.

Resonance model of kaon production

All production channels:

<table>
<thead>
<tr>
<th>No.</th>
<th>Reaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$pp \rightarrow p\Lambda K^+$</td>
</tr>
<tr>
<td>2</td>
<td>$pn \rightarrow n\Lambda K^+$</td>
</tr>
<tr>
<td>3</td>
<td>$pp \rightarrow p\Sigma^0 K^+$</td>
</tr>
<tr>
<td>4</td>
<td>$nn \rightarrow n\Sigma^- K^+$</td>
</tr>
<tr>
<td>5</td>
<td>$pn \rightarrow n\Sigma^0 K^+$</td>
</tr>
<tr>
<td>6</td>
<td>$np \rightarrow p\Sigma^- K^+$</td>
</tr>
<tr>
<td>7</td>
<td>$pp \rightarrow n\Sigma^+ K^+$</td>
</tr>
<tr>
<td>8</td>
<td>$nn \rightarrow \Delta^- \Lambda K^+$</td>
</tr>
<tr>
<td>9</td>
<td>$pp \rightarrow \Delta^{++} \Sigma^- K^+$</td>
</tr>
<tr>
<td>10</td>
<td>$\Delta^{++} n \rightarrow p\Lambda K^+$</td>
</tr>
<tr>
<td>11</td>
<td>$\Delta^- p \rightarrow n\Sigma^- K^+$</td>
</tr>
<tr>
<td>12</td>
<td>$\Delta^{++} p \rightarrow \Delta^{++} \Lambda K^+$</td>
</tr>
<tr>
<td>13</td>
<td>$\Delta^+ n \rightarrow \Delta^0 \Lambda K^+$</td>
</tr>
<tr>
<td>14</td>
<td>$\Delta^+ p \rightarrow \Delta^+ \Lambda K^+$</td>
</tr>
<tr>
<td>15</td>
<td>$\Delta^{++} n \rightarrow \Delta^{++} \Sigma^- K^+$</td>
</tr>
<tr>
<td>16</td>
<td>$\Delta^{++} p \rightarrow \Delta^{++} \Sigma^0 K^+$</td>
</tr>
<tr>
<td>17</td>
<td>$\Delta^+ n \rightarrow \Delta^0 \Sigma^0 K^+$</td>
</tr>
<tr>
<td>18</td>
<td>$\Delta^+ p \rightarrow \Delta^+ \Sigma^0 K^+$</td>
</tr>
<tr>
<td>19</td>
<td>$\Delta^{++} p \rightarrow \Delta^{++} \Lambda K^+$</td>
</tr>
<tr>
<td>20</td>
<td>$\Delta^0 \Delta^{++} \rightarrow \Delta^+ \Lambda K^+$</td>
</tr>
<tr>
<td>21</td>
<td>$\Delta^0 \Delta^- \rightarrow \Delta^0 \Lambda K^+$</td>
</tr>
<tr>
<td>22</td>
<td>$\Delta^{++} \Delta^- \rightarrow \Delta^{++} \Lambda K^+$</td>
</tr>
<tr>
<td>23</td>
<td>$\Delta^0 \Delta^- \rightarrow \Delta^+ \Lambda K^+$</td>
</tr>
</tbody>
</table>

Cross section parameterization:

$$\sigma(B_1 B_2 \rightarrow B_3 Y K) = a \left( \frac{s}{s_0} - 1 \right)^b \left( \frac{s_0}{s} \right)^c,$$

Note: this is what’s inside transport code

**np-reactions** isospin interrelations (one example):

$$\sigma(nn \rightarrow \Delta^- \Lambda K^+) = \sigma(pp \rightarrow \Delta^{++} \Lambda K^0)$$

$$= 3\sigma(pn \rightarrow \Delta^0 \Lambda K^+),$$

$$= 3\sigma(pp \rightarrow \Delta^+ \Lambda K^+) = 3\sigma(nn \rightarrow \Delta^0 \Lambda K^0),$$

almost no experimental data for np!

