Measurement of virtual photons radiated from Au+Au collisions at $E_{\text{beam}} = 1.23$ AGeV in HADES

Szymon Harabasz for the HADES collaboration

Motivation
Lepton identification
Combinatorial background subtraction
Excess yield extraction
Comparison to models
Summary
Electromagnetic Probes of Strongly Interacting Matter

- $\gamma, \gamma^*$: No strong final state interactions
  $\Rightarrow$ leave reaction volume undisturbed

- Reflect whole "history" of collision:
  - From pre-equilibrium phase
  - From QGP and hot hadronic gas
  - From meson decays after thermal freeze-out

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Schematic spectral distribution of lepton pairs emitted in ultra-relativistic heavy ion collisions

Low Energy ≠ Little Excitement

SPS, RHIC, LHC

Decrease $\sqrt{s_{NN}}$

SIS18

- Dilepton yield dominated by resonance decays, but underlying physics the same as the dressing of vector meson propagator
- Dense phase "lives" by far much longer than at higher energies, penalty → lower T
- Does (at least) most central part of fireball probe exotic regions of QCD phase diagram?

Central cell, UrQMD


See talk by F. Seck
Meet the HADES

Beams from SIS18: protons, nuclei, secondary pion beams, $E_{\text{kin}} = 1\text{-}2 \text{ GeV/u}$

**Search for very rare probes**
- Di-lepton production governed by the factor $\alpha^2$
- Branching ratio to $e^+e^- \sim 7.14 \times 10^{-5}$
- Vector meson production sub-threshold

→ **Fast detector** → interaction rate of 8 kHz
→ **Large acceptance** → full azimuth, $\theta$ from $18^\circ$ to $85^\circ$
→ **Mass resolution** → of the order of few %
→ **Good particle identification**
→ **Efficient track reconstruction**

Track multiplicity as large as 300 per event
(incl. fakes & secondaries)
→ **combinatorial background**

See talk by M. Lorentz
Electron Identification

Track quality selection
Energy loss
Particle velocity
Electromagnetic shower
Cherenkov radiation
→ two independent analyses:
  • Ring Finder
  • Backtracking

All combined in a multivariate analysis (neural networks)
Purity of single lepton identification at least 98 %
Electron Identification
Two Approaches to Detect Cherenkov Signal

Ring finder

1. Search for rings in the photodetection plane using pattern matrix or Hough transform
2. Use angular correlations to match rings with tracks in drift chambers

Backtracking algorithm

1. Identify lepton candidates using velocity and energy loss
2. Check the ring hypothesis around the expected ring enter

Motivation and advantages

- Ability to resolve overlapping rings
- Removal of close pairs ($\gamma$-conversion, combinatorial background)
1. Combinatorial background is estimated by:

\[
\langle BG_{+-} \rangle = k \cdot 2\sqrt{\langle FG_{++}\rangle \langle FG_{--}\rangle}
\]

2. With the \textit{k-factor}:

\[
k = \frac{[\epsilon_{+-} + \epsilon_+ (1 - \epsilon_{+-})][\epsilon_{+-} + \epsilon_- (1 - \epsilon_{+-})]}{2} = \frac{\langle FG_{+-}^{\text{MIX}} \rangle}{2\sqrt{\langle FG_{++}^{\text{MIX}} \rangle \langle FG_{--}^{\text{MIX}} \rangle}}
\]

3. This tells us that \textbf{not only geometry but also reconstruction efficiency} is important.

4. It is valid for \textbf{any event-by-event distribution of leptons} produced in the event.

**Take home**: k-factor from event mixing is well-founded mathematically and necessary in case of charge asymmetry of the detection!
Signal Determination

RICH Ring Finder (RF)

Backtracking (BT)
Invariant Mass Distribution

Results obtained with the two analysis methods agree

Agreement in the $\pi^0$-Dalitz region with the previously measured $1/2(np+pp)$ reference confirms the consistency of the reconstruction.

