Characterising the hot and dense fireball via virtual photons in HADES

Niklas Schild for the HADES Collaboration

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Exploring the QCD matter phase diagram

LHC energies $\sqrt{s_{NN}} = 2$ TeV
parton+parton collisions
Early Universe in the laboratory

Energies $\sqrt{s_{NN}} \approx 2 \ast m_N$ GeV
nuclear stopping
NS merger matter in the laboratory

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Focus on virtual and real photons

- **Heavy ion collisions** at $\sqrt{s_{NN}} = 2 - 3$ GeV
  - Different collision dynamics compared to higher energies
- **Pion and nucleon beams**
  - E.g. for reference measurements

Explore region of QCD phase diagram with high net-baryon density and moderate temperatures
The High-Acceptance-Di-Electron-Spectrometer

- Almost full azimuth angle coverage and polar angles between 18°-85° (0.5°-7°)
- Accepted trigger rate 16 kHz for HIC, 50 kHz for elementary reactions
- **New installments and upgrades:**
  - RICH photon detection plane
  - ECal
  - Forward detector
- 15-fold segmented target

HADES performance for electron identification

- Reconstruction efficiency ~ 60%
- Ag+Ag $\sqrt{s_{NN}}=2.42$ GeV
- HADES Performance

Upgrades in RICH detector allow for high efficiency and high purity electron sample

- Purity above 90%
- Pion suppression of $\sim 10^{-5}$
Outline

1. Reconstruction of (invariant mass) spectra
2. Dilepton flow analysis
3. Prospects/Outlook
Reconstruction of the dilepton spectra
Reconstruction of $e^+e^-$ signal

- Conversion rejection with RICH detector:
  - Pair opening angle $> 9^\circ$
  - Maximum number of photons per ring

![Graph 1](image1)

$1/N_{ee} \frac{dN_{\text{raw}}}{dM_{ee}}$ (GeV/c$^2$)$^{-1}$

- Ag+Ag $\sqrt{s_{NN}}$=2.55 GeV 0-40%
- HADES work in progress
- $0.1 < p_e (\text{GeV/c})^{-1} < 1.2, \alpha_{e^+e^-} > 9^\circ$

![Graph 2](image2)

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Reconstruction of $e^+e^-$ signal

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\[
\frac{dN_{CB}}{dM} = 2k \sqrt{\frac{dN_{++}}{dM} \frac{dN_{--}}{dM}}
\]
Extracting the in-medium contribution

- **Freeze-out cocktail:**
  - Simulated using Pluto event generator
  - Multiplicities to be measured from same dataset

- **Initial NN contribution:**
  - Reference measured for $\sqrt{s_{NN}} = 2.42$ GeV
  - For $\sqrt{s_{NN}} = 2.55$ GeV currently estimated using GiBUU 2021 release
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Clear excess is visible
Temperature determination

- Subtraction of freeze-out and initial contributions reveals **excess of thermal nature**
- Higher temperature for higher collision energy

\[
dN/dM \propto M_e^3 \exp\left(-\frac{M}{T}\right)
\]

\[
dN/dM \propto M_{ee}^{3/2} \exp(-M_{ee}/kT)
\]

\[
\chi^2/N = 1.4
\]

\[
kT = 77.9_{-1.3}_{-1.2_{\text{sys}}}^{+1.2}_{-2.3_{\text{sys}}}^{+3.0_{\text{stat}}}^{+0.6_{\text{NN}}} \text{ MeV}
\]

\[
k_bT = 73.4 \pm 2.3_{\text{stat}} \pm 2.6_{\text{sys}} \text{ MeV}
\]

Compare with*:

\[
kT_{Au+Au} \left( \sqrt{s_{NN}} = 2.42 \text{ GeV} \right) = 71.8 \pm 2.8 \text{ MeV}
\]

Differential analysis of dielectron spectra

- Large number of lepton pairs and high efficiency allows for multidifferential analysis, e.g.:
  - Centrality-dependent*
  - Angular distributions
  - Reconstruction of $p_t$ and $y$ spectra for varying mass bins

Analysis in bins of tranverse momentum $p_t$

- $\omega$-peak clearly visible at high $p_t$
- Disappearance of $\omega$-peak at small $p_t$
- Model comparison ongoing

https://indico.cern.ch/event/895086/contributions/4721205/
Flow analysis
Flow analysis procedure

\[ \frac{dN}{d\Delta \varphi} \propto 1 + 2 \sum_{n=1}^{\infty} v_n \cos(n \Delta \varphi) \]

\[ \Delta \varphi = \varphi_{ee} - \Psi_{RP} \]

- Event Plane \( \Psi_{EP} \) reconstructed from total transverse momentum in forward wall detector [1]
- Event plane resolution \( \mathcal{R}_n \) via Ollitrault method [2]
Flow analysis procedure

\[
\frac{dN}{d\Delta \varphi} \propto 1 + 2 \sum_{n=1}^{\infty} \nu_n \cos(n \Delta \varphi)
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The HADES Collaboration, arXiv:2208.02740

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\]

\[
\nu_n = \frac{\nu_n^{obs}}{\mathcal{R}_n}
\]

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Directed Flow $\nu_1$
Rapidity dependence

- Focus on mass region beyond $\pi^0$ mass
- Point symmetry around $v_1$ at midrapidity within uncertainties

Otherwise $\pi_0$ signal dominant
Transverse momentum dependence

Larger $v_1$ found at higher $p_t$
Elliptic Flow $\nu_2$
Elliptic flow over invariant mass

- Low masses dominated by $\pi^0$ Dalitz decay
- Negative $v_2$ consistent with pions
- Beyond $\pi^0$ mass $v_2$ consistently around zero for $120 < M_{ee} \text{ (GeV/c}^2\text{)} < 900$

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Multidifferential elliptic flow

$v_2$ consistently around zero for $120 < M_{ee} \text{ (GeV/c}^2\text{)} < 900$

Would agree with picture of dileptons as penetrating probes
Prospects

Isolate in-medium dilepton contribution

- Ongoing analyses to find $v_n$ and multiplicities of freeze-out hadrons

- Analysis of p+p collisions at $\sqrt{s_{NN}} = 2.55$ GeV (taken Feb2022) will provide NN reference

Determine radial flow

- Reconstruction of dilepton $p_t$ spectra as a function of invariant mass

Determine polarization of virtual photons

- First strides are taken in data analysis and preparation of theory predictions

\[
v_{n}^{\text{sig}} = v_{n}^{\text{tot}} + \frac{N_{bg}}{N_{sig}} (v_{n}^{\text{tot}} - v_{n}^{\text{bg}})
\]
Dilepton spectra are reconstructed for center-of-mass energies of 2.42 GeV and 2.55 GeV. Study of numerous fireball characteristics (e.g. temperature)

Collectivity is under investigation

Reconstruction of flow suggests no elliptic flow for thermal dileptons