$K^0$ production channels:

<table>
<thead>
<tr>
<th>Number of particles</th>
<th>Final state</th>
<th>What is in the model</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-body</td>
<td>$p \Sigma^+ K^0$</td>
<td>$p \Sigma^+ K^0$</td>
</tr>
<tr>
<td>4-body</td>
<td>$p \pi^+ \Lambda K^0$</td>
<td>$\Delta^{++} \Lambda K^0$</td>
</tr>
<tr>
<td></td>
<td>$p \pi^+ \Sigma^0 K^0$</td>
<td>$\Delta^{++} \Sigma^0 K^0$</td>
</tr>
<tr>
<td></td>
<td>$n \pi^+ \Sigma^+ K^0$</td>
<td>$\Delta^+ \Sigma^+ K^0$</td>
</tr>
<tr>
<td></td>
<td>$p \pi^0 \Sigma^+ K^0$</td>
<td>$\Delta^+ \Sigma^+ K^0$</td>
</tr>
</tbody>
</table>

Note:
1. Pion production goes exclusively through $\Delta$.
2. No angular anisotropies in production.
Tuning the resonance model

- Downscaling of exclusive channels in the model

**HADES exclusive**

- Factor 0.7
- Factor 0.7
- Factor 0.4
- Factor 0.7
K$^0$ in pp vs. tuned resonance model

- Analysis procedure benchmarks:
  - Symmetric rapidity distribution.
  - Systematics of the total cross section.
- KN potential is OFF.
- 3-body reactions in np (np → NYK) poorly constrained, scale factor 0.5 is applied to the Tsushima parameterizations.
- GiBUU simulations based on tuned resonance model describe data.
Kaon potential

Kaon-nucleon scattering

$K^0$ production in secondary processes

$K^0$ production in nucleon-nucleon reactions
Rapidity distribution and role of secondary reactions

- Significant contribution of secondary reactions at backward rapidities (~70%).
- Three main sources:
  - $\Delta N$-reactions. Rely on the resonance model (Tsushima et al.).
  - $\pi N$-reactions.
  - $K N$ scattering.

How well the two last processes are known?
Secondary processes: pion–nucleon reactions

- Elementary cross sections are known well and parametrized in the model.
- No angular distributions implemented in the model.

Kaon production in nucleon-nucleon reactions

Kaon production in secondary processes

Kaon-nucleon scattering

Kaon potential
Kaon–nucleon scattering

Elastic cross section

![Elastic cross section graph](image)

Total cross section

![Total cross section graph](image)


- Vacuum cross sections are well known.
- $K^0N$ scattering from isospin considerations.
- No angular distributions implemented in the model (some data are available).
Kaon–nucleon scattering

Elastic cross section

Vacuum cross sections are well known.

K⁰N scattering from isospin considerations.

No angular distributions implemented in the model (some data are available).

Total cross section

Kaon–nucleon scattering

Elastic cross section


Mean free path at normal nuclear density

Note: from $K^+p$ total cross section

- Vacuum cross sections are well known.
- $K^0N$ scattering from isospin considerations.
- No angular distributions implemented in the model (some data are available).
Rapidity distribution in pNb: sensitivity to the KN scattering

- Rapidity distribution is sensitive to the KN scattering.
- Data consistent with the vacuum KN cross sections.
Kaon potential

Kaon-nucleon scattering

$K^0$ production in secondary processes

$K^0$ production in nucleon-nucleon reactions
Effect of the potential in pNb: $p_t$–$y$ spectra

- Small systematical shift of $p_t$–spectra owe to the repulsive potential, favored by data.
- Uncertainties in the model parameters (np cross sections, ...).
- A better observable is needed to judge on the potential strength.
Ratio plots, variation of the model parameters

- Check if the ratio is stable against variation of the poorly known parameters.
- Further systematical checks are running ($\Delta N$, ...)

**GiBUU w. pot. KN scattering +20%**

**GiBUU w. pot. KN scattering −20%**

**GiBUU w. pot. np 3body −20%**

**GiBUU w. pot. np 3body +25%**
Final states with two pions (5-body) added to the model via $NN \rightarrow \Delta^{++} Y^* K$, $Y^*$ is $\Sigma(1385)$ or $\Lambda(1405)$.

Good description of the data.
$\Sigma^+(1385)$

$p(3.5\text{GeV}) + p \rightarrow \Sigma(1385)^+ + K^+ + n$

Important benchmark measurement.

Information about production mechanism.
Separation of Σ⁰(1385) and Λ(1405) possible.
Σ⁰(1385) cross section is found to be 6±2 μb.

G. Agakishiev et al. [HADES]
Hyperfine interactions 210 (2012), 45.
In-medium $K^0$ potential

In-medium ChPT repulsive potential, $\sim 35$ MeV ($\rho=\rho_0$, $k=0$)

$$m^*_K = \sqrt{m^2_K - \frac{\Sigma_{KN}}{f^2_\pi} \rho_s + \frac{C}{f^2_\pi} \rho s^3 + V_\mu V^\mu}$$


A. Larionov, private communication
Lambda(1116) in pN\(\bar{b}\) at 3.5 GeV

- High precision measurement done (1M Lambdas).
- Models don’t describe data well (yet).
- Role of baryonic resonances? \(N^* \rightarrow K \Lambda\).

