Exploring the hot and dense QCD matter with HADES

- Heavy ions, cold matter and elementary reactions.
- A, p, pion beams
- Probing the dense and hot matter with: electromagnetic probes, sub-threshold strangeness production, emission anisotropies, particle correlations (femtoscopy, resonances)...
- \( \text{Au+Au} \sqrt{s_{NN}} = 2.42 \text{ GeV} \) and \( \text{Ag+Ag} \sqrt{s_{NN}} = 2.55 \text{ GeV} \)
Thermal dielectrons at $\sqrt{s_{NN}} = 2.42$ GeV

- $e^+e^-$ invariant mass distribution fully corrected for acceptance

- Strong broadening of the in-medium $\rho$ spectral function
- Enable measurement of fireball temperature $\langle T_{\text{fireball}} \rangle = 72 \pm 2$ MeV

- Thermal rates folded over coarse-grained UrQMD medium evolution works at low energies
- Supports baryon-driven medium effects at SPS and RHIC (LHC).

HADES Collab., accepted for publication in Nature Physics
Verify the $\rho$-baryon coupling mechanism

$\pi^-$ beam $\sqrt{s} = 1.49$ GeV

e$^+$$e^-$ invariant mass distribution ratio to point-like contributions

- Dominance of the $N^*$ (1520) resonance
- Invariant mass and angular distributions (4 differential analysis) are consistent with
  - $\rho$ decays
  - VDM form factors (pion cloud)

G. Ramalho, T. Pena, Phys. Rev. D95 (2017), 014003
$\Phi$-AntiKaosn Interplay in Cold Matter


$\pi + C$

$\pi + W$

$d_C \approx 5 \, fm$

$d_W \approx 14 \, fm$

$\rightarrow$ Mean free path $\lambda_\pi = 1.5 \, fm$

($p_\pi = 1.7 \, GeV/c, \rho_B \approx \rho_0$)
Φ-AntiKaon Interplay in Cold Matter

Suppression of $K^-$ relative to $K^+$

Similar suppression for $\varphi$ like for $K^-$
**Φ-AntiKaon Interplay in Cold Matter**

- Suppression of $K^-$ relative to $K^+$
- Similar suppression for $\varphi$ like for $K^-$

In HADES acceptance:

$$(\phi/K^-)_C = 0.55 \pm 0.04^{(stat)} + 0.06^{(sys)}$$

$$(\phi/K^-)_W = 0.63 \pm 0.06^{(stat)} \pm 0.11^{(sys)}$$
High statistic multi-differential data

$p, d, t \quad v_1, v_2, v_3, v_4$

Au+Au at $\sqrt{s_{NN}} = 2.42$ GeV
High statistic multi-differential data

Comparison $p, d, t$ at mid-rapidity

Au+Au at $\sqrt{s_{NN}} = 2.42$ GeV

N. Borghini and J.-Y. Ollitrault, PLB 642 2006
High statistic multi-differential data

Comparison p, d, t at mid-rapidity

Sensitivity to the equation of state

UrQMD prediction: P. Hillmann et al.

Au+Au at $\sqrt{s_{NN}} = 2.42$ GeV

\begin{align*}
\rho, \ldots, t & \quad V_1, V_2, V_3, V_4 \\
\text{Scaling of } v_2 \text{ and } p_t \text{ with } A
\end{align*}
Sensitivity to the equation of state

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Au+Au at $\sqrt{s_{NN}} = 2.42$ GeV

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Sensitivity to the equation of state \( p, d, t \) \( v_1, v_2, v_3, v_4 \)

\[ v_4 = 0.5 v_2^2 \]

N. Borghini and J.-Y. Ollitrault, PLB 642 2006

High statistic multi-

Ideal-fluid scaling: the limit of the \( v_2 \) contribution to \( v_4 \) at large \( p_t \) is given by \( v_4 = 0.5 v_2^2 \)

\[ v_{4b} = \alpha \left( \frac{p_{\text{out}}}{p_0} \right) + \beta \left( \frac{p_{\text{out}}}{p_0} \right)^\gamma \]