Above 0.15 GeV/c$^2$ clear enhancement compared to the reference → Medium radiation
Constraining the Cocktail by the Measurements in the Same Experiment

**π₀ and η reconstruction**

- Conversion method
- Challenge: Low mass spectrometer!
- Conversion probability: ≈1%

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**π₀ and η reconstruction**

**Conversion method**

**Challenge:** Low mass spectrometer!

**Conversion probability:** ≈1%
Constraining the Cocktail by the Measurements in the Same Experiment

- Measurement of $\pi^+$ and $\pi^-$ yields, thus giving $\pi^0$
- In addition: Extraction of slope parameters of $\pi^+/-$

<table>
<thead>
<tr>
<th>Centrality</th>
<th>$A_{Part}$</th>
<th>$M(\pi^+ + \pi^-)/2$</th>
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</thead>
<tbody>
<tr>
<td>0-10%</td>
<td>303</td>
<td>13.4</td>
</tr>
<tr>
<td>10-20%</td>
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<td>150</td>
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<tr>
<td>30-40%</td>
<td>103</td>
<td>4.9</td>
</tr>
<tr>
<td>0-40%</td>
<td>191</td>
<td>9.4</td>
</tr>
</tbody>
</table>
Constraining the Cocktail by the Measurements in the Same Experiment

- $\pi^0$ from charged pions multiplicity, cross-checked with the conversion method
- $\eta$ from the $\gamma$ conversion
- $\phi$ from the $K^+K^-$ channel
- $\omega$ from the Statistical Hadronization Model
Quantifying the Excess
What is "Non-trivial" Physics?

HADES performed a thorough study of various collision systems in the same energy regime.

- Freeze-out contributions removed ($\pi^0$ by normalization, $\eta$ by subtraction)
- The remaining radiation in C+C is already present in N+N
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- Much stronger excess in Ar+KCI

![Graph showing data for different collision systems and their comparison]

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- On the other hand, enhancement is visible in p+Nb (for slow dileptons)
- Much stronger excess in Ar+KCl
- Even stronger excess in Au+Au
- Question of "medium" is about the effects beyond simple superposition of NN collisions
  → Regeneration of baryonic resonances
Subtracting the Reference

- Isolation of the excess by subtracting the experimentally measured reference
- How to describe the excess radiation theoretically?
Low-mass $e^+e^-$ Excitation Function

$\sqrt{s_{NN}} = 2.42, 17.3, 19.6-200$ GeV

\[ S_{NN} = 2.42, 17.3, 19.6 \quad \text{GeV} \]

Model: Rapp/Wambach/Hees

$\rho - \Delta/N^*$ couplings play substantial role in $\rho$ melting observed in UrHIC

At low energies the same couplings govern off-shell $\rho$ production by resonance decay

$\rightarrow$ HADES Au+Au with $\rho$ spectral function within the coarse graining framework
Vector Meson Dominance

- Data measured by HADES in exclusive $\pi^- p$ (secondary beam) reactions with $\sqrt{s} = 0.55$ GeV
- Strong deviation from unity show the time-like contribution to the resonance decay and confirm the validity of the VMD

$$F(q^2) \equiv \frac{\text{Exp.Excl.e}^+ e^-}{N(1520) \text{ QED}}$$

$N$ $N^*$ $\rho$ $\gamma^*$

$e^+$ $e^-$
Coarse Graining & Data

- Medium contribution calculated through $\rho$ in-medium spectral function with thermodynamic parameters obtained from UrQMD ambient

- Both calculations are consistent and in good agreement with measured data

Comparison to Transport

- HSD analysed in the same way as data:
  - constrain reference
  - subtracted from Ar+KCl (component-by-component)
- Incoherent sum of NN and \( \pi N \) Bremsstrahlung, \( \Delta \), \( \rho \)
- Both approaches agree well with the data → go for multi-differential analysis

Centrality dependence

$300 < M_{ee} < 700 \text{ [MeV/c}^2\text{]}$

Scaling $\propto A_{\text{part}}^\alpha$ with $\alpha \approx 1.3$

HADES Preliminary

- Two observables indicate the formation of longer-lived and hotter medium in the most central collisions
Summary and Perspectives

Conclusions

- HADES explores baryon rich matter at SIS 18
- Heavy-ion and elementary collisions are measured simultaneously
- Properly extracted dilepton excess yield agrees well with theory predictions