Courtesy O. Arnold
Dileptons: excess in light nuclear systems
Dileptons in nucleon-nucleon collisions
Dileptons: reference spectrum
Most approaches (QCD sum rules, coupled channel calculations) predict a substantial broadening (factor 5 to 10) and a small mass shift (2–3%) of the $\phi$-meson at normal nuclear density.


KEK–PS E325 Collaboration reported a mass shift of the $\phi$-meson of 3.4%, the only observation of the $\phi$ mass modification.

Physics case: $\phi$-meson in matter

ANKE results $pA$ at 2.83 GeV

M. Hartmann et al.

- Only very forward mesons were measured: accessible $\theta_\phi < 8^\circ$.
- Experience with kaons shows importance of a broad phase space coverage.
- HADES can do better here.
\[ A = \sum A_{tr}^{\alpha} (s) Q_{\mu_1 \ldots \mu_J}^{{\text{in}}} (S L J) A_{2b} (i, S_2 L_2 J_2) (s_i) \times Q_{\mu_1 \ldots \mu_J}^{{\text{fin}}} (i, S_2 L_2 J_2 S' L' J) . \quad (2) \]

\[ A_{tr}^{\alpha} (s) = \left( a_1^{\alpha} + a_3^{\alpha} \sqrt{s} \right) e^{i a_2^{\alpha}} \]

- $S, L, J$ — spin, orbital mom. and total angular momentum of the pp system
- $S_2, L_2, J_2$ — spin, orbital mom. and total angular momentum of the two particle system in fin. state
- $S', L'$ — spin, orbital mom. between the two particle system and the third particle with four mom. $q_i$
- multiindex $\alpha$ — possible combinations of the $S, L, J, S_2, L_2, J_2, S', L'$ and $i$
- $A_{tr}^{\alpha} (s)$ — transition Amplitude
- $A_{2b}^{\alpha} (i, S_2 L_2 J_2)$ — rescattering process in he final two-particle channel (e.g. production of $\Delta$)

http://pwa.hiskp.uni-bonn.de/

A.V. Anisovich, V.V. Anisovich, E. Klempt, V.A. Nikonov and A.V. Sarantsev

Resonances included in the solution

<table>
<thead>
<tr>
<th>Notation in PDG</th>
<th>old</th>
<th>Mass GeV/c²</th>
<th>Width GeV/c²</th>
<th>$\Gamma_{\text{AK}} / \Gamma_{\text{All}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>N(1650) $\frac{1}{2}^-$</td>
<td>$N(1650) S_{11}$</td>
<td>1.655</td>
<td>0.150</td>
<td>3-11%</td>
</tr>
<tr>
<td>N(1710) $\frac{1}{2}^+$</td>
<td>$N(1710) P_{11}$</td>
<td>1.710</td>
<td>0.200</td>
<td>5-25%</td>
</tr>
<tr>
<td>N(1720) $\frac{1}{2}^+$</td>
<td>$N(1720) D_{13}$</td>
<td>1.720</td>
<td>0.250</td>
<td>1-15%</td>
</tr>
<tr>
<td>N(1875) $\frac{1}{2}^-$</td>
<td>$N(1875) D_{13}$</td>
<td>1.875</td>
<td>0.220</td>
<td>?</td>
</tr>
<tr>
<td>N(1880) $\frac{1}{2}^+$</td>
<td>$N(1880) P_{11}$</td>
<td>1.870</td>
<td>0.235</td>
<td>?</td>
</tr>
<tr>
<td>N(1895) $\frac{1}{2}^-$</td>
<td>$N(1895) S_{11}$</td>
<td>1.895</td>
<td>0.090</td>
<td>?</td>
</tr>
<tr>
<td>N(1900) $\frac{1}{2}^-$</td>
<td>$N(1900) P_{13}$</td>
<td>1.900</td>
<td>0.250</td>
<td>0-10%</td>
</tr>
</tbody>
</table>
Solution for $pp \rightarrow p\Lambda K^+$: mass spectra

Data
10 solutions
4 best solutions
Solution for pp → pΛK⁺: angular distributions
Vector mesons in cold nuclear matter: models

E. Bratkovskaya et al.,

GiBUU model, J. Weil, ECT* Workshop 2013