Parameters: hard \( \text{EoS} \) soft \( \text{EoS} \)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>hard EoS</th>
<th>soft EoS</th>
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<tbody>
<tr>
<td>( \alpha ) [MeV]</td>
<td>-124</td>
<td>-356</td>
</tr>
<tr>
<td>( \beta ) [MeV]</td>
<td>71</td>
<td>303</td>
</tr>
<tr>
<td>( \gamma )</td>
<td>2.00</td>
<td>1.17</td>
</tr>
</tbody>
</table>

Au+Au at \( \sqrt{s_{NN}} = 2.42 \) GeV
HADES follows trend from higher energies STAR and NA49 data than trend from E895. 

→ room for structures?

Indications for charge-sign differences reported previously:


First time observation of significant charge-sign splitting!
Correlated pion – proton pairs

Au+Au at \(\sqrt{s_{NN}} = 2.42\) GeV

\(\pi p\)

\(\pi^+p\)
\[ \sigma(M) = a \frac{q^3}{q^3 + 180^3} \frac{1}{4 \left( \frac{M - M_0}{\Gamma_0} \right)^2 + 1} \]

where

\[ q = \sqrt{\frac{\left( M^2 - (M_p + M_\pi)^2 \right) \left( M^2 - (M_p - M_\pi)^2 \right)}{4M^2}} \]

\[ J. \text{Cugnon, M.C. Lemaire, Nucl. Phys. A 489, 781 (1988)} \]

\[ \pi^\pm p \text{ correlated yield} \]

Au+Au at \( \sqrt{s_{NN}} = 2.42 \text{ GeV} \)
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\[ \text{Au+Au at } \sqrt{s_{NN}} = 2.42 \text{ GeV} \]
Production scalings Au+Au at $\sqrt{s_{NN}} = 2.42$ GeV


arXiv:1812.07304
Production scalings $\text{Au+Au}$ at $\sqrt{S_{NN}} = 2.42$ GeV

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Strangeness

Dileptons

$\alpha = 1.45 \pm 0.06$
$\chi^2/\text{NDF} = 5.90/10 = 0.59$

Excess yield $\times 10^4$

$b \times \langle A_{\text{part}} \rangle^\alpha$
$\alpha = 1.44 \pm 0.17$

$0.3 < M_{\text{inv}} < 0.7 \text{ GeV/c}^2$
Production scalings $\text{Au+Au at } \sqrt{s_{NN}} = 2.42 \text{ GeV}$

Scaling $N \sim <A_{\text{part}}>^\alpha$ with parameter similar to that of strange hadrons and excess yield of virtual photons!

arXiv:1812.07304
\[ \text{Ag+Ag} \sqrt{s_{NN}} = 2.55 \text{ GeV} \]
Ag+Ag $\sqrt{s_{NN}} = 2.55$ GeV

HADES monitoring
Ag+Ag 1.58A GeV
Date: 01 April 2019
Event rate: 16-18 kHz
Collected events: $15268.68 \times 10^6$
Collected data: 359.23 TB
Last update: 6:00

Event Display

Anticipated Events
Recorded Events

March 2019

~ 15 billion events

PID: Velocity vs Momentum - RPC

$e^+ / e^-$ Cherenkov Rings

Online Hyperons: $\Lambda \rightarrow p + \pi^-$

signal $(u \pm 2\sigma) = (1.05 \pm 0.01) \times 10^5$
signal / background = 1.18
significance = 238.8
The new HADES ECAL

- Based on lead glass recycled from OPAL
- Refurbished and complemented with HADES TRB3 PADIWA read-out system based on commodity hardware
Ag+Ag $\sqrt{s_{NN}} = 2.6$ GeV: Virtual Photons

- $\frac{1}{2}$ of the CBM RICH photon detector
- Stable operation during 4 weeks of beamtime
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Summary

- Exponential falling di-electron spectrum, \( <T_{ee}> = 72 \text{ MeV} \), \( p \) melted.
- Universal production scaling as a function of \( \text{Apart} \) regardless strangeness content despite different production thresholds.
- Systematic measurement of \( v_1, v_2, v_3, v_4 \), femtoscopy and baryonic resonances.
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