Coming soon from dilepton analysis

- Completion of the e⁺e⁻ excitation function
- Extraction of a fireball lifetime → centrality dependence of the excess yield
- Extraction of an emitting source temperature?
  - Mass above 1 GeV/c² → statistics!
  - From mt spectra → when β is known

Outlook

- Now: HADES Upgrade
- FAIR phase 0: Ag+Ag at 1.65 GeV/u and pion induced reactions
- FAIR phase 1: SIS 100 → Ag+Ag at 3.5 GeV/u
Thank You for Your Attention
BACKUP SLIDES
Efficiency and Purity
Ring Finder Case

- Efficiency of different methods can be confronted by comparing total yields of identified leptons
- Most points lie in the same place – this indicates the stability of the "training" procedure

Purity is estimated based on measured data by reproducing random RICH ring-MDC track matches (matching tracks and rings from different HADES sectors)

Original distribution

Random matches

Signal

(for illustration of the method all pre-selected lepton candidates, without strict PID cuts, are shown)
Multi-differential Analysis

0-40% most central

0-10%

0-5%

5-10%

HADES Preliminary

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Centrality dependence

300 < \( M_{ee} < 700 \) [MeV/c\(^2\)]

- Two observables indicate the formation of longer-lived and hotter medium in the most central collisions.
Event Selection

- **DST gen 8**
- New standard event flags
- File lists of good sectors
- Track selection and sorting also standard
- Lepton identification:
  - Neural networks trained on data with two sets of input variables
  - Neural network trained on SIM like on data
  - Neural network trained on Geant PID
  - Hard cuts
  - **All based on RICH ring finder, no usage of backtracking**

<table>
<thead>
<tr>
<th>Bin</th>
<th>Centrality</th>
<th>(N_{\text{META hit, cut}} &gt;)</th>
<th>(N_{\text{META hit, cut}} \leq)</th>
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<tbody>
<tr>
<td>0</td>
<td>Multiplicity overflow</td>
<td>160</td>
<td>240</td>
</tr>
<tr>
<td>1</td>
<td>0-10 %</td>
<td>121</td>
<td>160</td>
</tr>
<tr>
<td>2</td>
<td>10-20 %</td>
<td>88</td>
<td>121</td>
</tr>
<tr>
<td>4</td>
<td>30-40 %</td>
<td>58</td>
<td>88</td>
</tr>
<tr>
<td>5</td>
<td>Multiplicity underflow</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Multiplicity overflow
- 0-10 %
- 10-20 %
- 20-30 %
- 30-40 %
- Multiplicity underflow

Multiplicities are given as x10^6.
Why We Need the k-Factor

[A. Adare et al. Phys. Rev. C 81 034911]

1. Assume that $e^+e^-$ are always produced in pairs (charge conservation)
2. The probability to register $n_p$ out of $N$ pairs is given by the **binomial distribution** $B(n_p,N,\varepsilon_p)$
3. **Out of the remaining pairs** there are three possibilities:
   a) No track is detected
   b) One $e^+$ is detected
   c) One $e^-$ is detected
4. They are described by the **multinomial distribution**
   $\omega(n_+,n_-)=M(n_+\varepsilon_+;n_-\varepsilon_-;N-n_p\varepsilon_+\varepsilon_-)$
Why We Need the k-Factor

[A. Adare et al. Phys. Rev. C 81 034911]

5. Number of all like-sign combinations of reconstructed leptons is:

\[ \langle n_{+-} \rangle = n_p^2 + n_p \sum_{n_+ = 1}^{N-n_p} n_+ \omega(n_+) + n_p \sum_{n_- = 1}^{N-n_p} n_- \omega(n_-) + \sum_{n_+ = 1}^{N-n_p} \sum_{n_- = 1}^{N-n_p} n_+ n_- \omega(n_+, n_-) \]

- Sum from \( \omega(n_+, n_-) \) over all possible \( n_- \)
- Sum from \( \omega(n_+, n_-) \) over all possible \( n_+ \)

6. Similar formula is for unlike-sign pairs:

\[ \langle n_{++} \rangle = \sum_{n_+ = 1}^{N-n_p} \frac{(n_p + n_+)(n_p + n_+ - 1)}{2} \omega(n_+) \]

7. To get the expected number of reconstructed pairs we average also over \( n_p \):

\[ \langle N_{+-} \rangle = \sum_{n_p} \langle n_{+-} \rangle B(n_p, N, \varepsilon_p) \]
Why We Need the k-Factor

[A. Adare et al. Phys. Rev. C 81 034911]

8. Next, averaging over $N$ produced pairs yields the foreground pairs:
\[
\langle FG_{+-} \rangle = \sum_N \langle N_{+-} \rangle P(N) = [\epsilon_p + \epsilon_+(1 - \epsilon_p)][\epsilon_p + \epsilon_-(1 - \epsilon_p)](\langle N^2 \rangle - \langle N \rangle) + \epsilon_p \langle N \rangle = \langle BG_{+-} \rangle + \langle S \rangle
\]

9. And similarly for unlike-sign…
\[
\langle FG_{++} \rangle = \sum_N \langle N_{++} \rangle P(N) = \frac{1}{2} [\epsilon_p + \epsilon_+(1 - \epsilon_p)]^2 (\langle N^2 \rangle - \langle N \rangle) = \langle BG_{++} \rangle
\]
\[
\langle FG_{--} \rangle = \sum_N \langle N_{--} \rangle P(N) = \frac{1}{2} [\epsilon_p + \epsilon_-(1 - \epsilon_p)]^2 (\langle N^2 \rangle - \langle N \rangle) = \langle BG_{--} \rangle
\]

10. And in the end the paper says, that when $\epsilon_+ = \epsilon_{++} = \epsilon_{--} = \epsilon_p$, then:
\[
\langle BG_{+-} \rangle = 2 \sqrt{\langle BG_{++} \rangle \langle BG_{--} \rangle} = 2 \sqrt{\langle FG_{++} \rangle \langle FG_{--} \rangle}
\]
Why We Need the k-Factor

Well, but if efficiencies are different, we are left with some ugly thing:

$$\langle BG_{+-} \rangle = \frac{[\epsilon_{++} + \epsilon_+(1 - \epsilon_{+-})][\epsilon_{+-} + \epsilon_-(1 - \epsilon_{++})]}{[\epsilon_{++} + \epsilon_+(1 - \epsilon_{++})][\epsilon_{--} + \epsilon_-(1 - \epsilon_{--})]} \frac{1}{2} \sqrt{\langle FG_{++} \rangle \langle FG_{--} \rangle}$$

Fortunately, the same formula stays valid in the event mixing, with the exception, that there is no signal there, and the unlike-sign foreground = like-sign background.

So, we can juggle and replace the factor with epsilons by:

(lower-case denotes the spectra from event mixing)

$$\langle BG_{+-} \rangle = \frac{\langle fg_{+-} \rangle}{2 \sqrt{\langle fg_{++} \rangle \langle fg_{--} \rangle}} 2 \sqrt{\langle FG_{++} \rangle \langle FG_{--} \rangle} \equiv k2 \sqrt{\langle FG_{++} \rangle \langle FG_{--} \rangle}$$

**Take home:** k-factor from event mixing is well-founded mathematically and necessary unless you are getting it = 1
Low-mass Dileptons at 1 – 2A GeV

- C+C: After \( \eta \) subtraction, coincides with \((pp+np)\)
- Ar+KCl: First evidence for radiation from the “medium” in this energy regime!
- Rapid increase of relative yield reflects the number of \( \Delta \)‘s/ N*’s regenerated in fireball

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S. Harabasz, P. Sellheim (PhD)
Observables: light vector mesons

Vector Meson Dominance

In low mass region ($M_{\parallel} < 1.1$ GeV):

$$\text{Im} \Pi_{em} \approx \text{Im} D_{\rho} + \frac{1}{9} \text{Im} D_{\omega} + \frac{2}{9} \text{Im} D_{\phi}$$

Vacuum

Both $\rho$ and $\gamma^*$ have $J^P = 1^-$

Medium

$\pi\pi$ interactions and baryonic excitations

Additional contributions to self-energy of the $\rho$ meson:

$$D_{\rho}(M, q; T, \mu_B) = \frac{1}{M^2 - m_{\rho}^2 - \Sigma_{\rho\pi\pi} - \Sigma_{\rho B} - \Sigma_{\rho M}}$$